# DRAFT

# Findings of the Mars
# Mars Forward Lunar Objectives
# Science Analysis Group


By the MEPAG Mars Forward Lunar Objectives Science Analysis Group

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## Executive Summary

The Mars Exploration Program Analysis Group (MEPAG) has completed a preliminary analysis of the June, 2006 draft list of possible lunar objectives from the perspective of its relevance to preparation for human missions to Mars. MEPAG has reached eight preliminary findings.

1) The issues associated with flying crewed missions to the Moon and to Mars are similar in some ways and quite different in others. Thus, only some of the developments/lessons learned associated with human exploration of the Moon will be directly relevant to Mars and a Mars-dedicated program will be necessary to resolve remaining issues.
2) Preparing for crewed missions to Mars will involve a four-component program consisting of Mars robotic precursors, preparation work at the Moon, work in LEO, and work done on the Earth. These four components are currently unevenly and incompletely planned.
3) The presently-considered lunar program has some relevance to Mars, and this relevance could be increased with revisions to some of the lunar objectives. Proposed rephrasing is described in the appendix to this report.
4) Carrying out the lunar investigations under consideration will not lead to a reduction in the requirements in MEPAG Goal IV (Prepare for Human Exploration). Goal IV considers measurements and technology demonstrations that can <u>only</u> be done at Mars.
5) There is an uncertain but potentially important relationship between lunar ISRU and martian ISRU that needs further study to enhance the potential of Mars ISRU.
6) The primary scientific linkages between Mars and the Moon were recently (2004) evaluated by MEPAG; those linkages are reaffirmed.
7) The draft list of lunar objectives is not missing objectives of importance to preparation for Mars.
8) The "Preparation for Mars" theme provides a compelling focus for the lunar program. The utility can be maximized by using "Preparation for Mars" as a prioritization criterion for lunar objectives.

# 1. Introduction and Background (from Jeff Volosin, NASA-HQ)

### 1.1 Purpose

In late 2005, the NASA Administrator stated that in 2006, NASA would initiate a process to define a compelling story to address two questions: "Why are we returning to the Moon?" and "What are we going to do when we get there?" The Exploration Systems Mission Directorate (ESMD) initiated an effort, with participation from the Space Operations Mission Directorate (SOMD) and the Science Mission Directorate (SMD), to define and implement a process to address these questions. The initial stage of this process focused on the need to facilitate broad community involvement in addressing these questions, identifying key objectives for the lunar exploration program and thus contribute to the development of a more inclusive and comprehensive Global Exploration Strategy. Inputs were to be solicited from academia, international space agencies, and private sector organizations. By collecting and analyzing these data, NASA would then be in a better position to define the role that the United States should play in lunar exploration as well as begin to develop an understanding of potential opportunities for broad cooperation and collaboration in the exploration of space.

### 1.2 NASA Exploration Workshop

To initiate this process, NASA held an Exploration Strategy Workshop in Washington D.C. in April of 2006. Over 180 engineers, scientists, entrepreneurs, and other exploration experts from the international community attended this Workshop and provided NASA with some initial thoughts on the answers to the two questions posed above, that were captured in the form of Themes and Objectives:

1) Why are we returning to the Moon? - Captured as lunar "themes" that provide a high-level compelling rationale for a return to the Moon. Example: *Use the Moon to prepare for future human and robotic missions to Mars and other destinations.*
2) What are we going to do when we get there? - Captured as lunar "objectives" that were defined as a set of closely associated specific tasks that when completely accomplished, would result in a significant accomplishment in at least one of the theme areas defined above. Example: *Characterize impact cratering flux over the Moon's geologic history.*

### 1.3 Additional Inputs

In addition to this Workshop, NASA solicited independent recommendations for lunar objectives from the public through a Request For Information (RFI) that was open through early May 2006.

### 1.4 Synthesis and Vetting Process

The result of these two activities led to the identification of 85 proposed lunar themes and over 800 proposed lunar objectives. Since these submissions were provided by many different individuals, NASA next initiated an internal Synthesis Team activity to remove duplication and combine similar proposals. The result of this synthesis effort was the identification of six unique lunar themes and 85 lunar objectives. In an effort to ensure that this resulting set of themes and objectives was thorough and complete, NASA next initiated a series of vetting processes

utilizing existing specific organizations that represented academic, international space agency and private sector scientific and exploration interests. These organizations included:
- 13 international space agencies
- All 10 NASA Centers
- The Lunar Exploration Analysis Group (LEAG)
- The Mars Exploration Program Analysis Group (MEPAG)
- The Lunar Architecture Team (LAT)
- The Lunar Commerce Roundtable
- The NewSpace 2006 Conference
- The NASA Advisory Council, Space Science Subcommittees
- The Next Generation Exploration Conference at Ames Research Center
- The Space Enterprise Council of the U.S. Chamber of Commerce

### 1.5 Resultant Product

The result of this process was the identification of an additional 100 lunar objectives and additional information that could be used to support the six themes identified earlier. As a result of the extensive engagement of the community in this assessment, more than 1,000 individuals had provided inputs to the process.

## 2. Basis for Assessment

### 2.1 MEPAG Goal IV Mars Human Precursor Study

A recent study was conducted by the MEPAG Mars Human Precursor Science Steering Group (MHP SSG) (Beaty et al., 2005) to analyze the priorities for precursor investigations, measurements, and technology/infrastructure demonstrations that would have a significant effect on the cost and risk of the first human mission to Mars. The purpose was to determine, in priority order, the ways in which the risk of a human mission to the martian surface can be reduced by means of robotic flight missions to Mars.

The scope of the MHP SSG study was to analyze the investigations of Mars by precursor robotic missions for the purpose of reducing mission risk/cost and increasing performance of a human mission to Mars. However, in order for a preparatory program to be complete, the following kinds of precursor investigations also need to be considered:

- Investigations that can be carried out at the Moon.
- Investigations that can be carried out in Earth-based laboratories or in Mars-analog field environments on Earth (other than on returned martian samples).
- Investigations of the space environment of relevance to a human mission other than those specifically at Mars.

The MHP SSG considered ONLY robotic precursor missions to Mars. However, the current MFLO SAG study builds upon the work of the MHP SSG in terms of identifying the major risk/cost to a human Mars mission and also opportunities to cost-effectively increase performance. The MFLO study differs from the MHP SSG study in that the MHP SSG study considered robotic precursor missions to Mars as preparation for a human Mars mission whereas this MFLO SAG study considers robotic precursor missions to the Moon in preparation for a human Mars mission.

### 2.2 Purpose and Scope of MFLO Review

ESMD has recently prepared a draft set of themes and objectives for lunar exploration that have been synthesized from several activities, including the NASA Exploration Strategy Workshop and a Request for Information. NASA's formal statement of its strategic goal linking Mars and the Moon is to "establish a lunar return program having the maximum possible utility for later missions to Mars and other destinations". This topic is critically important and will influence the architecture for upcoming lunar exploration.

The purpose of the MFLO review is to evaluate the draft lunar planning from the perspective of eventual application to Mars. MEPAG was thus invited by NASA Headquarters to review the synthesis report and address the following questions:

1. Have any themes or objectives been overlooked?
2. Are any themes or objectives redundant, hence ought to be combined?
3. Are any themes or objectives overstated or unachievable?
4. Are the themes and objectives clearly and unambiguously stated?

### 2.3 MFLO Analysis Process

The MFLO analysis included the following steps:

• An analysis of the primary ways in which human missions to the Moon and Mars are similar and different. This leads to more specificity in understanding which aspects of the lunar program are relevant to preparation for Mars.
• An evaluation of the priority of the draft lunar objectives from a Mars perspective. The list was prioritized in two ways: Relevance to "Prepare for Mars" (referring primarily to preparation for human Mars missions) and relevance to "Understanding Mars" (referring primarily to scientific knowledge regarding Mars as a planetary system).
• As needed, revising the lunar objective statements to make them appropriately Mars-relevant.

The team further considered:

• Does the conduct of the lunar program in any way allow us to reduce the requirements of MEPAG Goal IV (Preparation for Human Exploration)?
• What is the best way to maintain a Mars focus within the lunar planning structure?

### 2.4 MEPAG Validation Process

The MFLO assessment was conducted on a time scale of two weeks by a small 'tiger-team' that had extensive involvement in the development of the recent analysis of MEPAG Goal IV. Because of the timing, it has not yet been possible to carry out MEPAG's normal vetting process, so this should be considered an interim assessment.

The MFLO study will be vetted with the Mars community, however, through the standard MEPAG procedures. The initial findings of the MFLO SAG will be presented to the community at the upcoming MEPAG meeting in Washington, D.C. (January 2007). Community members will then have the opportunity to comment on the MFLO findings. These comments will be evaluated and incorporated as appropriate by the MFLO study team. Once the findings reach a state of consensus then the white paper will be published as an official MEPAG document.

## 3. Comparison of Human Missions to the Moon and Mars

In order to analyze the ways in which the various aspects of the lunar exploration program might be beneficial to Mars, it is helpful first to compare and contrast the essential aspects of missions to the two destinations.

### 3.1 Primary similarities between crewed missions to the Moon and Mars

The primary similarities that provide a basis for designing lunar systems with maximum utility for eventual application to Mars human missions are discussed here. Such utility is two-fold: 1) physical systems designs, the basic elements of which can be applied with customization to Mars and 2) relevant operational experience.

A. The most obvious similarity is the mutual need for high reliability life support systems as neither environment has the requisite water, atmosphere or food to sustain a crew on the surface. Thus for both destinations life-support must be provided for the full mission duration which includes both round-trip transit and surface stay-time. For the Moon it is feasible and practical, relatively speaking, to use a “brute force” system of supply and resupply with attendant disposal of used resources. In theory such an approach is also possible for Mars. However, the cost of delivering mass to and from Mars is so much greater, and the mission opportunities, which are limited by orbital mechanics, are so infrequent, that it may be mission limiting if alternatives cannot be developed. Such alternatives include closed-loop or nearly-closed-loop life support systems and, eventually, ISRU (in situ resource utilization). Both of these techniques, while not essential, would enhance long-duration lunar outpost missions. It is doubtful that a Mars mission architecture which was dependent upon these technologies would ever be undertaken without having first demonstrated “proof of concept” for these techniques in a prior application (not necessarily on the Moon - some could be done on Earth and the International Space Station (ISS)).

B. Sustaining the health of crews is essential for survival and for effectively attaining mission goals. Operating for prolonged periods in low-gravity (~ 1/6 Earth gravity for the Moon and ~ 1/3 Earth gravity for Mars), exposure to cosmic and solar radiation and exposure to pervasive dust are environmental conditions common to both the Moon and Mars. They differ only in degree. The long-duration implications of lunar gravity are unknown, as are the implications of martian gravity. Human exploration of the Moon will provide the first good, long-duration, data point between micro-gravity (ISS) and 1 g (Earth) which will go a long way towards understanding the implications of Mars gravity and for developing any needed counter-measures to mitigate serious physiological de-conditioning issues and help assure human health for long duration missions to Mars. Radiation is another matter of serious concern for the human exploration of space. Techniques developed for constructing radiation shielding on the Moon, using native (regolith) materials, the attendant computer models and improved understanding of the biological effect of high-Z cosmic rays can be directly transferred to Mars missions. The effects of lunar vs. martian dust is more problematic as both the chemical and physical characteristics of the dust are grossly different in the two environments. However, lessons learned in ameliorating both mechanical and physiological effects of lunar dust will produce a cadre of engineers steeped in the discipline of developing seals, filters, cleansing techniques, and overall less-susceptible mechanical and electrical designs. Similarly, physiologists must understand the implications of the inevitable crew inhalation of micron and sub-micron dust particles, of irritation of eyes and mucous membranes and of possible chemical reactivity (probably more serious on Mars with its known highly oxidizing dust).

C. Potential health hazards go beyond those which may be induced by gravity, radiation and dust. Judged by some to be the most challenging for a Mars mission are the psychological factors induced by a two-to-three-year isolation from home, with no quick abort possible and, relative to lunar missions, a greater likelihood of medical emergencies. While no simulation or lunar mission can impose the reality of “no early return”, long-duration lunar missions can aid in developing work/recreation/social interaction schemes designed to maintain a healthy mental outlook. And even in the lunar case, there could well arise medical emergencies which cannot be resolved with a three to four day abort to Earth. It, like launch vehicle losses, is simply a question of time.

D. Surface infrastructure and support requirements such as EVA (extravehicular activity) space suits, mobility systems and habitats are common elements of all Moon and Mars sortie and outpost missions. Again, designs will differ in detail yet the commonality of fundamental requirements for ease and flexibility of crew motion, reliable and repairable mobility systems and for highly functional yet homey, personalized habitats argues for high potential relevance.

E. Both Moon and Mars exploration programs need development of greater launch capacity and larger power systems than currently exist. While solar cells and fuel cells can in theory supply some of the needs, the development of nuclear surface power for lunar applications will be directly useful on Mars, especially if ISRU becomes practical; in fact, nuclear power may be enabling for ISRU, which in turn, is also likely enabling to long-term, sustainable human exploration.

F. Concerning scientific exploration per se, the basic techniques of geological and geophysical field research are well known and common to all planetary body explorations. They are fundamentally variants of what has been done on Earth and as was demonstrated on Apollo. New, however, is the potential for a significantly enhanced integrated robotic/human exploration. Long geophysical traverses, remote sampling and robotic assistants to do the drudge work and go into potentially hazardous locations are but a few examples of what can and ought to be done. Such an integrated approach will be valuable in lunar exploration but likely more so on Mars given the much higher cost per unit time of astronaut work.

A common theme runs through "primary similarities": to best prepare for eventual Mars human exploration, a constant awareness of and accommodation of the requirements for Mars must become part of the everyday thinking of lunar exploration. Even if some Mars "requirements" add incremental cost, the long-term payoff may well justify that investment. It is also likely that such investment will result in a more effective and productive lunar exploration.

### 3.2 Primary differences between crewed missions to the Moon and Mars

A. Both Mars and the Moon have very dry, rocky, dusty terrain and both have a lower gravity field than Earth. But the martian gravity level at its surface is more than twice that of the Moon, so that the relatively heavy portable life support systems (PLSS) built into spacesuits that were used in the Apollo missions would be far too heavy for use on Mars.

B. Mars also has a sensible atmosphere, which profoundly affects the engineering challenges of safe entry, descent and landing (EDL) as well as operations on the surface. The EDL phase of landed missions for Mars requires an aeroentry heat shield with thermal protection of the aft-body. All Mars missions to date have also used a large disk-gap band parachute deployed at supersonic velocities to further reduce the entry velocity. Retrorockets have been used for terminal propulsion, augmented by crushable legs or air bags. In many areas of Mars, the population of angular rocks is very high. On Mars, high near-surface winds must be accounted for in this terminal descent system.

C. The presence of an atmosphere and further distance from the Sun moderates temperature swings on Mars. On the Moon, peak daytime temperature of soil can reach +120 deg C or more, i.e., higher than the *boiling* point of $H_2O$. On Mars, excursions above the *freezing* point of $H_2O$ are brief, restricted in both location and season. The day-night temperature swings on the Moon are about 300 deg C in amplitude, whereas on Mars diurnal cycles vary by 60 to 100 deg C.

D. Lunar dust sticks to cloth because of the Velcro-like action of glass blebs on the surfaces of grains created by relentless bombardment by hypervelocity micrometeoroids. Small meteoroids encountering Mars are ablated and slowed in the martian atmosphere before reaching the surface. On the other hand, the martian dust is a far finer grain size than lunar regolith, presumably because of being created by a combination of physical and chemical weathering. Dust devils are common in many places on Mars, but absent on the Moon. Methods of filtration and cleaning to mitigate dust may be somewhat different, but could also have important similarities. Rovers on Mars have gotten bogged in low bearing-strength soils which so far have not been encountered on the Moon.

E. The Moon is much closer to Earth in distance and in travel time (although there is not a proportionate reduction in 'propulsion energy requirements' because lunar missions do not benefit from aeroentry, or atmospheric drag, which reduces descent delta-velocity requirements for Mars missions, whereas lunar missions require all-propulsive maneuvers).

Aborting from a lunar mission for reasons of crew safety is quite feasible, as Apollo 13 demonstrated, but aborting a Mars mission is almost out of the question after the first week or so in space, with the exception of forgoing a landing for a long, slow, free return abort. Communications latency to the Moon requires about three seconds in an optimum case, and is not significantly more difficult than delays using geosynchronous satellite links. For Mars, roundtrip light travel time is up to forty minutes, and dips to eight minutes for only a short portion of mission time. Teleoperation of rovers on Mars has proven to be a distinctly different operation mode from the "joysticking" that is possible for rovers on the Moon. For this reason, it is often thought that martian astronauts must have far greater operational autonomy than lunar astronauts have ever been afforded. The long time in space and inaccessibility for resupply for a Mars mission will likely demand closed-loop regenerative processing of life support commodities such as air and water. Such has not been found necessary for Moon, shuttle and space station operations because of their more limited duration missions and reasonably frequent ability to resupply from Earth.

F. In situ resource utilization (ISRU) at Mars is far different because of the availability of a key ingredient, carbon dioxide, in the atmosphere. Also, water is present in almost all martian soils and ice deposits are likely within a few meters of the surface at many mid and high latitudes on Mars. Neither $CO_2$ nor $H_2O$ are present at these high levels on the Moon, except possibly in permanently shadowed polar traps. Extraction of lunar oxygen will be from regolith minerals, whereas on Mars it can be from the atmosphere or soil water. The specific engineering systems will be different, but gaining experience in operability of systems requiring access and processing of surface materials at the Moon could demonstrate generic feasibility (or difficulty) of such systems for Mars (see Section 4.4 for a detailed discussion of the special case of ISRU).

G. Another key difference is the requirement for planetary protection, which is serious for forward contamination of Mars but with even more serious safeguards needed to assure protection against back contamination. Although the Apollo program had some measures in place to achieve these, it was quickly decided that they were not necessary and will not be required in future missions. Because the Moon is sterile, it can provide a useful testing ground, to assess the effectiveness of forward contamination preventative measures. should the lunar program be willing to develop its habitats and spacesuits with this as an engineering requirement.

**FINDING #1. The issues associated with flying crewed missions to the Moon and to Mars are similar in some ways and quite different in others. Thus, only some of the developments/lessons learned associated with human exploration of the Moon will be directly relevant to Mars and a Mars-dedicated program will be necessary to resolve remaining issues.**

### 3.3 Preparation for Mars Exploration

Preparing to send humans to Mars within acceptable risk standards will require a variety of precursor development work. We can organize this development work into four distinct portions according to venue: activities done at Mars, at the Moon, in Earth orbit, and on the Earth. As pointed out by Hinners et al. (2005), there is a well-defined progression in cost across this sequence—doing things at Mars is much more expensive than doing them on the Earth. This derives from the obvious but all-to-frequently unstated fact that as one moves away from Earth, the amount of data and the flexibility of experiment design, testing and re-test progressively decrease and the cost escalates dramatically. We cannot justify acquiring information at Mars if information of acceptable quality and utility can be acquired less expensively on Earth. As an example, experimenting with and developing a closed-loop space-qualified life support system is easier and cheaper to do on Earth followed by first flight demonstration on ISS.

- The NRC's Safe on Mars report (Space Studies Board, 2002), and the MEPAG Mars Human Precursor analysis (Beaty et al., 2005 and Hinners et al., 2005) are recent analyses of the measurements and flight demonstrations required at Mars to reduce the risk of the first Mars human mission to acceptable levels. In the case of the MEPAG analyses, it was assumed that any work that could be done at a lower-cost venue (Moon, LEO, Earth) would not be done at Mars, and was explicitly excluded from consideration. The NRC and MEPAG studies therefore have the form of a 'must-do' list for the Mars part of the problem.
- The present planning exercise regarding the Moon has the form of a large 'could-do' list, which as of this writing had not been distilled to its essential requirements. These various possible objectives are driven by a variety of reasons, only one of which is preparation for Mars. Thus, the standard for evaluating the degree of importance to Mars human preparation is different than for a dedicated Mars mission. We are not asking whether the same objective (from the perspective of Mars) can be accomplished less expensively in LEO or on Earth. It is a given that we will be going to the Moon, and it is up to us to derive as much benefit from the opportunity as possible.
- An analysis of the portion of the Mars preparation activity that could optimally be carried out in low Earth orbit or on Earth has not yet been produced.

It is becoming increasingly clear that a plan describing the full spectrum of activity required to prepare for the conduct of safe human missions to Mars is essential. Even though such a plan would need to be carried out over an extended period of time, and the work would certainly be sponsored by a variety of funding entities (on an international basis), without this we don't have a clear means of knowing how the pieces all fit together, how they relate to each other, and whether there are gaps that are not being worked at all. In particular, this would help us to understand the importance of the various R&D activities taking place on Earth at Mars analog field sites, in laboratories, in engineering test facilities, and by means of computer simulations.

**FINDING #2. Preparing for crewed missions to Mars will involve a four-component program consisting of Mars robotic precursors, preparation work at the Moon, work in LEO, and work done on the Earth. These four components are currently unevenly and incompletely planned.**

# 4. Analysis of Priority of Draft Lunar Objectives to Mars

## 4.1 Prioritization Scale

In assessing the relevance of the lunar objectives to Mars exploration and science, the MFLO SAG felt that a simple binary response was inadequate and that it is more useful to indicate the **degree** of relevance to Mars; Therefore, a prioritization scale, consisting of the following definitions, was developed and used to rate the degrees of relevancy.

Essential Precursor Requirement => An activity that must be performed on the Moon, as a precondition to human exploration of Mars, which is considered enabling and therefore is a firm requirement that must be met, and one that might only be achieved through the lunar exploration program.

High Relevance => An activity that, given the lunar program, could be performed on the Moon as a precursor to Mars exploration, which is considered of sufficient value and priority that it warrants a marginal investment to assure maximum relevance to Mars (i.e., there is a high correspondence between the activity at the Moon and the fidelity of a representative capability that is needed at Mars, and this is seen as a cost effective, and timely means to achieve this goal).

Medium Relevance => An activity that, while it could be performed on the Moon, might be more effectively accomplished by other means - Earth analogs, space station, robotics precursors, etc. (i.e., there is a less compelling rationale that these activities need to be demonstrated on the Moon, and/or, there may be more efficient (lower costs) or more relevant means (higher fidelity) to achieve these goals).

Low Relevance => An activity that is of low priority for the 'Mars Human Precursor-Lunar Program' (MHP-LP) that would be better demonstrated by other means. (i.e., demonstrating this on the Moon is of sufficiently low value that this should not be a part of the MHP-LP).

(No score, or 'X') => n/a - An activity, which while possibly serving other needs, is not seen as relevant to the MHP-LP.

### 4.2 General Relevance of Lunar Program to Preparation for Mars

The MEPAG MFLO SAG examined the draft lunar objectives from two perspectives including 1) relevance to preparation for Mars human missions and 2) relevance to better understanding Mars scientifically. MFLO study results indicate that a significant fraction of the lunar objectives have some (variable) degree of relevance to Mars. The qualifier is significant in that no objective was considered absolutely essential (i.e., absolutely required before one could conduct Mars human exploration). In other words, one could proceed today with preparation for Mars human exploration without an intervening lunar program. Notably, no Mars-relevant objectives were deemed missing from the lunar objectives. Neither of these observations negates the potential utility of lunar exploration in preparing for Mars; the lunar exploration program offers many opportunities to better prepare for Mars. In that spirit, the MFLO SAG examined the individual objectives and suggested modifications that could improve the relevance to Mars. Additionally, as mentioned in the previous section, a priority ranking was assigned to each objective, rather than simply checking the box of relevant or non-relevant. The lunar program has not yet incorporated this prioritization approach; we recommend that this be done as the total set of lunar objectives is further refined.

**<u>FINDING #3.</u> The presently-considered lunar program has some relevance to Mars, and this relevance could be increased with revisions to some of the lunar objectives. Proposed rephrasing is described in the appendix to this report.**

### 4.3 Relationship of Lunar Program to MEPAG Goal IV: Prepare for Human Exploration

MEPAG has conducted an analysis of the robotic science measurements and engineering/technology developments that could accomplish significant risk-reduction for Mars human exploration (MEPAG, 2006). The Goal IV study pertaining to "Prepare for Human Exploration" had two major objectives A: Obtain knowledge of Mars sufficient to design and implement a human mission with acceptable cost, risk and performance and B: Conduct risk and/or cost reduction technology and infrastructure demonstrations in transit to, at, or on the surface of Mars.

When Goal IV was developed, it was assumed that any work that could be done somewhere other than Mars (e.g. on Earth, in Earth orbit, on the ISS, or on the Moon) would be done in these alternative locations. Nevertheless, as a sanity check, the MFLO SAG examined Goal IV to re-assess whether any of its objectives could instead be accomplished on the Moon. The finding is "No", reinforcing that some objectives must be carried out at or on Mars well before one can conduct a human exploration mission. Our reassessment had an ancillary positive benefit of helping determine where selected lunar objectives could be made more relevant to Mars preparation. Our proposed re-writes of selected lunar objectives reflects that perspective.

**<u>FINDING #4.</u> Carrying out the lunar investigations under consideration will not lead to a reduction in the requirements in MEPAG Goal IV (Prepare for Human Exploration). Goal IV considers measurements and technology demonstrations that can <u>only</u> be done at Mars.**

### 4.4 A Special Case: ISRU Moon/Mars Linkages

Elements of ISRU (in situ resource utilization) constitute many of the objectives of the lunar exploration program. It is recognized as a potentially valuable technique to significantly reduce the mass carried to the Moon and thus reduce the cost of lunar exploration and to be relevant to Mars. Indeed, similar objectives have been stated for future Mars human exploration and MEPAG Goal IV addressed the Mars-unique aspects of ISRU. Given the greater cost of carrying mass to Mars, its application at Mars takes on greater importance; some believe that ISRU may be, along with other mass-saving approaches, enabling of a human Mars mission. That said, for both the Moon and Mars, the potential of ISRU is subject to major uncertainties regarding the nature of the resources present, their accessibility, future supply/demand relationships, and technical/economic factors involved in extraction, production, storage and utilization processes.

Developing and proving out certain basic ISRU capabilities on the Moon has direct relevance to its application to Mars. However, there are significant, non-trivial differences. On the Moon, regolith silicates and ilmenite are a known widely available resource. They each require extensive energy to extract oxygen and have unique processing requirements. The possibility that exploitable hydrogen exists in permanently shadowed polar regions gives hope that an easily extractable source of fuel will be available. For Mars, atmospheric $CO_2$ and hydrogen (most likely as water) are widely present and likely obviate the need to use silicates.

The ultimate value of lunar ISRU experience to future Mars application depends to a significant degree on resolution of many details concerning both the Moon and Mars. This uncertain but potentially important relationship between use of lunar ISRU and martian ISRU needs further study to enhance the potential of Mars ISRU.

**FINDING #5. There is an uncertain but potentially important relationship between lunar ISRU and martian ISRU that needs further study to enhance the potential of Mars ISRU.**

### 4.5 Science Linkages between the Moon and Mars

Lunar planetary science investigations are not required to prepare for human exploration of Mars. However, one of NASA's goals pertaining to the lunar program is to ensure "maximum possible utility for later missions to Mars". Based on this goal, there are important scientific concepts that could be developed on the Moon that will provide valuable insights into understanding Mars as a planet. The scientific linkages between the Moon and Mars were most recently examined in the MEPAG white paper *"Findings of the Moon→Mars Science Linkage Science Steering Group"* (Shearer et al., 2004). This analysis group reviewed this document and concluded that the basic scientific linkages were still valid.

The Moon→Mars Science Linkage Steering Group (2004) and the Exploration Strategy Workshop (2006) identified fundamental science themes that are relevant to understanding both the Moon and Mars. The science themes are cross-referenced in this discussion.

A. *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. 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. Understanding the internal structure and mantle dynamics of a second planetary body (the Earth being the first) will provide invaluable insights into the dynamical history of the martian mantle and core, the history of the martian magnetic field, and the evolution and structure of primary planetary crusts.

The Moon presents the best opportunity to geochemically characterize early fundamental processes of a planetary body of substantial size, including the early differentiation into component parts, the production of an early crust, and the genesis of basalts from various mantle depths. Much of the first billion years of planetary geochemical evolution is not available on Earth. In this regard the Moon and Earth represent end-member bodies in that the Moon reveals early geochemical processes, whereas the Earth is a continually active planet. Mars probably represents an intermediate case.

B. *Evolution of Planetary Surfaces*: 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. Understanding the character of the impact history of the inner solar system from 4.5-3.8 Ga is fundamental to reconstructing the planetary surface environments under which life arose, especially determining whether or not there was a "late cataclysm" or spike in impact cratering at 3.9 Ga. Further, the early impact history played a role in the early atmosphere, early tectonics, and the delivery of volatiles. All of these are tied to the important Mars theme of "follow the water". Also, impact history may have a role in planetary asymmetry that is relevant to understanding both the Moon and Mars.

Establishing a well-defined impact flux for the Earth-Moon system for the last 3.8 Ga is a step in better understanding the impact flux on Mars. Such an understanding will help to construct timelines for erosional, depositional, and volcanic features on Mars. Further, minor spikes in impact flux that have been suggested for the Earth-Moon system during this period of time may have been experienced by Mars. This clearly had an influence on evolution of life in the Earth-Moon system. Is it relevant for Mars?

C. *Record of Volatile Evolution and Behavior*: 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 where the study of lunar volatiles may be relevant to Mars. One example is "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.

D. *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. Therefore, astrobiology research questions provide many linkages between lunar exploration and Mars science goals. 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 (especially during the first billion years), the composition of large impactors and interplanetary dust particle (IDP) flux, the delivery of exogenous volatiles and organics molecules, history of solar activity (solar wind; flares) and the 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.

Fulfilling many of the scientific goals associated with these Moon-Mars linkages requires the development and utilization of instrumentation that is much more technologically complex than used by Apollo or current Mars exploration missions. Deploying (either robotically or by humans) and maintaining a long-lived and highly sensitive geophysical network on the Moon is relevant to deploying such a network on Mars. The sampling of diverse and environmentally hostile terrains on both the Moon and Mars is important for all themes listed above. Development of sample collection strategies that extend the capabilities of humans through robotics is critical. The development of deep drilling technologies provides 1) access to regions that are unexplored by surface studies and 2) links between the surface and the deep planetary interior.

**FINDING #6. The primary scientific linkages between Mars and the Moon were recently (2004) evaluated by MEPAG; those linkages are reaffirmed.**

### 4.6 Completeness

The MFLO-SAG was not able to identify any significant gaps in the form of objectives of importance to Mars that are not present in the draft list of lunar objectives.

**FINDING #7. The draft list of lunar objectives is not missing objectives of importance to preparation for Mars.**

### 4.7 Mars as a Core Theme for the Lunar Program

The MFLO team considered several different programmatic options to achieve the goal of keeping Mars exploration in the forefront of the lunar program. Since the lunar program will serve as a precursor to Mars exploration, it is important that the lunar program architecture be consistent with achieving the needs of a Mars precursor program.

The options considered for keeping Mars as a signpost out in front of the lunar program included:

1) Describe Mars exploration as a core theme (or goal) of the lunar program and use Mars exploration as a prioritization criterion for the lunar objectives.
2) Describe Mars exploration as a cross-cutting theme which may have the effect of emphasizing the multiple linkages to Mars in many different areas.
3) Make Mars exploration a specific lunar objective. The specific tasks associated with this objective would be broad and Mars-unique. This would potentially ensure that components

designed for use on the Moon could be used with little or no modification on Mars.
4) Describe Mars exploration as a prioritization criterion rather than a theme or objective. If the intent is to use Mars-relevancy as a way of optimizing the lunar program, this could be applied as a prioritization factor to all of the lunar objectives.

The MFLO SAG consensus regarding the best way to ensure that the lunar program is designed for maximum relevancy to Mars exploration is to *leave Mars as a core theme within the lunar program*. Considering Mars as a core theme within the lunar program helps to keep the relevancy of the lunar objectives over a broad range of topics consistent with the notion of utilizing the lunar program as a precursor for Mars exploration. Additionally, using Mars exploration as a prioritization criterion for the lunar objectives will also help ensure the maximum utility of the lunar program for future Mars exploration.

**FINDING #8. The "Preparation for Mars" theme provides a compelling focus for the lunar program. The utility can be maximized by using "Preparation for Mars" as a prioritization criterion for lunar objectives.**

## 5. References


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## 6. Appendix

Appendix 1 and Appendix 2 list specific lunar objectives with a perceived relevance to Mars exploration in terms of preparation for humans and science linkages, respectively. The charts also indicate the relevance assessments regarding Mars for each lunar objective. Note that these charts only contain those lunar objectives with a perceived relevance to Mars exploration and other lunar objectives with no perceived relevance to Mars are not listed here.

The information contained within the charts (Appendix 1 and Appendix 2) is as follows. The "Objective ID Number" references the specific objective originally listed in the draft lunar objectives. The "Name" column describes this objective in more detail. Within the "Name" category, cells in green represent the original text describing the lunar objective while cells in blue were rewritten by the MFLO SAG to provide more relevance to Mars. The "Prepare for Mars Priority" (Appendix 1) and "Relevance to Understanding Mars" (Appendix 2) columns indicate a high (H), medium (M), or (L) relevance to Mars exploration (see detailed explanation of ranking definitions in Section 4.1). The "Discussion" column captures the rationale of the MLFO SAG regarding the assessment of each lunar objective.

Appendix 3 is a list of acronyms used in this paper.

## APPENDIX 1: Lunar objectives with relevance to preparation for human Mars exploration.

| Objective ID Number | Name | "PREPARE FOR MARS" PRIORITY | Discussion |
|---|---|---|---|
| **mENVMON1** | Monitor space weather to determine risks to lunar and martian inhabitants. | **H** | Will need similar capability for Mars program; establishing the capability for lunar will make it easier to develop for Mars application; Part of global space weather network |
| **mEHM2** | Evaluate and employ dust mitigation techniques to protect crews, materials, and instruments during extended lunar stays using materials and techniques that will be available on a Mars mission (where applicable given the different dust characteristics of the Moon and Mars). | **H** | Dust environment on Mars more difficult - finer and oxidizing but basic techniques are applicable; dust is a potentially high hazard at both the moon and Mars and while the types of risks may be different, learning to control this at the moon would clearly benefit Mars. |
| **mTRANS2** | Demonstrate autonomous lander capability which utiizes technologies and operations relevant to autonomous landing on Mars. | **H** | Some commonaility in technology and operations which might be directly transferable; needed at the moon, some correspondence with Mars likely |
| **mOPS1** | Develop human surface operations capability on the Moon which is consistent with the operational requirements and restraints of a Mars mission. | **H** | Can't do nearly as will in other venues; Earth analogs less demanding, thus validation at the moon is useful |
| **mEOR1** | Provide opportunities to engage the public through direct and indirect participation in solar system exploration activities to increase public support of the space program. | **H** | Getting the public well involved in understanding how lunar prepares for Mars would be a good goal; public excitement about lunar exploration will help generate support for Mars exploration, as well |
| **mEOR2** | Extend awareness of space activities to diverse, non-traditional communities, utilizing non-traditional means, to enhance public engagement. | **H** | Getting the public well involved in understanding how lunar prepares for Mars would be a good goal; public excitement about lunar exploration will help generate support for Mars exploration, as well |
| **mEOR3** | Demonstrate the value of solar system exploration activities for Earth to raise public awareness of the exploration program. | **H** | Getting the public well involved in understanding how lunar prepares for Mars would be a good goal; public excitement about lunar exploration will help generate support for Mars exploration, as well |
| **mEOR4** | Provide opportunities to educate students through direct and indirect participation in solar system exploration activities to engage students in the space program. | **H** | Getting the public well involved in understanding how lunar prepares for Mars would be a good goal. Extend to Mars; public excitement about lunar exploration will help generate support for Mars exploration, as well, and in this case, more importantly will help develop the next generation of explorers, as well. |

| Objective ID Number | Name | "PREPARE FOR MARS" PRIORITY | Discussion |
|---|---|---|---|
| **mPE1** | Reduce bureaucracy associated with national space programs. | **H** | True, as we canot afford to implement this in any other way, but this is fundamental, independent of any specific goal or destination |
| **mPE2** | Define and execute a long-term exploration strategy, that includes the objectives of all stakeholders, to organize and time-phase future activities. | **H** | Concur that this is an essential step, and recognize that this is the purpose of the current more inclusive Exploration Program Planning (including this exercise), and that this is the equivalent of getting a community behind the Grand Observatories. |
| **mLSH3** | Develop and deploy Closed Life Loop Support Systems to increase self sufficiency of future long duration human exploration missions. | **H** | Basic goals and techniques will be useful for Mars prep. Could do much of this on ISS; while useful, this could be validated at ISS, which is a better analog for the worst case free return abort, and would directly benefit ISS, as well |
| **mTRANS1** | Utilize the commercial sector to provide transportation services on the Moon and to and from the Moon to increase access to the Moon and traversing the Moon. | **H** | Transportation elements and technology for lunar missions will contribute and/or be usable for Mars |
| **mOPS3** | Conduct Mars Analog tests on the lunar surface. | **H** | Of necessity, the lunar surface environment provides a useful analog to future Human Mars Missions, as Astronauts will be operating, for increasingly longer periods of time, in a reduced gravity field, hazardous radiation and dust laden environment, that is also remote, extreme and isolated, which provides opportunities to validate potential countermeasures that will be needed for future Human Mars Missions. |
| **mLSH1** | Provide safe and enduring habitation systems to protect individuals, equipment, and associated infrastructure. | **H** | Basic goals and techniques will be useful for Mars prep; this would be useful to Mars Exploration, as in many ways this is a more harsh environment for habitats than at Mars, and it is a better simulation than test chambers at Earth; however, the notion of evolving to greater closure over time at the moon is a costly, and higher risk approach, and this evolution should be accomplished on Earth and validated on the moon |
| **mLSH2** | Develop biologically based life support system components to support long duration human exploration missions. | **H** | Basic goals and techniques will be useful for Mars prep; Bioregenative LSS systems are critical for high loop closure, and while the environment is more challenging at the moon, this would be helpful to Mars, although ISS could validate the micro-g issue |

| Objective ID Number | Name | "PREPARE FOR MARS" PRIORITY | Discussion |
|---|---|---|---|
| **mHH1** | Study the effects of the lunar environment on human health. Understand the unique contributions of different environmental aspects (e.g. dust, fractional g, radiation) to improve our capability to understand, predict, and mitigate human health effects at Mars. | **H** | A good reference point. Can be done in conjunction with earth-based partial g simulators, i.e., validate models; this is one of the more compelling reasons to validate human countermeasures on the moon, however, the worst case scenaio would be a free-return abort from Mars, which could be validated on ISS |
| **mHH2** | Understand the affects of fractional gravity on human performance and human factors. | **H** | A good reference point. Can be done in conjunction with earth-based partial g simulators, i.e., validate models; although the Maritian gravity is ~ 2.3 times lunar, this is one of the few ways we can validate partial-g activities, prior to Mars, though this (human performance) is a lower ppriority than mHH1, it has the same higher rating, because of the unique environment required to evaluate this |
| **mLRU1** | Understand 1) the resource potential of the Moon and 2) the relative relevance levels of different lunar resources in terms of similarity of ISRU processing techniques at Mars. | **M** | Not directly applicable per se. Techniques, trade-offs, engineering implementation could be useful; The resources - including environental conditions are very different, the processes are different, etc. |
| **mLRU2** | Use lunar resources and the corresponding ISRU techniques that exhibit the highest degree of technology and operations extensibility to Mars ISRU. | **M** | Not directly applicable per se. Techniques, trade-offs, engineering implementation could be useful; The resources - including environental conditions are very different, the processes are different, etc., although the actual development and use of propellantss might inspire confidence for its use at Mars (though different) |
| **mENVCH3** | Characterize radiation bombardment of the lunar surface to a) better understand the operational environment of the Moon, b) validate and improve radiation modeling capabilities, c) use this knowledge to improve our understanding of the radiation environment of Mars. | **M** | To prepare for Mars, the radiation environment is best measured in free space over a long duration of time. This is currently underway by operational spacecraft. The experiment that has been proposed for Mars is to have radiation monitoring equipment simultaneously operating in martian orbit and on the surface, to assess the effects of the atmosphere on dose increases due to secondary radiation emissions. Lack of an atmosphere on the moon eliminates the possibility of a similar evaluation there. |
| **mENVCH4** | Characterize micrometeorite bombardment of the lunar surface to better understand the operational environment of the Moon. | **M** | This is applicable at Mars, especially for long stays in orbit or in-transit. |

| Objective ID Number | Name | "PREPARE FOR MARS" PRIORITY | Discussion |
|---|---|---|---|
| **mEHM1** | Develop radiation shielding materials and techniques for lunar surface operations to protect crews, materials, and instruments that are consistent with materials and techniques that will be available on a Mars mission. | **M** | Operational protocols to mitigate radiation hazards could be tested on the moon and will help evaluate the effectiveness of such approaches. There is no need for electronics or materials testing on the moon to evaluate radiation hazards, since there already exists a large data base for radiation effects on parts and materials based on dozens of spacecraft which operate under such conditions, and the state of the art in aerospace engineering has mitigated adverse effects for conditions equal to or exceeding the lunar environment. |
| **mPWR1** | Develop lunar power generation and storage systems required to facilitate increasing surface durations using techniques and systems that are applicable to a crewed Mars mission. | **M** | Power needs on Mars may require the development of nuclear reactors, especially if ISRU is to become viable. Development of large power sources and storage devices for the moon are likely to be transferable to Mars applications. |
| **mGINF5** | Develop lunar rescues systems with the maximum extensability to Mars. | **M** | Similar needs at Mars; experience directly transferable but there will be unique Mars requirements; a comparible capability required at Mars but requirements are different |
| **mLRU5** | Provide safe utilization of ISRU resources through demonstrations of systems with the highest degree of extensibility to Mars. | **M** | The development of lunar protocols for the safe operation and utilization of ISRU is of direct applicability to consideration of ISRU at Mars. It is an essential enabler. Initial protocols should be developed and thoroughly tested on earth prior to any planetary applcation. |
| **mLRU9** | Perform lunar resource excavation, transport, delivery, and construction on the lunar surface with techniques that provide the highest degree of extensibility to Mars. | **M** | The development of excavation, transport and delivery techniques for large amounts of surface material may have applicability to Mars. The transfer of experience will be a strong function of the specific ISRU approach. Use of water and the atmosphere on Mars would likely present greatly different challenges than the mining of bulk regolith on the moon (water in lunar polar regions has more direct applicability). |
| **mLRU10** | Develop and demonstrate the tools, technologies, and systems to extract and process the resources on the Moon that are most relevant to those on Mars. | **M** | The development of extraction and processing techniques may have general applicability to Mars. The transfer of experience will be a strong function of the specific ISRU approach. Use of water and the atmosphere on Mars would likely present greatly different challenges than the mining and processing of bulk regolith on the moon (water in lunar polar regions has more direct applicability). The greatly differing environmental conditions at Mars will necessitate significantly differing engineering solutions to, e.g., storage. It is dubious that commercial applications will be applicable to early Mars exploration. |

| Objective ID Number | Name | "PREPARE FOR MARS" | Discussion |
|---|---|---|---|
| **mGP5** | Use the Moon to stimulate next generation planetary protection policy and develop internationally recognized mechanisms to comply with policy, e.g., to prevent forward contamination of Mars and back contamination of the Earth/Moon system. | **M** | Present PP policy for Mars is incompatible with human missions (for example, the maximum allowable bioload is exceeded by the digestive tract of a single human). The policy will need to evolve to support future crewed missions. |
| **mOPS2** | Demonstrate remote training and planning in support of crewed Mars missions. | **L** | This type of demonstration can be done on earth; this is done routinely on Earth as part of mission training |
| **mNAV1** | Establish lunar GNC capabilities that are scalable to support a crewed Mars mission. | **L** | The techniques would be similar but not tough do at Mars without the lunar precursor; while needed at the moon, and potentially useful for Mars, the challenges are far more severe, and these would likely be mitigated with robotic Mars precursor missions, not lunar analogs |
| **mENVMON2** | Monitor real-time environmental variables on the lunar surface affecting safe operations utilizing technology and operations applicable to a crewed Mars mission. | **L** | Will need similar capability for Mars program but has to be done at Mars; of little direct benefit to Mars |
| **mGEO8-1** | Characterize lunar volatiles. | **L** | Has low relevance. Will provide some insight into the exogenous contribution to the Mars volatile reservoirs and the nature of pre-biotic components. |
| **mHH3** | Improve remote medical practice infrastructure and technology for fractional gravity; test health care systems on the Moon for use on Mars. | **L** | The development of improved medical techniques for long duration human space flight is needed. Those applicable to the lunar case, however, can provide a beginning basis for Mars application but will not be nearly sufficient. The Mars situation of much longer trip time, no possible abort to earth for most of the mission and a more likely occurrence of emergency medical situations will require more attention and investment than for the moon. |
| **mOSS1** | Conduct surface mission operations on the lunar surface to learn how to function on long duration planetary missions (with timescales applicable to early crewed Mars expeditions). | **L** | This has general applicability to Mars but will differ in specifics. Many of the suggested tasks appear to be applicable to ISS and earth analogs, both of which provide a better environment for experimentation prior to implementation. The lower gravity of moon and Mars does not appear to be a major factor. |
| **mCOM1** | Implement a reliable lunar telecommunications capability that is scalable to a system with capability to support a crewed Mars mission. | **L** | The challenges of communications on Mars appear to be significantly greater than on the moon due to the greater distance (thus lag time) and surface to surface transmission differences. Development of improved crew person-to-person communications and associated positional tracking techniques could be transferable. |

| Objective ID Number | Name | "PREPARE FOR MARS" | Discussion |
|---|---|---|---|
| **mSM1** | Develop and implement surface mobility systems to support both crew and cargo traverses over distances applicable to a crewed Mars mission. | **L** | The details of mobility on Mars will differ significantly due to a greatly differing environment and possibly tasks. The inherent safety issues suggest that mobility will always be limited to a safe "walk back" distance. This is an area where robotic assistants could play a major role. |
| **mOPS6** | Take advantage of the unique lunar envionment to create recreation activities for lunar crews and visitors. | **L** | The development of recreational activities will indeed be needed for both moon and Mars. Much can be learned from earth analogs (submarines, antarctic stations) and ISS. The possibility of commercial /tourist applications at Mars is not relevant for the foreseeable future. |
| **mLRU3** | Reduce reliance on Earth to create a self-sustaining lunar ecology. | **L** | If this means test and utilize integrated ISRU and ECLS systems, then **L** for technology and techniques |
| | NEW | **L** | Deep drilling is likely to be a desired capability at Mars. Development the tehniques for both robotic and human-tended drilling on the moon will have applications for Mars science and ISRU. |
| **mGP1** | Establish a global partnership framework to enable all interested parties (including non-space faring nations and private companies) to participate in lunar exploration. | **L** | Working this for the Moon might somewhat reduce barriers to cooperation re Mars |
| **mGP2** | Establish standards and common interface designs to enable interoperability of systems developed by a global community. | **L** | Working this for the Moon might somewhat reduce barriers to cooperation re Mars |
| **mGP3** | Establish the legal framework required to support global collaboration / cooperation on lunar exploration. | **L** | Working this for the Moon might somewhat reduce barriers to cooperation re Mars |
| **mGP4** | As necessary, establish appropriate legal governance of lunar surface and orbital activities to enable commercial and governmental involvement. | **L** | Working this for the Moon might somewhat reduce barriers to cooperation re Mars |
| **mOPS7** | Evaluate biological and biochemical contamination control protocols and astrobiology measurement technologies that will be used to search for life on the planets. | **L** | We separate astrobiology from planetary protection. The use of the moon, a sterile environment, to test the ability to maintain a pristine environment while conducting life-detection experiments or searches on Mars has merit. There is no similar (practical) terrestrail environment. |

# APPENDIX 2: Lunar objectives with relevance to understanding Mars

| Objective ID Number | Name | "RELEVANCE TO UNDERSTANDING MARS" PRIORITY | Discussion |
|---|---|---|---|
| mGEO1-1 | Determine the internal structure and dynamics of the Moon using a long-lived and extensive network of lunar seismometers. | H | (1) Understanding the internal structure and mantle dynamics of a second planetary body (the Earth being the first) will provide invaluable insights into the dynamical history of the martian mantle and core, the history of the martian magnetic field, and the evolution and structure of primary planetary crusts. (2) Deploying and maintaining a highly sensitive seismic network on the Moon is relevant to deploying a network on Mars. |
| mGEO1-2 | Determine the diversity of crustal rocks, including the nature of the magma ocean, to better understand planetary differentiation processes and the structural and geochemical components of the lunar crust and mantle, including their interactions. | H | (1) Understanding the internal structure and mantle dynamics of a second planetary body (the Earth being the first) will provide invaluable insights into the dynamical history of the martian mantle and core, the history of the martian magnetic field, and the evolution and structure of primary planetary crusts. (2) Deploying and maintaining a highly sensitive seismic network on the Moon is relevant to deploying a network on Mars. |
| mGEO4-1 | Characterize the flux of impacting bodies in the Earth-Moon system during early solar system history, with emphasis on time variations in flux of objects, the nature and origin of the impactors and their possible role in delivering volatiles, the nature o | H | Understanding the character of the impact history of the inner solar system from 4.5-3.8Ga is fundamental to reconstructing the planetary surface environments under which life arouse. Further, the early impact history played a role in the early atmosphere, early tectonics, and the delivery of volatiles. All of these are tied to the important Mars theme of follow the water. Also impact history may have a role in planetary asymmetry. |
| mGEO4-2 | Characterize the crater production function (i.e., impactor flux as a fuction of size) for the Moon over the past 3.5 billion years. | H | Establishing a well defined impact flux for the Earth-Moon system for the last 3.8 Ga is a step in better understanding the impact flux on Mars. Further, minor spikes in impact flux that have been suggested for the Earth -Moon system during that period of time may have been experienced by Mars? Clearly an influence on evolution of life in the Earth-Moon system. An influence on the evolution of potential habitats on Mars? (misspelling of function) |
| mGEO6 | Understand the nature and history of solar emissions. | H | Reconstructing the history of the sun has high relevance to potential evolution of life on Earth and Mars. |
| mOPS7 | Evaluate biological and biochemical contamination control protocols and astrobiology measurement technologies that will be used to search for life on the planets. | M | The understandings gained in assessing these PP implications will be of relevance to the design of experiments searching for life on Mars. |

| Objective ID Number | Name | "RELEVANCE TO UNDERSTANDING MARS" PRIORITY | Discussion |
|---|---|---|---|
| mGP5 | Use the Moon to stimulate next generation planetary protection policy and develop internationally recognized mechanisms to comply with policy, e.g., to prevent forward contamination of Mars and back contamination of the Earth/Moon system. | M | The understandings gained in assessing these PP implications will be of relevance to the biological exploration of Mars,perhaps including the strategies for MSR. |
| mGEO5-2 | Study meteorite impactors on the Moon. | M | Understanding the character of the impact history of the inner solar system from 4.5-3.8Ga is fundamental to reconstructing the planetary surface environments under which life arouse. Further, the early impact history played a role in the early atmosphere, early tectonics, and the delivery of volatiles. All of these are tied to the important Mars theme of follow the water. Also impact history may have a role in planetary asymmetry. This task is less important than mGEO4-1 |
| mGEO1-4 | Understand the origin and structure of the Moon. | M | Modified summary to remove discussion of exogenous (delivered from outside the Moon) volatile reservoirs. This is considered in mGEO8-1. Understanding the endogenous volatile reservoirs and mantle volatile budget on the Moon is relevant to Mars it provide |
| mGEO1-3 | Understand the origin and structure of the Moon. | M | Characterizing these geophysical parameters in a planetary body other than Earth enables a more fundamental understanding, but of the importance of these parameters on Mars. |
| | NEW | M | Deep drilling is likely to be a desired capability at Mars. Development the tehniques for both robotic and human-tended drilling on the moon will have applications for Mars science and ISRU. |
| mGEO2 | Characterize new impact events similar to those that would degrade more quickly on other planets. | L | Contribute to our understanding of recent impact flux in the Earth-Moon system that could then be compared to Mars. (also misspelling of morphology) |
| mPWR1 | Develop lunar power generation and storage systems required to facilitate increasing surface durations using techniques and systems that are applicable to a crewed Mars mission. | L | |
| mOPS3 | Conduct Mars Analog tests on the lunar surface. | L | |
| mLRU9 | Perform lunar resource excavation, transport, delivery, and construction on the lunar surface with techniques that provide the highest degree of extensibility to Mars. | L | |

| Objective ID Number | Name | "RELEVANCE TO UNDERSTANDING MARS" PRIORITY | Discussion |
|---|---|---|---|
| mLRU3 | Reduce reliance on Earth to create a self-sustaining lunar ecology. | L | |
| mGEO8-2 | Characterize lunar volatiles. | L | (1) Modified summary statement to remove exploration tool for resource search and replace water with volatiles. The polar deposits are H deposits (H or H2O). (2) Exploration for resources on the Moon will be different than exploration on Mars. |
| mGEO5-1 | Study meteorite impactors on the Moon. | L | Relevance given in value statement. |

# APPENDIX 3. Acronym list

EDL – Entry, Descent, and Landing
ESMD – Exploration Systems Mission Directorate
EVA – Extravehicular Activity
GRB – Gamma Ray Burst
IDP – Interplanetary Dust Particle
ISRU – In Situ Resource Utilization
ISS – International Space Station
LAT – Lunar Architecture Team
LEAG – Lunar Exploration Analysis Group
LEO – Low Earth Orbit
MEPAG – Mars Exploration Program Analysis Group
MFLO SAG – Mars Forward Lunar Objectives Science Analysis Group
MHP-LP – Mars Human Precursor Lunar Program
MHP SSG – Mars Human Precursor Science Steering Group
NASA – National Aeronautics and Space Administration
PLSS – Portable Life Support System
RFI – Request for Information
SOMD – Space Operations Mission Directorate
SMD – Science Mission Directorate