Findings of the Moon_Mars Science Linkage Science Steering Group

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PREAMBLE

Introduction

The new solar system exploration initiative proposed by the President of the United States refocuses NASA by establishing an exciting long-term vision that integrates robotic and human exploration programs around focused science goals and milestones. Within this new direction of solar system exploration, the scientific linkages between Moon and Mars have become increasingly important. Owing to the proximity of the Moon to Earth, there are important technological and scientific concepts that could be developed on the Moon that will provide valuable insights into both the origin and evolution of the terrestrial planets and be feed-forward to the scientific exploration of Mars. This document identifies important lunar scientific and technology goals and evaluates them with regard to how they could provide valuable insights for Mars. This evaluation is done within the context of the Mars Exploration Program as defined by the *MEPAG Scientific Goals, Objectives, Investigations, and Priorities,2004* document, the vision of Moon science developed by the Lunar Exploration Science Working Group (LExSWG), and solar system exploration programs described in the *Solar System Exploration Roadmap* (NASA Office of Space Sciences) and *New Frontiers in the Solar System: An Integrated Exploration Strategy* (NAS National Research Council). The main thrust of this document is to establish lunar-science priorities within the context of Mars exploration. On the basis of their relevance to important solar system problems, a set of lunar priorities were a consequence of this exercise and we anticipate that further discussion along these lines will continue in a different forum.

The Moon_Mars Science Linkage Science Steering Group (MMSSG) was formed within the oversight of the Mars Exploration Program Analysis Group (MEPAG) in response to a request from NASA HQ to develop an analysis of the science-based activities on the lunar surface that would benefit the scientific exploration of Mars. The steering group consisted of 16 members with scientific backgrounds in varies aspects of lunar and martian science. The science steering group met through biweekly teleconferences from mid-April 2004 to the end of June 2004. The steering group and subcommittees communicated by e-mail throughout the process. The committee identified important lunar problems that remained to be addressed or reappraised. The committee then evaluated these important lunar science themes within the context of the scientific exploration of Mars. The committee also identified important technological demonstrations that would be instrumental to the scientific exploration of the Moon and Mars, and important for eventual manned occupancy of both planetary bodies. Priority criteria were established for lunar science by subcommittees and agreed to by the full steering group. One set of priority criteria was set within the context of lunar exploration and the second was set within the context of MEPAG priorities. Using these established criteria, lunar science themes and their importance to Mars exploration were prioritized. Both the lunar-science priorities on their own and the lunar-science priorities within the framework of Mars are presented in this document. In addition, the science steering group developed specific case examples of an activity on the Moon and then characterized them in terms of high-level functional requirements, with examples of how the activity would specifically benefit Mars. A draft report was circulated to the MEPAG executive committee and discussed in detail during the June 30-July 2, 2004 MEPAG meeting in Monrovia, California. Insights derived from these discussions were incorporated into this final report.

<u>Relative Prioritization</u>. In summary, the Moon_Mars Science Linkage Science Steering Group (MMSSG) has identified 20 science-based activities that would be of clearly defined benefit to the already prioritized scientific exploration of Mars. These activities fall into two overall groups, with 10 elements each: 1) science investigations, and 2) demonstrations of science-relevant engineering or technological approaches. The relative priority of each list of 10 elements was assessed using pre-established criteria, and in a general way, the comparative priority of the two lists can be determined. However, there was **no** attempt to determine the priority of the ensemble set of the derived 20 possible lunar activities relative to any of the following:

- Options for advancing martian science by carrying out similar investigations directly at Mars.
- Options for demonstrating technology or infrastructure at Earth, rather than at the Moon.
- Options for advancing lunar science through alternate investigations that do not have a linkage to Mars.

The MMSSG is aware that judging scientific priority in broader context such as this commonly involves political and programmatic factors that are outside the scope of science-based prioritization, such as budget, NASA's strategic directives, the status of existing engineering programs, and other factors. However, within the scope that MMSSG has operated, the priorities developed may provide a useful framework for NASA decision-making.

Assumptions for this Study

This analysis is based on the following lines of thought:

- Evaluate how MEPAG's scientific objectives for Mars (and their derivative investigations and measurements) could be enhanced by a first application on the Moon.
- Determine whether demonstrations of engineering capability at the Moon could have significant feed forward to the Mars scientific exploration program.
- Determine whether any of the primary scientific exploration goals and objectives for the Moon are linked to the goals and objectives for Mars.

The analysis included both an assessment of the potential ways in which the scientific objectives for the exploration of Mars can be advanced, and their priorities. The full charter of the MMSSG is contained in Appendix I. Several assumptions were made concerning the identification and prioritization of lunar science within the context of the exploration of Mars. We first assumed scientific priorities for the exploration of Mars that are described in the MEPAG Goals document:

> Scientific Goals, Objectives, Investigations, and Priorities: 2003. Unpublished document (http://mepag.jpl.nasa.gov/reports/MEPAG_goals-3-15-04-FINAL.doc)

Lunar science objectives were partially prioritized based on the most recent consensus-based description of lunar-science goals, objectives, and investigations that was developed by the Lunar Exploration Science Working Group (LExSWG). This information is available in the following reports:

> Planetary Science Strategy for the Moon, Lunar Exploration Science Working Group, July 1992, JSC document JSC-25920, 26 pp.
> Lunar Surface Exploration Strategy, Lunar Exploration Science Working Group (LExSWG), Final Report, February, 1995, 50 pp.

We also assumed a Lunar Reconnaissance Orbiter (LRO) mission to the Moon in 2008, a robotic landed mission by 2010, and a TBD schedule of robotic lunar missions until a first human return to the lunar surface in 2020. This SSG was asked to focus its effort on martian and lunar surface science, rather than orbital science.

This document is structured to first present an overview of the Moon as a unique vantage point for solar system exploration and general themes for Moon_Mars science linkages. This is followed by an outline of criteria used for prioritization of science investigations. Individual science investigations are explored with regards to linkage between Moon and Mars, relevance to lunar and martian science, and measurements that could be made on the lunar surface. These investigations are then prioritized with regards to their relevance to the exploration of Mars.

MOON_MARS SCIENCE LINKAGES

Early Planetary Evolution and Planetary Structure

The Moon has been and will continue to be the scientific foundation for our understanding of the early evolution of the terrestrial planets. The detailed geologic record of these early events has long since vanished from the Earth and has been at least partially erased from Mars. The Moon contains the remnants of one of the basic mechanisms of early planetary differentiation: magma ocean. These remnants are in the form of a primary planetary crust and subsequent crustal additions that were products of melting of magma-ocean products in the lunar mantle. The idea of a magma ocean has been extended by many investigators to the Earth, Mars, and even to asteroids (Benz and Cameron, 1990). Isotopic studies of basalts from both the Moon and Mars suggest a similarity in their early differentiation in that that their mantle sources formed very early and rapidly. Both bodies also exhibit planetary asymmetry that may reflect processes that functioned during early differentiation. Clearly, the differences in size and formation between the Moon and Mars have affected the style of differentiation and early magmatism. However, the Moon provides a valuable and nearly complete end-member model for a style of planetary differentiation and early planetary magmatism.

Four Moon-Mars themes were identified to fit within this subject:

- *Composition and Structure of Planetary Interiors*
- *Early Planetary Differentiation*
- *Planetary Thermal and Magmatic Evolution*
- *Planetary Asymmetry*

Evolution of Planetary Surface

Some surface modification processes will be very similar for the Moon and Mars, and others will differ due to the presence of fluid erosion and chemical weathering on Mars. The Moon retains the history of the early impact environment of the inner solar system, at the time when life may have first arisen on the Earth and perhaps Mars. The bombardment history of the Moon and Mars may be similar, and this history will help to construct timelines for erosional, depositional, and volcanic features on Mars. It will also provide valuable insights into the potential habitability of the early surface of Mars.

Three Moon-Mars themes were identified to fit within this topic:

- *Impactor Flux versus Time*
- *Interpreting Geologic Environments*
- *Structure and Composition of Planetary Regoliths*

Record of Volatile Evolution and Behavior

This is perhaps the most important overall theme for the major stated goals for the Mars Exploration Program of life, water, and climate. Among these three themes, the origin and history of endogenic volatiles will be the most important theme for Mars. Because the Moon is volatile-poor and has no atmosphere, lunar science has only little to contribute to the origin and history of planetary volatiles. As Mars and the Moon are at nearly opposite ends of the volatile spectrum for rocky planets, most of the volatile science studies to be conducted on Mars are not possible on the Moon. There are several special cases were the study of lunar volatiles may be relevant to Mars. "Energetic particles", whose composition and interaction have been well studied on the Moon and whose study on Mars will probably be limited to determination of near-surface exposure histories. The characterization and exploitation of possible water-ice at the lunar poles may be important as a resource for human exploration. In addition, it provides insight into the transport of volatiles on airless planetary bodies. Another special case is the nature of lunar endogenic volatiles that provide insights into the nature of volatile reservoirs in early planetary mantles.

Three Moon-Mars themes were identified to fit within this topic:

- *Energetic Particle History*
- *Origin and History of Endogenic Volatiles*
- *Origin and History of Exogenous Volatiles*

Human Resource Issues

Most recent architectures for the human exploration of Mars have included the principle of using martian resources to produce propellant for the return trip. A long-term human outpost on Mars and on the Moon can also benefit from applying local resources to outpost support in areas that include construction of facilities to providing reservoirs of important consumables (water, oxygen, nitrogen, etc.) from local resources. The Moon is viewed as a place where the basic principles can be tested for the first time. Although the lunar and martian environments differ in detail, there are important similarities. For example, it may prove desirable to extract water from hydrated minerals in the Martian regolith, which will require processes similar to those that might be used to extract hydrogen or water ice from the lunar regolith. Many subsystems such as electrolysis cells, gas liquefaction systems, life support, operational autonomy, surface mobility, and storage and handling systems, will be common for the Moon and Mars. In addition, the Moon can be an important location for the study of the long-term effects on humans and human activity in less than 1-g environments. This understanding is critical to the safety of the first astronauts who will spend extensive time traveling to and exploring the surface of Mars.

Lunar resources are most useful on the Moon, but if propellants are available on the Moon, may also be transported into space. Thus, lunar propellant production might also benefit Mars exploration, for which very large amounts of propellant are required in space, and which bears a transportation cost that might be somewhat mitigated by the availability of supplies on the Moon. Any long-term utilization of the lunar surface, for science, resource development, or test beds for planetary exploration technologies, will benefit from the development of lunar resources. Because the Moon is a more likely venue for commercial development than Mars, commercial opportunities may exist in lunar resource development.

Two scientific issues link the Moon and Mars in this area. In both cases, better understanding is needed of the distribution, form, and concentration of the resources, particularly water, which is important for production of propellant as well as human life support. The form and concentration of deposits may determine the processes that can be used for extraction. If the resources are to be extracted from surface materials, better characterization is required of the physical properties of surface materials (i.e., the regolith) to allow excavation and movement of materials from the surface into processing systems.

Because of its important applications, water is probably the most valuable early resource that will be produced on either the Moon or Mars. Propellant production can be, but is not necessarily related to production of water. A variety of other resources exist on both bodies that will find application in human exploration and development scenarios.

Three Moon-Mars themes were identified to fit within this topic:

- *Water as a Resource*
- *In-situ Fuel Sources*
- *Exploration and Processing of Planetary Materials*

Science-Based Technological Demonstrations on the Moon

Because of its proximity to Earth, the Moon provides a functional technological testbed for developing technical capabilities for the scientific exploration the Mars by robots and by humans. Testbed examination of robotic drilling, in-situ measurements, sample selection and return, and astrobiological measurements may be accomplished on the lunar surface. Deployment and testing of a seismic network and other geophysical tools (i.e., heat flow) may be tested (and will produce useful and high-priority science) on the Moon. Although most of these probably could be done first on Mars, the technical feasibility of these measurements can be significantly advanced and associated risks mitigated on the basis of a lunar testbed experience.

Seven Moon-Mars themes were identified to fit within this subject:

- *Communication & Ranging Systems*
- *In-situ Resource Utilization (ISRU) Technology Demonstrations*
- *Drilling Technologies*
- *Seismic Net Technologies*
- *Assess Bio-Organic Contamination*
- *Sample Selection and Characterization technologies and Strategies*
- *Sample Return Technologies*

Astrobiology

Astrobiology is the quest to understand how habitable planets form and how inhabited worlds evolve, as well as the prospects for life beyond the Earth (Jakosky et al., 2004). Therefore, astrobiology research questions provide many linkages between lunar exploration and Mars science goals. Broadly, these linkages can be divided into two categories: historical and technological.

Historically, the Moon preserves unique information about events and processes that have affected the habitability of the entire inner Solar System, including early Mars. Such events include:

- *Impact chronology (esp. during the first billion years)*
- *The composition of large impactors, interplanetary dust-particle(IDP) flux, etc.*
- *Delivery of exogenous volatiles and organics molecules*
- *History of solar activity (solar wind; flares)*
- *Occurrence of nearby supernovae and Gamma Ray Burst (GRB) events*

The record of such events is obscured on Earth. Although it is somewhat better preserved on Mars, the lunar record is much more accessible. Hence, the Moon is the ideal place to improve our understanding of some of these events. In addition, the Moon can provide a testbed for technologies designed to examine these issues on Mars. Rather than set astrobiology apart as an isolated topic of investigation, the astrobiological relevance of such linkages is woven throughout this white paper.

Technologically, the Moon provides a uniquely accessible planetary-scale sterile environment useful for assessing engineering goals of astrobiological importance, especially for life detection and planetary protection. For example, we can envision conducting control experiments of life detection technologies to assess the potential for unanticipated false positives in outside, highly controlled laboratory settings. Additionally, the Moon is an ideal place to assess the effectiveness of technologies designed to minimize "forward contamination" of other planetary surfaces by robotic or human explorers.

PRIORITIZATION

As various science topics were identified by the MMSLSG, these were organized into related science themes (A), resource themes (B), and technology themes (C). These themes include the major lunar science topics identified in the 1995 LExSWG report, plus some additional topics that recognize the importance of martian volatiles within the exploration program. Criteria to prioritize these themes were established to rank them with regard to (1) understanding the Moon within the context of major solar-system processes and (2) their importance in better understanding Mars.

Lunar Criteria

Three criteria were identified by which to prioritize the Category A science themes according to their importance to lunar science. These criteria are:

1) The intrinsic scientific value of each theme for advancing our understanding of the Moon. This criterion evaluates the perceived importance of each science theme without regard to the ease or difficulty of being able to advance knowledge about that theme.
2) The degree to which a potential set of investigations is likely to make major contributions to answering major scientific questions posed by the theme. This criterion evaluates the anticipated degree to which various experimental approaches are likely to contribute significant knowledge about the theme.
3) Feasibility within the emerging strategy for precursor robotic lunar missions in support of human exploration.

Slightly different criteria were used to rank the Category B resource themes and the Category C technology themes. These were ranked in a manner analogous to the A-themes:

1) Overall importance of each theme to advancing the Moon-Mars Exploration goals.
2) The degree to which a given resource or test-bed endeavor is likely to make contributions to characterizing a valuable resource or developing an important process for use in the broad science exploration program.

A subcommittee of the MMSLSG discussed and individually ranked each investigation according to each criterion. The criteria rankings were given equal weighing to derive an overall lunar science ranking for each theme. The full MMSLSG established the final ranking of these investigations. Rating of lunar investigations that were incorporated into the prioritization based on Mars criteria are listed in Table 1.

Table 1. Prioritization of lunar investigations based on lunar science perspective. The investigations have not been rated within each priority group.

	Category A	Category B	Category C
High Priority			
	Structure and Composition of Planetary Interiors	Water as a Resource	Sample Selection and characterization
	Planetary Differentiation		Sample Return Technologies
	Impactor Flux vs. Time		Drilling Technologies
Moderate Priorities			
	Thermal & magmatic Evolution		Seismic Net Technologies
	Origin and History of Exogenous Volatiles		Communication & Ranging Systems

	Planetary Asymmetry		
	Regolith History		
	Interpreting Geologic Environments		
Lower Priorities			
	Energetic Particle History	Exploration and Processing of Planetary materials	ISRU Technology Demonstrations
	Origin and History of Endogenic Volatiles	In situ Fuel Sources	Assess Bio-organic Contamination

Martian Criteria

Four criteria were identified by which to prioritize the Category A science themes according to their importance to martian science. These criteria are:

1) The intrinsic scientific value of each theme for advancing our understanding of Mars if the investigation was first carried out on the Moon. This criterion evaluates the perceived importance of each science theme without regard to the ease or difficulty of being able to advance knowledge about that theme.
2) Degree of alignment with MEPAG's priority system for Mars exploration (Appendix II).
3) The degree to which a potential set of investigations is likely to make major contributions to answering major scientific questions posed by the theme. This criterion evaluates the anticipated degree to which various experimental approaches are likely to contribute significant knowledge about the theme.
4) Degree of criticality of the possible lunar activity to one or more future Mars missions (or surface measurement activities.

These criteria were not given the same weight in establishing priorities. The criteria that reflected a strong linkage to Mars were given a higher score.

Slightly different criteria were used to rank the Category B resource themes and the Category C technology themes. These were ranked in a manner analogous to the A-themes.

1) If successfully carried out at the Moon, the value to our ability to correctly plan and successfully implement the future Mars exploration program.
2) Importance that these measurements/demonstrations be carried out by the lunar robotic program prior to 2020.
3) General affordability of these measurements/ demonstrations.
4) Our technical ability to carry out these measurements/ demonstrations by the lunar robotic program prior to 2020.

A subcommittee of the MMSLSG discussed and individually ranked each investigation according to each criterion. The criteria rankings were not given equal weighing to derive an overall Mars linkage ranking for each investigation. The criteria that reflected a strong linkage to Mars were given a higher weight. The full MMSLSG established the final ranking of these investigations. In each category listed below, investigations are ordered by prioritization based on Moon _ Mars linkages. Prioritization of lunar investigations based on martian criteria is listed in Tables 2. Comparison between prioritization based solely on lunar criteria and martian criteria is presented in Appendices III and IV.

Table 2. Prioritization of lunar investigations based on Mars science perspective. The investigations have not been rated within each priority group.

	Category A	Category B	Category C
High Priority			
	Impactor Flux vs. Time		Sample Selection and characterization
	Origin and History of Exogenous Volatiles		Sample Return Technologies
			Drilling Technologies
High-Moderate Priorities			
	Thermal & magmatic Evolution	Water as a Resource	Seismic Net Technologies
	Interpreting Geologic Environments		ISRU Technology Demonstrations
	Regolith History		
Moderate Priorities			
	Origin and History of Endogenic Volatiles	In situ Fuel Sources	Communication & Ranging Systems
			Assess Bio-Organic Contamination
Lower Priorities			
	Structure and Composition of Planetary Interiors	Exploration and Processing of Planetary materials	
	Planetary Differentiation		
	Planetary Asymmetry		
	Energetic Particle History		

Criteria for Overall Priorities

The criteria for overall priorities are based on the overall priorities established by the lunar and martian priorities.

1) The importance of the investigation for understanding Mars as defined by martian priorities (Table 2).
2) The importance of the investigation for understanding the Moon as defined by lunar priorities (Table 1).

The criteria rankings were not given equal weighing to derive an overall linkage ranking for each investigation. The criteria that reflected a strong linkage to Mars were given a higher weight. A more detailed discussion of these criteria and prioritization of investigations are discussed in the summary (Table 3 and 4).

Relative versus Absolute Priorities

We should emphasize some of the limitations of the set of priorities that are presented in this document. Our analyses were deliberately restricted (see "Charter", Appendix I) to consideration of those scientific investigations and technical demonstrations which provide linkages between goals for Mars exploration and those for lunar exploration. Thus there are many crucial investigations on Mars which do not figure prominently in our priorities, simply because the application to the Moon is weak or nonexistent. Similarly there are important lunar questions which are not addressed due to their lack of direct relevance to Mars. Thus these priorities specifically reflect the importance of the potential feed-forward of lunar investigations for Mars exploration. In order that they are not taken out of context, it should be born in mind that these are *relative priorities*, divorced from the intrinsic value of the particular goals and investigations. The assignment of absolute priorities, which would clearly be extremely useful, requires a more far-reaching evaluation of NASA's scientific, exploration, and programmatic goals, and is beyond the scope of this group's charter. For example, we were not asked to attempt a cross prioritization of lunar investigations which may benefit Mars and investigations directly at Mars.

CATEGORY A. INVESTIGATIONS RELATED TO THE PROCESSES OF TERRESTRIAL PLANET FORMATION AND EVOLUTION.

1. Investigation: Impactor Flux versus Time.

The lunar surface has a unique record of the first billion years of impact history and records the chronology of inner-solar-system evolution in a cumulative form. The impactor flux places a boundary condition and a time scale on planetary differentiation, the early addition and loss of volatiles, and subsequent geological and biological evolution. The martian time scale is thought to be similar to that of the Moon, although the rate of collisions at Mars' impact history might be higher due to its close proximity to the asteroid belt. The lunar crater production function depends on a few sample dates, with a multi-billion-year gap between the Imbrian and Copernican ages. To first order, this function is thought to be uniform, although significant deviations may exist. Likewise new studies indicate that early basin production may also be non-uniform. To address these issues - as well as to counter the crater saturation effects that can affect crater size/density distributions on uniform and datable lunar surfaces - better relative and absolute calibration are required. Furthermore, inferences on the source of impactors in the solar system responsible for the observed cratering distribution can be obtained from their compositional properties.

Measurements: The lunar investigation requires age determinations of uniform surfaces of varying ages where impact melts and volcanic flows are present. Additional remote observations of crater distributions in conjunction with such age measurements are critical. The composition and stratigraphy of highland ejecta need to be determined so as to trace samples back to their origins. Compositional variations of impactors with time need to be correlated with possible multiple changes in the source of impactor in the solar system, and with cataclysmic events in the early solar system. A better understanding of the physical and geochemical effects of both basin-scale and smaller impactors will contribute to the calibration of the impact time scale.

2. Investigation: Origin and History of Exogenous Volatiles.

Moon-Mars Science: Being a volatile-poor body, most volatiles on the lunar surface derive from the solar wind or from volatile-rich objects (e.g., comets) that collide with the Moon. Evidence for significant hydrogen concentrations near the lunar poles have led to the suggestion that polar regions perpetually in shadow may contain various cometary volatiles, including water, which could be used as a resource. Compared to the Moon, Mars is a volatile-rich object for which the exogeneous or original complement of volatiles has been partly modified throughout martian history. Differentiating between those volatile characteristics inherited by Mars and those generated over time is important to understand the origin and evolution of the atmosphere, interactions between the atmospheric and surface, and whether compounds necessary for life might have been present on early Mars. Study of ancient volatiles trapped at the lunar poles, if such can be identified, may help to define the composition of early cometary volatiles on Mars.

Measurements: Lunar investigations require detailed composition and isotopic measurements of volatile components possibly trapped in perpetually shadowed areas near the lunar poles. Drilling or other means of access to the subsurface may be required to access ancient volatiles and to decipher how volatiles become concentrated at the poles. Martian investigations may require the detailed compositional and isotopic measurements of volatile components that are trapped within the Martian crust and that have not been significantly altered over time.

3. Investigation: Decipher planetary thermal and magmatic evolution.

Moon-Mars Science: Although the Moon and Mars formed and evolved in different ways, deciphering the thermal and magmatic evolution of each is fundamental to understanding the dynamics of their interiors and the expression of mantle processes on their surfaces (Shearer and Papike, 1999). For Mars in particular, it is important to evaluate whether thermal and magmatic processes may have provided energy and suitable habitats for the development of life. For lunar science, this investigation will track the dynamics of the lunar interior and changes in those processes with time. Shallow and surface processes, too, will be evaluated including the nature and location of basalt sources over time, variations in rates of magma production over time and space, and the history of crust and lithosphere growth. Similarly for Mars, this investigation will evaluate igneous processes through time and evaluate the vertical structure, chemical and mineralogical composition of the Martian crust. In addition, it will be important to evaluate the extent, locations, and persistence of geothermal heat that might have supported a subsurface biosphere.

Measurements: Despite the differences in formation and evolution of the two bodies, an investigation such as this will use similar techniques to investigate similar geologic processes. For the Moon, the investigation will require defining the distribution, composition, and age of basalts that pre-date basin formation and those that represent the last stages of mare volcanism. Similarly, the distribution of heat-producing elements, to evaluate heat flow, and the chemical/isotopic composition of volcanic rocks both within and outside the more volcanically active region need more detailed investigations.

4. Investigation: Interpreting Geologic Environments

Moon-Mars Science: Determining how materials found at the planet's surface formed, whether at the surface or in an interior setting, is key to understanding past and present geologic environments. On the Moon, where the surface is dominated by impact craters and deposits at all size scales, the capability to read the geologic history as recorded in minerals and rocks is crucial to understanding original igneous relationships, whether intrusive or extrusive, and to distinguish the different facies of impact-generated materials. Almost all lunar surface formations are part of the regolith and have been displaced from the site of their origin. Thus the capability is needed to determine composition, mineralogy, and texture of a rock to interpret what geologic formation it came from and thus to understand its origin. Knowing the global distribution of rock types and geologic formations is one of the keys to evaluating crust formation and modification scenarios. Thus mineral and rock determination and detection is needed on the scale of individual rocks at the surface of the planet as well as from orbit.

In addition to relationships described above, Mars' past geologic environments include water interactions at the surface and in the subsurface, and interaction with the atmosphere. The latter continues today. Thus an additional and extremely important priority for Mars exploration is to investigate rocks formed at or near the surface in sedimentary or hydrothermal environments, and those altered by physical and chemical weathering. The capability to determine mineralogy, rock type, and rock textures and fabrics are also key to understanding the environment in which they formed or were altered.

Measurements: Lunar minerals and rock types are well known from the lunar samples, and the distribution of major rock types (or mixtures thereof) as reflected by regolith and megaregolith compositions sensed remotely from orbit is known to a crude first order. However, the rock types and variations that occur locally, on a scale that would be of concern for further scientific exploration and for possible development of the Moon, including resource evaluation and exploitation, are not well known for other than the Apollo landing sites. Further unmanned lunar investigations need the capability to determine mineralogy and rock type/texture. On the surface, in-situ methods are required that can determine definitive mineralogy and lithology from fixed or mobile (roving) platforms. For locations that are inaccessible to such platforms, standoff capabilities (m to 10's of m) are needed. Available remote sensing includes Earth-based spectroscopic data and crude orbital multispectral data; modern hyperspectral measurements and global coverage with high mineral specificity and spatial resolution are needed. For Mars, these same general measurement requirements exist, but the breadth of mineralogy to which instruments must be sensitive is greatly expanded by the presence of water and potential enrichments of other volatile elements, and by more oxidized surface conditions. Orbital remote-sensing exploration to date is far superior for Mars than for the Moon.

5. Investigation: Characterize the structure and composition of planetary regoliths.

Moon-Mars Science: Characterizing the structure and composition of lunar and martian regoliths is critical to our understanding of the development of the outer skin of planets; this fragmental outer skin includes much of the material seen in multispectral observations from telescopes and from missions. While detailed studies of the lunar regolith have been done for the Apollo and Luna returned samples, we do not yet have good age and rate control for the many complex processes that produce and modify the lunar regolith. Such time control can be acquired by sampling fossil or buried regolith sandwiched between datable lava flows or impact-melt rock layers using either drill cores or impact crater walls to sample the fossil regolith. Armed with this time control, we can determine the rate at which regoliths are formed, and whether that rate has varied over geologic time, we can determine the production rate for agglutinates and other impact-melt phases, we can determine the variation of grain size and size-distribution curves with accurately known exposure time, we can determine the build-up rate for individual solar-wind species, and we can determine the lateral transport rate by characterizing the degree of contamination of local material by distant material. The Moon constitutes the end member in a spectrum of planetary regoliths formed by a combination of physical and chemical processes. Earth is at the other end, and Mars is in between. As an end-member, the Moon is critical to understanding both the absolute rates of regolith formation and alteration, and the relative rates of the processes that alter the regolith. For Mars, the lunar data on these rates provides a starting anchor point for assessing the relative intensities of impact regolith-producing processes and chemical and physical weathering processes. This anchor point can only be established using carefully age-dated fossil regoliths.

Measurements: For the Moon, these studies require carefully located regolith sandwiched between datable volcanic or impact melt rock units. The necessary detailed studies can only be done on returned samples. The best sampling approaches are core samples (10's of meters will be necessary) or from sidewall sampling of craters that have penetrated fossil regolith "sandwiches" bounded by datable rocks. Ideally, samples should come from the both oldest and the youngest volcanic terrains. Areas with relatively short time intervals between flows would be ideal. In highland regions, identifiable overlapping melt sheets from larger impacts or even basin-forming impacts might provide good age control. For Mars, a better understanding of the martian regolith is required before pursuing this line of investigation.

6. Investigation: Origin and History of Endogenic Volatiles.

Moon-Mars Science: Characterization of the presence and distribution of volatile elements among planetary bodies provides fundamental information on differentiation processes and the mechanisms of planetary formation in the Solar System. On the Moon, volatile elements from endogenic processes or internal sources such as volcanism are rarely found. Unlike the Earth, lunar materials show little sign of the past presence of water; CO_2 and CO gases were probably the dominant volcanic gases on the Moon. The major exceptions are the volatile-element enriched coatings found on samples of pyroclastic glass beads from the Apollo 15 and 17 landing sites. These volatile- and metallic-element (Fe and Ti) enriched remnants of ancient volcanic eruptions on the Moon provide clues to the nature of the early lunar interior and to the distribution of potential resource materials for future exploitation. By contrast, minerals and gases from Mars may be substantially more enriched in water. This investigation allows us to understand the varieties, abundances, and distribution of volatile elements released from the lunar interior, to characterize their depths of origin, and to understand the processes controlling their loss and possible transport to regions such as the lunar poles. Characterization of lunar endogenic volatiles provides context for studies of endogenic and exogenic volatiles on Mars, and may lead to a more comprehensive understanding of the surface and subsurface distribution of volatile species on Mars, how these may have changed through time, and the origin and evolution of the martian atmosphere.

Measurements: The lunar investigation requires in-situ examination and sampling of lunar pyroclastic deposits, compositional studies of their surface coatings and interiors, and petrologic analysis of their depths of origin. In addition, this investigation requires identification, characterization, and sampling of volatile reservoirs at the lunar poles, with emphasis on comparative analyses of endogenic versus exogenic volatile species.

7. Investigation: Early Planetary Differentiation.

Moon-Mars Science: The Moon and Mars underwent planetary-scale differentiation early in their histories that may have involved early core formation followed by the crystallization of magma oceans on these bodies. A record of this earliest phase of differentiation on both bodies is preserved in the structure and composition of their interiors and in the range of ancient rock types exposed on their surfaces. Therefore, an understanding of the earliest differentiation history of the Moon could help to place constraints on the mechanisms and time scales involved in similar processes that may have occurred on Mars. The style of differentiation may partially dictate the pathway along which a planetary body may evolve. Investigation of early lunar differentiation history can be done through detailed characterizations of the internal structure of the Moon as well the compositions and ages of the rocks from the far-side lunar highlands and those exposed in large impact craters and basins.

Measurements: This lunar investigation would require geophysical as well as geochemical and petrographic measurements. The geophysical measurements require the establishment of a global network of seismometers that would help to resolve the deep and shallow structure of the Moon. The geochemical and petrographic measurements require the sampling and analysis of lunar rocks from the ancient highlands (particularly from the far-side, which are not represented in the Apollo collections) as well as those representing deep crustal lithologies that have been exposed at the lunar surface by large impacts.

8. Investigation: Characterize the structure and composition of planetary interiors.

Moon-Mars Science: Characterizing the structure and composition of planetary interiors is fundamental for understanding the origin and differentiation of a planet, dynamical mantle processes, surface evolution, tectonics, magmatism, and magnetic field. This investigation provides constraints for the bulk composition of the Moon, its origin, and the manner in which it differentiated. Characterization of crust, mantle, and core structural domains anchors our understanding of lunar asymmetry, mantle dynamics, magnetic field, and the current thermal state of the Moon. The lunar structure provides a record of early planetary processes that may prove essential to the interpretation of basic mechanism of martian differentiation and early dynamical processes of the martian interior. This may lead to a more comprehensive understanding of early

Mars: the nature of the primordial crust, the origin of the hemispheric dichotomy, the release of water from the mantle, and evolution of the early magnetic field and its effects on the atmosphere and radiation shielding.

Measurements: The lunar investigation requires high-resolution seismic, far-side gravity and topography measurements. These geophysical measurements require the establishment of a global seismic network consisting of multiple seismometers. Far-side gravity and topography measurements must be made using orbital spacecraft. In addition to geophysical measurements, this investigation also requires examination and sampling of deep crustal lithologies that are exposed at the lunar surface and basalts that are outside of the Apollo era collection sites. These samples provide windows into the Moon's lower crust and mantle.

9. Investigation: Planetary Asymmetry.

Moon-Mars Science: Both Moon and Mars exhibit asymmetry in composition and structure on a global scale. On the Moon, asymmetry is manifested by the distribution of rock types and thickness of crust, an offset between center of figure and center of gravity, and by the distribution and extent of volcanism (Jolliff et al., 2000). The lunar crust is thicker and the feldspathic lunar highlands are concentrated on the eastern lunar near side and on the northern far side. Volcanism is most extensive on the western lunar near side, and that area appears to have been a locus of extended igneous activity relative to other parts of the Moon. On Mars, a north-south hemispheric dichotomy exists, with older and more rugged highlands to the south, and a smoother, resurfaced character in the northern hemisphere. Causes of these two different manifestations of planetary asymmetry are unknown. They may be related to early differentiation, early giant impact bombardment, or subsequent modifications by internal processes. In the case of the Moon, the asymmetry appears to be related to earliest differentiation of the planet into crust and mantle resulting from solidification of a global magma ocean, and the effects of asymmetric distribution of heat-producing materials may have played a key role in the subsequent 2-3 billion years of thermal and magmatic evolution. In the case of Mars, relationships between planetary asymmetry and thermal and volcanic evolution are as yet unknown.

Measurements: Key to understanding planetary asymmetry is to characterize the internal structure, distribution of rock types and compositions, ages of different geologic terranes (broad regions that experienced a common geologic history), and heat flow from the interior. Specific investigations include seismic networks, gravity (lunar far-side gravity is not well known), heat flow (distributed network), and accurate topography/altimetry (lunar topography is not well known in comparison to Mars). In-situ geochemical analyses at key surface locations and improved global geochemical measurements (e.g., X-ray spectrometry) are also needed. Ages of rocks from a variety of locations and an understanding of the setting in which they formed (see A10) are also needed.

10. Investigation: Energetic Particle History.

Moon-Mars Science: Throughout solar-system history the lunar surface has acted as a collector for the solar wind and solar and galactic energetic particles (Rao et al., 1994). From studies of the lunar regolith we have gained a better understanding of the composition and energetics of particles that stream from the Sun and of the likely isotopic composition of some volatile components in the early nebula from which the planets formed. The relative elemental and isotopic composition of implanted solar wind and energetic solar particles, as measured in a variety of lunar regolith phases, is generally easier to determine than is the flux and energy distribution of highly energetic solar protons over past eons. Yet, the highly energetic solar (and possibly galactic) particles have been the greater influence on the evolution of the atmospheres of Mars and the Earth. Most of the lunar-acquired information about solar particles characterizes solar emissions over the last ~2 billion years, as ancient, undisturbed regoliths have not been easily identified or accessible. Energetic solar and galactic protons create nuclear reactions on the surface of many solid planetary bodies, and through such reactions the composition of some elements can be determined from orbit. In the case of Mars, charged solar particles are attenuated within the atmosphere, where they serve to erode the upper atmosphere over time, producing mass-fractionation effects in some species. Highly energetic galactic particles produce nuclear products in the surfaces of the moon and Mars, and this process can be used to study regolith formation and mixing. This application of GCR particles, however, is covered under theme A4 above.

Measurements: For the Moon new information about the composition of solar emissions can come from studying preserved paleo-regoliths or basalt surfaces, which can be accessed by drilling to ancient basalt flows or by accessing benches within crater walls. To determine the flux and energy distribution of very energetic solar particles requires very specialized samples in which depth profiles of nuclear products can be measured. Whereas paleoregoliths may be common and accessible in basalts ~3-4 giga-years in age, optimal materials >4 giga-years in age may have been strongly altered by the intense early bombardment and may be difficult to find. For Mars direct study of solar emissions is probably not possible. The effects of energetic particles on the atmosphere of Mars today can be understood through orbital measurements of atmospheric escape processes and through study of the isotopic compositions of certain volatile species in the atmosphere and the solid planet.

CATEGORY B. EVALUATE HUMAN-RELATED RESOURCE ISSUES ON THE MOON TO BETTER PREDICT THEIR STATE/USEFULNESS ON MARS.

1. Investigation: Water as a Resource.

Moon-Mars Science: Water is an important resource for human exploration missions and can be used both for life support and for fuel. Both the Moon and Mars are suspected and known, respectively, to have significant quantities of water at or near the surface and in the atmosphere. Water can presumably be extracted directly from the lunar environment in the polar regions where it appears to be segregated in permanently shadowed craters. The source for water in the lunar polar craters is assumed to be from comets. Water can also be manufactured from H and O both of which are widespread across the lunar surface. H is implanted by solar wind; O occurs within the regolith, derived from the lunar basalts.

Water is critical for human survival. Even in a closed-loop system there are some losses that must be replaced. Having a supply of in situ water (direct or manufactured) eliminates the need to bring it from the Earth. The constituents of water (H and O) are critical elements for fuel, both rocket engine propellant and fuel cell materials.

Measurements*:* H is known to be widespread across the lunar surface and has been measured directly in returned samples of the regolith and detected by secondary neutron spectroscopy at both equatorial and polar latitudes. The H that occurs in the polar environment is interpreted to be in the form of water ice, but water ice has not been unequivocally confirmed. O is an important element in lunar basalts and has been measured in returned samples. The critical measurements for use of water as a resource would be to determine the amount, purity, and its form (e.g., massive vs. dispersed ice) in permanently shadowed lunar craters. Having an understanding of the quantity, quality and form of the water would allow an assessment of the relative merits of mining H and O as separate phases compared with the mining of polar water ice and of the types of techniques to be employed for extraction.

2. Investigation: In situ Fuel Sources.

Moon-Mars Science: The lunar and Martian regoliths contain potential components of rocket propellant that could be produced *in-situ*, avoiding the need to transport them from Earth. Water and carbon compounds, if present at the lunar poles, solar wind hydrogen and carbon in the regolith, and oxygen produced by reduction of ilmenite or pyroclastic glass are the principal potential sources on the Moon. On Mars, there may be significant concentrations of bound water in the regolith and accessible liquid water beneath, which could be used for producing hydrogen/oxygen propellant or, in combination with carbon dioxide from the atmosphere, methane and oxygen. These constituents also could be used as fuel for fuel cells or as expendables for human life support systems. The extraction of propellant from regolith minerals would use similar approaches for both Moon and Mars, including excavation, thermal extraction, water electrolysis, and oxygen, hydrogen or methane liquefaction. A lunar propellant production demonstration could influence the design of human missions to Mars as well as demonstrate the validity of the concepts for propellant production from the regolith on Mars.

Measurements: The principal uncertainties in the lunar database with respect to propellant production are the distribution, form, concentration, and the physical properties of hydrogen-containing deposits in permanently shadowed areas at the lunar poles. Better understanding of the 3-dimensional distribution of carbon and hydrogen in the non-polar regolith could be important. The economics of lunar propellant production are highly sensitive to the concentration of hydrogen (or hydrogen and carbon) because these are typically the least abundant of elements on the Moon, so that finding locations that have much larger concentrations than the average is important. Because the scale of a useful polar ice deposit can be quite small (100 m^2 x 3 m deep regolith could produce 6 metric tons of propellant if the water concentration is 1%, 30 metric tons if the concentration is 5%), lunar surface exploration will be required, with subsurface detection capability that may be provided by a drill or similar sampling tool. Measurements should include: determination of the form of hydrogen and other volatiles by mass spectrometry and differential thermal analysis; local distribution of hydrogen and ice, by active neutron spectroscopy and sub-surface electromagnetic sounding; and physical properties of surface and sub-surface materials by cone penetrometer or analysis of drilling or other mechanical system that interacts with the surface. The capability to determine the isotopic composition of hydrogen and carbon would add scientific value, but is not required for resource evaluation.

3. Investigation: Exploration and Processing of Planetary Materials.

Moon-Mars Science: Demonstration of identification and processing of resources in lunar missions can validate their use in Mars missions. Many non-volatile materials can be manufactured from natural oxides and silicates occurring in the regolith on the Moon or Mars. Systems need to be developed to process planetary materials at surface environments with similar constraints – low ambient pressure, partial – gravity. Exploration for the distribution of resources from orbit and with new techniques on surface is needed. Surface exploration techniques are needed to establish mineralogy of martian materials that could provide resources – e.g. X-ray diffraction; differential thermal analysis. A wide variety of manufactured products could be made from Martian regolith – glass, ceramics, composites that could assist human exploration

Measurements: Demonstrate the ability to identify resources on the lunar surface. Demonstrate the ability to extract minor/trace constituents from lunar regolith through physical beneficiation and chemical extraction.

CATEGORY C. DEMONSTRATIONS AT THE MOON TO GAIN EXPERIENCE, MITIGATE RISK, IMPROVE PERFORMANCE, AND CONFIRM CAPABILITY.

1. Investigation: Sample Return.

Moon-Mars Science and Technology Linkage: Sample return missions allow the full range of analytical techniques, available in laboratories on Earth, to be used to extract qualitatively and quantitatively the maximum information from a given returned sample. This allows high sensitivity, high precision, and low contamination studies to be performed in an optimum fashion. Complementary investigations can be done in sequence and in consortium modes. Specific investigations can be suggested based on detailed prior investigations on the same samples. Furthermore, parts of the returned samples are routinely saved, in their pristine condition, and are available as new analytical techniques are developed and new imaginative investigators become interested in the unique returned samples. For example, for the Apollo returned samples: a) U-Th-Pb techniques with sufficiently low contamination were developed several years after the end of the Apollo missions and permitted the identification of the putative Lunar Cataclysm at 4.0 Ga ago; b) the Sm-Nd dating technique was developed seven years after return of the samples and was applied successfully to measure ages and to identify the long-term preservation of mantle sources for mare basalts; c) thirty years after return of the samples, new techniques for platinum group elements, using negative ion mass spectrometry, were developed and applied to identify the detailed nature of the exotic (meteoritic) components in the lunar regolith and in lunar breccias, which trapped the contributions to the Moon at ~ 4 Ga ago.

Demonstrations: The development of capabilities for samples returned from the Moon has direct application to techniques applicable to samples returned from Mars. In particular, the detailed and meticulous work required for the search for conditions compatible with the development of life on Mars, and possible evidence for past or present life on Mars may require the use of full-up, high sensitivity and specificity analytical techniques, available in terrestrial laboratories. Similarly the techniques developed to address the thermal evolution and the development of a crust, mantle, and core on the Moon, have direct applicability to the similar evolution of Mars. There is a need for additional samples returned from the Moon, since the Apollo and Russian missions were restricted to the equatorial regions on the Moon. Specific scientific investigations on the Moon would take advantage of the potential return of new samples from the back side of the Moon, the South Pole-Aitken Basin, and the lunar poles. The specific scientific questions to be addressed include better definition of the early impact history of the Moon and inner solar system (e. g., especially prior to 4.0 Ga) and the better understanding of the development of the lunar magma ocean and the preservation of distinct chemical and isotopic reservoirs within the lunar mantle, which served as sources for the mare basalts erupted in the interval 4-3 Ga. Samples can be returned from the Moon and from Mars with relatively simple in-situ characterization techniques, in order to pick interesting and non-redundant samples. Limited mobility on the surface is acceptable given the effective mechanisms for mixing materials on the regoliths of both planets.

2. Investigation: In situ Analysis for Improving Sample Selection Strategies.

Moon-Mars Science and Technology Linkage: Robotic spacecraft will continue to be the method of exploring Mars for a significant period of time and will be used as both precursors to and contemporaneous with human exploration of Moon. The ability of these robotic systems to analyze material either for complete in situ analysis or a screening tool for the selection of samples to be returned to the Earth provides a powerful enhancement of the total science. The ability to conduct relatively sophisticated mineralogical, molecular, chemical and isotopic analysis on both silicate materials and ice can provide substantial insight into the nature of the material, be it lunar or martian, rock or ice. The evolution of capability from the first Surveyor measurement to those made by the MER rover show how much can be learned from in situ analysis.

Demonstrations: Additional capabilities are in various stages of development and both demonstration and use on the Moon, as a prelude to Mars, will result in increased science return.

3. Investigation: Drilling Technologies.

Moon-Mars Science and Technology Linkage: The surfaces of Mars and the Moon are characterized, over large regions, by regoliths comprised of mixed dust and rock. Many scientific questions require access to the subsurface. For example, there are likely to be few volatile species within the upper 10 cm of the lunar regolith due to solar wind exposure. Likewise, many compounds of interest for astrobiology are more likely to lie below the surface of Mars, shielded from UV exposure. Subsurface sampling also holds the potential for obtaining a time record of climate (Mars) or solar wind fluctuations (Moon). The capability to drill to depths of perhaps several meters, and to return "pristine" samples, is thus of high priority for the Moon and Mars.

Demonstrations: Drilling in planetary regoliths presents a number of challenges. Astronauts found it difficult to obtain cores from the lunar regolith, which is well compacted below the upper few cm. Robotic planetary drilling or scraping to date has been performed only to depths of a few cm, and there is considerable development needed to demonstrate the capability.

4. Investigation: Seismic Technologies-Studies.

Moon-Mars Science and Technology Linkage: A seismic network is required to understand the inner workings of any solid planetary body. The Apollo program deployed 4 seismometers, but all were on the near-side, relatively close to each other and installed by astronauts. The structure and composition of the lunar deep interior is still unknown as is the crustal structure on the far side. Such a network would be critical for the characterizing the depth of regolith in some regions, defining crustal/mantle heterogeneity, and delineating the composition and size of the lunar core. It would also test the lunar magma ocean hypothesis. Installation of a lunar seismic network would provide insights into deploying a robust seismic network on Mars. The Moon provides a testbed environment that is in close proximity to Earth, and is seismically quite requiring long-lived and sensitive seismometers. A martian seismic network could acquire evidence of continuing tectonic (magmatic) activity, nature of the internal structure and composition, and characterization the shallow subsurface in some regions (e.g., extent of potential aquifers). In addition to seismic studies of the Moon and Mars, the developing the ability to deploy a network on a planetary surface is fundamental to studies of other terrestrial planets and moons.

Demonstrations: An important demonstration would be the deployment of sensitive, broadband seismometers on both the near side and far side of the Moon. This would test technical approaches for emplacing highly sensitive seismometers on a planetary surface and operating them over extended periods of time. Additional geophysical tools could be added to the seismic tools.

5. Investigation: Assess Bio-Organic Contamination.

Moon-Mars Science and Technology Linkage: The search for evidence of *extant* life on Mars requires the development and application of novel technologies to detect signs of biological activity. In addition, this search requires that the risk of forward contamination of the Martian surface by terrestrial microbes be minimized during future exploration activities. Such contamination could also perturb the Martian biota, if it exists. The interpretation of biosignatures of *extinct* life, such as carbon isotope variations, might also be complicated by the activity of modern microbes, or by biogenic compounds, brought to Mars from Earth. The same holds true for investigations into molecular precursors of life, such as organic compounds.

Demonstrations: The lunar surface is a completely sterile *natural* environment. Therefore, the Moon offers a unique opportunity to assess Mars-bound technologies and protocols designed to detect signs of life as well as those intended to minimize forward contamination. Such testing is impossible on Earth outside of idealized conditions in the laboratory. Life detection approaches intended for Mars could be tested in control experiments on the lunar surface to minimize the risk of future "false positives" or other ambiguities on Mars. The risk of forward contamination could be assessed by sensitive analyses of organic compounds, microbial residues and surviving organisms on and around future lunar spacecraft.

6. Investigation: ISRU Technology Demonstrations

Moon-Mars Science and Technology Linkage: The use of in-situ resources on either the Moon or Mars will not become reality before there are demonstrations, probably at the level of robotic mission experiments that have sufficient robustness to demonstrate the viability of the technology to extract and process the planetary resources. The most important demonstration will be the first one, whether it is done on the Moon or on Mars. This will remove a level of uncertainty in a manner similar to that in which the demonstration of ion propulsion on the Deep Space 1 mission cleared the way for a myriad of applications of the technology on subsequent missions. Although the surface environment and contents of useful materials are different for the Moon and Mars, there are some cases in which the extraction technology may be similar (for example, extraction of ice or solar wind volatiles from the regolith on the Moon and extraction of water from hydrated regolith minerals on Mars) and for many processes, subsystem elements can be common (for example, excavation and materials handling systems, heating chambers, Sabatier reactors, gas and fluid handling, water and CO_2 electrolysis, and H_2, O_2 and CH_4 liquefaction). For systems such as these, which transport solids, liquids and gases, in some cases in multi-phase systems, the behavior of the systems at reduced gravity will have to be demonstrated before the technology can be adopted for missions.

Demonstrations: Testing the extraction and/or production of water, hydrogen, oxygen and methane is generally regarded as the highest priority because of the application of these products in spacecraft propellant and for human life support systems. Demonstration of the specific technologies for accomplishing these processes, either for the lunar polar shadowed craters, where some of the products may exist, or for typical lunar regolith, will be a first step toward eventual deployment for human and robotic missions. There are several approaches to demonstration that must be considered. These include: (1) demonstration of the subsystem components (e.g. valves, Sabatier reactors) in the relevant environment; (2) end-to-end demonstrations of complete systems, preferably with long enough production times to provide information on the robustness or expected lifetime of systems in the lunar environment; and (3) full demonstrations of extraction technologies aimed at providing data suitable for scaling to production quantities. These should be selected depending on the maturity of the Earth-based technology, adequate models to predict performance in the lunar environment, and to some extent, development schedule compared to the expected time at which the technology would be used. The highest priority demonstrations would appear to be: (1) extraction of water or hydrogen from lunar polar soils, conversion to H2/O2, and liquefaction of H2 and O2.; (2) production of oxygen from either mare or highlands regolith; (3) demonstration of the use of one or more of these compounds on the lunar surface, which would require transfer of the compounds to a test article, such as a hopper or a fuel cell on a rover.

7. Investigation: Communication and Ranging Systems.

Moon-Mars Science and Technology Linkage: Lunar surface science goals, such as a global seismic network or South Pole-Aitken basin studies, may require landings on the far side. Potential areas of exploration at the lunar poles may also be out of direct line-of-site contact with Earth during all or part of the year. Communications with surface experimental packages thus require an orbital relay capability. Measurements of the gravity field for the lunar far side will also require at least two orbital spacecraft that can be used to measure relative velocity shifts. In the most capable mode, such orbital assets could form a global positioning system for the Moon, which could be used for long-term studies of internal structure. A similar "Mars GPS" network could improve the geodetic grid, allow enhanced studies of internal structure, and provide continuous communications with landed packages.

Demonstrations: Given current terrestrial GPS capabilities, relatively little technology development is required to achieve the Moon-Mars goals. There is also little need for this technology to be first demonstrated at the Moon.

FINAL PRIORITIES

The final priorities in this report are summarized in Tables 3 and 4. Although we did not attempt to develop a detailed cross-prioritization of all 20 elements, but the comparative priorities of elements in the two lists can be seen in a general way; e.g. a high priority item in list A can be assumed to be of generally higher overall priority than a low priority item in list B+C. A more detailed implementation guide for selected science themes are outlined in Appendix IV in an "AO style" format. These investigations and demonstrations are prioritized based on their linkage to Mars exploration. Highest scientific priorities recognized by this steering group were Impactor Flux versus Time and Origin and History of Exogenous Volatiles (Table 3). There appears to be no scientific investigation that must be done on the Moon prior to the investigation being done on Mars. However, in many cases, the Moon provides a planetary frame of reference for better understanding Mars. For example, the Moon provides an example of one style of planetary differentiation: Magma Ocean. How far early differentiation deviates on Mars from this style of differentiation is important for understanding the origin of Mars and the pathway on which it evolved.

As discussed above, the lunar science (A category) themes (Investigations related to the processes of terrestrial planet formation and evolution) were ranked into three categories (Table 1) based on overall importance to advancing scientific understanding of the Moon and the degree to which identified investigations are likely to make major contributions to advancing knowledge about the important science questions. The ten lunar science themes were also ranked into four categories according to how strongly they linked to MEPAG Investigations (Table 2). These procedures allow a hierarchical scheme that builds on these two results to establish *Overall Science Priorities* in Moon-to-Mars science links. These priorities reflect, simultaneously, an attempt to answer two questions: "How strongly is the lunar science theme connected to MEPAG goals?" and "How important is the theme, in and of itself, for advancing lunar science?"

The *Overall Science Priorities* were slanted towards Mars science goals as the MMSSG Charter makes it clear that the SSG should consider first and foremost how to define science-based activities on the lunar surface that would benefit the scientific exploration of Mars. Thus in establishing an overall priority, a strong linkage of a lunar theme to a MEPAG Investigation trumps a theme that has a strong lunar science impact but is less linked to MEPAG goals for Mars.

Table 3. *Overall Science Priorities.*

HIGH PRIORITY
Impactor Flux vs. Time
Exogenous Volatiles

HIGH-MEDIUM PRIORITY
Thermal and Magmatic Evolution
Interpreting Geologic Environments

MEDIUM PRIORITY
Endogenous Volatiles
Interior Planetary Structure
Early Planetary Differentiation
Regolith History

LOW PRIORITY
Planetary Asymmetry
Energetic Particle History

Categories B and C were also rated in a similar manner. High to Medium priority technology demonstrations include: in-situ sample selection and analysis, sample Return technologies, drilling technologies, ISRU Technology Demonstrations, seismic technologies/Studies, and water as a resource (Table 4). These technology demonstrations need not be done on the Moon prior to Mars. However, as exploration drives martian science to new levels of complexity prior demonstrations on the Moon will refine exploration strategy, diminish risk, and improve performance.

Table 4. ***Overall lunar technology (Categories B and C) priorities based on linkages to Mars exploration.***

HIGH- MEDIUM PRIORITY:
In-situ sample selection and analysis
Sample Return
Drilling technologies

MEDIUM PRIORITY (higher):
Seismic technologies/Studies
Water as a Resource

MEDIUM PRIORITY (lower):
In-situ fuel resources
Assess Bio-Organic Contamination

LOW PRIORITY:
ISRU Technology Demonstrations
Communication and ranging systems
Exploration and Processing of Planetary Materials

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APPENDIX I
CHARTER

Mars-Moon Science Linkages (MMSL) Science Steering Group

Request from NASA HQ

Given the recently announced presidential vision for exploration of the Moon and Mars, NASA HQ formally requests that MEPAG consider how to define the science-based activities on the lunar surface that would benefit the scientific exploration of Mars. This analysis will need to be derived from multiple approaches:

- Evaluate how MEPAG 's scientific objectives for Mars (and their derivative investigations and measurements) could be enhanced by a first application on the Moon.
- Determine whether demonstrations of engineering capability at the Moon could have significant feed forward to the Mars scientific exploration program.
- Determine whether any of the primary scientific exploration goals and objectives for the Moon are linked to the goals and objectives for Mars.

Starting assumptions

1. Assume scientific priorities for the exploration of Mars are described in the MEPAG Goals document (http://mepag.jpl.nasa.gov/reports/MEPAG_goals-3-15-04-FINAL.doc).
1. The most current reference material for lunar science can be found at http://www.lpi.usra.edu/lunar_return/.
1. Assume a Lunar Reconnaissance Orbiter (LRO) mission to the Moon in 2008, a robotic landed mission by 2010, and a TBD schedule of robotic lunar missions (perhaps on an annual basis?) until a first human return to the lunar surface in 2020. Results from any given lunar mission can influence a martian mission scheduled 6-7 years later.
1. Return to the Moon is motivated by its use as a test-bed for human exploration of Mars, which must encompass science, utilization of accessible resources, operational scenarios involving humans interacting with robotic systems, and technology demonstrations of direct benefit to planned activities on Mars.
1. This SSG is asked to focus its effort on martian and lunar surface science, rather than orbital science. This is because of the assumption that eventual human missions to Mars will go to the martian surface, and the assumption that orbital science has recently been sufficiently defined for current purposes through the recent planning for 2005 MRO and 2008 LRO.

Requested Tasks:

1. Develop a quantitative analysis of the potential ways in which the scientific objectives for the exploration of Mars can be advanced through any of the following activities:
    a. Scientific investigations on the Moon
    a. Demonstrations of science-related hardware, including instruments, science tools, and/or sample preparation systems
    a. Demonstrations related to spacecraft operations.

   Traceability of these possibilities to the objectives described in the MEPAG Goals document is essential.
1. Develop an assessment of the priority of the possibilities outlined in Task #1. Prioritization criteria should include:
    a. Degree of alignment with MEPAG's priority system for Mars exploration.

a. Degree of criticality of the possible lunar activity to one or more future Mars missions (or surface measurement activities)
a. Intrinsic scientific value (for both Mars and the Moon).
a. Feasibility within the emerging strategy for precursor robotic lunar missions in support of human exploration.

<u>Methods</u>

- SSG membership should include experts in both Mars and the Moon, with expertise in instrument investigations and sample analysis of both bodies.
- The SSG is asked to conduct its business primarily by teleconferences, e-mail, and or web-based processes. In addition, there is adequate budget to convene 1 or 2 face-to-face meetings, as required.
- Logistical support will be provided by the Mars Program Science Office at JPL.
- The Mars-Moon SSG must be well coordinated with the Mars Human Precursor Testbed (MHPT) SSG, and there may be a need for dual membership on both SSG's for some colleagues.

<u>Timing</u>

- The SSG is asked to carry out its deliberations in two phases, and to start by mid-April, 2004.
- Phase I. Scoping analysis. These results will be presented to MEPAG at its June 30-July 2, 2004 meeting, and that presentation will be the basis for a significant discussion. In preparation for this, a draft report should be presented to the MEPAG Executive Committee no later than two weeks before the MEPAG meeting.
- Phase II. Refined analysis. Details to be defined based on results from Phase I and input received at the MEPAG meeting.
- Assume for planning purposes that the final report of the SSG needs to be completed within 2-3 months of the MEPAG meeting.
- NASA HQ is forming a lunar science planning team parallel to that of MEPAG, under the working name of LEPAG. LEPAG may jointly sponsor this activity. When LEPAG comes into existence, we plan to reconsider the charter, add any additional elements needed by LEPAG, add a few more members, and let the effort continue.

<u>Report Format</u>

- It is requested that the results of this analysis be presented in the form of both a Powerpoint presentation and a white paper. Additional supporting documents can be prepared as needed. After the white paper has been accepted by program management (including the MEPAG executive committee), it will be posted on a publicly accessible web site.
- The report should not include any material which is a concern for ITAR (as is true of everything done by MEPAG).

APPENDIX II

Linkages between Lunar Investigations and MEPAG Goals

Lunar Science Investigations	Linkage to MEPAG (2003) Goals GOAL-OBJECTIVE-INVESTIGATION
Structure and Composition of Planetary Interiors	Goal II, Objective B, Investigations 3 Goal III, Objective B, Investigations 1,2,3
Planetary Differentiation	Goal II, Objective B, Investigations 3 Goal III, Objective B, Investigations 1,2,3
Thermal & magmatic Evolution	Goal I, Objective C, Investigation 2 Goal III, Objective A, Investigation 4 Goal III, Objective B, Investigations 1,2,3
Origin and History of Exogenous Volatiles	Goal I, Objective A, Investigation 1,2,3 Goal I, Objective B, Investigation 1,2,3 Goal II, Objective A, Investigation 1 Goal II, Objective B, Investigations 3 Goal III, Objective A, Investigation 5
Impactor Flux vs. Time	Goal II, Objective B, Investigations 3 Goal III, Objective A, Investigations 3, 4, 11
Planetary Asymmetry	Goal III, Objective B, Investigations 1,2,3
Regolith	Goal II, Objective B, Investigations 3 Goal III, Objective A, Investigation 9
Interpreting Geologic Environments	Goal III, Objective A, Investigations 4,9 Goal III, Objective B, Investigation 3
Energetic Particle History	Goal I, Objective A, Investigation 3 Goal I, Objective B, Investigation 2 Goal I, Objective C, Investigation 3 Goal II, Objective B, Investigation 2
Origin and History of Endogenic Volatiles	Goal I, Objective A, Investigation 2 Goal I, Objective B, Investigation 2,3 Goal II, Objective A, Investigation 1 Goal II, Objective B, Investigations 3
Water as a Resource	Goal IV, Objective B, Investigations 8,9
In situ Fuel Sources	Goal IV, Objective B, Investigation 7
Exploration and Processing of Planetary Materials	Goal IV, Objective B, Investigations 8,9, 10
Communication & Ranging Systems	Goals I,II, III, IV
Drilling Technologies	Goal IV, Objective B, Investigations 9
Life Detection & Planetary Protection	Goal I
ISRU Technology Demonstrations	Goal IV, Objective B, Investigations 9
Sample Selection and characterization	Goals I,II, III, IV
Sample Return Technologies	Goals I,II, III, IV
Seismic Net Technologies	Goal III, Objective B, Investigations 1,2,3

APPENDIX III

Comparison between priorities to Mars science and lunar science for Category A.

riority to lunar science	LOW	MEDIUM	MED-HIGH	HIGH
HIGH	Early Planetary Differentiation, Interior Planetary Structure			Impactor Flux vs. Time
MEDIUM	Planetary Asymmetry	Regolith Hist,.	Interpreting Geologic Environ, Thermal & Magmatic Evolution	Exogeneous Volatiles
LOW	Energetic Particle History	Endogeneous Volatiles		

Priority to martian science

APPENDIX IV

Comparison between priorities to Mars science and lunar science for Categories B and C.

Priority to lunar exploration	LOWER	MEDIUM	HIGHER
HIGH			C1 In-situ sample selection & analysis C3 Drilling technology C7 Sample Return
MEDIUM	B2 In situ fuel resources	C4 Seismic technology C6 ISRU technology	B1 Water as a resource
LOW	B3 Exploration & processing of materials C2 Communication & ranging systems	C5 Assess Bio-Organic Contamination	

Priority for Moon-Mars Linkage

APPENDIX V

Examples of “AO-style" writeups for select major lunar science themes

Investigation A2. Origin and History of Exogenic Volatiles

- Objective:

Identify, characterize, and quantify near-surface exogenic volatiles in lunar polar regions

- Investigations:

(a) Confirm the presence of volatiles in the upper regolith
(b) Determine and quantify their spatial distribution in 3-D so as to evaluate their cosmic history and economic significance
(c) Characterize their elemental composition, concentration, physical and chemical state

- Measurements:

(a) Active sounding of the upper X m of regolith to determine the presence of volatiles in cryogenic traps (radar)
(b) Characterize thermal properties of regolith at XX km spatial resolution (heat low probes and thermal IR)
(c) Determine surface morphological effects of volatile condensation/sublimation cycles (high-resolution radar imaging)
(d) Characterize mechanical properties (landers and penetrators)
(e) Determine the elemental composition of surface volatiles (neutron, gamma rays)
(f) Determine molecular composition and distribution (soil heating experiments)

Investigation A3. Decipher Planetary Thermal and Magmatic Evolution

- Objective:

Characterize the thermal and magmatic history of the Moon

- Investigation(s):

(a) Characterize the volume of erupted volcanic material as a function of time
(b) Characterize the global lunar heat flow
(c) Characterize the interior density structure of the Moon

- Measurements:

(a) Determine the depth of mare basalts across the Moon to XX m vertical accuracy at XX km spatial resolution (e.g., radar sounding or seismic profiling)
(b) Measure the surface heat flow of the Moon to XX W/m2 accuracy on spatial scales no coarser than XX km (e.g., heat flow penetrators)
(c) Determine the depth of crust, mantle, and core layers to XX km accuracy on spatial scales no coarser than XX km (e.g., global seismic network)

Investigation A1. Impactor Flux versus Time

- Objective:

Determine the size-frequency distribution and time variability of the impactor population in the Earth-Moon system.

- Investigations:

(a) Characterize the ages of lunar basins >XX km in diameter

(b) Characterize the small impactor population within the past XX b.y.

- Measurements:

(a) Returned lunar samples, or in situ age dating, adequate to provide age dates for major basins.

(b) Returned lunar samples, or in situ age dating, adequate to constrain ages of mare basalt units larger than XX km^2 in extent.

Investigation A5. Characterize the structure and composition of planetary regoliths

- Objectives:

Determine the process of regolith formation and subsequent modification.

Determine the inventory of potential regolith resources, including volatiles.

- Investigation(s):

(a) Characterize the vertical structure of the lunar regolith, and its variability between mare and highland provinces.

(b) Characterize the distribution of lunar resources on horizontal scales of XX km.

- Measurements:

(a) Orbital regolith probing by long-wavelength imaging radar; shallow seismic or electrical studies; drilling to depths of at least 10 m.

(b) IR spectroscopy, radar probing for mineral mapping; orbital and in situ measurements of volatiles (neutron, gamma-ray, mass spectroscopy).