

An Analysis of the Precursor Measurements of Mars Needed to Reduce the Risk of the First Human Mission to Mars

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Executive Summary

The Mars Human Precursor Science Steering Group was chartered by MEPAG in June 2004 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. Based on this analysis, the MHP SSG proposes the following revised phrasing for MEPAG's Goal IV, Objective A, and within it the investigations that follow (in priority order). The measurements needed to carry out these investigations are described in the subsequent sections of this white paper.

All of the measurements listed below, which are listed in priority order by the degree of impact on risk reduction, would have value to planning the human exploration of Mars (and most particularly the first human mission to the martian surface, for which our lack of knowledge will be greatest). However, the authors of this report are not in a position to determine how much risk needs to be removed in order for the first human mission to be judged acceptably safe. Thus, we cannot a priori determine how many of these measurements need to be successfully completed (i.e. required) before the first human mission can fly. Obviously, a larger precursor program will reduce the risk more than a smaller precursor program. However, the decision on safety thresholds must be deferred to others.

Recommended revision to MEPAG Objective IVA.

Objective A. Obtain knowledge of Mars sufficient to design and implement a human mission with acceptable cost, risk and performance.

The following four investigations are of indistinguishable high priority.

- 1A. Characterize the particulates that could be transported to mission surfaces through the air (including both natural aeolian dust and particulates that could be raised from the martian regolith by ground operations), and that could affect hardware's engineering properties. Analytic fidelity sufficient to establish credible engineering simulation labs and/or performance prediction/design codes on Earth is required.
- 1B. Determine the variations of atmospheric dynamical parameters from ground to >90 km that affect EDL and TAO including both ambient conditions and dust storms.
- 1C. Determine if each martian site to be visited by humans is free, to within acceptable risk standards, of replicating biohazards which may have adverse effects on humans and other terrestrial species. Sampling into the subsurface for this investigation must extend to the maximum depth to which the human mission may come into contact with uncontained martian material.
- 1D. Characterize potential sources of water to support ISRU for eventual human missions. At this time it is not known where human exploration of Mars may occur. However, if ISRU is determined to be required for reasons of mission affordability and/or safety, then, therefore the following measurements for water with respect to ISRU usage on a future human mission may become necessary (these options cannot be prioritized without applying constraints from mission system engineering, ISRU process engineering, and geological potential):

The following investigations are listed in descending priority order.

2. Determine the possible toxic effects of martian dust on humans.

3. Derive the basic measurements of atmospheric electricity that affects TAO and human occupation.
4. Determine the processes by which terrestrial microbial life, or its remains, is dispersed and/or destroyed on Mars (including within ISRU-related water deposits), the rates and scale of these processes, and the potential impact on future scientific investigations.
5. Characterize in detail the ionizing radiation environment at the martian surface, distinguishing contributions from the energetic charged particles that penetrate the atmosphere, secondary neutrons produced in the atmosphere, and secondary charged particles and neutrons produced in the regolith.
6. Determine traction/cohesion in martian soil/regolith (with emphasis on trafficability hazards, such as dust pockets and dunes) throughout planned landing sites; where possible, feed findings into surface asset design requirements.
7. Determine the meteorological properties of dust storms at ground level that affect human occupation and EVA.

1. Introduction and Background

1.1. General

Over the past five years or so, there have been two major studies of the robotic program needed to serve as a precursor to the first human mission to the martian surface: MEPAG [2001; revised 2004] and the NRC's Safe on Mars report [NRC, 2002]. Although these studies are both important, for several reasons it was necessary to reconsider them. NASA's new Vision for Space Exploration (announced January 2004) includes a number of important planning details that previously had been missing (e.g. general objective, timing and budget), and requires reconsideration of precursor priorities. In addition, the recent discoveries of the unprecedented orbital campaign at Mars, with the Mars Global Surveyor, Odyssey and ESA Mars Express missions, as well as the extraordinary, and surprising findings of the Mars Exploration Rovers on the surface of Mars, have provided a rich set of data that has dramatically altered our understanding of Mars, in a way that both enhances the feasibility of conducting human missions to Mars (i.e., the apparent abundance of near-global, subsurface water, at some depth), while also presenting new potential hazards that must be mitigated (i.e., particularly the increased possibility of biohazards if liquid water is found to be present, and accessible, below the martian surface). Finally, the NRC study was limited to hazards related to the martian environment, and mission planning also needs to include risks of other kinds, as well as precursor technology demonstrations and infrastructure emplacement.

The MHP SSG prioritizations also differ from previous roadmapping activities (e.g. the Bioastronautics roadmap, where risk priorities were solely based on potential impacts to crew health, possibly long term) for two reasons. First, the MEPAG analysis addressed overall mission risks, including system and hardware risks, not just risks to humans. Second, the MHP SSG ranked risk priority based on evaluation of how Mars flight measurements could buy-down that risk. Even if risk was high, if measurements could not buy it down, then priority ranking decreased.

HOW DOES THIS REPORT EXTEND NRC'S (2002) SAFE ON MARS REPORT?

- The NRC focused on environmental hazards to humans; this report also considers Mars-related risks to the flight or surface systems that could affect the probability of achieving full mission success.
- This report determines the relative priority to the identified investigations and measurements, as input to future risk-cost-schedule-engineering trade-off analysis.
- This report considers the precursor program needed to support a single landed human mission in 2030; NRC had an open-ended analysis with no constraint on the number of human missions and the possibility of a nearer-term first human mission.
- This report distinguishes between Long and Short mission surface stay times, with separate priorities and risk assessments.
- This report is focused on the specific measurements needed, including the required precision and accuracy.

For all of these reasons, in 2004, MEPAG chartered the Mars Human Precursor Science Steering Group (MHP SSG) to reconsider the description of its Goal IV (Preparation for Human

Exploration). The charter for the MHP SSG is attached to this report as Appendix 1. In summary, the purpose is 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 flight missions to Mars. In carrying out its charter, the MHP SSG was organized into two major teams: The Measurements subteam, and the Technology/Infrastructure subteam. This white paper represents the report of the Measurements subteam.

Because human missions to Mars will face a large number of risks, it is easy to think of LOTS of precursor investigations and demonstrations that will have some effect on risk reduction. However, the size of the impact of different precursor efforts on risk reduction is far from equal. In a cost-constrained program, it is important to understand these relative priorities. MEPAG measurement prioritizations presented here can be integrated into broader planning activities for human missions by outlining high priority measurements to be made on upcoming missions (both lunar precursor testbed missions and robotic missions to Mars).

1.2. Assumptions

- Assume that there will be a series of robotic missions to Mars, of as yet unknown character and timing, that will be capable of carrying out investigations and measurements, and doing technology/infrastructure demonstrations.
- Assume the first dedicated robotic precursor mission is scheduled for flight in the 2011 launch opportunity, and that the first human mission is scheduled in approximately 2030.
- Assume that a separate sequence of Mars missions, with a primary objective of robotic scientific exploration, will be carried out in addition to the human precursor sequence.
- Assume that the infrastructure associated with the science missions (e.g. the telecommunications infrastructure) is available for use by the human precursor missions.
- Assume for the purpose of this analysis that the 2030 mission and all of the precursor missions are funded by NASA without financial support from international partners.
- Assume the first human mission includes a landed human element.
- Assume that both the “short-stay” (~30 sols) and “long-stay” (~300 sols) missions are still under consideration; separate analyses of the precursor program are needed for each.
- For the purpose of this study, an analysis of the precursor program needed to support only the first human mission to Mars has been developed. The timing and character of human missions beyond the first one are too uncertain at this time. Obviously, additional precursor investigations may be needed to support recurring human missions.
- The human site will have been certified for landing safety with data from robotic missions before the humans land.

1.3. Scope

The scope of this analysis is 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. The authors note that in order for the program to be complete, the following kinds of precursor investigations also need to be considered, but they are considered within this analysis only to the extent required to directly support robotic flight missions.

- 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.

1.4. Definitions

- Soil. The unconsolidated material at the surface of Mars, without implication as to whether it contains an organic component. As used in this report, this term encompasses the following three components: dust which is widely circulated, presumably homogeneous, and fine grained; dune material which presumably is coarser grained and may not be globally mixed and may not account for a large fraction of material; and the regolith which includes material derived from bedrock with an unknown size frequency distribution and origin (presumably a combination of physical and chemical weathering).
- Acronyms: All acronyms are listed in Appendix 2.

NOTE: This document is intended to support future planning, and as such it mentions possible future flight projects that have not been approved. NASA's flight missions can be implemented only after they have achieved compliance with National Environmental Policy Act and Council on Environmental Quality (CEQ) laws. Additionally, some proposed missions would also require launch approval by the Office of the President.

2. Risk/Cost Analysis

2.1. Introduction

The MHP SSG was asked to analyze the precursor missions that would reduce the cost, reduce the risk, and increase the performance of the first human mission to Mars (Appendix 1).

- Cost. After extensive discussion, we concluded that a reasonably complete analysis of cost-reduction approaches would need to begin with a baseline cost model, which in turn would need to start with baseline mission engineering. Since we do not have either of these at this time, with one exception we deferred all discussion of cost reduction precursors to a future analysis team. That one exception is ISRU, which has a very obvious potential impact on mission cost (see section 3.5).
- Performance. The specific objectives and basic functionality of the first human mission have not yet been established. Without this starting point, it is not possible to do a meaningful analysis of the precursor program that would increase the performance. We considered starting from the *de minimus* mission, and evaluating performance increases relative to that, but we could not realistically define even this starting point. Again, the MHP SSG chose to defer this analysis to a successor team, when the baseline mission is better understood.
- Risk. The MHP SSG therefore spent most of its efforts on risk analysis, and on the precursor investigations and measurements that could reduce those risks.

2.2. Assumptions, Methodology

Terminology.

- Hazard - A state or condition that could potentially lead to undesirable consequences, depending on how a mission interacts with it.
- Risk - The combination of 1) the probability (qualitative or quantitative) and associated uncertainty that a program or project would experience an undesired event; and 2) the

consequences, impact, severity and/or associated uncertainty of the undesired event were it to occur.

- Opportunity - A state or condition that could potentially lead to desirable consequences.

Design Risk. There are many different types of risk, including cost risk, schedule risk, astronaut safety risk, risk to mission objectives, and many others. For a human mission, all of these types of risk would eventually be analyzed using systematic, quantitative, risk analysis methods. However, quantitative risk analysis requires a specific engineering implementation, which we do not currently have. The MHP SSG study therefore focused on what could be called design risk--the risk that the mission would use a faulty design because of incomplete information. It is clear that many other risks, such as the safety risk, would depend on the architectural approach, or mission scenario, and a primary purpose of the precursor program is to reduce uncertainty about the martian environment so that correct engineering design decisions can be made.

Risk Threshold. All risks for the first human mission will need to be dealt with in one of two ways: accept the risk, or mitigate against the risk through engineering. The latter, of course, requires information about the hazard to be mitigated in order to arrive at an improved design that has lower risk. Although the MHP SSG found that it could assess risk magnitudes in a qualitative way and could place risks in relative priority order, it is not in a position to determine the maximum overall acceptable risk to the mission, and therefore which risks MUST be mitigated in order to achieve that threshold.

Expected value of perfect information. An important concept in risk mitigation is the expected value of perfect information. In considering investing in precursor information (either by flight missions, or by research), one needs to ask, 'if we knew this information perfectly, what value would be added as compared to where we are today with our imperfect data set?' Note that in the real world, this will represent an upper limit on potential risk reduction, since actual research and flight experiments may not generate perfect information for a variety of reasons. A key point is that if perfect information from a given investigation does not have the desired effect on risk reduction, the investigation may not be worth doing. Since the purpose of a precursor measurement program is to buy down the risk by investing in advance knowledge, the value of the information must exceed its cost in order to be justified. Risk levels with precursor missions (Table 1) were determined assuming data is successfully collected on the precursor mission in accordance with the measurement criteria outlined in this document.

2.3. Risk Categories

The first human mission to Mars would be exposed to a very large number of risks. A preliminary version of an overall risk taxonomy was developed as a part of the MHP discussions, but it needs further refinement before it can be usable in planning. The MHP SSG found that when considered from the perspective of design risk that can be reduced by precursor measurement, this set of risks could be grouped into 6 major categories. Each was assigned a team of experts to analyze the issues and trades in detail, and their analyses are reported in Section 3 of this report.

- Risks related to biohazards
- Risks related to martian particulates originating both from airborne dust and soil
- Risks related to radiation hazards
- Risks related to the atmospheric hazards
- Risks related to terrain and trafficability hazards

- Risks related to ISRU (assuming it is part of the human mission)
- Risks related to regolith geotechnical properties

2.4. Integrated Risk Priorities

2.4.1. Prioritization Criterion

Each of the expert teams listed in Section 2.3 prepared an analysis of the risks in their subject area, along with an analysis of the possible precursor investigations that could reduce those risks. An important point is that each of these expert teams was asked to identify only precursor investigations for which there is no potential to obtain minimum necessary information in a less expensive way than by flying a mission to Mars (e.g. in an Earth-based laboratory, by computer simulation, in the Space Station, or on the Moon). These risks and investigations were merged in a major integration meeting in September 2004. Priorities for measurements were based on how robotic measurements can reduce all mission element risks, including crew health and safety as well as hardware and system functions. The prioritization criterion was straightforward: **The magnitude of the expected effect of a precursor flight measurement on risk reduction.**

In applying this criterion, the integration team encountered several examples of each of the following conditions, both of which result in the assignment of low priority to a proposed precursor investigation. This has caused some differences with prior studies.

- Large risks for which precursor measurements have a small effect.
- Small risks for which precursor measurements have a large effect.

Finally, for the purpose of this study we analyzed only the precursor investigations needed to reduce the risk of the first human mission, rather than a sustained campaign. This also has resulted in overall investigation priorities somewhat different from previous studies. We recommend subsequent studies to address additional risk factors that might result from other mission scenarios, such as sustained long-term human presence on Mars, which would require investigations that are beyond the scope of this study.

2.4.2 Process

The MHP SSG took a rigorous and structured approach to prioritizing the risk categories for a human Mars mission and determining the relative value of a robotic precursor investigation for each identified risk. This process is described below.

1. The discussions of the MHP SSG took place at two scales. One was in focus teams organized along technical lines (Biohazard, Dust/Soil, Radiation, Atmosphere, Terrain & Trafficability, ISRU), and the other was in broader integration exchanges that included representatives of each of the focus teams.
2. A long list of potential risks to the human mission was identified by the MHP SSG (the highest-priority portion of which is shown in Table 1). These risks are listed as “Risk Categories” in Table 1.
3. The relative magnitude of these risks was assessed for both the long- and short-stay human mission scenarios assuming the absence of a robotic precursor mission. The MHP SSG discussed risk to mission safety, risk to mission performance, and cost, but ultimately all of these

can be integrated into design risk. Assumptions for risk in the absence of a precursor program assume basic engineering and for many of these risks there are engineering-based partial preventive solutions. Each “Risk Category” was rated 1 (low risk) to 5 (high risk). The assignment of risk level is subjective and risk levels cannot be directly compared to each other. These rankings are shown in Table 1 under “risk/cost, no precursor”.

4. “Risk Categories” were then assessed for both the long- and short-stay human mission scenario assuming a robotic precursor mission is conducted prior to sending humans. This analysis again considered the impact on risk to mission safety, mission performance, and cost. This analysis assumed “perfect information”: The necessary information to mitigate the corresponding risk would be collected from the appropriate location at the appropriate time by the precursor mission and would yield the maximum benefit in terms of increasing our knowledge to mitigate the risk. This analysis thus assumed the maximum potential benefit from the precursor mission in terms of risk reduction. Each “Risk Category” was rated 1 (low risk) to 5 (high risk). These rankings are shown in Table 1 under “Risk W. Mars precursor”.

5. The relative reduction in risk to the human mission given a successful robotic precursor mission was then determined. This was accomplished by comparing the risk without a precursor mission with the risk assuming a successful precursor mission. The difference in the risk with and without the precursor mission is the delta (Δ) value shown in Table 1. Risk categories with the highest Δ values thus represent risks that can be mitigated to the highest degree with a successful precursor mission.

2.4.3 Findings

The “Risk Categories” in Table 1 are listed in descending order of their Δ value for the long stay mission; hence risks closer to the top of the table could be reduced the most with a precursor program. Items in yellow have either a risk of 3 or higher or the value of the precursor measurement is at least 1. Thus, these are the most valuable applications of a precursor program.

There are key differences in the risk profiles for the short and long stay mission scenarios. For the long-stay mission, the number of risks with high priority is much longer than for a short stay mission. Risk category 1 in Table 1 (which relates to ISRU) was not assessed for the short stay mission. The MHP SSG recognizes the possibility that ISRU may not be a required component of a short stay mission and for this reason, we could not include it within a comparative prioritization process—it will likely turn out to be either very important or irrelevant. The MHP SSG recommends further study of the relationship between ISRU, the duration of the first surface stay, and possible multi-mission human scenarios.



Several key findings related to risk buy-down and prioritization of precursor measurements are as follows:

- There is a high emphasis on understanding the distribution, accessibility, quality, and quantity of water as well as technology validation for ISRU for a long stay mission scenario. Recent robotic missions including Mars Global Surveyor, Mars Odyssey, and Mars Express have increased our knowledge about the abundance of water resources on Mars and ISRU is considered essential for a long stay human mission. ISRU-related

risks can be significantly mitigated with a precursor missions (Δ value = 3.0). Additional details can be found in Section 3.6.

- Characterization of atmospheric wind shear and turbulence is a high priority investigation. Successful EDL and TAO activities rely on accurate knowledge of the martian atmosphere to predict and compensate for spacecraft trajectory anomalies. Risks associated with EDL and TAO can be significantly mitigated with precursor measurements (Δ value = 3.0). Additional details can be found in Section 3.2.
- Characterization of the radiation environment both on the surface of Mars and in orbit are needed in order to validate the radiation transport models. The models are expected to be accurate but have known weaknesses that can best be probed by comparing their predictions to data obtained in situ, both above and below the atmosphere. Radiation-related risks are listed under Risk Categories 12 and 13 in Table 1. Additional details can be found in Section 3.4.
- Characterization of the martian dust (including particulates raised from the regolith during surface operations) is a relatively high priority item. Such investigations are important for mission hardware design to mitigate the effects of abrasion, adhesion, corrosion, and damage from potential electrical discharge, or arcing, as well as to mitigate potential adverse effects on human health from dust inhalation, and exposure (Δ values range from 2.0-3.0). Additional details can be found in Section 3.3.
- The greatest biohazard risk is back contamination and the associated potential hazards to terrestrial biota if martian life is transported back to Earth. Forward contamination of Mars and the potential false positive indication for life on Mars and/or hybridization with martian life is the next highest biohazard risk. Both risks can be significantly mitigated with a precursor mission (Δ values range from 1.5-3.0). Additional details can be found in Section 3.1.

Table 1. Relative Priority of Risks to the Short- and Long Stay Missions, and the Effect of Precursor Measurements on changing those Risks.

Ref.	Risk Category	Short Stay Mission			Long Stay Mission		
		risk/cost, no precursor	Risk w. Mars precursor		risk/cost, no precursor	Risk w. Mars precursor	
1	Water accessibility/usability at the landing site not as assumed.	N/A	N/A	####	5	2	3.0
2	Wind shear and turbulence affects EDL and TAO.	5	2	3.0	5	2	3.0
3	Back PP--Martian life affects Earth's biosphere.	5	2	3.0	5	2	3.0
4	DUST: Adverse effects of dust on mission surfaces.	5	2	3.0	5	2.5	2.5
5	Direct dust hazards to crew (toxicity).	4	2	2.0	5	3	2.0
6	Dust storm electrification, affecting TAO.	4	2	2.0	4	2	2.0
7	Geotechnical risks associated with near-surface materials (regolith).	4	2	2.0	4	2	2.0
8	Forward PP--Terrestrial contamination affects science.	4	2.5	1.5	5	2.5	2.5
9	Deleterious dust storm effects on surface operations.	2	1	1.0	3	2	1.0
10	Proliferation (and mutation?) of terrestrial life in s/c, hab.	2	1	1.0	2	1	1.0
11	Terrain impedes rover trafficability.	2.5	2	0.5	3	2	1.0
12	Chronic radiation exposure exceeds career safety limits.	1	1	0.0	3	2.5	0.5
13	Acute radiation exposure (e.g. in a severe solar event).	1.5	1	0.5	2	1.5	0.5
14	Photochemical reactions in the atmosphere--adverse effects.	1.5	1	0.5	2	1.5	0.5
15	Landing site hazards (e.g. cliffs, large rocks).	1.5	1	0.5	1.5	1	0.5
16	Comm. losses & nav alterations caused by atm. and topographic conditions.	1.5	1	0.5	1.5	1	0.5
17	Lander attitude is inadequate for egress or TAO.	1	0.5	0.5	1	0.5	0.5
18	Slope hazards--affects both EDL and rover mobility.	1.5	1.5	0.0	1.5	1.5	0.0
19	Risk from previously-ignored radiation sources.	1	1	0.0	1	1	0.0
20	Seasonal condensation causes electrical failures.	1	1	0.0	1	1	0.0

3. The Effect of Precursor Investigations and Measurements on the Reduction of the Risk of Human Missions to Mars

3.1. Measurements related to biohazard risks

3.1.1 Introduction

The specific objectives in the area of Biohazard / Planetary Protection were to:

- Identify and prioritize risks in the areas of Biohazard and Planetary Protection that are unique to a human mission
- Identify and prioritize investigations to address the highest risks
- Identify and prioritize measurements to be made in Earth laboratories and at Mars to address the highest risks

3.1.2 Risks

The most significant risk identified by the Biohazard Focus Team is that associated with the possibility of transporting a replicating life form to Earth, where it is found to have a negative effect on some aspect of the Earth's ecosystem (Risk #3 in Table 1). This is known in the planetary protection discipline as "back contamination". By definition, risks are a combination of probability and consequences. In the case of the back contamination risk, most scientists would agree that the probability of a negative consequence is very low (but as summarized by the Space Studies Board, 1997, "non-zero"), but the consequences could potentially be very large. A related, relatively low risk derives from martian life forms released in the surface habitat. Such life forms could pose a health hazard to the crew on Mars. Since the astronauts who visit the martian surface are assumed to be coming back to Earth (and in this sense are an extension of the Earth's biosphere), the risk of their infection by martian organisms is included within this risk.

A second risk identified by the Biohazard Focus Team is that associated with Planetary Protection "forward contamination" – the risk of terrestrial life transported to Mars. One concern focuses on local or widespread contamination of the martian surface, leading to possible false positive indications of life on Mars (Risk #8 in Table 1). A related risk, with lower consequences, concerns round-trip terrestrial life forms returned to Earth upon completion of the human mission. This could also lead to false positive indications of life on Mars.

3.1.3 Investigations to Address Risk #3 – Martian Life Transported to Earth

Does martian life exist?

First of all, a consensus finding of the MHP SSG is that it is not realistic to assume that a returning human mission that has visited the martian surface will have no uncontained martian material associated with it. This would mean no dust on the outside of the spacecraft, in the air filters, in the airlocks, on the outside of sample containment vessels, or anywhere!! Finding an engineering solution to this would be too complex (and the complexity would add a different kind of risk) and too expensive. Thus, the precursor information of most value is whether the

dust and other martian particulates that would be present in or on a returning spacecraft (other than deliberately collected samples, which can be held in sealed containers) have life forms associated with them, and if so, whether that life is hazardous.

Fortunately, answering this question does not require proof that extant life is absent everywhere on Mars. That (and its inverse question, is life present, and if so where) are very large questions that lie at the heart of the Mars Exploration Program (MEPAG's Goal I), and it may take many missions over an extended period of time to answer. There could well be environmental niches (e.g. the deep subsurface) that are occupied by life, but for which there is no transport mechanism to the human landing site.

KEY BIOHAZARD QUESTIONS: The Biohazard Focus Team concluded that the following two questions need to be answered in the negative in order for the mission to be judged free, to within acceptable risk standards, of biohazards:

- Qa. Is life present in the airborne dust, such that aeolian processes could provide a vector for its transport across the martian surface?
- Qb. Is life locally present in the regolith and/or rocks at the human landing site (down to the maximum depth to which the human mission will interact with the subsurface)?

In situ vs. sample return investigations

The only quantitative data to date are derived from the Viking lander life detection [Horowitz, 1986 and references therein] and gas chromatograph – mass spectrometer experiments [Biemann et al., 1977]. These results are generally interpreted to indicate that replicating microbial life is rare or absent in the surface soil at two widely separated locations on Mars, and further that these soils do not contain organic compounds at abundances above a detection limit of 1 ppb. The accepted explanations for these results encompass the high levels of solar ultraviolet radiation and the apparent oxidizing conditions encountered in the surface soil [Klein et al., 1992]. However, the Viking results do not address the possibility of martian life at concentrations below detection limits in the soil, nor the possibility of more abundant life in other locations on or below the surface. The Viking experience illustrates the striking challenge facing any attempt to discover martian life via in situ analysis—a definitive positive result could be obtained (if the experiment was designed correctly), but it will be impossible to obtain a definitive negative result, since there would always be questions about whether we used the right life detection test. We need definitive negative answers to the Key Biohazard Questions listed above.

In the planning (approximately 2000-2002) for the receipt of contained martian samples returned by a hypothetical round-trip robotic mission, a major and well-designed effort was put into defining the tests that would allow professionals who are responsible for protecting public safety to make a consensus decision about whether or not the samples are safe with respect to the possibility of biohazards [Rummel et al., 2002]. The advantage of investigations based on sample return is that the full power of analytic instrumentation that exists on Earth can be brought to bear, complex sample preparation procedures can be carried out, tests involving mechanical difficulty and/or live organisms can be attempted, detailed systems of positive and negative control standards can be established, and early unanticipated results can be followed up with a revised analysis plan. The outcome of these discussions was that a first draft large (but defined) list of tests was constructed. By definition, a sample that passes those tests can be

interpreted to be safe. This is exactly the same outcome needed for the Key Biohazard Questions listed above—we need a definitive negative answer. For this reason, the Biohazard Focus Team has concluded that investigations based on sample return will be required to achieve answers with sufficient confidence to at least Question Qa. Moreover, since Qa involves a global transport mechanism, a sample from anywhere on Mars that the wind blows would be sufficient to answer the question.

An issue for Question Qb is one of sampling significance. It will not be possible to know exactly where a human EVA might plan to go, and to pre-sample everywhere along that path. Fortunately, employing the concept of geologically based environments, it is possible to define larger entities within which a sample can be assumed to be representative. These environments include, as a minimum, the surface soil and the atmosphere. The human crews could also come in contact with subsurface material at depths below the (UV-irradiated, oxidizing) surface layer or in rock or ice-rich materials not sampled by Viking [Space Studies Board, 2002a]. In addition, Mars has different geological terrains, and future missions may define zones with different biological potentials.

The complete definition of these environments is not necessary at this time, and can be deferred to future workers who will have more complete information. However, the Biohazard Focus Team has concluded that as long as we have a definitive negative answer to Question Qa (by means of sample return), it may be possible to design screening investigations to answer Question Qb by in situ means. Measurements could include:

- Analysis of the martian atmosphere, dust, near-surface soil, deep soil, rock and ice to determine the concentrations of: gases of potential biological importance, organic carbon, organic compounds
- Assays to identify and quantify martian life (if found) and biohazard (if determined) in the specific environments to be encountered by human crews

If martian life is found, is it hazardous?

If martian life is found in any sample, that life must be assumed hazardous until proven otherwise [Space Studies Board, 1997; 2002b]. Hazard determination is complex, and involves the understanding of possible hazard to Earth's biosphere, crew health, and potential spacecraft and habitat equipment and materials. These determinations may require extensive experiments, which would be carried out in laboratories on Earth. This assessment must, at a minimum, satisfy the recommendations of "A Draft Test Protocol for Detecting Possible Biohazards in Martian Samples Returned to Earth" [Rummel et al., 2002].

3.1.4 Investigations to Address Risk #8 – Terrestrial Life Transported to Mars

Can terrestrial life survive and reproduce on the martian surface?

Important questions for a human mission involve the survival and reproduction of terrestrial microorganisms on the martian surface. A key corollary is to determine the rate of destruction of organic material by the martian surface environment. Many details of these questions can, and should, be addressed in terrestrial simulation laboratories, rather than by deliberately placing terrestrial organisms on the martian surface.

Can terrestrial life, or its remains, be dispersed on Mars ?

This question addresses a wide variety of dispersal mechanisms, many of which are being investigated in the existing Mars science program and in recommendations for other Focus Groups. For instance, it will be important to determine the mechanisms and rates of martian surface aeolian processes which disburse organic contaminants. It will also be important to determine the mechanisms of transport of surface organic contaminants into the martian subsurface, and in particular, into a martian aquifer. A parallel study, currently being addressed by the Mars Technology Program Planetary Protection effort, seeks to determine the adhesion characteristics of organic contaminants on landed mission elements, and the conditions and rates under which these contaminants are transferred to the martian environment.

FINDING: PROPOSED INVESTIGATION AND MEASUREMENTS

1C. Determine if each martian site to be visited by humans is free, to within acceptable risk standards, of biohazards which may have adverse effects on humans and other terrestrial species. Sampling into the subsurface for this investigation must extend to the maximum depth to which the human mission may come into contact with uncontained martian material.

Measurements:

- a. Determine if extant life is widely present in the martian near-surface regolith, and if the air-borne dust is a vector for its transport. If life is present, assess whether it is a biohazard. For both assessments, the required measurements are the tests described in the Draft Test Protocol. (Note #1: To achieve the necessary confidence, this requires sample return and analyses in terrestrial laboratories. Note #2: The samples can be collected from any site on Mars that is subjected to wind-blown dust. Note #3: At any site where dust from the atmosphere is deposited on the surface, a regolith sample collected from the upper surface is sufficient--it is not necessary to filter dust from the atmosphere.)
- b. At the site of the planned first human landing, conduct biologic assays using in-situ methods, with measurements and instruments designed using the results of the above investigation. All of the geological materials with which the humans and/or the flight elements that will be returning to Earth come into contact need to be sampled and analyzed. (Note #4: It is recommended that a decision on whether human landing sites after the first one require a lander with biological screening abilities be deferred until after Measurement a) has been completed.)

3.1.5 Measurements to be made in Earth Laboratories

The Biohazard Focus Group identified and prioritized measurements to be made in Earth laboratories to address the highest risks.

The clear priority will be assays made on samples collected on Mars and brought to Earth by robotic missions. Representative samples of the atmosphere, dust, near-surface soil, deep soil, rock and ice must be tested for evidence of martian life [Space Studies Board, 1997]. That life, if found, must be fully characterized, and its potential for biological hazard must be determined. Current recommendations for measurements to test for evidence of life and biological hazard are contained in of “A Draft Test Protocol for Detecting Possible Biohazards in Martian Samples Returned to Earth” [Rummel et al., 2002].

Other measurements, important to forward Planetary Protection, should be conducted in simulated Mars environments. Terrestrial microorganisms should be tested for evidence of survival and genetic adaptation under simulated martian conditions [Schuerger et al., 2003].

Finally, the potential for forward contamination by robotic and human missions must be understood. Microbial assays should be undertaken to fully characterize the microbial populations of spacecraft assembly cleanrooms and to fully characterize the microbial populations shed by humans [Venkateswaran et al., 2002].

3.1.6 Measurements to be made at Mars

The biohazard and planetary protection risks to a human mission depend strongly on whether, and when, evidence of martian life is found. Measurements by precursor missions can reduce uncertainty and, to an extent, risk in either case.

FINDING: PROPOSED INVESTIGATION AND MEASUREMENTS

4. Determine the processes by which terrestrial microbial life, or its remains, is dispersed and/or destroyed on Mars (including within ISRU-related water deposits), the rates and scale of these processes, and the potential impact on future scientific investigations.

Measurements:

- a. Determine the rate of destruction of organic material by the martian surface environment.
- b. Determine the mechanisms and rates of martian surface aeolian processes which disperse organic contaminants.
- c. Determine the adhesion characteristics of organic contaminants on landed mission elements, and the conditions and rates under which these contaminants are transferred to the martian environment.
- d. Determine the mechanisms to transport surface organic contaminants into the martian subsurface, and in particular, into a martian aquifer.
- e. Determine if terrestrial microbial life can survive and reproduce on the martian surface.

Before martian life is found

Chemical and isotopic indications of possible martian life can be measured in the martian atmosphere, dust, near-surface soil, deep soil, rock and ice at any landing site, to determine if such indications are widespread or localized. Such measurements were initially attempted by the Viking gas chromatograph - mass spectrometers [Biemann et al., 1977], and improved measurements should be possible using the instruments on the Mars Science Laboratory. The remote sensing suite on Mars Express is already producing maps of minerals, including clays and hydrates, that are often found in terrestrial localities affected by hydrocarbons. The 2005 Mars Reconnaissance Orbiter, with extremely high resolution and hyperspectral imaging, may permit confident identification of altered minerals and fossil hot springs.

Evidence for the products of metabolism can also be measured in the atmosphere, dust, near-surface soil, deep soil, rock and ice at any landing site to determine if metabolizing organisms are widespread or localized. Such measurements were initially attempted by the Viking life detection experiments. None of the spacecraft currently at Mars, nor those planned for the next decade, has the capability to improve on these measurements. Flight experiments to measure the metabolism

of unknown martian organisms do not appear to be justified until those organisms are shown to exist in returned samples. These measurements are assumed to be within the purview of a future Mars Science Program.

If martian life is found

In the event that in situ investigations or a sample return mission provides evidence for martian life, subsequent investigations can be targeted to the characteristics of that life. Prior to a human mission it would be imperative to test for evidence of the discovered martian life and possible biohazards via robotic spacecraft in the specific environments to be encountered by human crews.

3.2. Measurements related to atmosphere risks

3.2.1 Introduction

The martian atmosphere is the origin of many possible hazards to both humans and equipment. The unknown thermodynamic properties of the bulk gas fluid, including unexpected turbulence in the near-surface boundary layer [[Zurek et al., 1992](#)], represent risks during vehicle entry, descent and landing (EDL). Major dust storms may also affect EDL and adversely affect a human explorer's ability to perform extravehicular activities (EVAs). More recent laboratory [[Eden and Vonnegut, 1973](#)] and terrestrial desert studies [[Renno et al., 2004](#)] indicate that triboelectric effects within dust storms can give rise to large electric fields which might prove hazardous to both explorers and equipment. The Atmosphere Focus Team collected such hazards and assessed the likelihood and consequences of their risks. The results are included in this section.

The scope considered by the Atmosphere Focus Team includes all atmospheric risks to the success of a human mission from the ground level to the ionosphere. Discussions included variations in atmospheric parameters that affect flight and surface activities, electrical effects of the atmosphere, photochemistry, dust storms, communication and other topics.

3.2.2 Primary Risks

Table 2 indicates the primary risks anticipated to human explorers. The Atmosphere Focus Team was in unanimous agreement that the primary atmospheric risks lies in the EDL and TAO periods, when vehicles are susceptible to turbulent wind forces and atmospheric density anomalies that can alter planned trajectories. Other high rated risks include dust storm electricity generation/discharge and surface operations during dust storms; these are included primarily because so little information currently exists regarding the phenomena, making great uncertainty in any assessment and mitigation plan.

3.2.3 Current State of Knowledge

Table 2 also lists the current state of knowledge for the top-level atmospheric risks. It is noted that in Investigation (1), (2), and (3), the information set is not complete enough (or non-existent in some cases) to initiate an educated hazard assessment and mitigation plan.

3.2.4 Desired Future State of Knowledge

Table 2 lists the recommended state of the investigations being considered by the Atmosphere Focus Team. Note that in most cases, there is a distinct mismatch between the requirements to understand a hazard as represented in the recommended state of knowledge and the current knowledge base.

Table 2. Current and Recommended Knowledge for Atmospheric Investigations

Hazard Investigation	Hazard Description	Current State of Knowledge	Recommended State of Knowledge
1) Fluid variations from ground to >90 km that affect entry, descent and landing (EDL) and take-off, ascent and orbit insertion (TAO)	Winds and turbulent layers in boundary layer (0-20 km) and density anomalies at max dynamics pressure (30-60 km) may alter vehicle trajectory during aerocapture and precision landing. Possibly detrimental if densities inaccurately estimated and if winds and instability/turbulence beyond planned tolerances.	To date, four EDLs provide V, T, and ρ profiles for use in models. Some remote-sensed atmospheric information from MGS/TES, but limited and not always accurate. Boundary layer turbulence and structure not well measured or understood. Turbulence from dust storm convection/thermal inflation not quantified. Past mission aerobraking has provided limited amount of data from 95-170 km.	Vertical profiles of V, T, and ρ , especially from 0-20 km and 30-60 km, obtained globally (all lat and long), with high temporal and spatial resolution, obtained over a long baseline (> 1 martian year). Surface/near surface measurements of V, T, and P to connect surface heat to BL turbulence. GCMs with capability to connect atmospheric state and variability from surface to >150 km.
2) Atmospheric electricity that affects TAO and human occupation	Electric fields in convective dust storm may exceed breakdown, leading to discharge, arcing, RF contamination. Discharge to ascending vehicle is potentially serious issue during take-off (e.g., Apollo 12). High levels of atmospheric electricity may limit EVAs.	Tests limited to lab and terrestrial desert electric field studies of mixing dust. No in situ measurements on Mars, to date.	DC and AC electric fields, and atmospheric conductivity over a martian year. Package recommended to fly at least once to assess the risk.
3) Dust storm meteorology that affects human occupation and EVA	Local, regional and even global dust storms are likely to occur for a long-stay mission. Storms can last for months. Storm opacity in the cores may be large enough to reduce EVA times, delay departure times, and external maintenance of habitat. (e.g., Gulf War II dust storm)	Viking lander provided some opacity information from edge of storm, but no data from inner core region of storm.	Global V, T, ρ , and dust opacity as a function of time and height, over a long (> 1 martian year) baseline
4) Reactive atmospheric chemistry that creates a toxic or corrosive environment	The Viking LR/GEX experiments indicate that some highly reactive agent is omni-present in the environment, possibly being of atmospheric origin.	Basic atmospheric composition measurements known. Reactive species H ₂ O ₂ , at trace level, just recently detected and bounded.	Mass spectrometer from 2-100 AMU in near surface at many locations and over long durations to detect any isolated pockets of reactive gas buildup.
5) Atmospheric / Ionospheric effects on communication and navigation	Dust storm RF contamination and ionospheric anomalies may adversely affect comm. & nav system.	To date, no comm./ nav failure, but communication in major dust storms has not been tested.	Ionospheric density as a function of lat, long and height over long baseline, and surface AC E-field measurements in dust storms to determine RF contamination level.

3.2.5 Investigations, Measurements, and Priorities to Reduce Risk(s) and/or Costs

3.2.5.1 Investigations and Measurements

The green-colored insets identify the Atmosphere Focus Team's top-rated investigations and associated measurements. The three primary investigations outlined include (as numbered from composite list in Executive Summary):

- 1B. Determine the atmospheric fluid variations from ground to >90 km that affect EDL and TAO including both ambient conditions and dust storms.
- 3. Derive the basic measurements of atmospheric electricity that affects TAO and human occupation.
- 7. Determine the meteorological properties of dust storms at ground level that affect human occupation and EVA.

The Atmosphere Focus Team recognizes that meteorological effects of dust storms are included in both Investigation 1B and 7. While it is tempting to merge these two investigations, the dust storm risk to human explorers during EDL is considered much greater (inflated, highly turbulent atmosphere) than the dust storm risk to humans already on the ground (limited visibility). Hence, dust storm ground-level effects have been separated from those of EDL.

3.2.5.2 Risk Mitigation and Reduction

The Atmosphere Focus Team identified five major categories of risk to a human exploration to Mars (Table 2), and a description of the category and mitigation strategy is presented.

1. Wind shear, turbulence, and density anomalies that may create uncompensatable trajectory offsets during EDL and TAO (Risk #2 in Table 1). Unexpected fluid variations are a concern, primarily in two regions: between 30-60 km and 0-20 km. The region between 30-60 km is a critical region for aerocapture, where the dynamic pressures of an incoming body are the greatest, and maximum acceleration occurs. A density miscalculation in this region can lead to both an offset in anticipated landing location and/or higher than expected descent velocities. Given a direct entry scenario for a human mission, accurate densities in this region are critical to the safety of the crew. The region between 0-20 km contains the highly variable planetary boundary layer. During daytime, the surface heats the lower atmosphere (with cooler air above) creating a naturally unstable situation [Zurek et al., 1992]. These instabilities can manifest themselves as convective systems with both turbulence and shear wind flows. Unforeseen increases in topographically-driven winds (e.g., katabatic winds) can also create unexpected shears. As a result, the incoming vehicle (now moving relatively slowly for precision landing) may experience oscillations, a change in orientation, and/or large wind drift offsets. During the MER/Spirit EDL, lower-than-modeled middle atmosphere densities and unexpected oscillations near parachute deployment occurred that nearly exceeded safe ranges.

To mitigate this situation, the Atmosphere Focus Team suggests a strategy parallel to the study of terrestrial weather, where forecasts are derived based upon advanced modeling, but using timely measurements to both set the initial conditions and in validation. The primary objective is to improve and enhance the martian global circulation models (GCMs) and mesoscale models, so that forecasting can occur to derive the mean state and variability in atmospheric conditions for

EDL. First, **in situ meteorological V, T, and ρ during EDL and at the surface (lander package)** should be a standard measurement obtained on every future landed mission. This recommendation extends to the upcoming MSL opportunity. Regarding EDL measurements, the number of profiles obtained between the present and a 2030 human mission would greatly improve the data set already available [[Seiff and Kirk, 1977](#); [Magalhaes et al., 1999](#)] for model validation/initiation (by over a factor of 2). Regarding surface/near-surface measurements, long-term measurements are critical in setting accurate model initial conditions of the surface heat energy driver responsible for lower/middle atmosphere instabilities. Landed packages can also remotely sense the structure and turbulence in the boundary layer above [[Smith et al., 2004](#)], thereby linking this surface heat energy to its associated boundary layer turbulence. Second, to obtain complete coverage in space and time, an **orbital remote-sensing weather station** is recommended to obtain vertical profiles of V, T, and ρ around the globe with high temporal and spatial resolution, particularly emphasizing heights between 0-20 km and 30-60 km. Orbital remote sensing techniques to derive the atmospheric state at ground and regions from the ground to 20 km are evolving. Remote sensing of winds in the boundary layer will require a separate development effort. Landed remote sensing tools exist to measure thermal activity [[Smith et al., 2004](#)] but a development effort is required to obtain independent wind measurements.

These measurements are recommended to make the forecasting tools (the circulation models) as accurate as possible. Consequently, a parallel effort is recommended for advancing the model capabilities, including GCM improvement in resolution and in the incorporation of modeling to greater heights (preferable surface to > 100 km). Mesoscale models require improvement in realistic boundary conditions that match the measurements and integrate into larger GCMs.

Implicitly incorporated into these recommendations is the collection of atmospheric state and variability during unstable dust storms. Such storms give rise to lower/middle atmosphere temperature increases that inflate the atmosphere (even measured above 100 km altitude) and are a source of instability-related fluid waves and turbulence. Numerical models need to predict the turbulence within and in the vicinity of more violent, unstable dust storms.

During any actual human EDL in 2030, the Atmosphere Focus Team suggests bringing all available assets to bear, with an orbital platform providing the most timely density and wind profiles, along with numerical models which fill in coverage and identify potentially unstable atmospheric situations based on the recent remote-sensed profiles in the landing site region. Finally, in analogy to launch preparation from Earth, the Atmosphere Focus Team suggests a pre-descent “weather sounding probe” be deployed just prior to human entry, this sent along the identical path anticipated for the human-containing vehicle to determine regions of high variability along the descent path. For the return trip, pre-ascent weather probes can be sent from ground upward to derive high altitude meteorological conditions before launch from Mars.

The Atmosphere Focus Team recognizes that the recommended measurement and modeling efforts must be initiated at the earliest opportunity in order to incorporate the full range of expected atmospheric variations into the EDL system design and testing. Requirements for EDL design have to be formulated much earlier than the actual 2030 human mission, thus supporting measurements in 1B should be obtained prior to design initiation. This requires that the orbital meteorological asset be robustly built in order to remain at Mars from the pre-EDL

design period through the actual implementation of EDL and/or the possibility of sending successive integrated remote-sensing meteorological systems on successive orbiters.

FINDING: PROPOSED INVESTIGATION AND MEASUREMENTS

1B. Determine the atmospheric fluid variations from ground to >90 km that affect EDL and TAO including both ambient conditions and dust storms.

Measurements:

- a. Measure v , P , T and ρ in the upper, middle and lower atmosphere during EDL. Obtain as many profiles at various times and locations as possible (requested for ALL landed missions). Sample rate should be high enough (~ 100 Hz) to quantify turbulent layers. Specific direct or derived measurements include:
 - Density from 120 km to surface ranging from high altitude values of 10^{-9} to near-surface values of 10^{-1} kg/m³, $d\rho = 1\%$ of local ambient, rate= 100 Hz
 - Pressure from 120 km to surface ranging from high altitude values of 10^{-7} to near-surface values of 15 mb, $dP = 1\%$ of local ambient, rate =100 Hz
 - Temperature 60-300 K, $dT = 0.5$ K, rate= 100 Hz (direct measurement may be slower)
 - Directional Wind Velocity, 1-50 m/sec, $dv = 1$ m/s, rate= 100 HzParticular emphasis on measurements between 0-20 km to quantify boundary layer wind and turbulence and 30-60 km where vehicle dynamic pressure is large.
- b. Monitor surface/near-surface $v(z)$, P , $T(z)$, and ρ as a function of time. Quantify the nature of the surface heating driver and associated boundary layer turbulence at altitudes above station. Data defines the initial conditions for high altitude modeling. Obtain data from as many locations as possible (requested for all landed missions). Surface/near surface packages should measure directly:
 - Pressure, at surface, 0.005 mb to 15 mb, $dP = 2$ microb, full diurnal sampling, rate= >10 Hz
 - Velocity, at surface, 0.05-50 m/sec, $dv = 0.05$ m/s, horizontal and vertical, full diurnal sampling, rate= 10 Hz
 - Air temperature, at surface, 150-300 k, $dt = 0.04$ k, full diurnal sampling, rate= 10 Hz
 - Ground temperature 150-300 k, $dt = 1$ k, full diurnal sampling, rate= 1 Hz
 - Air temperature profile, 0-5km, <1km resolution, 150-300k, $dt=2$ k, full diurnal sampling, rate=1 Hz
 - Velocity profile, 0-5km, <1km resolution, 1-50 m/sec, $dv=1$ ms/, horizontal and vertical, full diurnal sampling, rate=1 HzOpacity, visible, depth 0.2-10, $d\tau = 0.1$, once every 10 min

2. Dust storm electrification may cause arcing, affecting TAO (Risk #6 in Table 1). Based on laboratory studies and terrestrial desert tests, there is a growing body of evidence that dust devils and storms may develop dipole-like electric field structures similar in nature to terrestrial thunderstorms [Farrell et al., 2004]. Further, the field strengths may approach the local breakdown field strength of the martian atmosphere, leading to discharges [Melnik and Parrot, 1998]. A hazard during the vulnerable human return launch from Mars would be a lightning strike to the ascending vehicle. Apollo 12 suffered a lightning strike at launch, upsetting the

navigation and electrical system. During human occupation of Mars, dust storm discharges and induced electrostatic effects may also force human explorers to seek shelter, reducing EVA time, habitat maintenance, etc. Mitigation strategies include avoidance of aeolian dust clouds both at launch and during human EVA periods. However, to date, there are no measurements of martian atmospheric electricity to evaluate the consequences of the proposed risk. The Atmosphere Focus Team suggests placing an atmospheric electricity (DC and AC E-fields, conductivity) package on at least one future landed missions to assess the risk.

FINDING: PROPOSED INVESTIGATION AND MEASUREMENTS (cont.)

- c. Make long-term ($\gg 1$ martian year) remote sensing observations of the weather (atmospheric state and variations) from orbit, including a direct or derived measurement of:
 - Aeolian, cloud, and fog event frequency, size, distribution as a function of time, over multi-year baseline.
 - Vertical temperature profiles from 0-120 km with better than 1 km resolution between 0-20 km, 1-3 km resolution between 20-60 km, 3 km resolution > 60 km and with global coverage over the course of a sol, all local times [*Development work required for T from surface to 20 km*].
 - Vertical density/pressure profiles from 0-120 km with better than 1 km resolution between 0-20 km, 1-3 km resolution between 20-60 km, 3 km resolution > 60 km and with global coverage over the course of a sol, all local times [*Development work required for ρ from surface to 20 km*].
 - 3-D winds as a function of altitude, from 0-60 km with better than 1 km resolution below 20 km, and 1-3 km resolution between 20-60 km, and with global coverage over the course of a sol, all local times [*Development work required at all altitudes for an independent means to derive V , with special emphasis from surface to 20 km*].Note particular emphasis on measurements between 0-20 km to quantify boundary layer wind and turbulence and 30-60 km where vehicle dynamic pressure is large.
- d. At time of human EDL and TAO, deploy ascent/descent probes into atmosphere to measure P, V, and T just prior to human descent at scales listed in 1Ba.

Note: We have not reached agreement on the minimum number of atmospheric measurements described above, but it would be prudent to instrument all Mars atmospheric flight missions to extract required vehicle design and environment information. Our current understanding of the atmosphere comes primarily from orbital measurements, a small number of surface meteorology stations and a few entry profiles. Each landed mission to Mars has the potential to gather data which will significantly improve our models of the martian atmosphere and its variability. It is thus desired that each opportunity be used to its fullest potential to gather atmospheric data. Reconstructing atmospheric dynamics from tracking data is useful but insufficient. Properly

3. During crew occupation and EVA, dust storms may affect visibility, restrict departure times, limit EVAs, and hamper regular habitat maintenance (Risk #9 in Table 1). Operations in a major dust storm can be stalled due to obscured visibility and adhering dust. On Mars, global dust storms can last for 3 months [Zurek et al., 1992], with possible crew internment for long periods (especially if there is a passage of high opacity core regions). Mitigation strategies include designing low maintenance habitats and EVA systems and/or

avoiding human occupation at times when storms are expected. The ability to predict the large seasonal storms has greatly improved with MGS/TES, but regional and local storms appear quasi-random [Cantor, 2003]. To assess the risk, lander meteorological packages (like those suggested in point 1 above) should also have the capability to assess dust density/opacity. A remote-sensing orbital weather station (like that described in point 1 above) would have the capability to monitor dust storm frequency, size, occurrence and thermodynamic characteristics over a long baseline, and act to alert surface-stationed astronauts of impending storm activity.

4. Photochemical reactions in the atmosphere may create chemically-reactive gases that lead to corrosive or toxic environments (Risk #14 in Table 1). Landed missions have yet to fail because of a corrosive/reactive agent, but certain locations and seasons may favor the increased production of reactive chemicals [Delory et al., 2005; Atreya et al., 2005]. A mitigation strategy is to avoid occupation and EVA during chemically active periods and/or active locations. Special non-reactive coverings may have to be designed for EVA suites and habitats. Mass spectrometers placed at various locations on the surface can monitor the presence of reactive chemicals that are produced beyond trace levels. Orbital platforms are not considered effective since measured columnar densities may not indicate concentration levels at the surface.

FINDING: PROPOSED INVESTIGATION AND MEASUREMENTS

3. Derive the basic measurements of atmospheric electricity that affects TAO and human occupation.

Measurements:

a. Basic measurements:

- i. DC E-fields 0-80 kV/m, dV=1 V, bandwidth 0-10 Hz, rate = 20 Hz
- ii. AC E-fields 10 uV/m – 10 V/m, Frequency Coverage 10 Hz-200 MHz, rate = 20 Hz, with time domain sampling capability
- iii. Atmospheric Conductivity 10^{-15} to 10^{-10} S/m, ds= 10% of local ambient value
- iv. Ground Conductivity $> 10^{-13}$ S/m, ds= 10% of local ambient value
- v. Grain charge $> 10^{-17}$ C
- vi. Grain radius 1-100 um

b. Combine with surface meteorological package to correlate electric forces and their causative meteorological source > 1 martian year, both in dust devils and large dust storms. Combine requirements for 1Bb with 3a above.

5. Atmospheric conditions on Mars, at times, may lead to communication losses and navigation anomalies (Risk #16 in Table 1). Ionospheric variations/scintillations can disrupt RF propagation [Safaeinili et al., 2003] and electrical activity (discharges) in dust storms [Renno et al., 2003] can be a source of RF interference. Strategies are already applied to mitigate ionospheric disruption by transmitting at frequencies well above the peak ionospheric plasma frequency. Mitigation strategies in electric dust storms may also be the application of judicious choice in frequency selection to avoid noisy, contaminated frequency bands. However, fundamental information of dust storms RF emission is suggested to make this choice. An atmospheric electricity package with AC E-field sensing capability (like that suggested in point 2) is capable of deriving the intrinsic RF emission within a dust storm.

3.2.6 Impact on MEPAG Goal IV and Changes in Criticality

The primary atmosphere-related investigations, those of understanding the fluid properties of the atmosphere and atmospheric electricity, remain high priorities in both original and latest version of the MEPAG goals. The criticality of both has increased slightly, with fluid variations being considered the highest priority in the overall Goal IV investigations (Investigation 1B). One reason for the change of criticality was the difficult EDLs experienced by the robotic MERs, which punctuated the need for timely and accurate measurements of the atmospheric state at descent.

3.2.7 Required Developments

The Atmosphere Focus Team recommends research and technology investments in remote sensing meteorological tools, particularly methods for (1) orbital remote-sensing of atmospheric winds at all altitudes independently of temperature/density-derived methods, (2) orbital remote-sense of the surface and near surface (0-20 km) V, T, and ρ , especially in the turbulent boundary layer, and (3) landed remote sensing of vertical V and T profiles up to 5 km. The Atmosphere Focus Team also recommends further development of GCM and mesoscale codes, including improvements in resolution and spatial coverage (particularly height).

FINDING: PROPOSED INVESTIGATION AND MEASUREMENTS

7. Determine the meteorological properties of dust storms at ground level that affect human occupation and EVA.

Measurements:

- a. P, V, T, n, and dust density (opacity) as a function of time at the surface, for at least a Martian year, to obtain an understanding of the possible meteorological hazards inside dust storms. Surface Package measure directly:
 - i. Same as requirement for 1Bb with added
 - ii. Dust size 1-100 μm
 - iii. Dust density 2-2000 grains/cc
- b. Orbiting weather station: optical and IR measurements to monitor the dust storm frequency, size and occurrence over a year, & measure terrain roughness and thermal inertia. Climate sounder would enable middle atmosphere temperature measurements. In situ density or spacecraft drag sensors could monitor the dust storm atmosphere inflation at high altitudes. Same as requirement 1Bc.

3.3. Measurements related to Dust/Soil risks

3.3.1 Introduction

Apollo astronauts learned first hand how problems with dust impact lunar surface missions [NASA, 1969a; 1969b; 1971a; 1971b; 1972; 1973]. After three days, lunar dust contamination on EVA suit bearings led to such great difficulty in movement that another EVA would not have been possible. Dust clinging to EVA suits was transported into the Lunar Module [Connors, 1994]. During the return trip to Earth, when micro gravity was reestablished, the dust became airborne and floated through the cabin. Crews inhaled the dust and it irritated their eyes [Kennedy and Harris, 1992]. Some mechanical systems aboard the spacecraft were damaged due to dust contamination. Study results obtained by robotic martian missions indicate that martian

surface soil may be oxidative and reactive [Zent and McKay, 1994]. Exposures to the reactive martian dust may pose an even greater concern to crew health and integrity of the mechanical systems.

As NASA embarks on planetary surface missions to support its Exploration Vision, the effects of these extraterrestrial dusts must be well understood and systems must be designed to operate reliably and protect the crew in the dusty environments of the Moon and Mars [National Research Council, 2002].

The Dust/Soil Focus Team evaluated potential hazards to human support surface systems caused by the presence of martian dust and developed recommended investigations and measurements by MHP missions to mitigate the risks.

Impacts on MEPAG Goal IV

In order to provide guidance to Mars Human Precursor mission designers to gather information needed to bring our understanding of martian dust, soil and toxicology to the recommended state of knowledge, the Dust/Soil Focus Team recommends modifying Goal IV. Investigation 2, “Chemical and toxicological properties”, should be expanded to include specific measurements. In addition, dust and soil should be broken out of investigation 5, “engineering properties of the martian surface, and characterize topography, and other environment characteristics and measurements.” Specific recommendations are provided in the Precursor Investigations topic in this section.

3.3.2 Risks and Priorities

The Dust/Soil Focus Team identified four major hazardous conditions associated with martian dust; adhesion and accumulation, inhalation and ingestion, dust storms and biology (Table 1). The Dust/Soil Focus Team then developed risk statements, consequence, likelihood and context [Murphy et al., 1996]. (Dust storm risks were addressed by the Atmosphere Focus Team and Biohazard risks were addressed by the Biohazard Focus Team). The Dust/Soil Focus Team identified numerous risks that were subsets of higher level risks. The higher level risks are shown below. The lower level risks are labeled “subset risks”.

3.3.3 Primary Risks

Dust Adherence and Accumulation

Failure Due to Abrasion and Accumulation (Risk #4 in Table 1):

Risk Statement: If abrasion and adhesion properties of martian dust are not understood, systems may not be properly designed. If critical mechanical systems fail due to abrasion and adhesion of dust accumulated on systems, loss of science, injury or loss of crew member(s) may result.

Consequences: 3-5, loss of science, severe injury or loss of crew.

Likelihood: 5, surface life support systems do not yet exist to handle abrasion and adhesion of dust in martian environments.

Context: Abrasive properties of dust accumulating on surfaces and penetrating systems could lead to failure of air generation and delivery, carbon dioxide removal, fire detection (causing false alarms) and suppression, EVA suits, rovers, windows, visors, and optics. If critical life support systems completely fail, rescue or mission termination is not feasible due to the laws of orbital mechanics.

Subset Risks:

- If dust adheres to photovoltaic cell surfaces it may occlude the surface enough to produce a significant reduction in power available for the mission. Degraded power might result in inability to perform scientific activities and vital safety systems may not function properly.
- If dust adheres to radiator surfaces it may compromise radiator performance enough to cause overheating of life-support and other systems. If the crew is overheated serious injury or loss of life might result.
- If dust adheres to sealing surfaces it may compromise the ability of airlocks to contain a habitable atmosphere. If sufficient oxygen is not available the crew could suffer asphyxiation. Compromised seals may lead to dust penetration.
- If dust adheres to mechanical surfaces it may clog rotational or sliding bearings and cause wear sufficient to compromise their action. If EVA equipment is not usable the crew may not be able to perform science activities.
- If dust adheres to optical surfaces, including view ports and camera lenses, it may compromise the ability of astronauts to move about the planetary surface. If crew is unable to move about the surface the result would be reduced science.
- Scratching and scoring of optical surfaces when attempting to remove the dust may compromise the ability of astronauts to move about the planetary surface. If crew is unable to move about the surface the result would be reduced science.
- Cleaning and maintenance activities to manage dust would divert the crew from performing science. Spares and consumables would need to be delivered to the crew resulting in additional costs to the program.

Failure of Electrical Systems (Risk #4 in Table 1):

Risk Statement: If electrostatic properties of martian dust are not understood systems may not be properly designed. If critical electrical life-safety systems fail due to dust accumulation on systems, injury or loss of crew member(s), or loss of science would result.

Consequences: 3-5, loss of science, severe injury or loss of crew.

Likelihood: 5, surface life support systems do not yet exist to handle electrical effects of the dust in martian environments.

Context: Electrical properties of dust accumulating on surfaces and penetrating systems could lead to failure of air generation and delivery of electronics, carbon dioxide removal, fire detection and suppression, EVA suits, rovers, windows, visors, optics, and power generation systems. The martian regolith may be so insulating that a common electrical ground would not be established among structures, vehicles and astronauts, resulting in electrical discharge when they come into contact, causing injury to astronauts or failure of electronic systems. If critical

life support systems completely fail, rescue or mission termination is not feasible due to the laws of orbital mechanics.

(Probable mitigation solution for electrical grounding risk already exists. On Pathfinder, all ground wires are connected to a common buss and ground through the atmosphere via corona discharge).

Subset Risks

- Dust accumulating in electrical contacts may cause a short. If the habitat or space suit system loses power and the crew is unable to repair the system, it would lose its capability to provide oxygen and remove carbon dioxide. If dust accumulates in battery contacts it would result in significant power drain.
- Electrostatic discharge due to charge buildup could result in failure of critical components and injury or loss of crew.

System Failure Due to Corrosive Effects of Dust (Risk #4 in Table 1):

Risk Statement: If corrosive properties of martian dust in the presence of water or other reactive chemicals are not understood systems may not be properly designed. If critical life-safety systems fail due to corrosive effects of dust accumulated on systems, injury or loss of crew member(s) may result.

Consequences: 4-5, severe injury or loss of crew.

Likelihood: 5, corrosion control in life support systems does not yet exist to function in martian dusty environments.

Context: Corrosive properties of dust accumulating on surfaces and penetrating systems could lead to failure of air generation and delivery, carbon dioxide removal, fire detection and suppression, EVA suits, rovers, windows, visors, optics, and power generation systems. Materials selection is dependent on the corrosive properties of martian dust. Because condensation, frost, EVA activities such as drilling and humidity in the habitat environment may contribute to oxidation, this risk applies to both interior and exterior surfaces.

Subset Risks:

- If dust adhering to photovoltaic cell surfaces comes into contact with moisture it may become corrosive and degrade the surface enough to produce a significant reduction in power available for the mission. Degraded power might result in inability to perform scientific activities and vital safety systems may not function properly.
- If dust adhering to sealing surfaces comes into contact with moisture it may become corrosive and compromise the ability of airlocks to contain a habitable atmosphere. If sufficient oxygen is not available the crew could suffer asphyxiation.
- If dust adhering to optical surfaces, including view ports and camera lenses, comes into contact with moisture it may degrade the surfaces and compromise the ability of astronauts to move about the planetary surface. If crew is unable to move about the surface the result would be reduced science.

Dust Inhalation and Ingestion

Dust Toxicity to Crew (Risk #5 in Table 1):

Risk Statement: If the crew inhales or ingests dust, adverse health effects may result.

Consequences: 2-5, mild illness to loss of crew

Likelihood: 5, Dust in the human environment resulting from human interactions of the martian surface may be inevitable, and dust mitigation strategies for the human habitation modules are currently not developed.

Context: Dust transported into the habitat via leakage or EVA suits may decrease effectiveness of air, water and food management systems and lead to inhalation and ingestion of dust particles. The properties of soils, which can produce medical impact to humans on planetary surfaces, include both physical and chemical reactions with skin, eyes and mucous membranes.

Sub micron particles could lead to effects similar to black lung disease. Peroxide is chemically reactive. Martian dust may also contain toxic materials and trace contaminants. Very small particles, especially in low gravity, stay in the atmosphere longer and increase chances of inhalation. Electrostatically charged particles adhere to tissue and create bronchial deposits. Possible toxicity (acute pulmonary distress and systemic effects) caused by nanoparticles, if present in the martian atmosphere, should be considered as an added risk.

Since the site specific lung deposition of inhaled medical aerosol particles depends, among other factors, upon the aerodynamic size and electrostatic charge distributions and the gravitational forces, respiratory drug delivery may be compromised due to reduced and zero gravity conditions.

Subset Risk: Inhalation or ingestion of the dust may cause irritation or disease that can compromise an astronaut's health and their ability to carry out mission objectives. Transport of these species to the humid atmosphere of the habitation module may cause the generation of additional toxic and corrosive species.

Risk Mitigation and Reduction

Risk mitigation would entail designing robust systems to function reliably in Mars' dusty environment. Obtaining recommended measurements is the first step in mitigating the risks. Developing simulated martian dust is the next step. (Simulants are discussed further in Section 3.3.6). These simulants would be used in simulated martian environment laboratories to validated granular materials models and computer simulations and for testing promising technologies and flight hardware to ensure flight systems perform reliably in the martian environment. Mission planners may select a landing site that has lower dust content on the surface to reduce the amount of dust affecting surface systems, thereby mitigating the risk.

3.3.4 Current State of Knowledge

Martian dust physical properties, such as particle size distribution, particle hardness, particle shape, clod size, clod hardness, particle density, friction angle, cohesion, adhesion, dielectric characteristics, magnetic effects, elemental composition, and reactivity have been modeled based on observations from surface rovers and orbital spacecraft [Matijevic, 1997].

Models indicate particle size is .1 to 2000 μm , particle hardness is 1 to 7 on Moh's hardness scale, dust particles are tabular, angular and rounded, particle density is 2.6 to 3.0 g/cm^3 , friction angle is 18° to 40°, dielectric characteristics are $K' = 1.9^d$, cohesion is 0 to 20 kPa, and adhesion is 0.9 to 79 Pa [Greeley and Haberle, 1991; Shorthill, 1976]. Observations indicate the dust is magnetic [Hviid et al., 1997]. Direct measurements detected Si, Al, Fe, Mg, Ca, Ti, S, Cl and Br in the soil [Rieder et al., 1997]. The soil, probably slightly acidic, is generally oxidized but may be reactive.

3.3.5 Desired Future State of Knowledge

To reduce risk for the first human Mars mission, Earth-based laboratory and computer simulations and toxicological studies need to be performed to ensure that human systems operate properly and crew health is protected. Physical property parameters predicted by models should be verified in situ by direct measurement to ensure that Earth-based simulations and studies are valid.

In order to design human systems that would properly function in the dusty martian environment specific knowledge should be obtained to provide simulation and study designers with detailed chemical and physical properties of martian dust and sand to understand adhesive, electrostatic, and abrasive properties [NRC, 2002]. These properties include shape and size distribution, mineralogy, electrical and thermal conductivity, triboelectric and photoemission properties, chemistry of relevance to predicting corrosion effects, polarity and magnitude of charge on individual dust particles and concentration of free atmospheric ions with positive and negative polarities.

To protect the crew from potential hazards of martian dust, reactive, corrosive and irritant properties need to be understood [NRC, 2002]. To obtain the needed information requires assays for chemicals with known toxic effect on humans, e.g., oxidizing species such as CrVI; characterization of soluble ion distributions; understanding of reactions that occur upon humidification and released volatiles; knowledge of shapes of martian dust grains sufficient to assess their possible impact on human soft tissue (especially eyes and lungs), and determination of toxic response in animals should be performed.

3.3.6 Investigations, Measurements, and Priorities to Reduce Risk(s) and/or Cost

The Dust/Soil Focus Team evaluated each risk and recommended investigations that would be needed to provide data to mitigate the risk. It also prioritized measurements based on the probability and consequence of risks, evaluating if investigations must be performed in situ or if the mitigation could be performed on Earth using existing data to create simulated martian environments or computer software, and considering cost of performing in-situ measurement versus the value of the data that would be obtained.

The need for martian dust/regolith simulant(s)

An important strategy for reducing the risks related to the effects of granular materials on both engineering and biological systems is to establish one or more martian dust/regolith simulants. Widely accepted standard materials make it possible to compare technology performances from different laboratories and to generate empirical rather than theoretical data. For risks associated with MEPAG Goal IV Investigation 1A, we recommend using the simulants to test dust

accumulation on various types of materials; dust repellant, removal and cleaning technologies; various types of decontamination procedures; flight hardware designs; reliability, maintainability and waste minimization technologies; and operational procedures. For risks associated with MEPAG Goal IV Investigation 2, we recommend using simulants to perform in-vitro and in-vivo laboratory exposure testing, laboratory animal tests, establishment of respiratory and inhalation limits, and the development of operational procedures, mitigation methods, and exposure levels. Investigation 1A addresses Risk #4 in Table 1 ("Adverse effects of dust on mission surfaces"). Investigation 2 addresses Risk #5 in Table 1 ("Direct dust hazards to crew (toxicity)").

FINDING: PROPOSED INVESTIGATION AND MEASUREMENTS

1A. Characterize the particulates that could be transported to hardware and infrastructure through the air (including both natural aeolian dust and particulates that could be raised from the martian regolith by ground operations), and that could affect engineering performance and in situ lifetime. Analytic fidelity sufficient to establish credible engineering simulation labs and/or performance prediction/design codes on Earth is required.

Measurements

- a. A complete analysis, consisting of shape and size distribution, mineralogy, electrical and thermal conductivity, triboelectric and photoemission properties, and chemistry (especially chemistry of relevance to predicting corrosion effects), of samples of soil from a depth as large as might be affected by human surface operations. Note #1: For sites where air-borne dust naturally settles, a bulk regolith sample is sufficient—analysis of a separate sample of dust filtered from the atmosphere is desirable, but not required. Note #2: Obtaining a broad range of measurements on the same sample is considerably more valuable than a few measurements on each of several samples (this naturally lends itself to sample return). Note #3: There is not consensus on adding magnetic properties to this list.
- b. Polarity and magnitude of charge on individual dust particles suspended in the atmosphere and concentration of free atmospheric ions with positive and negative polarities. Measurement should be taken during the day in calm conditions representative of nominal EVA excursions. Note #4: This is a transient effect, and can only be measured in situ.
- c. The same measurements as in a) on a sample of air-borne dust collected during a major dust storm.
- d. Subsets of the complete analysis described in a), and measured at different locations on Mars (see Note #2). For individual measurements, priorities are:
 - i. shape and size distribution and mineralogy
 - ii. electrical
 - iii. chemistry.

In addition, Mars regolith simulants are needed for geotechnical modeling. A large amount of work can be done in terrestrial laboratories (and in terrestrial computers) in this area, but the models need to be based on some ground truth—they would rely heavily on simulants for initial development. The relative priority of regolith-related geotechnical risks, and the kind of information that would be needed to address them (possibly including both in situ measurement of regolith in its undisturbed state, and full characterization of a regolith sample) are not yet clear.

The one currently available martian simulant (JSC Mars-1) is of uncertain relevance, because we simply don't have enough information about all of the appropriate properties of the martian regolith. Most obviously, we have incomplete information about the mineralogy, the grain size distribution, or the particle shape of the martian regolith, and as of this writing, we have measurements of its chemistry at only five landing sites. **This study assumed that dust properties at one site would be representative of global dust because global dust storms would homogenize the dust. However, heavier particle properties may vary from location to location.** Several types of simulated regolith are expected to be needed to support different kinds of tests. For example, when evaluating a technology for adhesion, the simulant may need to represent the electrostatic and magnetic properties of martian dust. For toxic effects, a simulant may represent the corrosive properties of dust that could lead to illness.

Measurement 1A.a would provide data to create simulants with abrasivity (shape, size, mineralogy), adhesion (size, electric and thermal conductivity), electrical (electrical conductivity), and corrosion (chemistry) properties representative of martian dust. These simulants can be used in artificial martian environments to test promising technologies for dust removal, cleaning, sealing and corrosion prevention. This investigation was deemed the highest priority because, given the Apollo experience, the probability of occurrence of the risk associated with these properties is very high as is the consequence as described earlier in the risk discussion.

Measurement 1A.b would provide data (triboelectric and photoemission properties) to use in simulant development for testing electrical grounding systems. This information is needed to create computer and laboratory simulations to ensure the systems designed to ground electrical systems are adequate.

FINDING: PROPOSED INVESTIGATION AND MEASUREMENTS

2. Determine the possible toxic effects of martian dust on humans.

Measurements:

- a. For at least one site, assay for chemicals with known toxic effect on humans. Of particular importance are oxidizing species such as CrVI. (May require MSR).
- b. Fully characterize soluble ion distributions, reactions that occur upon humidification and released volatiles from a surface sample and sample of regolith from a depth as large as might be affected by human surface operations.
- c. Analyze the shapes of martian dust grains sufficient to assess their possible impact on human soft tissue (especially eyes and lungs).
- d. Determine if martian regolith elicits a toxic response in an animal species which is a surrogate for humans.

Measurement 1A.c would provide information to assist engineers in determining if mitigation technologies determined to be effective in martian environments created with simulants based on Measurement 1A.a are also effective during martian environmental dust storms. It would also provide data for computer simulations. The Dust/Soil Focus Team prioritized this measurement as less than Measurement 1A.a because of the possibility that the properties measured in Measurement 1A.c could be modeled in computer or laboratory simulations. However, ground-truthing is important to validate the models, so it remains a high priority.

Measurement 1A.d determines if dust and soil are homogenous across the planet. The Dust/Soil Focus Team believes that the upper layers of regolith are homogenous, however, this assumption has not been validated. If the properties of the dust vary widely by region new simulants may need to be developed for missions depending on the destination. Also, if additional risks related to lower layers are identified by the granular materials community in the future, this information would be useful in mitigating those risks.

Measurement 2a through 2d address Risk #5. These measurement have equal priority and the data from each would be used develop simulants for toxicological studies as described above.

Importance and Reasoning

The likelihood of risks associated with investigation 1A are very high. We know from our Apollo missions that dust rendered space suits useless after three days. Abrasion and accumulation of dust on systems led to failure and degradation. We know that abrasion and accumulation of dust would lead to adverse consequences [NASA, 1969a; 1969b; 1971a; 1971b; 1972; 1973].

On the other hand we have some evidence that dust may adversely affect crew health [[Lam 2002a](#); [Lam, 2002b](#); Connors et al., 1994]. However, we do not have as high a level of confidence in the existence of toxicity as we have in the abrasive and adhesive properties of martian dust. Therefore, the likelihood level of risks associated with investigation 1A are deemed higher than those associated with investigation 2.

If we do not build our systems to handle dust, a catastrophic failure could happen very quickly, and given the laws of orbital mechanics, there may be no way home. On the other hand, toxic materials inhaled by the crew may lead to chronic illness, probably after the crew returned home, which could be treated on Earth. So, given the time to effect, Investigation 1A is deemed higher priority than Investigation 2.

Further, the mitigation of risk associated with measurements obtained by Investigation 1A, would lead to limiting the amount of dust entering the EVA suit and brought into the habitat after EVA activities that would naturally reduce risks associated with Investigation 2. Additionally, sensitive electronics that control life safety systems may require an even cleaner environment than the crew requires.

Given the above analysis Investigation 1A is deemed a higher priority than Investigation 2.

Timing, Frequency and Location

Measurements 1A.a. and 1A.b require one-time sampling and analysis at a single location. Measurement 1A.c also requires one-time sampling and analysis at a single location, however, this measurement must be performed during a major storm. Measurement 1A.d requires sampling and analysis be performed at high and low albedo and a polar region.

The Dust/Soil Focus Team assume that the dust is homogenous because global dust storms would distribute the dust across the planet. However, even if the parameters were obtained by

measurement rather than models, extrapolating an entire planet from a single measurement would result in low confidence in our knowledge. Moreover, nearly all our data is for the surface, globally distributed wind born layer of dust, not for what may lie beneath. Therefore the Dust/Soil Focus Team recommended investigation 1A.d.

Measurements for Investigation 2 require one-time sampling and analysis at a likely landing site for the first human mission.

Dust, soil and toxicology measurements should be performed as soon as possible to provide engineers with the time needed to develop engineering techniques to mitigate the risks [National Research Council, 2002].

Possible Research and Technology investments needed to obtain the recommended measurements are:

- Suspended dust electrical properties measurement
- Suspended dust physical properties measurement
- Lightweight trace element analysis

3.4. Measurements related to radiation risks

3.4.1 Introduction

Radiation encountered on a mission to Mars would present two kinds of exposures to the crew, chronic and (possibly) acute (Risk #12 and Risk #13 in Table 1). The chronic exposure comes from the Galactic Cosmic Radiation (GCR), which is a continuous, low-dose source of charged particles. The GCR consists of energetic atomic nuclei of all species from hydrogen to uranium, fully stripped of their electrons. (Ions heavier than iron are rare.) These nuclei are not encountered on Earth because of its thick atmosphere and planetary magnetic field, but in deep space they cannot be entirely avoided under realistic shielding scenarios. Chronic exposure to radiation can produce “late” effects, i.e., effects that are manifested years, perhaps decades, after exposure. The late effects of greatest concern are increased cancer risk and damage to the central nervous system (CNS). Acute radiation exposures are possible when strong Solar Energetic Particle (SEP) events occur. In SEP events, very large fluxes, dominated by protons, are accelerated to energies sufficient to traverse a few grams per square cm of matter. Very high-flux SEP events have been seen, producing doses that might have caused acute effects and possibly death to unshielded or lightly shielded humans outside the geomagnetosphere [Wilson et al., 1998]. A good introduction to and discussion of the issue of radiation exposures on deep-space missions can be found in a 1996 report by the Space Studies Board of the National Research Council [NRC, 1996]. In this report, we expand on the discussion of radiation issues in “Safe on Mars” [NRC, 2002]; the conclusions reached by the MHP Radiation Focus Team are substantially the same as those reached in that report. We will discuss both chronic and acute exposures in more detail below. Since this subject matter is unfamiliar to many readers, we first define some relevant terms. For additional definitions, see the Review of Particle Properties [Eidelman et al., 2004].

Linear Energy Transfer (LET or L) – A charged particle traversing loses energy principally by ionization. Energy lost by the charged particle is transferred to the medium, with some energy escaping in the form of energetic delta-rays. The amount of energy transferred is, in radiation biology, referred to as Linear Energy Transfer (abbreviated LET or sometimes just L), and is given in units of energy/length. Ionization energy loss is described with great accuracy by the Bethe-Bloch equation, which gives a reasonable approximation of LET under most conditions.

Dose – Radiation dose is defined as the energy transferred to a medium (usually tissue or water) per unit mass. The standard unit of dose is the Gray, abbreviated Gy, equal to one joule per kilogram. Assuming the medium in question is water, and assuming charged particle equilibrium, the dose at a point can be related to the integral particle fluence (particles per cm²) as a function of LET, $\phi(L)$, as follows:

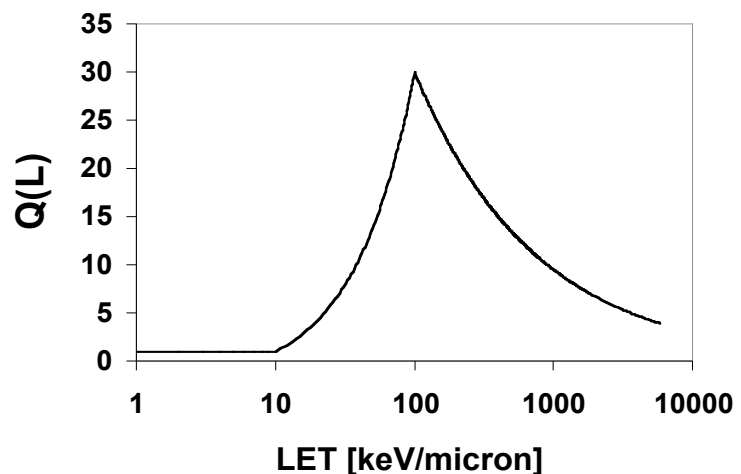
$$D(nGy) = \frac{0.1602}{\rho} \int \frac{d\phi}{dL} L dL$$

where D is in nanoGray, L is in units of MeV/cm and ρ is in units of g/cm³.

Quality Factor – Different types of radiation vary in their effects on biological systems. To account for this, the current risk assessment methodology employs (for “mixed field” radiation as encountered in spaceflight) a weighting factor called the quality factor, Q which is defined to be solely a function of LET. The current functional form of Q vs. LET is shown in Figure 1; it is determined by the International Commission on Radiation Protection [ICRP, 1990], using a sizable database obtained in decades of research in radiobiology. Q is defined for cancer risk and hereditary effects only, and since it represents the current state of knowledge, it is subject to change. The biological effects of energetic heavy ions such as those in the GCR are not well understood at present, which makes use of the quality factor controversial in some parts of the space radiation research community. Further, Q has been determined using particles of considerably lower energy than are typical for Galactic Cosmic Rays. And if heavy ions also cause damage to, e.g., the central nervous system, the present paradigm based on Q breaks down because CNS damage does not result from exposure to low LET radiation. Thus the entire present paradigm of radiation risk assessment rests on data that are of questionable applicability to long-duration spaceflight.

Radiation such as x-rays, energetic protons, etc., have LET below 10 keV/μm and Q of 1. Between 10 and 100 keV/μm, Q rises. Iron ions in the GCR typically have LET in the range from 150-200 keV/μm, which is why iron is the leading contributor to dose equivalent in the GCR.

Dose equivalent – Dose equivalent, H , is related to cancer risk. The space radiation environment is a



“mixed field” of different particle types, energies, and LETs. The mixed-field average quality factor is given by

$$\bar{Q} = \int \frac{d\phi}{dL} Q(L) L dL / \int \frac{d\phi}{dL} L dL$$

and dose equivalent is given by $H = \bar{Q}D$. The unit of dose equivalent is the Sievert (Sv). An exposure to 1 Gy of radiation with $Q = 1$ gives a dose equivalent of 1 Sv.

Acute Exposures – Doses above 1 Gy, received in a short time, cause immediate deleterious health effects. Doses above 5 Gy are typically lethal. Historically, such exposures have occurred only in accidents and in the bombings of Hiroshima and Nagasaki. Acute effects during spaceflight could occur if astronauts are exposed to a large SEP event at a time they have little or no shielding.

Chronic Exposures – Chronic exposure at a low dose-rate is unavoidable for humans traveling in deep space. Long-term health effects of chronic radiation exposure include increased incidence of cancer, cataracts, and damage to the central nervous system. Mitigation strategies include shielding (which is difficult given mass constraints and the physics of GCR transport) and improved propulsion systems to reduce flight duration. Active shielding approaches have been investigated but do not appear viable. A modest depth of shielding can either reduce or increase the dose equivalent received by crew, depending on the composition of the material used.

Long-term Health Effects – Studies of the A-bomb survivors provide the largest database for determining long-term health effects of radiation exposure [NRC, 1990]. The applicability of those data to exposures received in flight is dubious, given the radically different exposure modes. On Earth, exposures large enough to show statistically significant effects in a surviving population have only occurred when a dose of low-LET radiation was received in a short time. In deep space, the situation will be quite different, as crew will receive a high-LET radiation at a very low dose rate.

HZE – The high-charge ($Z > 2$) and high-energy particles in the GCR are sometimes referred to as “HZE” particles. This is a convenient shorthand we will use here.

ALARA and Career Limits – The ALARA principle (“as low as reasonably achievable”) guides NASA’s approach to radiation protection. NASA is legally and ethically obliged to keep radiation exposures as low as possible. The radiation astronauts receive in flight is much different from that received by, e.g., nuclear reactor workers; this means that NASA, with input from the research community, must determine its own specific guidelines. Limits are now set to keep an astronaut’s career exposure below the value that is believed to increase his or her lifetime risk of a fatal cancer by less than 3%. Since the lifetime risk of an individual depends on age and gender, the career limit depends on age and gender. Least susceptible are older males; most susceptible are younger females. Career limits have not yet been defined for deep-space missions. Limits for low-Earth orbit range from 0.5 to 4 Sv.

Galactic Cosmic Radiation (GCR) – The GCR consists of fully stripped atomic nuclei of all known species. GCR particles originate outside the solar system. About 87% of GCRs are protons, 11% helium nuclei, 1% electrons, and 1% ions heavier than helium. Though not highly abundant, the heavier ions contribute significantly to radiation exposures in deep space. Typical differential flux distributions peak in the energy region of several hundred MeV/nucleon. The flux is on the order of 0.1 to 1 particle $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$, varying inversely with solar activity.

Solar Energetic Particles (SEPs) – SEP fluxes are dominated by protons; occasionally energetic helium ions are also seen, and in very rare events high-energy heavy ions are seen [Tylka and Dietrich, 1999]. For the most part, however, when discussing SEPs, we are referring to protons with typical energies below 100 MeV. Fluxes above 10^4 particles $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ have been seen, e.g., by GOES in the $E > 10$ MeV proton channel in the Halloween 2003 event. In some events, there can be large fluxes of more energetic (and hence more penetrating) protons as well. The event of Sep. 29, 1989 had an event-integrated flux of > 100 MeV protons in excess of 10^8 particles cm^{-2} .

3.4.2 Primary Risks

To summarize the preceding section, radiation presents two types of risks to crew, chronic and acute. Chronic exposure to the GCR increases the probability of an individual developing a fatal cancer (or other serious illness) over the course of his or her lifetime. Acute exposure to SEPs can have immediate deleterious health effects. Chronic exposures cannot be prevented, and must instead be managed; in stark contrast, **acute exposures must be prevented** through a combination of proper shielding of spacecraft and habitats, and early warnings.

3.4.3 Current State of Knowledge

The current state of knowledge of the relevant physics (flux of particles, effects of shielding materials) is good. In contrast, the knowledge of the relevant radiobiology is far from complete. The radiobiology of HZE particles is the subject of a ground-based effort using the new NASA Space Radiation Laboratory facility at the Brookhaven National Laboratory. The biological problem is extremely difficult, because there are many endpoints (cancers in different organs, damage to the CNS, cataract induction, etc.) and many levels at which one needs to understand both radiation effects and the abilities of living systems to correctly repair themselves. This side of the problem presents far larger uncertainties than the physics side. Of particular interest for MHP is the role that neutrons would play in the exposures crewmembers would receive on the martian surface. The biological effects of neutrons are a subject of ongoing debate, and a revised set of weighting factors (used to convert from fluence to dose equivalent) has recently been proposed by the ICRP. This, and other uncertainties in the biological effects of radiation, are issues that the MHP program cannot address.

To accurately calculate the dose equivalent requires knowledge of the types and energies of particles present. In space, it is impractical to measure all the relevant particles that impinge on the crew. Also, radiation protection requires that dose to sites internal to the body – where it is impossible to place detectors – must be estimated. Therefore, predictions of radiation exposures in spaceflight, as well as post-mission assessments, will continue to depend on transport models. **MHP should address this essential issue in radiation safety: the validation of radiation transport models that predict the detailed flux of particles on the martian surface.**

Ideally, a space radiation transport model would reproduce both the incident radiation (GCR and SEP) and all the mechanisms relevant to transport of the incident particles through matter. Not surprisingly, current models fall short of the ideal, but some are still found to be fairly accurate when compared with flight data and/or data obtained at particle accelerators. However, as has been pointed out in many contexts, no matter how perfect one might hope to make a model, there is no substitute for experimental verification. Further, SEP events are presently (and perhaps intrinsically) unpredictable, so that one cannot hope to make a predictive model for that part of the dose. Existing models include the BRYNTRN [Wilson et al., 1989] and HZETRN [Wilson et al., 1991] codes developed originally at NASA-Langley. There are ongoing efforts to bring other well-established high-energy physics codes such as HETC and FLUKA to bear on the problem. Many sources have contributed to the current state of knowledge, including flight data acquired over several decades. As new data that bear on the problem become available, they are incorporated into the transport models. For predicting the GCR flux, including its modulation by the solar cycle, a recent paper [O'Neill and Badhwar, 2004] reports a highly accurate computer code that reproduces the latest ACE/CRIS data. In the study of SEP events, a large database of events exists, with an active community of researchers working to understand (and perhaps predict) the exact mechanisms of particle acceleration. Most relevant to MHP, orbital data on charged particles and neutrons have been acquired by instruments on the 2001 Mars Odyssey spacecraft – MARIE for charged particles, and the Neutron Spectrometer and High-Energy Neutron Detector for neutrons [Saunders et al., 2004].

To assess the radiation environment on the surface of Mars, we must take account of the sources of energetic particles (GCR and SEP events) and the ways in which Mars itself modifies the flux. Table 3 summarizes the main components of the radiation environment on the surface. The GCR flux at the top of the atmosphere is reasonably constant in time (it is modulated over the course of the solar cycle and varies in total particle count by factors of 2-3 from solar min. to solar max.) and does not differ significantly between Earth and Mars. In SEP events, depending on the relative position of Mars and Earth, the fluxes of particles can be entirely different in the two locations.

Table 3

<i>Source of particles</i>	<i>Interaction in atmosphere</i>	<i>Interaction in surface</i>	<i>Resulting surface radiation(s)</i>
GCR	Energy loss	N/A	Intact GCR at reduced energies (small % stop).
GCR	Nuclear	N/A	Fragmentation products: lighter ions than were incident, high-energy neutrons.
GCR	N/A	Nuclear	Large fluxes of thermal and epithermal neutrons, smaller flux of high-energy neutrons.
SEP	Energy loss	N/A	Vast majority of stopped, no effect on surface.
SEP	Nuclear	N/A	High fluxes of energetic neutrons.

Charged particles arriving at Mars traverse the atmosphere before reaching the surface. The distributions of ion species and energies are modified by energy loss and nuclear interactions. Because of their very different energies and the resulting differences in propagation through the atmosphere, we discuss SEPs and GCR particles separately.

Typical SEPs have ranges less than the column depth of the atmosphere, meaning that they stop far short of the surface. Although most or all primary SEPs are stopped in the atmosphere, each incident particle has a non-zero probability of producing a neutron via a nuclear interaction; this is true – though less probable – even for protons stopping high in the atmosphere. Because neutrons do not lose energy through ionization, they can penetrate considerable depths before interacting. Thus one of the main concerns from a large SEP event while the crew is on Mars is the production of large neutron fluxes at the surface. Also, in very rare SEP events, high fluxes of protons in the 100-1000 MeV range have been observed. At these energies, many protons would penetrate to the surface of Mars and pose a hazard of acute exposure to unprotected crewmembers. A high-level decision will be required as to whether mission designers need to account for such rare events, or whether the risk is so remote that it must simply be accepted despite the potentially dire consequences.

Unlike SEPs, the great majority of GCR protons have ranges that are much greater than the column depth of the martian atmosphere. Many heavier particles in the GCR also have sufficient energy to reach the surface of Mars, but they also have significant probabilities for undergoing nuclear interactions with nuclei in the atmosphere. The result of such interactions is fragmentation of the incident nucleus into two or more lighter nuclei, which generally emerge from the collision with approximately the same velocity that the incoming nucleus had prior to the collision. Thus the flux of GCR heavy nuclei is significantly smaller on the surface than it is at the top of the atmosphere (though the total flux may be equal to, or greater than, the incident flux). For example, for an iron ion in CO₂, the interaction length is approximately 15 g cm⁻². This means that, for an atmospheric column depth of 16-22 g cm⁻², less than 1/e, or 37% of those incident on the top of the atmosphere reach the surface intact, while 63% will fragment into lighter ions, which typically impart lower dose and dose equivalent than the incident iron ions would have had they reached the surface. Because of nuclear interactions of HZE particles, and because some low-energy GCR particles are stopped before reaching the surface, the atmosphere provides some shielding against the GCR. Nuclear interactions of GCR particles in the atmosphere also produce a continual, small flux of downward high-energy neutrons, but this is orders of magnitude smaller than the neutron flux that can be produced in a large SEP event.

Particles are also produced in martian regolith. GCR particles can penetrate the soil and undergo interactions with nuclei in the soil, producing excited “target” nuclei which decay by particle emission to lower-energy states. The emitted particles include gamma rays, protons, neutrons, and alphas. Particles are emitted with no favored direction; some go up and out of the regolith. Charged particles have little chance of exiting the regolith because they are mostly very low energy and ionization energy loss causes most of them to stop after a short distance. Neutrons, however, can and do escape the regolith and will therefore add to dose received on the surface. The neutrons produced in the regolith are often referred to as albedo neutrons.

Estimates of GCR Dose and Uncertainties

The current state of knowledge is perhaps best illustrated by a discussion of the predicted GCR doses and associated uncertainties for a Mars mission. To make the discussion independent of the chosen mission profile and propulsion method, we begin by putting the results in units of dose equivalent received per day, and then we examine two scenarios. Because SEP events are

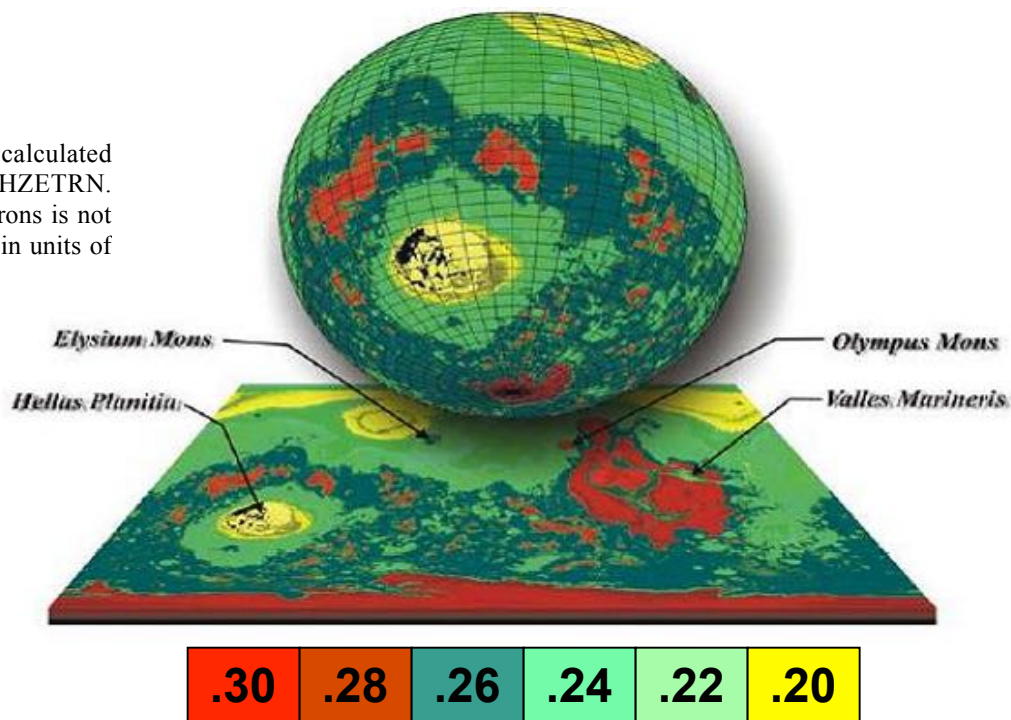
unpredictable, we defer that part of the discussion. In the absence of information about shielding of the transit vehicle or surface habitat, we assume no shielding for purposes of this discussion. (A likely scenario is that the transit vehicle will be fairly well shielded, the surface habitat modestly shielded, and astronauts working on the surface will have little to no shielding. In this case, all GCR doses are likely to be slightly lower than those given here, and the relative contribution from the surface stay will be slightly larger than shown here. The extent to which the relative contributions will be different from those given here is heavily dependent on the shielding details.)

Table 4 shows estimated dose equivalent rates in transit and on the surface, with the two major surface contributions shown separately. The calculations are for solar minimum, when GCR dose is highest. For solar maximum, the numbers can be scaled down by a factor of about 2. The uncertainty in the prediction for any given time in the solar cycle is expected to be about $\pm 30\%$. The surface dose rate from the primary GCR is always lower than the dose rate in transit by at least a factor of two, due to the shielding from a planetary surface. The atmosphere accounts for an additional increment of shielding, the amount of which depends significantly on altitude. At JSC, surface maps color coded by radiation dose equivalent rates have been created [Saganti et al., 2004], using the HZETRN code and MGS MOLA data. Albedo neutrons were not included

Table 4 – GCR Dose, Solar Minimum Conditions, No Shielding

	H, mSv/day	Comment
Transit	2.5 ± 0.8	
Surface	0.7 ± 0.3	Excludes albedo neutrons
Surface	0.4 ± 0.4	Albedo neutrons
Surface, all contributions	1.1 ± 0.5	

Figure 2 – Mars radiation globe calculated with the NASA transport code HZETRN. The contribution from albedo neutrons is not included. The color-coded scale is in units of Sieverts per year.



in the calculation. The result for solar minimum is shown in Fig. 2, with a range of 0.2 – 0.3 Sv/yr. In the following, we take the middle of the range, 0.25 Sv/yr., as the dose excluding the albedo neutron contribution, which is calculated separately.

To compute the albedo neutron dose in Table 4, the calculated neutron spectrum on Mars (the solid red line in Fig. 3) was crudely convoluted with a fluence-to-dose equivalent curve [Eidelman et al., 2004]. The uncertainty has been set equal to the value to indicate that this is the most likely calculation in which there would be a significant error. The important result of the calculation is that, even with the neutron contribution included and uncertainties folded in, the total dose equivalent rate on the surface is significantly less than in transit.

With these results, we can consider various simplified mission scenarios and determine the contribution of the surface exposure to the mission total. We can write a simple equation for the total: $H_{GCR} = (2.5 \pm 0.8)_{transit} + (1.1 \pm 0.5)_{surface}$ where H_{GCR} is the GCR dose equivalent in mSv and the times $t_{transit}$ and $t_{surface}$ are given in days. With current propulsion systems that require about 400 days in transit, the GCR dose equivalent would be in excess of 1 Sv from transit. Surface stays up to 100 days would contribute only about 10% to the overall GCR exposure. If improved propulsion methods can reduce the transit time substantially, and/or if long surface stays are considered, the relative importance of the surface dose equivalent and the associated uncertainty in the neutron component increase significantly. This could also be true if there were a revision (upward) of the neutron fluence-to-dose-equivalent curve.

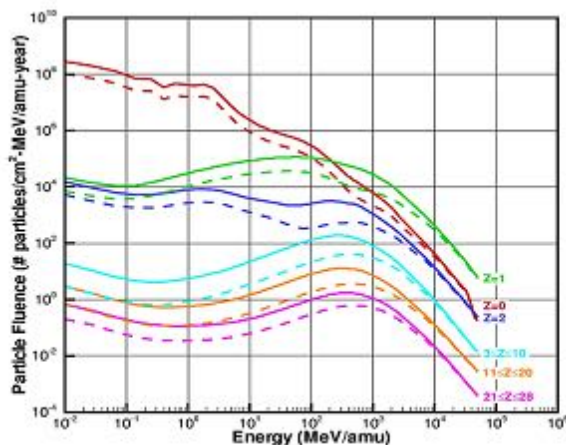


Figure 3— Neutron and charged particle fluxes on the surface of Mars, calculated with HZETRN. The neutron curve was used for the estimate of the albedo neutron contribution to the surface dose. Solid lines represent solar minimum conditions, dashed lines solar maximum. The red lines are the neutron fluxes.

Estimates of SEP Dose and Uncertainties

Given that we cannot predict the exact nature of future SEP events, perhaps the most instructive way to approach the question of SEP exposures on a Mars mission is to make use of calculations done using spectra measured in previous events [Simonsen et al., 1990; Simonsen et al., 1993]. The calculations use transport models to predict dose and dose equivalent on the surface of Mars, given an input spectrum at the top of the atmosphere. We stress that the cases studied so far have used spectra measured at Earth rather than at Mars, and that is not a particularly good approximation, since (1) particle spectra can be entirely different in the two locations, and (2) even if Earth and Mars are magnetically connected to the same active region on the sun, the

radial gradient reduces the flux at Mars by a factor of r^{-n} , where n is likely between 2 and 3. Thus, at 1.5 AU, the radial gradient gives at least a factor of 2 reduction.

Two highly relevant studies were performed by the NASA-Langley radiation group. The calculations, done in the early 1990's, used the HZETRN and BRYNTRN codes, which have subsequently been revised, most significantly in the heavy-ion transport done by HZETRN. The values calculated for GCR doses on the surface of Mars are therefore not in agreement with current estimates, which are about 50% higher. However, the SEP part of the calculation should still be valid. In 1993, Simonsen and Nealy reported on the three major SEP events in 1989, the largest being the October event. This event also had the hardest spectrum (i.e., more of the flux at high energies). Assuming a pure CO₂ atmosphere at Mars, they calculated dose and dose equivalent as a function of depth. At a depth of 16 g cm⁻², the large event would have produced a skin dose equivalent of about 0.6 Sv, and about 0.3 Sv at the blood-forming organs, or BFO, which are shielded by tissue and bone and are highly sensitive to radiation. The shielding of the BFO is assumed to be 5 g cm⁻² of water-equivalent mass. It is important to note that the radial gradient was not factored into the calculation, so the results likely overestimate the dose equivalent by a factor of 2-3. While the exposure from this event is under 1 Sv, and therefore sub-acute, it nonetheless would contribute significantly to the total for the mission, being equal to that received from the GCR over hundreds of days on the surface of Mars.

There are a few additional features of the SEP event calculations that are noteworthy. First, a more intense event and/or one with a harder spectrum than the October 1989 event could result in acute exposures to crew working outside of shielded areas, particularly if crew is unable to return to a shielded environment within several hours of the event's onset. Second, the large difference between skin and BFO doses is due to the relatively low energies of the particles in SEP events; in contrast, GCR doses decrease much less in going from skin to BFO. Third, no shielding from a habitat or spacesuit is included in the calculation. In the case of a large SEP event, crew would be advised to return to shelter and stay inside for the duration of the event, further reducing the exposure. Third, because SEP event exposures would be to protons and neutrons, which are low-LET radiation, the risk calculations are likely to be more reliable than are the estimates of risk from GCR exposure, since the latter is strongly dependent on the poorly-understood health effects of HZE particles. (This is because, in a SEP event, nearly all particles have $Q=1$, and calculation of dose equivalent does not depend on the controversial high-LET portion of the quality factor curve.) Finally, assuming that a particle detector system capable of measuring charged particles and neutrons is operating on Mars during a large SEP event, the data would not be very useful unless there is a simultaneous measurement, in orbit, of the flux of particles at the top of the atmosphere. Simultaneous measurement of the "input" (incident particles) and "output" (flux at the surface) would provide a stringent test of transport models. **We therefore recommend that a radiation detector be placed in Mars orbit, on a schedule that would permit simultaneous operation with the landed detector system.** The orbiting detector can be a comparatively simple, low-power, low-mass system optimized for SEP events.

Effects of Remanent Martian Magnetism

The MGS magnetometer experiment [Acuña et al., 2001] has shown that, although there is no planetary dipole field at Mars, there are regions of remanent magnetism. Although the fields do interact with the comparatively low-energy particles in the solar wind, they are too weak to have

a significant effect on the high-energy GCR particles or on moderately energetic SEPs. Very low energy SEPs will be deflected away from magnetic regions, but these would stop in the upper atmosphere even in the absence of magnetic fields. As a consequence of the deflection of low-energy SEPs, a small reduction in the number of secondary neutrons that reach the surface may be seen in magnetically protected regions. The net shielding effect of the fields, therefore, is expected to be negligible during solar quiet time, and small (possibly negligible) during SEP events.

Other Possible Exposures

Two potential sources of radiation exposure were pointed out by members of the working group. First, there is certainly ^{238}U present in martian regolith, although the concentration is not known. In principle, the radon gas could diffuse into a buried habitat accumulating in sufficient concentrations to pose a hazard. Fortunately this radon hazard is easily mitigated by insuring that ventilation of the gas into the martian atmosphere competes effectively with diffusion into the habitat. Another possible concern is that martian dust may have higher concentrations of alpha-emitting radioactive nuclei than does dust on Earth or it may be retained in the lungs much longer. Since efforts would be made to reduce dust inhalation in any case, there does not seem to be a pressing need for measurements of dust radioactivity.

Radiation Effects on Electronics

In addition to posing direct risks to the health of crew members, radiation also poses a potentially serious risk to crew through the mechanism of damage to electronics essential to life support. As this issue affects the aerospace industry and the military, a well-developed infrastructure exists to study radiation effects and to design hardware capable of withstanding considerable doses of radiation. The success of these efforts is manifested in the continuing successful operation of much hardware in deep space. The most relevant examples of this success are the Mars Exploration Rover vehicles, which have operated on the surface of Mars for over a year at the time of this writing. In their cruise to Mars, the MER's withstood the very large solar events of Halloween 2003 and have survived on the surface despite several subsequent events, including a significant hard-spectrum event in mid-January 2005. In short, radiation effects on electronics are at present much better understood, and more preventable, than effects on living organisms.

3.4.4 Desired Future State of Knowledge

Transport model validation remains the highest priority for radiation investigation, which is the same conclusion reached by the "Safe on Mars" panel. Below, we list a small number of highly-relevant ground-based experiments that could contribute in this area prior to the first MHP mission. Ultimately, though, a direct comparison of charged particle and neutron spectra obtained on the surface of Mars to those predicted by transport models is needed. This would lead either to improvements of the models, or to a consensus that the models are already adequate according to some pre-determined criteria for their accuracy. As helpful as ground-based experiments may prove to be, they are no substitute for data obtained *in situ*.

As discussed above, the physics part of the radiation problem is fairly well understood, and we can categorize and make some quantitative estimates of the radiation health risks to astronauts on a Mars mission. Improved understanding of HZE radiobiology would reduce the uncertainties on those estimates. **However, there is an additional risk that is not always described as such:**

the possibility that, due to large uncertainties on the physics side, concerns about radiation would force mission planners to include shielding mass that might turn out to be unnecessary were the problem better-understood. The penalty for launching excess mass, and perhaps landing it on Mars, is very high; in the absence of greater certainty about the risks, radiation shielding mass could be a major cost driver of a human mission. It is therefore beneficial from a programmatic perspective to obtain the needed knowledge early in the MHP program so that accurate calculations of shielding requirements can feed forward into the designs of spacecraft and habitats.

Definition of Model Validation

We have repeatedly referred to “validation” of transport models as the main goal of measuring the radiation on the surface of Mars. However, a universally agreed-upon definition of validation is elusive. To that end, the Radiation Focus Team suggests that **NASA should sponsor a limited, focused workshop on the martian surface radiation environment**, providing direction for a coordinated effort to optimize instrument requirements in advance of placing a radiation instrument on a MHP Lander/Rover. Modeling of radiation at the martian surface requires an understanding and integration of the sources, nuclear interactions, and the properties of Mars itself – the atmosphere, surface, and subsurface, including temporal and spatial variations. Experiment design should be optimized through a collaboration of NASA’s Radiation Health Officer, radiation transport modelers, experimentalists, and experts in Mars’ atmosphere, surface and subsurface. An early workshop could set the stage for optimal use of MHP opportunities to perform the needed validation of transport codes.

3.4.5 Investigations, Measurements, and Priorities to Reduce Risk(s) and/or Cost

The dose from albedo neutrons on the surface is the least understood of the various contributions to radiation exposure on a Mars mission. Transport model predictions of this contribution should be viewed with some skepticism, since neutron production is thought to be a weak point of the models. Data from Odyssey can be extrapolated to give an estimate, but results are model dependent since one must account for the transport of neutrons from the surface through the atmosphere. **Therefore, a surface neutron measurement with a detector that has a well-understood response is the highest priority radiation measurement for MHP.**

Since hydrogen is an excellent moderator of neutrons, the surface dose from albedo neutrons will be highly dependent on the location(s) chosen on the surface and the water ice content of the regolith in that location. It would be of considerable interest to do two measurements, one in icy terrain presumably near the poles, and one in a more equatorial region away from the large ice concentrations.

We note that a low-mass (~ 1 kg) radiation instrument has been selected as part of the 2009 Mars Science Laboratory. The instrument is designed to measure both energetic charged particles and neutrons. **The MHP SSG Radiation Focus Team – which has no overlapping personnel with the instrument team – strongly supports the inclusion of this detector as a much-needed first step in the model validation process.** Because the mass of the instrument is so low, it would not provide all of the data that are needed for model validation, and more detailed measurements would remain necessary even after the successful conclusion of MSL.

Nonetheless, any “ground truth” that can be obtained would be extremely valuable, particularly in the area of neutron flux.

Measurements on the Martian Surface and In Orbit

Measurements of both neutrons and charged particles on the surface of Mars are intended to provide the data needed for transport model validation. The consensus of the Radiation Focus Team is that the weak point in the current models is in the calculation of neutron dose equivalent on the martian surface. The neutron component is present at all times due to the GCR, and is enhanced, possibly by orders of magnitude, during large SEP events. In typical SEP events, neutrons are the main source of dose on the surface, since virtually all of the charged particles stop in the atmosphere. Validation of transport codes would be advanced by landing a well-characterized neutron detector system that is capable of measuring over a wide energy range, with the further capability to distinguish between albedo neutrons coming up from the regolith and neutrons traveling downward from the atmosphere. In conjunction with this system, it would also be helpful to have a modest charged-particle spectrometer on the surface, and a similar spectrometer in orbit.

Duration, Frequency, Location

Because measurement of the particle flux on the surface during a large SEP event is a high priority, and because the exact timing of events is unpredictable, it would be most useful to have a detector system in place that can operate for several years during solar maximum. It would be most advantageous to have this in place at or shortly after the time of the next solar maximum, which occurs in 2011. It would also be advantageous for the charged-particle detector to operate for several years during solar maximum. Assuming, as seems likely, that it would be quite compact, it would have a small geometry factor and it would be necessary to integrate the data over many weeks to get good statistics on the high-LET end of the spectrum.

Since the presence of large amounts of water ice in the regolith has a large effect on the effective dose from albedo neutrons, it would be useful to have at least two detectors, one in icy terrain and the other in dry terrain. This would provide an additional test of the ability of the model codes to predict the effective dose from neutrons under different conditions. To simplify the analysis of the data and to minimize systematic errors, the Radiation Focus Team recommends that two copies of the same detector system be landed in very different locations.

Use of Existing Data Obtained in Mars Orbit

The Radiation Focus Team suggests that neutron data from Odyssey’s Neutron Spectrometer (NS) and HEND be carefully analyzed to determine the neutron doses at various latitudes. (It is probably sufficient to integrate over longitude.) This task requires that the data from both instruments be normalized to absolute fluxes, rather than relative fluxes which have been used in analyses to date. First results have been reported by Mitrafanov et al. [2004]. A similar analysis should be performed on Odyssey NS data. These results would be extremely useful, but would not be as reliable as measurements made on the surface, since the neutron fluxes in orbit differ from those on the surface due to transport through the atmosphere.

Ground-Based Precursor Investigations

It is possible to advance the state of knowledge with one or more ground-based experiments in advance of the first MHP mission. One piece of the problem can certainly be addressed with experiments on Earth – or, more precisely, above Earth. Because the martian atmosphere presents a column depth of about 22 g cm^{-2} of CO_2 to incident GCR particles, it is possible to nearly recreate these conditions by flying a balloon to at 85,000 ft above Antarctica. Missions of this type have been successfully flown by NASA for many years. Although the composition of Earth's atmosphere is somewhat different than Mars', the differences in transport are small. (From the perspective of nuclear physics, carbon, nitrogen, and oxygen nuclei are all similar targets.) A balloon-borne experiment to perform this measurement should carry high-resolution charged particle detectors and neutron detectors capable of measuring high-energy neutrons. The Deep Space Test Bed (<http://sd.msfc.nasa.gov/cosmicray/DSTB/DSTB.htm>) that is being prepared by NASA's Space Radiation Shielding Project could carry out such an experiment.

A second part of the problem can, conceivably, be addressed by Earth-based experiments. It is possible, at facilities such as the NASA Space Radiation Laboratory, to accelerate protons and heavy ions to energies typical of the GCR. If one could produce a good approximation of martian regolith, it could be put in beams of GCR-like particles and the resulting albedo particles could be measured. This would provide a stringent test of the models under well-controlled circumstances, but it hinges on the availability of a realistic simulation of martian regolith.

Technology Development

GCR particles and SEPs have been studied in flight experiments for decades. State-of-the-art detectors such as ACE/CRIS [Stone et al., 1998] and the High Energy Telescope and Low Energy Telescope energetic particle spectrometers that would fly on the STEREO mission have capabilities that meet or exceed the requirements for charged-particle measurements on the surface of Mars and in orbit. Little or no new technology is needed for the charge particle measurements relevant to MHP. However, one essential capability for measurement of the Mars surface radiation environment has not yet been demonstrated in flight: the ability to measure a neutron spectrum over a wide energy range, with at least crude directional capability (distinguishing the downward-going neutrons produced in an atmosphere from upward-going albedo neutrons produced in regolith). These capabilities exist in accelerator-based particle detectors on Earth, but packaging such an instrument for flight may present some technical difficulties. Since neutrons can only be detected by the recoil protons they produce, a detector gains efficiency by adding hydrogenous mass. The challenge would be to build a compact, low-mass system with reasonable efficiency.

3.4.6 Summary

The strong consensus of the Radiation Focus Team is that despite the relatively good state of knowledge, measurements are needed both on the surface of Mars and in orbit in order to validate the radiation transport models. The models are expected to be accurate but have known weaknesses that can best be probed by comparing their predictions to data obtained *in situ*, both above and below the atmosphere.

We suggest revising some of the language in the MEPAG document that describes the radiation investigation. First, it is inaccurate to say that “Soil and dust from the Martian surface offer(s) a readily available source of shielding material” – it is not the case that dust can be used as a

shield. Further, shielding properties of the martian regolith against GCR particles may be far less than optimal; it may instead be better to use regolith blended with a hydrogenous compound for the construction of shielding. Second, though knowledge of the UV spectrum is highly desirable for a number of reasons, exposure to UV is not a problem comparable in scope to the risks presented by exposure to GCR particles, SEPs, and the secondary particles they produce. Crew would be protected from UV radiation by habitat walls, spacesuits, and visors.

FINDING: PROPOSED INVESTIGATION AND MEASUREMENTS

5. Characterize in detail the ionizing radiation environment at the martian surface, distinguishing contributions from the energetic charged particles that penetrate the atmosphere, secondary neutrons produced in the atmosphere, and secondary charged particles and neutrons produced in the regolith.

Measurements:

- a. Measurement of charged particles with directionality. Identify particles by species and energy, from protons to iron nuclei in the energy range 20-1000 MeV/nuc.
- b. Measurement of neutrons with directionality. Energy range from 1 keV (or lower) to 100 MeV (or higher).
- c. Simultaneous with surface measurements, a detector should be placed in orbit to measure energy spectra in Solar Energetic Particle events.

3.5. Measurements related to Terrain/Trafficability risks

3.5.1 Introduction

Martian terrain is a hazard to any landed mission, including human missions. First, flight to the martian surface may result in loss of a vehicle and crew if there is an incomplete knowledge of the terrain (Risk #15 and Risk #18 in Table1). Further, terrain location and morphology knowledge directly affects the approach and landing philosophy, including whether the human pilot would be expected to conduct the actual landing, as in Apollo, or whether the landing would be entirely automatic. Second, the ability to rove significant distances would be affected strongly by vehicle design, one concern of which would be tire/wheel design and the clearance needed between a vehicle underside and the local fine scale terrain (Risk #11 and Risk #18 in Table 1). Third, operations, exploration, and science investigations of a human mission may be limited in geographic extent if risks related to martian terrain are not minimized with precursor measurements (risk to science return). For example, the distance the Apollo astronauts were allowed to travel on their rovers (for science) was restricted to the distance they could walk for safe return to the lunar module in the event that the rover became stuck in the lunar terrain.

As an example of these mobility hazards, the Mars Exploration Rover Opportunity became unexpectedly mired in soft dune material on April 26, 2005, and was not able to get free until June 4 (see Figure 4). During this period, wheel rotation commands were sent that would have moved the rover a total of approximately 200m, but actual movement was only about 1m--average wheel slippage was 99.5%. For a human mission, this could have severe consequences.



Figure 4. Image taken on Sol 482 from the front hazard camera onboard the Mars Exploration Rover Opportunity. The rover was mired in soft dune material which severely limited the rover's mobility.

For the purpose of this analysis, we assume that a landing site certification process would continue to be in place for all landed missions (including the first human mission), and that this certification process would be an essential part of the mission planning and development process. Landing site certification is not something that can productively be assigned to a long-lead robotic precursor program (for one thing, the landing site is not likely to be specified until much closer to the time of the mission). For the purpose of the MHP analysis, therefore, we have focused on the precursor measurements needed in addition to the site certification process.

3.5.2 Some thoughts about landing site certification

Although the site certification process has not yet been defined, the MHP SSG identified several aspects that should be considered by the future team that establishes it. It is clearly beyond the scope of the MHP SSG to determine the maximum acceptable risk related to landing site hazards, but the issues below would need to be considered.

Issue #1. Establish terrain knowledge of “lander-scale” terrain obstacles for each landing site (horizontal location and vertical height) to an accuracy consistent with the design of landing systems and mission rules

- Establish terrain knowledge error to ~10 meters vertical and ~100 meters horizontal within the landing ellipse of each potential landing site [Note: Present average MOLA resolution is 300 m vertical by 3 km horizontal [Zuber et al., 1992], with better resolution for locations where ground tracks overlap and multiple measurements have been made (~1 meters vertical and ~100 meters horizontal [Smith et al., 2001]). We estimate that we would need an order of magnitude better for a landing site ellipse only, so data collection at this scale would not be needed for the whole planet. In addition, the HiRISE instrument on the 2005 orbiter should provide stereo imaging sufficient to meet this information need.
- Establish slope angles within landing ellipse for EDL and for surface asset design for ease of trafficability.
 - Measure slopes at 1 km, 100 m and 10 m length scales to within 1 degree [Note: consistent with landing site engineering data required by MER landing site selection team, as presented in Golombek et al., 2003; manned/cargo landers

would be at least as robust as MER landers, so an increase in precision is not required.]

Issue #2. Establish rock abundance at potential landing sites to a scale consistent with lander footpad design; and if timing permits, feed these data into the lander design process. This relates to the risk of coming to rest in a tilted attitude due to a rock lodged under a footpad (preventing a safe egress, or a stable habitat or proper attitude for future departure from the martian surface).

- Measure rock abundances to within ~ 5%.
- Measure rock size distribution with the ability to distinguish rock sizes ~0.1 m [This is consistent with the landing site engineering considerations from Golombek et al., 2003 for the MER sites, and is reasonable given a) the size of landing footpads for a manned/cargo lander; b) the likely measurement capability by 2020].

FINDING: PROPOSED INVESTIGATION AND MEASUREMENTS

6. Determine traction/cohesion in martian soil/regolith (with emphasis on trafficability hazards, such as dust pockets and dunes) throughout planned landing sites; where possible, feed findings into surface asset design requirements.

Measurements:

- a. Determine vertical variation in in-situ soil density within the upper 30 cm for rocky areas, on dust dunes, and in dust pockets to within 0.1 g cm⁻³.
- b. Determine variation in in-situ internal angle of friction of soil for dust dunes and dust pockets to within 1 degree.
- c. Determine soil cohesion for rocky areas, dust dunes and in dust pockets to within 0.1 kN m⁻².
- d. Precision imaging to Mars Reconnaissance Orbiter High Resolution Imaging Science Experiment (MRO HiRISE) standards (30 cm/pxl) for selected potential landing sites

For basic design of mobility systems, the following measurements are needed (not just at the dust pockets and dunes, but also on the consolidated soil surfaces where we may do most of the driving): (i) rolling resistance (the torque that soil applies to a rolling wheel while driving), (ii) traction test (torque required to spin a wheel while the rover is held stationary), and (iii) shape/size of the resulting wheel ruts while driving normally. Note #1: These three things will probably be measured routinely on all Mars rovers. Note #2: ISRU excavation could require hauling larger loads (soil/ice payload) than what we have ever hauled in the past. Therefore they will need these data to properly design wheels and chases (e.g., rover and large structure mobility systems), avoiding energy-wasteful designs or risk of getting bogged down.

3.5.3 Terrain/trafficability Risks

The scope considered for terrain risks includes meter to sub-meter scale elements that would affect manned and robotic rover travel, as well as are needed for large vehicle foot pad design, such as rocks of various sizes and the presence of features such as dunes and local dust accumulations. A critical mission operations question that needs to be addressed, particularly for the first landing, is the degree of landing risk that would be acceptable, as balanced against the scientific interest in a particular landing site. It is a generally held corollary that the most interesting landings sites from a science perspective are in the most difficult landing sites to access. Early definition of risk levels would help define acceptable landing sites, and would provide a better definition of the hazard that the large and small scale terrain features would pose

to future human exploration. Surface operations risks include (Risks #11, #15, and #18 in Table 1):

- Landing in terrain that has slopes too steep for rover capabilities
- Landing in soft dust that would prevent the safe deployment of the habitat
- Landing in soft dust that would make the deployment of rovers difficult
- Roving into soft dust that would cause a rover to get stuck and require it to be abandoned (loss of rover for future EVAs)

3.5.4 Proposed Investigations and Measurements

Thermal inertia measurements must be sufficient to identify dust accumulations that would cause either roving or landing hazards. The TES instrument was able to achieve 3 km/pixel on Mars Global Surveyor. Definition of a particular landing hazard is, in part, related to the landing ellipse for a given landing craft, which does not exist yet for a Mars lander associated with a human mission. However, we can estimate that having a knowledge of dust accumulations that are on the order of 1 km² would be sufficient to do adequate landing site and rover traverse determination. Therefore, we would expect to require an order of magnitude better resolution than TES. Penetrometry and trenching experiments have been done on previous spacecraft as far back as Surveyor and the Viking Landers, so this should not require a significant increase in technology development. Imaging needs should be met by present and future orbital spacecraft (e.g., Mars Express, 2005 Mars Reconnaissance Orbiter).

3.6. Measurements related to ISRU risks

3.6.1 Introduction

ISRU as a general term refers to all in situ resources that may be of value, including building materials, water, oxygen for breathing, natural shielding materials, and other things. Of these many possibilities, the one that has by far the greatest potential to affect the design of human missions to the martian surface is the availability of water resources. In order for the potential savings to be realized, accurate information needs to be obtained relatively early, so that the knowledge can be incorporated into the mission design.

A number of design reference missions (DRMs) have been developed for the human exploration of Mars (e.g. [Drake, 1998](#); [Hoffman and Kaplan, 1997](#)). In support of the Vision for Space Exploration, multiple architecture concepts continue to be evaluated to determine what capabilities and technologies need to be developed to enable the human exploration of Mars. These kinds of studies make it clear that there is a significant challenge to launch and land the heavy vehicles required for human exploration. Two of the largest masses needed on Mars are propellants for ascent from the martian surface, and consumables for life support. If it were possible to reduce the mass brought to Mars by either obtaining or manufacturing these from local resources, it would make a dramatic difference in the mass budget of the mission. Because of the potential significant mass, cost, and risk reduction benefits associated with incorporating ISRU into mission plans, close examination of resource availability along with mission surface durations, pre-positioning of critical assets, etc. is required.

The precursor measurement program needs to focus on crustal water resources for two reasons: (1) Water is by far the most valuable of the martian resources, because of its potential use (via ISRU) in offsetting huge mass requirements for both life support systems and ascent vehicle propellant, and (2) Knowledge of crustal water resources (location, concentration, chemistry, and mineralogical form) is far more speculative than for other resources. By comparison, our ability to assess the feasibility of making beneficial use of the atmosphere is not limited by uncertainty in whether the atmosphere is (or is not) present at a given landing site.

3.6.1 Description of risks

Even though within the past the last few years, data obtained from Mars Odyssey spacecraft suggests that water is widely available in the top ~1 meter of the martian surface, the individual data pixels represent the average conditions over a very large region (on the order of 100 km x 100 km), and the actual conditions at any individual site within that could be very different than the average. Thus, there is a risk that resources assumed to be present at a human landing site are not present in the quantity, quality, or location assumed. These risks are easily addressable by precursor measurements, and are described as Risk #1 in Table 1.

Thus, the MHP SSG concluded that the primary risks associated with planning for ISRU that can be addressed by means of precursor measurements are those connected to distribution and accessibility of crustal water deposits (Risk #1 in Table 1). Moreover, since ISRU may be enabling for human Mars missions, these measurements have the highest priority.

3.6.1 Proposed Investigations and Measurements

In order to realize the potential value of such deposits to human missions to the martian surface, a well-conceived and executed exploration program for martian water deposits is needed. This exploration program will need to be analogous to resource exploration programs on Earth, and consist of a reconnaissance phase followed by a site-specific deposit definition phase. This exploration program will have the effect of progressively increasing knowledge certainty of one or more martian water resource deposits in much the same way that on Earth resource exploration goes through the sequence of potential, possible reserves, probable reserves, and proven reserves.

The required exploration plan will need to start with formulation of a series of testable geological models for water-bearing deposits that could be accessed by a credible production system. These hypothetical water deposits should be organized by production system: shallow bulk mining methods, well-based methods, and other TBD production systems.

- For bulk minable water resource deposits, components of this exploration program might include:
 - a. Understanding assumptions regarding constraints on the resource deposit imposed by the production system (e.g. maximum depth, material hardness, etc.)
 - b. Defining specific targets with elevated potential
 - c. Prioritizing targets
 - d. Assessing the characteristics of the deposit necessary to support design of the production system (including, but not limited to, depth, concentration, state, geotechnical properties of the material to be mined/processed, water chemistry, and degree of deposit heterogeneity/homogeneity).

- For subsurface liquid water resources, components of this exploration program might include:
 - a. Understanding assumptions regarding constraints on the resource deposit imposed by the production system (e.g. maximum depth)
 - b. Defining specific targets with elevated potential. This would require geophysical data.
 - c. Prioritizing targets
 - d. Assessing the characteristics of the deposit necessary to support engineering design (possibly including depth, reservoir P-porosity-permeability, geotechnical properties of the material penetrated by a well, water chemistry, and thermal properties of the well path).

It is important to note that the overall objective (for the purpose of retiring this risk) is not to define all of the water deposits on the planet, but to establish to within a reasonable degree of confidence that at least one deposit of water, with minimum acceptable characteristics (concentration, quality, quantity, depth, state) and in a location consistent with both mission landing safety considerations and with the mission's objectives, exists.

As of this writing, there are four general classes of water deposit on Mars that may have the potential to meet this need:

Perceived to have higher priority

1. The top few meters of the regolith in specific areas near-equatorial region (approximately $\pm 30^\circ$) identified by Odyssey as having elevated hydrogen content.
 - Possible Measurements. (i) concentration of hydrogen as a function of depth, (ii) the mineralogical form of the hydrogen, (iii) composition and concentration of other volatiles and potential impurities released with water when regolith is heated, and (iv) the heterogeneity of these measurements within a local region accessible by state of the art rovers.
2. Shallow (within a few meters of the surface) subsurface ice deposits poleward of approximately 40° to 55° latitude.
 - Possible Measurements. (i) identify and determine the depth, thickness, and concentration of water in subsurface ice deposits to a few meters depth and at a horizontal resolution comparable to that of a martian base (perhaps 100 m), (ii) determine the demarcation profile/latitude where near-surface subsurface ice formation does and does not occur. Note: Phoenix will obtain relevant data, but at a higher latitude.

Perceived to have lower priority

3. Surficial frozen water in the polar ice caps.
 - Possible Measurements. depth, thickness, and concentration of near-surface water/ice. Subsurface liquid water, at a depth shallow enough that it can be reached by drilling.
 - Possible Measurements. (i) orbital radar surveys (e.g. SHARAD), (ii) landed EM studies at the scale of 100 m or so, (iii) down-hole measurements of porosity, permeability, water saturation, temperature, pressure, and any other parameters of relevance to predicting fluid flow.

- Note: If MHP Precursor in situ measurements discover near-surface water availability in usable quantities at moderate latitudes, the need for polar measurements and/or drilling for deep water are likely to diminish or even disappear, since a ready near-surface resource would be available.
4. Subsurface liquid water deposits, accessible using wells.

In addition to the precursor measurement program, engineering assessments and possible precursor missions to validate and quantify the water extraction process based on the resource measurement assessment would need to be undertaken.

FINDING: PROPOSED INVESTIGATION AND MEASUREMENTS

1D. Characterize potential sources of water to support ISRU for eventual human missions. At this time it is not known where human exploration of Mars may occur. However, if ISRU is determined to be required for reasons of mission affordability and/or safety, then the following measurements for water with respect to ISRU become necessary (these options cannot be prioritized without applying constraints from mission system engineering, ISRU process engineering, and geological potential):

Measurement Options:

- a. Perform measurements within the top few meters of surface regolith in a location within the near-equatorial region (approximately $\pm 30^\circ$) that Odyssey indicates is a local maximum in water content, to determine: (i) concentration of water, (ii) composition and concentration of other volatiles and potential impurities released with water when regolith is heated, and (iii) three-dimensional distribution of measurements i & ii within a 100 meter x 100 meter local region.
- b. Perform measurements to (i) identify and determine the depth, thickness, and concentration of water in subsurface ice deposits to a few meters depth at approximately 40° to 55° latitude, (ii) determine the demarcation profile/latitude where near-surface subsurface ice formation does and does not occur.
- c. Perform measurements in the polar region (70° to 90°) to determine the depth, thickness, and concentration of near-surface water/ice.
- d. Measurements for water at other locations and depths are not precluded but require further scientific measurements and/or analysis to warrant consideration.

At this time there is no definitive list of criteria for selecting the sites on Mars where human exploration would occur. Should water-based ISRU be incorporated into human mission plans, the availability of usable quantities of water to a high degree of confidence would be one of the criteria used in selecting potential mission landing sites. Regardless of all the selection criteria, exploration to locate accessible Mars water resources is needed.

3.7. Measurements related to regolith geotechnical risks

3.7.1 Introduction

There are a number of risk issues in the general area of soil/regolith mechanical properties, and these are collectively grouped as Risk #7 in Table 1.

During the Apollo and Viking programs considerable effort was expended to study the cratering of the regolith when a rocket launches or lands on it [Romine, *et al*, 1973; Alexander, *et al*, 1966; Roberts 1964; Clark and Land 1963; Scott and Ko; Ko 1970; Foreman 1967; Clark 1970; Hutton, *et al*, 1980]. That research ensured the success of those programs but also demonstrated that cratering will be a serious challenge for other mission scenarios. The most violent phase of a cratering event is when the static overpressure of the rocket exhaust exceeds the bearing capacity of the soil or sufficiently fluidizes it to excavate vertically beneath the surface. This bearing capacity failure (BCF) produces a small and highly concave cup in the surface. The shape of the cup then redirects the supersonic jet – along with entrained debris – upward toward the spacecraft. This has been observed in terrestrial experiments but never quantified. The blast from such an event will be qualitatively different than the cratering that occurred in the Apollo and Viking programs, because BCF had been successfully avoided in all those missions. In fact, the Viking program undertook a significant research and development effort and redesigned the spacecraft specifically for the purpose of avoiding BCF [Romine, *et al*, 1973]. (See Figure 5.) However, it will be unavoidable in the Martian environment with the large landers necessary for human exploration.

Furthermore, cratering (with or without BCF) will be a significant issue when there is an attempt to land multiple mission-critical spacecraft within short distances of one another,

whether on the Moon or Mars. It is possible that the first spacecraft to land may be damaged by the spray from the second spacecraft's landing. The co-landing of critical hardware has never been done before, but we do have some relevant experience because the Apollo 12 Lunar Module (LM) landed 155 meters away from the deactivated Surveyor 3 spacecraft. Portions of the Surveyor were then returned by the astronauts to Earth for analysis [Cour-Palais 1972; Jaffe 1972]. It was found that the surface of the Surveyor 3 had been sandblasted by a high-speed shower of sand and dust particles during the LM's landing. The sandblasting cast very sharp, permanent "shadows" onto the spacecraft which very accurately pointed away from the point on the regolith directly beneath the LM. Judging by the sharpness of the shadows and the lack of curvature allowable for the particles to fit the trajectory, the

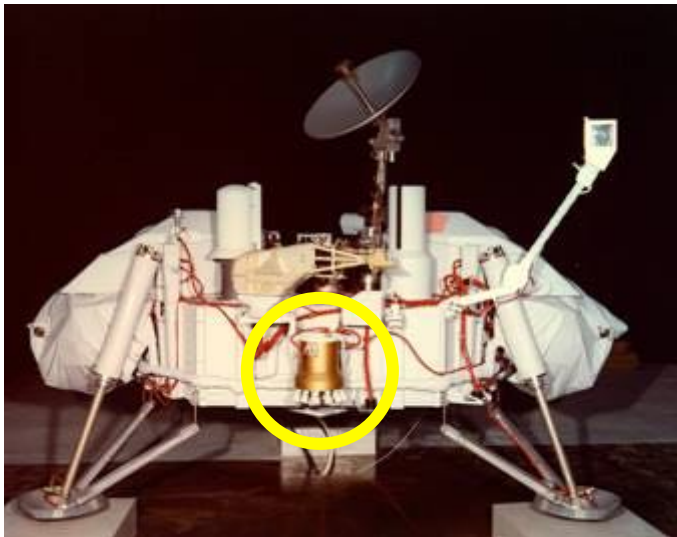


Figure 5.

Each of the three retro-rockets on a Viking lander had 18 small nozzles instead of one large nozzle. The multi-nozzle engine was developed specifically to prevent bearing capacity failure of the regolith beneath the exhaust jets.

particles must have been moving in excess of 100 m/s. Furthermore, every cavity and opening in the spacecraft was filled with grit by the high-speed spray. Co-landed spacecraft must be designed to withstand the blast and contamination of the cratering.

To manage the soil/plume interactions, we must have some basic knowledge of the Martian surface and near subsurface to a depth that may be reasonably excavated by the plume.

In addition to the plume/soil interaction problem, there are other reasons to measure the geotechnical characteristics of the Martian soil. Apollo astronauts in the early missions experienced difficulty obtaining core samples of the lunar soil due to the soil's unexpected

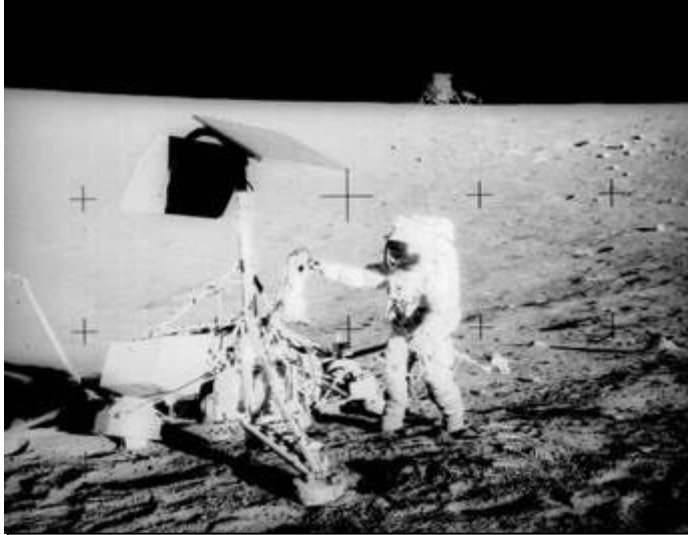


Figure 6.

Surveyor 3 spacecraft with Apollo 12 LM in background. The Surveyor spacecraft experienced substantial blast effects from the LM landing 155 meters away.

mechanical properties. As the program progressed, geotechnical analysis of the soil improved the core sampling tool design, thereby enabling the scientific goals of the missions. This demonstrated the importance of considering the soil for its engineering properties, and not just as an object of scientific investigation. In the new vision to explore the Moon and Mars, engineering with the soil will take on a vastly greater role as a fundamental resource in ISRU. This necessitates excavation, beneficiation and processing of the regolith materials in order to obtain the consumables that will enable the overall mission. Difficulties working with the soil, such as were experienced in the early Apollo program, would have a much greater detrimental impact upon a program that relies on ISRU, and hence the

mechanics of Martian regolith must be thoroughly investigated early in the design of the program.

Martian geotechnical properties have been measured by five lander spacecraft within the top several centimeters of the surface using scoops and wheels to trench the surface, and using wheels for traction tests [e.g., [Matijevic 1997](#)]. The mechanical properties of the deeper subsurface, however, have never been measured. Furthermore, remote sensing and other data have implied the existence of water ice in the regolith, but its effects on regolith mechanics have never been experimentally investigated.

To enable the engineering design of hardware to interact with soil, measurements are usually made *in situ* to determine the soil's fundamental physical properties or more often its behavior measured against mechanical indices (standard geotechnical tests). Terrestrially, those tests are often the basis of design protocols that develop hardware or structures compatible with the characteristics of a particular soil. These protocols are based upon a wealth of terrestrial experience, and unfortunately that experience does not exist for the Martian environment and soil. Hence, it is not clear that the standard mechanical indexes could lead directly to developing

reliable and efficient hardware for a safe and cost effective program when extrapolated to that environment.

Furthermore, it is difficult to specify which such indexing tests would be most pertinent to ISRU resource extraction and construction activities, since those activities are still largely undefined at the present time. At the present, it is necessary to rely on a selection of the typical indexing tests, as well as on the more fundamental physical properties tests, and then supplement those measurements with a program of experimentation (*in situ* and with simulants), modeling (to help extrapolate what is known into what is still unknown), and finally *in situ* system demonstration validating the final design, where necessary.

3.7.2 Hazards related to mechanical properties of near-surface materials

Martian near-surface materials have the potential to constitute a hazard for a number of mission critical activities, including:

- Scientific sampling of the near subsurface by autonomous or manual (crew) methods
- Excavating or boring into the regolith to extract ice-rich soil or other subsurface resources at a sufficient rate and with a specified energy budget
- Beneficiation of the geomaterials extracted from the regolith by reliable autonomous processes
- Artificial heat loads (such as from nuclear reactor or a habitation module) placed on the surface, which may drive volatiles from the subsurface
- Construction activities that utilize the regolith
- Interaction of the soil with a launching or landing rocket plume
- Rover trafficability across the regolith/soil (addressed previously in Sec.3.5, along with other trafficability issues).

Some adverse consequences that may result from interaction with these hazards:

- Geotechnical properties of the subsurface different than predicted, making excavation of resources impossible or at an inadequate rate
- Flow properties of geomaterials is different than predicted, making ISRU processing hardware jam or fail to function
- Bearing capacity and long-term (3+ year) weakening or differential settlement of the soil beneath the mechanical and thermal load of surface assets may produce asset instability or unexpected mechanical stress or may affect scientific experiments or ISRU processes
- Soil/Rocket Plume interaction damages the landing spacecraft
- Soil/Rocket Plume interaction damages the surrounding hardware (ISRU, etc.)
- Regolith degassing after engine cutoff blows back soil, which contaminates the landed spacecraft
- Soil/Rocket Plume interaction leaves landed spacecraft unstable

3.7.3 Breakdown of geotechnical risks

3.7.3.1 Sub-Risk 1: Subsurface Geotechnical Properties Different Than Predicted

Risk Statement: If soil cohesion, shear strength, density, compaction, volatile content and specific energy of boring or chipping are not properly bounded in the vertical column above and within the source of water ice, then an excavator, boring unit, beneficiator, or resource extractor may not produce ice-rich soil at a rate sufficient for scheduled human arrival or not at all. In a contingency it may not be able to resupply water to the crew after their arrival. Failure may result in loss of science or loss of crew. Also, crew equipment for manual access to the subsurface may not be optimally designed if the subsurface is more or less cohesive than expected.

Context: If surface soil lacks sufficient cohesion, collapsing material into a bore hole may make it impossible to extract desired subsurface materials. If shear strength, density, or compaction are greater than expected, the device(s) may lack power or energy to produce sufficient quantities or at a sufficient rate. If specific energy is greater than expected, processing may be inefficient or impossible.

3.7.3.2 Sub-Risk 2: Flow Properties Of Geomaterials Different Than Predicted

Risk Statement: If the flow properties of excavated geomaterials (due to their cohesion, density, compaction, volatile content, electrostatic properties and/or particle sizes/shapes) and their relative significance in the Martian environment (low and seasonally variable atmospheric pressure which affects Darcian versus Knudsen flow regimes, reduced surface gravity, and low humidity) are not properly bounded for materials extracted from the vertical column within the area of ISRU excavation, then an ISRU processing unit may become jammed and fail to process resources at a rate sufficient for scheduled human arrival or not at all. In a contingency it may not be able to resupply water to the crew after their arrival.

Context: Terrestrial experiments show that granular materials that would otherwise flow freely in a terrestrial environments will behave like a cohesive powder when flowing in reduced gravity due to the relatively greater significance of Van der Waals, electrostatic, and other cohesive forces. Terrestrial experiments have also shown that granular materials display qualitatively different convective heaping characteristics when the pore pressure is below 10 Torr [Behringer, *et al*, 2002]. The mechanical properties of the excavated soil due to its volatiles, cementing, or other physical characteristics may make ISRU processing hardware inoperable or unreliable if not properly anticipated. The up-scaling design process used for terrestrial processing plants will not be possible for Martian ISRU processes due to inaccessibility of the Martian environment, including gravity. Hence, there will be a greater reliance on modeling during the design process of ISRU hardware. This necessitates a sufficient knowledge of the regolith flow properties to adequately model them.

3.7.3.3 Sub-Risk 3: Differential Settling of the Regolith

Risk Statement: If heat and mechanical load of surface assets drive volatiles from the subsurface over a period of several years (during ISRU build-up period), the regolith may weaken or differentially settle beneath the surface assets. This may result in a loss of upright posture which could impede ISRU processing flows, result in the asset tipping, make entries or access point to

be misaligned or inaccessible, and mechanically strain the interfaces of connected assets resulting in a loss of seal integrity. Scientific experiments may also be disturbed by differential settlement.

Context: There is a general uncertainty about the Martian subsurface which *potentially* could allow for a weakening of the subsurface and differential settlement over the duration of a mission (including ISRU processing time prior to crew arrival). This may be especially true if the volatile content is high in the near subsurface. Thermal loads provided by the operational hardware such as nuclear fission reactor or heated habitation module may over the course of several years drive sufficient volatiles from the subsurface to result in a settling of an inch or more. This may be exacerbated for heavier elements such as ISRU processing or storage units when they are loaded with geomaterials or consumables. Worst case could be a sudden loss of competence beneath one or more spacecraft footpads.

3.7.3.4 Sub-Risk 4: Soil/Rocket Plume Interaction Damages the Landing Spacecraft

Risk Statement: Excessive material ejected in vertical direction may affect spacecraft landing by spoofing its landing sensors, imparting differential momentum to the bottom of the spacecraft, or damaging critical components by direct impact of rocks or pebbles. Falling debris may blanket radiators, solar cells or critical instruments.

Context: Substantial prior experience exists only through Apollo and Viking programs, both of which were predicted to produce plume effects significantly different than will occur for a large-scale human-tended mission on Mars. Terrestrial tests and analysis have demonstrated the Mars bearing capacity fails when static overpressure of rocket exhaust plume exceeds about 20 kPa. Viking spacecraft was redesigned to just stay beneath this limit. The method used for Viking will not scale for human tended spacecraft and as a result bearing capacity failure will probably be unavoidable. For supersonic flow in an atmosphere, a ground jet normally proceeds laterally and radially away from the gas stagnation region beneath the spacecraft. However, the onset of bearing capacity failure or local fluidization of the soil beneath the plume will produce a cavity that results in a vertical deflection of the ground jet. Terrestrial tests have shown that this will result in a geyser of ejected material traveling vertically due to the high concavity of the excavated hole into which the plume is pointed.

3.7.3.5 Sub-Risk 5: Soil/Rocket Plume Interaction Damages the Surrounding Hardware

Risk Statement: Excessive material ejected in lateral direction may damage surrounding ISRU or scientific or other assets.

Context: Terrestrial (and lunar) experience shows that prior to (or in the absence of) a vertical eruption of ejecta, the material is initially ejected in the lateral direction at high velocity. After vertical eruption, there may be a widening of the crater that results in a re-broadening of the ejection cone. This may rain material down upon surrounding hardware. Due to the low density of the Martian atmosphere, terminal velocity of the material is very high. Surrounding hardware may be damage by rocks, or its critical sensors damaged by sand or dust, or its solar panels or

radiators blanketed by debris.

FINDING: PROPOSED INVESTIGATION AND MEASUREMENTS

Contribution to Investigation #1D. For approaches that involve acquiring and mechanically processing natural near-surface water-bearing material, characterize its geotechnical properties.

Measurements:

1. Determine the following mechanical and physical properties of regolith (soil and/or ice/soil mixtures) representing the resource deposit type of interest to a depth at least as great as the maximum proposed depth of access:

- (i) Cohesion to within 0.1 kPa
- (ii) soil density, before and after volatiles are expelled thermally, to within 0.1 g/cm³
- (iii) an index test of shear strength
- (iv) specific energy of excavation or boring to within 5 J/cm³

Contribution to Investigation #1A. Characterize at least one regolith deposit with a fidelity sufficient to establish credible engineering simulation labs and/or software codes on Earth to solve engineering problems related to differential settlement of the regolith, and plume/soil interactions.

Measurements:

1. For one site on Mars, measure the following properties of the regolith as a function of depth to 1 meter:

- (i) Particle shape and size distribution
- (ii) Ice content and composition to within 5% by mass
- (iii) Soil density to within 0.1 g/cm³
- (iv) Gas permeability in the range 1 to 300 Darcy with a factor of three accuracy.
- (v) Presence of significant heterogeneities or subsurface features of layering
- (vi) An index of shear strength
- (vii) Flow Rate Index test or other standard flow index measurement

2. Repeat the above measurements at a second site in different geologic terrane:

Note #1. Because there is a large engineering lead-time required to solve the geotechnical problems, these data must be obtained early in the precursor program.

Note #2. These measurements should be made in a competent soil deposit as opposed to loose drift material (cohesionless sand dunes), as landing is expected to attempt to avoid the looser material. Also, if mission planners select high latitude polar deposits for a human landing site, geotechnical data will be required from a representative location of those deposits.

Contribution to Investigation #6.

Measurements:

1. No measurements in addition to those already described in Section 3.5:

3.7.3.6 Sub-Risk 6: Regolith Degassing After Engine Cutoff Blows Back Soil

Risk Statement: Blowback of soil after engine cutoff may contaminate engine preventing a safe

restart or may contaminate other critical spacecraft mechanisms and sensors.

Context: Experiments have shown that the soil beneath a rocket plume is highly fluidized by the impinging high-pressure gas. At engine cutoff the soil rebounds (is carried upward by escaping gas from the soil) resulting in a large, central core eruption. Since this is aimed directly at the rocket engine, material may enter the bell or the combustion chamber, which would make it dangerous to restart the engine. A hot spot due to a small amount of contamination in the engine may result in engine failure. Rebounding soil may also contaminate sensors or mechanisms.

3.7.3.7 Sub-Risk 7: Soil/Rocket Plume Interaction Leaves Landed Spacecraft Unstable

Risk Statement: If excavation of the soil produces a crater of significant size, this may place the lander's legs onto the craters' sloped surfaces, resulting in spacecraft instability. Removal of loose overlying material may also reveal uneven bedrock features just beneath the surface, and the lander would be forced to settle onto an unexpectedly uneven surface. Excessive weakening of the subsurface material through thermal and pressure loading and/or fluidization by forced diffusion into the pores may also result in the landed spacecraft being unstable.

Context: No study has ever been done to scale the cratering phenomena for a spacecraft landing in a planetary atmosphere where the spacecraft is the size of those currently being considered for human tended missions to Mars. An atmosphere partially collimates the jet, making the cratering much worse than experienced in Apollo. The larger Martian surface gravity also increases the effect on Mars relative to the Moon. Simple scaling estimations predict that large scale cratering may be possible, although further laboratory work is needed to determine whether the problem is severe. Experiments have shown that the presence of a boundary condition beneath the near limited region, and this results in significant fluidization of the overlying soil until engines have subsurface (e.g., bedrock or an impermeable cryosphere) constrains the diffusing gases into a been shut off. Early engine shutoff and freefall (as was done in Viking) to minimize soil interaction with the plume may be dangerous for a large lander.

3.7.4 Investigations and measurements required to reduce geotechnical risk

To reduce these risks to an acceptable level, much progress can be made using investigations in terrestrial laboratories using martian simulants and in computers using models. However, in order for this experimental/theoretical work to be credible, the work MUST have a foundation of real data regarding the conditions on Mars.

Terrestrial laboratory investigations with simulants are needed to characterize the mechanical properties of ice-rich soil, the effectiveness of ISRU techniques (excavation, processing, construction, etc.), volatilization of subsurface ices by surface heat loads, predicted differential settlement that may occur due to such volatilization, and plume/soil interactions plus mitigation techniques. Development of soil geotechnical models is also needed to extrapolate such terrestrial tests to Martian environmental conditions (gravity and atmospheric/pore pressure). Along with these terrestrial investigations, *in situ* measurements are needed to determine the subsurface boring properties concomitant with the location of subsurface water characterization (see Sec.3.6), and particle size distribution and properties analysis at a sampling of depths

beneath the surface to inform physical modeling of the soil.

The severity of the soil/rocket plume interaction has not been sufficiently investigated in terrestrial experiments and so it is unknown whether any measurements are needed at the specified landing site. At the present it is assumed that they will not be needed and so measurements will be made at any one soil deposit on Mars (not cohesionless sand dunes), and/or at any one area of polar deposits if the intended landing site will be on polar deposits. These measurements are needed to reasonably model and predict the cratering effects to aid the design of mitigation technologies. One such measurement requires specific explanation: the gas permeability of the soil or soil/ice mixture. To some degree, the fluidization dominates the extent of the cratering, and the fluidization depends on the gas permeability over a certain range determined by the scaling of the cratering physics. Permeability that is in the very low range should not be a concern because it will not admit sufficient gas over the time scale of a rocket landing to fluidize the soil. Nor is permeability in the very high range, which indicates the material is well vented and hence will not fluidize. The measurement is needed in the range where soil fluidization will be effected, and this is inferred to be in the 1 to 300 Darcy range by comparison with typical soils fluidized by impinging gas jets during terrestrial experiments.

3.8. Measurements related to other risks

Since risk is a combination of probability and consequence, all risks are not equal. If we were to compile a list of all of the risks faced by the first human mission to Mars, and sort it by risk magnitude, there would be a very long tail of lower priority risk issues. The purpose of this report is place some emphasis on the high priority risk issues that can be mitigated by means of a precursor program—it is outside our scope to provide full analysis for issues that have been judged to be low priority either because of a low perceived overall risk, or because the risk cannot be reduced using precursor data. Further analysis is deferred to successor study teams. Some of these issues are listed at the bottom of Table 1, including:

- Risk #16 Comm. losses & nav alterations caused by atmospheric and topographic conditions.
- Risk #17 Lander attitude is inadequate for egress or TAO.
- Risk #19 Risk from previously-ignored radiation sources.
- Risk #20 Seasonal condensation causes electrical failures.

However, if data of relevance to these issues can be acquired without excessive incremental impact, it would clearly be beneficial to the overall program.

4. Additional considerations for human missions to Mars after the first one

As dictated by the MHP SSG charter, this study focuses only on robotic precursor missions needed to achieve success on the first landed human mission to Mars (see Section 1.2). The analysis presented in this study does not consider robotic precursors that would be necessary for subsequent human missions and/or the development of a sustained human presence on Mars.

However, the U.S. Vision for Space Exploration calls for “sustainable human and robotic missions to Mars and beyond” [NASA, 2004] and therefore multiple human missions to Mars are required to fulfill this Vision for Exploration.

While the risks outlined in the Report, are, of course, also relevant to subsequent human missions or sustained human presence at Mars, additional risk factors are inherent in a series of human missions when compared to the first human mission to Mars. Many of these added risks are related to the extended exposure of humans and machines to the martian environment, as well as to the anticipated diversity of sites which could introduce variable risks, such as the potential increased biologic risks associated with possible contact with liquid water. These additive risks require increased understanding of environment and its impact on safety as well as the drive need for increased overall system reliability and lifetime for extended missions. Further, long-term human missions on Mars would necessarily require increased autonomy and increased reliance on the available resource at Mars to sustain human activity there. Therefore, additional robotic missions would be necessary to support a series of human missions and help mitigate these added risks. Finally, as the missions become more complicated we need to ensure that crew time for cleaning and maintenance is minimized to ensure that time is still left for performing the mission objectives. So, as missions mature, we need to test mission systems in situ *before we need them* to ensure they are reliable and easily maintainable.

An assessment and prioritization of the risks associated with multiple human landings on Mars is beyond the scope of this study. A representative sample list of such risks associated with human mission scenarios supporting a long-term sustained presence on Mars that could be mitigated by robotic precursor missions is presented below in no priority order. This list is not intended to be an exhaustive statement that captures all the increased risks associated with longer-term human activity at Mars, rather it is offered as example topics which require additional detailed studies which could be used to frame requirements for future precursor missions needed to mitigate the anticipated increased risk factors.

- **Dust.** Dust poses a significant risk to the human mission in terms of adhesion and accumulation, inhalation and ingestion, dust storms and biology (see Section 3.3). Due to increased durations for each human mission, dust would become an even greater problem. ISRU and other technologies may become more sophisticated and the increased mission durations would require more rigorous dust management techniques. More sophisticated dust control technologies should be developed and tested in situ.

- **ISRU.** A long-term human occupation of Mars would require the use of in situ resources for life support, energy systems, and/or propellant production. In situ validation of new technologies and resource extraction may be required.

- **Habitats.** Robust surface structures would be required for long-term human occupation, scientific studies, subsystem operations, storage, etc. The development and validation of construction techniques using local materials as well as in situ repair and fabrication (autonomous or human-assisted) may be required. In situ testing of subsystems (closed life support, power, thermal, communications, etc.) may also be needed.

• **Biological Studies.** The adaptation of plant, animal, and microbial species over multiple generations should be investigated to understand the biological response at various levels to the martian environment. Also, the development and testing of greenhouses would provide a systems level test of a plant growth module and would test the response of biological life support components to the martian regolith and dust, radiation environment, and partial gravity.

• **Life Support.** Several options exist in terms of life support systems. Bioregenerative life support systems can produce food and recycle air & water in a closed loop system. Physical/chemical systems are another option for providing life support which are commonly used in current spacecraft. ISRU is a third option which could be used to produce usable air and water for life support purposes. The development of a sustainable life support system imposes different requirements than for a one-time human mission. These life support options must be evaluated for a long-term human mission and technologies validated in situ.

• **Surface Power Generation.** A cost-effective, long life surface power source is required to support a long-term human presence on Mars. Several options exist including nuclear, solar, isotopic, electrochemical, and chemical sources. Again, the development of a sustainable power source imposes different requirements than for a one-time human mission (particularly, the long-surface stay missions, as compared to short-stay surface missions). These options must be evaluated for a long-term human mission and technologies validated in situ.

• **Planetary Protection.** The MHP SSG has identified back contamination as the highest risk associated with Planetary Protection (see Section 3.1). Martian lifeforms could be hazards to terrestrial biota and/or hazardous to astronaut crews during transit to Earth. Depending on the mission architecture, multiple human missions to and/or from Mars may provide additional opportunities for possible martian and terrestrial biota interactions which could increase the risk of adverse biologic interactions.

• **Biohazards.** A sustained human presence would inevitably lead to human interaction with environments not previously contacted during the first landed mission. For example, a deep drilling operation or an expedition to the polar cap would introduce possibilities for forward and/or back contamination that would not be encountered on a simple expedition to the equatorial regions. Proposed MEPAG revisions require sample return and analyses in terrestrial laboratories for any site on Mars to be visited by humans. This requirement may need to be re-evaluated for applicability to the scenario of a sustained human occupation involving frequent investigations of new regions on Mars.

• **Communications and Navigation.** Technology demonstrations may be required for enhanced communication and navigation capabilities for a long-term human mission. A sustained presence on Mars would likely result in longer-range sorties from the primary landing site and/or multiple human bases which necessitates accurate navigational capabilities as well as communication among EVA crews, Habitat crews, and Earth-based teams. Technology development and in situ validation may be required.

• **Long-Term Exposure.** Materials and equipment on the martian surface would be exposed to the martian environment for longer durations to support a sustained human presence when

compared to the first human mission to Mars. An exposure facility on the martian surface (similar to the Long Duration Exposure Facility (LDEF)) may be needed to test the effects of the ambient martian environment (radiation, dust, thermal, etc.) on various materials.

• **Increased EDL accuracy.** As human exploration expands, there would likely be a build up of capability (posts, outposts, expedition bases, research laboratories, etc.) at selected sites of scientific interest, or where needed resources may be available. Therefore increased overall EDL systems performance to accurately land at these sites would be essential.

5. How many places on Mars?

In addition to identifying the needed measurements, and their required accuracy and precision, the MHP SSG considered which measurements need to be made once for the entire planet, which need to be made at multiple locations, which need to collect data over an extended period of time, and which need to be made specifically at the human landing site. These relationships are summarized in Table 5.

Table 5. Summary of Location Considerations for High-Priority Human Precursor Investigations.

Investigation	Carry out once at Mars	Measurements needed at multiple sites	Measurements needed over time	Precursor measurement needed at the human landing site
1Aa-b. Basic dust/soil properties	X	?		
1Ac. Airborne dust in dust storms	X			
1B. Atmospheric variations		X	X	
1Ca. Biohazard--dust	X			
1Cb. Biohazard—site spec.				X
1D. Water for ISRU		X		X
2. Toxicology of dust	X			
3. Atmospheric electricity		X	X	
4. Forward PP	X		X	?
5. Ionizing radiation	X		X	
6. Terrain trafficability	X	?		?
7. Dust storms	X		X	

It was not true for the Moon, but many have concluded that it is inconceivable that humans would land in a place where landers and rovers have never been. As shown in Table 5, the MHP SSG has agreed with this, and has called for at least one measurement (#1Cb) to be done specifically at the human landing site. Although many useful measurements could be made by this penultimate lander mission, note that if site selection happens late in the process, the information may arrive too late to influence mission engineering. In addition, although this would undoubtedly be a subject of future discussion, we did not conclude that sample return from the human landing site is required.

6. Conclusions

6.1. Summary of recommendations for further studies.

- a. The MHP SSG recommends definition of a baseline mission architecture for the first human mission to Mars.
 - We need a more complete understanding of possible engineering approaches to mitigating the risks described in this paper, and their effects on cost, risk, and performance.
- b. We recommend that a long-lead multi-disciplinary advance planning team be assembled to evaluate and prioritize possible objectives for the first human mission. We recognize that this would evolve many times between now and the time the mission actually flies, but for planning purposes it is helpful to have a starting point from which incremental improvements can be made.
 - Important distinctions need to be made between what reduces mission risk and also enhances probability of meeting or exceeding all mission goals, versus what needs to be done to ensure the safety of astronauts and meeting minimum mission success criteria.
- c. We recommend that the above baseline mission be evaluated in the following ways:
 - Establish a cost model, so that opportunities to use precursor investments to achieve cost savings can be identified
 - Establish a quantitative probabilistic risk assessment (PRA) model, which can be used as a starting point for a systematic, comprehensive risk reduction strategy.
 - Evaluate opportunities for performance enhancement with minimal incremental cost or risk.

We recommend that an analysis of the exploration program necessary to define water-related resources necessary to support ISRU be completed.

6.2. Summary of the relationship of principal findings of MEPAG [2001], NRC [2002], and this study. (Numbers to the left of the investigation statements are relative priority).

MEPAG (2001)		NRC (2002)		MEPAG (2005)	
		Not listed in priority order	Soil, dust: engineering	1A	Soil, dust: engineering
3	Atmospheric characterization			1B	Atmospheric characterization
			Biohazard--Back PP	1C	Biohazard--Back PP
4	Water-related ISRU			1D	Water-related ISRU
2	Soil, dust: humans		Soil, dust: humans	2	Soil, dust: humans
6	Atmos. electricity			3	Atmos. electricity
				4	Contam.--Forward PP
1	Ionizing radiation		Ionizing radiation	5	Ionizing radiation
5	Traversability hazard		Traversability hazard	6	Traversability hazard
				7	Dust storm meteorology

		3D terrain--landing site safety	8E	3D terrain--landing site safety
		Rocks--landing site safety	8D	Rocks--landing site safety

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APPENDIX 1. Charter of the Mars Human Precursor Science Steering Group

Introduction

NASA Headquarters is in the process of developing multi-Enterprise plans for robotic missions to Mars as precursors to future human exploration activities. As a consequence, NASA (and its Mars Exploration Program) would like to solicit inputs from the general science, technology and engineering community about measurement requirements and technology demonstrations that must be implemented beginning with the 2011 launch opportunity to Mars. In particular, the newly formed Exploration Systems Office at NASA HQ (Code T) has specifically requested the assistance of the Mars Program Office at NASA HQ (Code S) in planning a program of one or more robotic missions to Mars to serve as precursors to an eventual human mission to Mars. One of the specific task-directed requests from the colleagues within Code T follows:

Task Request from Code T (in cooperation with Code S):

On the basis of the President's Vision for Space Exploration (NPD31), NASA is investigating what specific robotic Mars missions would be appropriate as precursors to sending humans to Mars. These missions would focus primarily on risk and cost reduction for the future human missions. In assessing the potential for risk reduction, NASA's Office of Exploration Systems requests an analysis of the factors that could lead to increased safety / reliability, evolvability and flexibility of the program, development risk and schedule mitigations, and affordability.

Therefore, NASA Headquarters (via the Director and Lead Scientist of the Mars Exploration Program) has requested that MEPAG form an SSG in order to develop some of the inputs necessary to form a detailed response to this request. The findings of this SSG would be folded into mission-architecture studies to be conducted by NASA's JPL, as well as delivered to the leaders of NASA's MEP at NASA Headquarters.

Starting assumptions

Assume a continuous series of Mars robotic precursor missions prior to human exploration. It is not yet known whether launches in every opportunity are justified.

Assume the first dedicated robotic precursor mission is scheduled for flight in the 2011 launch opportunity.

Assume the first human mission is scheduled in approximately 2030.

Assume that a separate sequence of Mars missions, with a primary objective of robotic scientific exploration, would be carried out in addition to the human precursor sequence. Assume that the infrastructure associated with the science missions (e.g. the telecommunications infrastructure) is available for use by the human precursor missions.

Requested Tasks:

Phase I:

Identify the activities that should be performed by these human precursor robotic missions for the purpose of reducing cost and/or risk of human exploration missions. The activities identified should include measurements, technology demonstrations, and infrastructure capabilities.

For measurement-related activities:

Identify and justify new measurements that can be acquired by robotic missions to Mars that would contribute to the overall cost or risk reduction objective. Classify by whether the measurement would need to be made on the surface, in the atmosphere, in martian orbit, or elsewhere (i.e., specify vantage point or vantage points).

Establish preferred / required sequential relationships (for measurement sets, etc.)

Suggest the number of distinct sites needed for each of the measurements in order to achieve cost and risk reduction (i.e., both locally within a landing zone, as well as across the entire planet) as well as the necessary characteristics of the different sites.

Prioritize the measurement options and include specific precisions, accuracies, and any temporal constraints

For technology demonstrations and infrastructure:

identify technology flight demonstrations needing to be performed on Mars to reduce risk to human flight systems

prioritize technology demonstrations and infrastructure and suggest preferred / required sequential relationships

Develop a preliminary definition of the characteristics of landing sites suitable for human exploration. This would include scientific potential as well as safety and risk factors. Note that this is not a site selection, since that would be dependent on several factors that would not be known for years.

Phase 2:

Using the results from Phase 1, integrate the measurement and technology demonstration / infrastructure capabilities and prioritize among all capabilities and include any preferred / required sequential relationships. This will constitute fundamental input into mission architecture planning.

The following activity will be led by the Mars Program Advance Studies Office at JPL, making use of the SSG's inputs, and with some degree of interaction with the SSG Team.

Using the output result from Phase 2, and the constraints from the current Mars program funding and mission profile, identify no less than 2 possible mission architectures for the robotic human precursor missions across the next decade (2011-2020+). Describe in particular the measurement, technology, and infrastructure capability priorities associated with the proposed 2011 robotic human precursor mission.

Possible Future Phase:

Although NASA has a need to link the planning for exploration activity at Mars and the Moon, the processes are as yet undefined. It is possible that NASA will ask this SSG to identify any measurements, technologies, and/or infrastructures that you would suggest be included in human precursor missions to the Moon.

Timing, Reporting

Interim results are requested on each of the above phases according to the following schedule:

Phase 1 Deliverables: Oct 1, 2004

Phase 2 Deliverables: Nov. 1, 2004

It is requested that the final results be presented in the form of both a Powerpoint presentation

and a white paper. Although the conclusions and findings of this overall body of work are required by Dec. 1, 2004, final documentation in the form of a white paper may continue for a short time beyond this date. A suggested deadline for the white paper is 12-31-04. Contingent on priority and schedule availability, the SSG study team should be prepared to present the findings of this effort at the April, 2005 MEPAG meeting, and beforehand to the Director/Lead Scientist of the MEP, as well as leaders of the Office of Exploration Systems.

Bruce Jakosky, MEPAG Chair

Jim Garvin, Lead Scientist Mars/Moon, NASA HQ (Code S)

Dan McCleese, Chief Scientist, Mars Program (JPL)

APPENDIX 2. Acronym list

ACE/CRIS – Advanced Composition Explorer/Cosmic Ray Isotope Spectrometer
ALARA – “as low as reasonably achievable”
BCF - Bearing Capacity Failure
BFO – Blood Forming Organs
BRYNTRN – A NASA-LaRC transport code (“Baryon Transport”)
CEQ – Council on Environmental Quality
CNS – Central Nervous System
DRMs – Design Reference Missions
EDL – Entry, Descent, and Landing. The sequence associated with spacecraft passage from the top to the bottom of the martian atmosphere.
ESA – European Space Agency
ESMD – Exploration Systems Mission Directorate at NASA HQ
EVA – Extra-Vehicular Activity
FLUKA – A widely used particle physics Monte Carlo program; the name refers to the origin of the code, FLUktuierende Kaskade, which performed a nuclear cascade calculation.
GCM – atmospheric Global Circulation Model
GCR – Galactic Cosmic Rays
GEX – Gas Exchange; an instrument on the 1975 Viking mission
GOES – Geostationary Operational Environmental Satellite
HEND – High-Energy Neutron Detector; part of the Gamma Ray Spectrometer suite of instruments on the 2001 Mars Odyssey mission
(<http://grs.lpl.arizona.edu/content/learning/aboutgrs/>)
HETC – High Energy Transport Code
HiRISE – High Resolution Imaging Science Experiment; an instrument on the 2005 Mars Reconnaissance Orbiter mission (<http://hirise.lpl.arizona.edu/>)
HZE – High Charge (Z) and Energy (E)
HZETRN – NASA-JSC and LaRC transport code for HZE particles
ICRP – International Commission on Radiation Protection
ISRU – In Situ Resource Utilization
JSC – Johnson Space Center, a NASA field center located in Houston, TX
LDEF – Long Duration Exposure Facility
LET – Linear Energy Transfer
LM - Lunar Module (Apollo program lander)
LR – Labeled Release (experiment on Viking lander)
MARIE – Martian Radiation Environment Experiment; an instrument on the 2001 Mars Odyssey mission (<http://marie.jsc.nasa.gov/>)
MEPAG – Mars Exploration Program Analysis Group
MGS – Mars Global Surveyor. A NASA orbiter launched in 1996.
MHP SSG – The Mars Human Precursor Science Steering Group (the authors of this report)
MOLA – Mars Orbital Laser Altimeter; an instrument on the 1996 Mars Global Surveyor mission (<http://ltpwww.gsfc.nasa.gov/tharsis/mola.html>)
MSL – Mars Science Laboratory; a proposed future Mars mission, currently under consideration for launch in 2009.
NRC – National Research Council.

NS – Neutron Spectrometer; part of the Gamma Ray Spectrometer suite of instruments on the 2001 Mars Odyssey mission (<http://grs.lpl.arizona.edu/content/learning/aboutgrs/>)
PRA – Probabilistic Risk Assessment
SEP – Solar Energetic Particle
SHARAD – Shallow Radar; an instrument on the 2005 Mars Reconnaissance Orbiter mission.
TAO – Take-off, ascent, and orbit insertion; the inverse of EDL
TES – Thermal Emission Spectrometer; an instrument on the 1996 Mars Global Surveyor mission (<http://tes.asu.edu/>)