Mars Science Goals, Objectives, Investigations, and Priorities: 2012

Mars Exploration Program Analysis Group (MEPAG)

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TABLE OF CONTENTS

PREAMBLE

In 2000, the Mars Exploration Program Analysis Group (MEPAG) was asked by NASA to work with the science community to establish consensus priorities for the future scientific exploration of Mars. Those discussions and analyses resulted in a report entitled *Scientific Goals, Objectives, Investigations, and Priorities*, which is informally referred to as the "Goals Document" (MEPAG 2001[1]). The initial report proved to be very useful for guiding program implementation decisions. It also has become clear since then that the report requires regular updates in light of new results from Mars and changes in the strategic direction of NASA. For this reason, MEPAG periodically revises the Goals Document (MEPAG 2004[2]; MEPAG 2005[3]; MEPAG 2006[4]; MEPAG 2008[5]; MEPAG 2010[6]; and this document). As was the case with previous versions, the Goals Document is presented as a statement of community consensus positions.

The MEPAG Goals Document is organized into a four-tiered hierarchy: goals, objectives, investigations, and measurements. The goals have a very long-range character and are organized around major areas of scientific knowledge and highlight the overarching objectives of the Mars Exploration Program (Arvidson *et al*., 2006[7]). Expanded statements of these goals are found in the report, but they are commonly referred to as Life, Climate, Geology, and Preparation for Human Exploration. Developing a comprehensive understanding of Mars as a system requires

[1] MEPAG (2001), Scientific Goals, Objectives, Investigations, and Priorities, in Science Planning for Exploring Mars, JPL Publication 01-7, p. 9-38. Available on the web on the MEPAG website, under Reports, Science Goals Document, Archive: http://mepag.nasa.gov/reports.cfm.

[2] MEPAG (2004), Scientific Goals, Objectives, Investigations, and Priorities: 2003, G. J. Taylor, ed., 23 p. white paper posted July 2004 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.nasa.gov/reports.cfm.

[3] MEPAG (2005), Mars Scientific Goals, Objectives, Investigations, and Priorities: 2005, 31 p. white paper posted August 2005 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.nasa.gov/reports.cfm.

[4] MEPAG (2006), Mars Scientific Goals, Objectives, Investigations, and Priorities: 2006, 31 p. white paper posted February 2006 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.nasa.gov/reports.cfm.

[5] MEPAG (2008), Mars Scientific Goals, Objectives, Investigations, and Priorities: 2008, 37 p. white paper posted September 2008 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.nasa.gov/reports.cfm.

[6] MEPAG (2008), Mars Scientific Goals, Objectives, Investigations, and Priorities: 2008, 37 p. white paper posted September 2008 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.nasa.gov/reports.cfm.

[7] Arvidson, R.E., Allen, C.C., DesMarais, D.J., Grotzinger, J., Hinners, N., Jakosky, B., Mustard, J.F., Phillips, R., and Webster, C.R., (2006). Science Analysis of the November 3, 2005 Version of the Draft Mars Exploration Program Plan. Unpublished report dated Jan. 6, 2006, 13 p, posted January, 2006 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.nasa.gov/reports.cfm.

making progress in all three science areas, while the goal of preparing for human exploration is different in nature. Thus, MEPAG has not attempted to prioritize among the four goals. A general theme of understanding whether or not habitable zones and life have existed, or do exist, on Mars has emerged within the framework of understanding Mars and all its elements---interior, surface, and atmosphere—as a highly interactive and complex system. However, some of the fundamental science questions included in each goal may address the evolution of Mars as a planet more directly than habitability. Nonetheless, answers to those fundamental questions affect our analysis of habitability issues and ultimately improve the effectiveness of the Mars Exploration Program.

Each Goal includes one to three objectives that embody the strategies and milestones needed to achieve the Goal. Objectives are presented in priority order, because there is often an order within which the scientific questions can most logically be answered, and/or some objectives are perceived to be more important than others. In the present version of the Goals Document, there are a total of 9 objectives, eight of which are scientific in nature, and one of which relates to knowledge needed to prepare for human missions to Mars.

A series of investigations that collectively would achieve each objective is also identified. While some investigations could be achieved with a single measurement, others would require a suite of measurement types conducted across multiple missions. Each set of investigations is independently prioritized for each objective.

Measurements constitute the fourth tier of the hierarchy. Measurements are made by instruments that could be built and flown to Mars. MEPAG has only considered scientific objectives that are amenable to measurements (i.e., theoretical modeling, laboratory analysis, telescopic observations are not considered). As measurement capabilities and techniques evolve, detailed measurement requirements should be defined by Principal Investigators, Science Definition Teams, and Payload Science Integration Groups for program missions and by the Principal Investigator and Science Teams for competed missions. These requirements can then contribute to program planning. An important exception to this strategy, however, is the measurement set associated with Goal IV Objective A, which relates in part to environmental data sets necessary to reduce the risk of future human missions to acceptable levels. In that case, a clear criterion exists (degree of impact on risk reduction) that enables those measurements to be listed in priority order.

Completion of all the cited investigations would require decades and it is possible that many investigations are so complex that they might never be truly completed. Thus, evaluations of prospective missions and instruments should be based on how well the investigations are addressed and how much progress might be achieved in that context. While priorities should influence which investigations are conducted first, they should not necessarily be done serially, except where it is noted that one investigation should be completed first. In such cases, the investigation that should be done first was given a higher priority, even where it is believed that a subsequent investigation would be more important.

Some general thoughts on mission technology planning

The goals, objectives, and investigations all indicate that several crucial technical capabilities require additional development. The most important of these are: (1) *Global access*--high and low latitudes, rough and smooth surfaces, low and high elevations, in addition to precision landing. (2) *Access to the subsurface*, from a meter to hundreds of meters, directly (e.g., drilling) and indirectly (e.g., geophysical sounding). (3) *Access to time varying phenomena* that would require the capability to make measurements over long periods (e.g., climate studies covering from one to several Martian years). (4) *Access to microscopic scales* with instruments capable of measuring chemical and isotopic compositions and determining mineralogy *as well the ephemeral or continuous presence of liquid water on microscopic scales*. (5) *Planetary protection and sample handling* that would involve implementation of cleaning methods, contamination control, sample acquisition and processing methods, and sample packaging/sealing for possible return to Earth. (6) *Advanced instrumentation*, especially *in situ* life detection and age dating.

Orbital and landed packages could make many of the high priority measurements, but others might require that samples be returned from Mars. As noted in other MEPAG and National Academy of Science reports, study of samples collected from known locations on Mars and from sites whose geological context has been determined from remote sensing measurements have the potential to significantly expand our understanding of Mars. A full discussion of these issues is beyond the scope of this document, but has been addressed by MEPAG science analysis groups, as well as by the 2011 Planetary Sciences Decadal Survey.

Notes relating to this version (2012) of the Goals Document

In this revision of the Goals Document, Goal IV received sustantive revisions and Goal III received minor revisions. The descriptions of Goals I and II, as well as Section V are unchanged from the 2010 version of this document. For Goal IV, a revision was necessitated by the work of the Mars Precursor Science Analysis Group (P-SAG). The P-SAG, jointly sponsored by MEPAG and SBAG, was asked to identify Strategic Knowledge Gaps (SKGs) associated with potential human missions to the martian system for the Science Mission Directorate and the Human Exploration and Operations Mission Directorate, identify Gap-Filling Activities (GFAs), which include potential technology demonstrations for the Office of the Chief Technologist[8] that could be pursued in a near-term, cost-constrained integrated program of Mars exploration, and relate these activities to the science objectives for the martian system. Goal IV was subsequently revised to bring it into alignment with the completion of the P-SAG final report in 2012.

Section of the Goals Document	**Last Signif. Update**
Goal I – Determine if Life Ever Arose on Mars	2010
Goal II – Understanding the Processes and History of Climate on Mars	2008
Goal III – Determine the Evolution of the Surface and the Interior of Mars	2008
Goal IV – Prepare for Human Exploration	2012
Section V – Cross-Cutting Strategies	2010

[8] As of February 2013, the Space Technology Mission Directorate became responsible for technology demonstrations, rather than the Office of the Chief Technologist.

Major organizers and contributers to previous versions:

Previous versions of the MEPAG Goals document are posted on the MEPAG website at: http://mepag.jpl.nasa.gov/reports.cfm.

2010 version: Jeffrey R. Johnson, Tori Hoehler, Frances Westall, Scot Rafkin, Paul Withers, Jeffrey Plescia, Victoria Hamilton, Abhi Tripathi, Darlene Lim, David W Beaty, Charles Budney, Gregory Delory, Dean Eppler, David Kass, Jim Rice, Deanne Rogers, and Teresa Segura

2008 version: Jeffrey R. Johnson, Jan Amend, Andrew Steele, Steve Bougher, Scot Rafkin, Paul Withers, Jeffrey Plescia, Victoria Hamilton, Abhi Tripathi, and Jennifer Heldmann,

2006 version: John Grant, Jan Amend, Andrew Steele, Mark Richardson, Steve Bougher, Bruce Banerdt, Lars Borg, John Gruener, and Jennifer Heldmann

2005 version: John Grant

2004 version: G. Jeffrey Taylor, Dawn Sumner, Andy Steele, Steve Bougher, Mark Richardson, Dave Paige, Glenn MacPherson, Bruce Banerdt, John Connolly, and Kelly Snook

2001 Version: Ron Greeley

GOAL I: DETERMINE IF LIFE EVER AROSE ON MARS

The search for evidence of past or extant life is a key driver of the Mars exploration program. The general notion that Earth and Mars may have been relatively similar worlds during their early histories, combined with the relatively early emergence of life on Earth, has led to speculation about the possibility of life on Mars. Current and emerging technologies would enable us to evaluate this possibility with scientific rigor.

The implications of such an investigation are far reaching. Finding life on another world would have great impact at both social and scientific levels, and would undoubtedly motivate a variety of follow-up investigations to understand how that life functioned or functions; which attributes of structure, biochemistry, and physiology are shared with terrestrial life; what mechanisms underlie those attributes that differ; and whether Mars preserves evidence relating to the origin of that life. An apparent negative result (noting that it is not possible to demonstrate definitively that life *did not* take hold on Mars) would also be important in the context of understanding life as an emergent feature of planetary systems. If a careful investigation yields no evidence of life in systems that could clearly have both supported and preserved evidence of it, it would become important to understand whether such absence could be understood in reference of differences between Earth and Mars in the nature, extent, and duration of conditions that could support the origin and proliferation of life.

Life-related investigations also serve as a unifying theme for Mars system science. Habitability and the potential emergence and fate of life are intimately linked to the evolving planetary environment. Understanding the interplay of factors ranging from geophysical to climatological is thus an essential part of the search for evidence of life on Mars.

Presumably, the search for life would ultimately take the form of dedicated life-detection missions. Importantly, however, a variety of precursor missions – both landed and orbital – could and should be employed to develop a detailed and global perspective on where and how to conduct those dedicated missions. The purpose of this document is to lay out such a strategy.

Challenges Inherent in a Search for Extraterrestrial Life: The Need for a Working Model

Any effort to search for life beyond Earth must confront the potential for bias and "tunnel vision" that arises from having only one example – terrestrial life – on which to base our concepts of habitability and biosignatures. Such efforts should accommodate the possibility for exotic organisms that may differ in biochemistry or morphology, by conceiving life, habitability, and biosignatures in general terms. Nonetheless, the design and implementation of search-for-life strategies and missions would require concreteness, and therefore a working model of what would be sought.

It is difficult (and perhaps not presently possible) to define life, but for the purposes of formulating a search strategy, it is largely suitable to simply consider life's apparent properties – what it needs, what it does, and what it is made of. To this end, the NRC Committee on an

Astrobiology Strategy for the Exploration of Mars assumed that hypothetical Martian life forms would exhibit the following characteristics[1] (quoting verbatim):

- They are based on carbon, hydrogen, oxygen, nitrogen, phosphorus, sulfur, and the bio-essential metals of terrestrial life.
- They require water.
- They have structures reminiscent of terran [Earth-based] microbes. That is, they exist in the form of self-contained, cell-like entities rather than as, say, a naked soup of genetic material or free-standing chemicals that allow an extended system (e.g., a pond or lake) to be considered a single living system.
- They have sizes, shapes and gross metabolic characteristics that are determined by the same physical, chemical, and thermodynamic factors that dictate the corresponding features of terran organisms. For example, metabolic processes based on the utilization of redox reactions seem highly plausible. But the details of the specific reactions, including the identities of electron donors and electron acceptors, will be driven by local conditions and may well not resemble those of their terran counterparts.
- They employ complex organic molecules in biochemical roles (e.g., structural compounds, catalysis, and the preservation and transfer of genetic information) analogous to those of terran life, but the relevant molecules playing these roles are likely different from those in their terran counterparts.

This set of characteristics is adopted here as a working model. The bearing of this model on the approach to characterizing habitability and seeking biosignatures is discussed briefly below, and in greater detail in the Appendix to Goal I.

Delineating Objectives: Past versus Extant Life

Finding evidence of *either* past or extant life on Mars would be a watershed event. However, significant differences exist in the strategies, technologies, target environments, and forms of evidence that would be most appropriate in searching for ancient versus extant life. For example, it is generally thought that definitive evidence of life in ancient samples might only be obtained through return of samples from Mars to Earth, whereas some investigations for extant life might be best, or obligately, conducted *in situ*. Likewise, it might be necessary to access the Martian subsurface to find currently habitable zones, while a variety of environments that are presently accessible at the surface of Mars exhibit evidence of previously habitable conditions. For this reason, separate Objectives are delineated for ancient and extant life (Objectives A and B, respectively), with associated investigations that are specifically tailored to each search type. Ancient systems are given higher priority here based on a majority view that deposits formed in various ancient habitable environments are presently more accessible to characterization at the level of detail needed to constitute a viable search for evidence of life. However, recent findings (e.g., the reported detection of methane on Mars, and an expanding understanding of the potential for extant photosynthesis-independent subsurface life on Earth) emphasize the significance of potential subsurface habitats on Mars. The order of priority should thus remain open to reversal based on new findings, technology, or a changing consensus with respect to the accessibility of presently habitable environments.

<u>Delineating Investigations: Habitability, Biosignatures, and Preservation Potential</u>

Mars presents a diverse array of environments that may vary widely in the type, abundance, and quality of biosignature evidence they could or do preserve. The targeting of life-detection missions should thus be strongly informed by assessment of (a) habitability, i.e., how much and what sorts of evidence of life a given environment could expectedly have accumulated when/if it was inhabited, and (b) biosignature preservation potential, i.e., what sorts of evidence of life could have accumulated, how well differing lines of evidence could have been preserved, and what information may have been lost, to the point in space and time at which we could access it. The structure of Objectives A and B below reflects this notion, with separate investigations for characterizing habitability and preservation potential that would serve as precursors to life-detection investigations. Within the context of Objectives A and B, the chief purpose of the habitability and preservation potential investigations would be to inform life detection, and they should be conducted in this spirit, rather than as ends to themselves. A third Objective (C) recognizes the stand-alone importance of investigating the long-term evolution of habitability in the context of planetary processes. The concepts of habitability, biosignatures, and preservation potential, as they bear on Goal I and Mars exploration, are discussed in detail in the appendix. Key considerations are as follows:

<u>Habitability</u>:

In the context of Mars exploration, "habitability" has been previously defined as the potential of an environment (past or present) to support life of any kind, and has been assessed largely in reference to the presence or absence of liquid water. To support site selection for life-detection missions, additional metrics should be developed for resolving habitability as a continuum (i.e., more habitable, less habitable, uninhabitable) rather than a one-or-zero function, and this would require that additional determinants of habitability be characterized. Based on the working model above, the principal determinants of habitability for life on Mars would be: the presence, persistence, and chemical activity of liquid water; the presence of thermodynamic disequilibria (i.e., suitable energy sources); physicochemical environmental factors (e.g., temperature, pH, salinity, radiation) that bear on the stability of covalent and hydrogen bonds in biomolecules; and the presence of bioessential elements, principally C, H, N, O, P, S, and a variety of metals. An expanded discussion of the bearing of these factors on habitability is included in the appendix.

Preservation Potential:

Once an organism or community of organisms dies, its imprint on the environment begins to fade. Understanding the processes of alteration and preservation related to a given environment, and for specific types of biosignatures, is therefore essential. This is true not only in the search for fossil traces of life, but also for extant life. For example, metabolic end-products that are detected at a distance, in time and space, from their source, may be subject to some level of alteration. Degradation and/or preservation of physical, biogeochemical and isotopic biosignatures is controlled by a combination of biological, chemical and physical factors, and a combination that would best preserve one class of features may not favorable for another. These factors include diagenetic processing from water, heat, and pressure, radiation and oxidation degradation, and physical destruction by impact shock, wind and water agitation and fragmentation, abrasion, and dissolution. These factors might have varied substantially from one potential landing site to the next, even among sites that had been habitable at sometime in the past. *Characterization of the environmental features and processes on Mars that preserve specific lines of biosignature evidence is a critical prerequisite in the search for life.*

Accordingly the selection of landing sites should assess the capacity for any candidate sites to have preserved such evidence. Further discussion of preservation potential may be found in the Appendix.

Biosignatures:

Biosignatures can be broadly organized into three categories: physical, biomolecular, and metabolic. Physical features range from individual cells to communities of cells (colonies, biofilms, mats) and their fossilized counterparts (mineral-replaced and/or organically preserved remains) with a corresponding range in spatial and temporal scale. Molecular biosignatures relate to the structural, functional, and information-carrying molecules that characterize life forms. Metabolic biosignatures comprise the unique imprints upon the environment of the processes by which life extracts energy and material resources to sustain itself – e.g., rapid catalysis of otherwise sluggish reactions, isotopic discrimination, biominerals, and enrichment or depletion of specific elements. Significantly, examples can be found of abiotic features or processes that bear similarity to biological features in each of these categories. However, biologically mediated processes are distinguished by speed, selectivity, and a capability to invest energy into the catalysis of unfavorable processes or the handling of information. It is the imprint of these unique attributes that resolves clearly biogenic features within each of the three categories. A detailed discussion of biosignatures appears in the Appendix.

Ordering and Prioritization of Goal I Objectives, Investigations, and Sub-investigations

Objectives are listed in priority order, based on the rationale outlined above (see "***Delineating objectives…***"). Within Objectives A and B, Investigations are listed in preferred order of execution (not priority), based on the rationale outlined above (see "***Delineating investigations…***"). More specifically, the habitability Investigations (A.1 and B.1) and preservation potential Investigations (A.2 and B.2) are considered prerequisite "screening" to support the life detection Investigations (A.3 and B.3), which have overall highest priority within each Objective. Priority is implied in the ordering of Sub-investigations within Objectives A and B, and Investigations within Objective C. However, it should be noted that an Investigation would not be "complete" without the conduct of each Sub-investigation. In this case, priority implies a sense of which Sub-investigations would yield the greatest "partial progress" with respect to a given Investigation.

Objective A: Characterize past habitability and search for evidence of ancient life

1. Characterize the prior habitability of surface environments, with a focus on resolving formerly more habitable versus less habitable sites.

   Sub-investigations are focused on establishing overall geological context and constraining each of the factors thought to influence habitability. Importantly, it must be noted that the purpose of such investigations is to constrain *ancient* conditions by inference, based on the presently available record of such conditions. Data relevant to each sub-investigation could potentially be obtained by orbital measurements – in particular, by characterizing morphology and mineralogy in concert. Such measurements should be heavily utilized as a screening tool with which to target landed platforms capable of more detailed measurements.

1.1. Establish overall geological context.
1.2. Constrain prior water availability with respect to duration, extent, and chemical activity.
1.3. Constrain prior energy availability with respect to type (e.g., light, specific redox couples), chemical potential (e.g., Gibbs energy yield), and flux.
1.4. Constrain prior physicochemical environment, emphasizing temperature, pH, water activity, and chemical composition.
1.5. Constrain the abundance and characterize potential sources of bioessential elements.

2. Assess the potential of various environments and processes to enhance preservation or hasten degradation of biosignatures. Identify specific environments having high preservation potential for either individual or multiple types of biosignatures.
   2.1. Determine the major processes that degrade or preserve complex organic compounds, focusing particularly on characterizing oxidative effects in surface and near-surface environments (including determination of the "burial depth" in regolith or rocks that may shield from such effects), the prevalence, extent, and type of metamorphism, and potential mechanisms and rates for obscuring isotopic or stereochemical information.
   2.2. Identify the processes and environments that preserve or degrade physical structures on micron to meter scales.
   2.3. Characterize processes that preserve or degrade environmental imprints of metabolism, including blurring of chemical or mineralogical gradients and loss of stable isotopic and/or stereochemical information.

3. Search for evidence of ancient life in environments having high combined potential for prior habitability and preservation of biosignatures (as determined by A.1 and A.2).
   3.1. Characterize organic chemistry, including (where possible) stable isotopic composition and stereochemical information. Characterize co-occurring concentrations of possible bioessential elements.
   3.2. Seek evidence of possibly biogenic physical structures, from microscopic (micron-scale) to macroscopic (meter-scale), combining morphological, mineralogical, and chemical information where possible.
   3.3. Seek evidence of the past conduct of metabolism, including: stable isotopic composition of prospective metabolites; mineral or other indicators of prior chemical gradients; localized concentrations or depletions of potential metabolites (especially biominerals); and evidence of catalysis in chemically sluggish systems.

Objective B: Characterize present habitability and search for evidence of extant life

1. Identify and characterize any presently habitable environments.

   Sub-investigations are built on the assumption that, because liquid water is not presently stable at the surface of Mars, any modern habitable environments would be in the near- to deep-subsurface. Sub-investigations are focused (and priorities based) on the information needed to fully characterize habitability in such environments without reference to the present ability or difficulty in obtaining such information. The purpose of this approach is to accommodate potential future missions and technologies that might enable direct measurements to be made by virtue of direct access to the subsurface. However, orbital platforms might be capable of providing some information in each category, either by direct measurement (e.g., radar sounding to search for possible aquifers) or by inference (e.g., trace gas emissions that may imply a source region having liquid water and well constrained redox conditions). Significant use should be made of such orbital measurements in providing global screening-level constraints on subsurface habitability.

1.1. Identify areas where liquid water presently exists, with emphasis on reservoirs that are relatively extensive in space and time.
1.2. Identify areas where liquid water (including brines) may have existed at or near the surface in the relatively recent past including periods of significant different obliquity.
1.3. Establish general geological context (e.g., rock-hosted aquifer or sub-ice reservoir; host rock type)
1.4. Identify and constrain the magnitude of possible energy sources (e.g., water-rock reactions, radiolysis) associated with occurrences of liquid water.
1.5. Assess the variation through time of physical and chemical conditions in such environments. Of particular importance are temperature, pH, and fluid composition.
1.6. Identify possible supplies of bioessential elements to these environments.

2. Assess the potential of specific processes and types of environments to affect the preservation or degradation of signatures of extant life.
   2.1. Evaluate the physicochemical conditions of actual surface regolith or rock environments in terms of the potential for degrading or preserving biosignatures, and the effects of these processes on specific types of potential biosignatures.
   2.2. Evaluate the potential rate of physical degradation from wind abrasion, dust storms, dust devils, and frost action.
   2.3. Evaluate the physicochemical conditions at depth in regolith, ice, or rock environments in terms of the potential for degrading or preserving biosignatures.

3. Search for extant life at localities identified by Investigations B.1 and B.2.
   3.1. Seek evidence of ongoing metabolism, in the form of rapid catalysis of chemically sluggish reactions, stable isotopic fractionation, and/or strong chemical gradients. Seek biogenic gases, which have potential to migrate from potentially habitable deep subsurface environments to surface environments where they might be accessible to remote or *in situ* characterization.
   3.2. Characterize organic chemistry and co-occurring concentrations of bioessential elements, including stable isotopic composition and stereochemistry. Analyses might include but should not be limited to known molecular markers of terrestrial life, such as membrane lipids, proteins, nucleic acid polymers, and complex carbohydrates.
   3.3. Seek evidence of organic and mineral structures or assemblages that might be associated with life. Seek evidence of mineral transformations bearing evidence of biological catalysis (e.g., depletion of possibly bio-essential elements in mineral surfaces).

Objective C: Determine how the long-term evolution of Mars affected the physical and chemical environment critical to habitability and the possible emergence of life

In Objectives A and B, the principal aim of characterizing habitability is to inform the selection of sites for potential subsequent life-detection missions. However, understanding the factors and processes that give rise to habitable conditions at planetary and local scales, and how those conditions might change in concert with planetary and stellar evolution, is an important stand-alone pursuit for Mars science. Investigations below focus on constraining the major planetary processes that collectively affect habitability through time.

Investigations:

1. Characterize the evolution of the Martian hydrological cycle, emphasizing likely changes in the location and chemistry of liquid water reservoirs.

2. Constrain evolution in the geological, geochemical, and photochemical processes that control atmospheric, surface, and shallow crustal chemistry, particularly as it bears on provision of chemical energy, and availability (abundance, mobilization, and recycling) of bioessential elements.

3. Constrain the nature and abundance of possible energy sources as a function of changing water availability, geophysical and geochemical evolution, and evolving atmospheric and surface conditions.

4. Evaluate the presence and magnitude of oxidative or radiation hazards at the surface and in the shallow crust.

Appendix to Goal I

The specific approach and methods involved in any search for life beyond Earth depend critically on how the concepts of life, habitability, and biosignatures are conceived. Below, these concepts are discussed in specific reference to Mars exploration and the strategy outlined in this document.

Life

The NRC Committee on the Limits of Organic Life noted that the only unquestionably universal attribute of life is that it must exploit (and therefore requires) thermodynamic disequilibrium in the environment, in order to perpetuate its own state of disequilibrium. Beyond this absolute, the Committee cited a set of traits that it considered likely be common to all life[2]:

- It is chemical in essence, and most probably consists of interacting sets of molecules having covalently bonded atoms, including a diversity of "heteroatoms" (such as N, O, P, etc. in terrestrial organisms) that promote chemical reactivity.
- It probably requires a liquid solvent to support such molecular interactions.

- It probably employs a molecular system capable of Darwinian evolution.

Reference to the known characteristics of life on Earth can serve to add detail and constraint within each of these categories, but heavy reference to this single example carries the risk of "terracentricity" – a potential to overlook life that may be unlike our own. A key challenge for Mars astrobiology is thus to find a point of balance between the all-encompassing generality of the descriptions above and the specificity and concreteness that comes from reference to life on Earth. The NRC Committee on an Astrobiology Strategy for the Exploration of Mars developed a working set of characteristics of life (as quoted above) that reflects such a balance, and which serves as the basis for the approach outlined here. This approach generally corresponds to the following logic:

The relative similarity of Earth and Mars (in comparison to, for example, gas giants or icy moons) suggests that differences in life forms that originated independently on the two bodies would likely occur at a secondary, rather than first-order level. That is, notions of life that differ at the fundamental levels of biochemical scaffolding (alternatives to carbon) or required solvent (alternatives to water) require planetary conditions and chemistries that differ dramatically from those of either Earth or Mars. However, differences from terrestrial life become increasingly possible, and ultimately probable, with increasing levels of biochemical specificity. These considerations bear differently on the conceptualization of the habitability and life detection objectives. For the most part, habitability relates to the core needs and attributes of life, so a presumed first-order similarity between terrestrial and Martian life allows terrestrial notions of habitability to be applied, with somewhat relaxed boundary conditions, to Mars. On the other hand, as developed in studies of terrestrial systems, biosignatures (especially organic molecular/ biosignatures) commonly represent extremely specific attributes of biochemistry (e.g., specific lipids or particular sequences of amino or nucleic acids), morphology, or process. While such specific markers of life would be unquestionably valuable if detected on Mars, the likelihood that the *same* markers (the same specific choices of biomolecules) would arise through an independent origin and elaboration of life seems low. Thus, while life detection strategies for Mars should ideally allow for the detection and characterization of Earth-like biosignatures, highest priority should be given to approaches and methods that define and seek biosignatures in a broader sense. Strategies for framing and applying concepts of habitability and biosignatures are addressed in greater detail below.

Prebiotic Chemistry

Even if life itself never existed on Mars, the planet could have hosted, and might still preserve evidence of, a pre-biotic chemistry. Identifying aspects of such chemistry on Mars would make an important contribution to our overall understanding of life as an emergent feature of planetary systems. Prebiotic chemistry can be conceived as the set of chemical processes – including chemical synthesis, non-genomic molecular evolution, and self-organization of structures and catalytic cycles – that collectively lead to the emergence of minimally functional life. Here, "minimal functionality" is assumed to be conferred by a compartmentalized, interacting set of molecular systems for (a) information storage; (b) catalytic function; and (c) energy transduction. Progress in understanding any of these processes would constitute an important contribution in the context of Goal I. However, the most tractable near-term focus may be to understand the processes – whether endogenous synthesis from simple molecules or delivery from exogenous sources – that supply basic biochemical building blocks, such as sugars, amino acids, and nucleobases, as well as comparable alternatives that are not used in present terrestrial living systems but might nonetheless play a role in an emerging biochemistry. More advanced stages of prebiotic chemistry – which could be viewed as partially complete representations of each of the main classes of biosignatures described below – could be difficult to discern from degraded remnants of living cells. The potential for confusing prebiotic chemicals or structures with degraded biosignatures emphasizes the importance of establishing multiple lines of evidence in definitively identifying life. In particular, finding evidence of extreme selectivity in isotopic composition or stereochemistry would be a strong indicator of life, rather than prebiotic chemistry. As with life itself, the emergence of prebiotic chemistry must be considered within the context and boundary conditions supplied by the physicochemical environment, and evidence of such chemistry will be subject to the same processes of degradation as evidence of life. Thus, investigations relating to prebiotic chemistry should be pursued within the framework and context provided by the habitability and preservation potential investigations that are outlined above.

Defining and Quantifying Habitability

In the context of Mars science, habitability has thus far been defined (for example, in the NRC "An Astrobiology Strategy for the Exploration of Mars") as the potential of an environment to support life. Assessment of this potential has focused to a very large degree on determining whether liquid water was or is present in the environment in question. These constitute an inherently "binary" approach to habitability – liquid water was either present or was not; life could either be supported, or could not – that has served to identify a wide spectrum of apparently water-formed (nominally habitable) Mars environments. Reference to life on Earth – with habitats that exhibit a continuum from sparsely to densely inhabited – suggests that significant variation in habitability could likewise exist within the set of water-bearing environments on Mars. As described above, the main purpose of Habitability Investigations A.1 and B.1 is to narrow and prioritize the search space for life detection efforts. Investigations and methodologies capable of resolving "more habitable" environments from "less habitable" ones should therefore be emphasized. A key challenge for the coming decades of Mars exploration is thus to augment the liquid water metric that has served as a guide to habitability with additional metrics that would aid in prioritizing sites for potential life detection missions. Although a consensus approach for characterizing "relative habitability" does not yet exist within the Mars community, it is clear that additional resolving power in any model would depend on the ability to resolve (by measurement or inference) variations in each of the parameters thought to underpin habitability:

- A solvent capable of supporting complex biochemistry. For terrestrial life, liquid water (above minimum chemical activity levels) is an absolute requirement.
- A source of energy to drive metabolism. Organisms on Earth require energy availability to meet discrete minimum flux and Gibbs energy requirements. Light (from the near infrared to visible range) and chemical energy are known to be utilized by life on Earth; the viability of alternative energy sources has yet to be sufficiently explored or validated.
- Raw materials for biosynthesis. All life on Earth requires the elements C, H, N, O, P, and S, and also variously requires many "micronutrients" (notably transition metals). Traditionally,

these are collectively referred to as "bioessential elements". As applied in this document, this term refers primarily to C, N, O, P, and S.

- Sustained physicochemical (environmental) conditions that allow for the assembly, persistence, and function of complex structures and biomolecules (especially biopolymers, like proteins and nucleic acid polymers, whose backbones contain relatively labile bonds). Extremes of temperature, pH, radiation, and salinity can, individually or in combination, render an environment uninhabitable.

Given the working model and rationale described above, habitability shall be considered to correspond closely to the parameters known to constrain life on Earth. While environments that could be habitable for exotic organisms may be missed by this approach, it is appropriately conservative. Conditions that could support terrestrial life can be said to be definitively habitable. Some level of divergence from a strictly Earth-centric view of habitability can also be adopted by (a) focusing more on "core requirements" (e.g., water, carbon, and energy) than on requirements that underpin the more specific attributes of biochemistry (e.g., micronutrient requirements), and (b) allowing for the possibility, at least at a screening level, that Martian organisms might conceivably transcend the currently known physicochemical boundaries (e.g., the biologically tolerated temperature range) of life on Earth.

Whatever models emerge for resolving habitability may differ in parameterization of, and sensitivity to, each of these basic factors that underpin habitability. Yet all will be supported by an effort to constrain "degree" in reference to each parameter: How long liquid water was available, at what chemical activity level, and whether intermittently or continuously; How much energy was available, in what forms, and how fast it could have been delivered into a system; What concentrations or fluxes of bioessential elements were present, and what processes may have served to mobilize or cycle them; And what range of temperature, pH, radiation level, and other relevant environmental parameters an environment may have experienced. All such measurements should be placed, to the greatest extent possible, within geological and environmental context.

While the ability to resolve almost any of these parameters would likely be greater with landed platforms and instruments, a key aspect of the proposed habitability investigations is the capability of orbital measurements to yield several lines of "screening level" information, beyond evidence of liquid water. Of particular interest is the ability of combined morphological and mineralogical evidence to establish geological context and place screening-level constraints on possible energy sources and physicochemical regimes; and of trace gas and other measurements to infer conditions of formation in subsurface source regions. Such measurements should serve as a key initial step in resolving habitability among the variety environment types that could be targeted for life-detection investigations.

Biosignature types and contamination challenges

Biosignatures can be broadly organized into three categories: biomolecular, metabolic, and structural. Significantly, examples can be found of abiotic features or processes that bear similarity to biological features in each of these categories. However, biologically mediated processes are characterized by speed, selectivity, and a capability to invest energy into the catalysis of unfavorable processes or the handling of information. It is the imprint of these unique attributes that resolves clearly biogenic features within each of the three categories. Most of the biosignatures can be, to a certain degree, imitated by non-biological processes. Robust identification of traces of life therefore requires a variety of evidence, ideally from the following three categories.

1. Biomolecular. Life invests energy into the synthesis of complex structural, functional, and information-carrying molecules. Identifying terrestrial versions of these molecules (e.g., membrane lipids, proteins, and nucleic acid polymers, respectively) on Mars would aid in attributing a biological origin, but would likewise increase the importance of ruling out terrestrial contamination. Likewise, because these represent specific biochemical "choices," our search must allow for alternative possibilities. Accordingly, the methods employed should be as inclusive as possible with the broad spectrum of organic compounds, and should seek to capture information about structure, complexity, and organization. In synthesizing the suite of biomolecules that constitutes a functional organism, life also concentrates key elements (e.g., C, N, P, S, and various micronutrients, in terrestrial life) in stoichiometric ratios, and evidence of such co-occurring elements (particularly in organic form) should be sought. Finally, the enzymatic processes that synthesize biomolecules frequently also impose significant kinetic isotope fractionation effects and exhibit high stereochemical or enantiomeric selectivity. These additional layers of information within the basic organic chemistry should be sought when possible.

2. Metabolic. In constructing and maintaining itself, life extracts energy and material resources from its surroundings, and may leave unique overprints on the environment in the process. Photosynthetic energy harvesting is evident in light-absorption by pigments (for example, characteristic deep absorption features in the NIR to visible) and may confer on organisms an ability to build up significant redox disequilibrium in their surroundings (as with the strong oxidizing effect of oxygenic photosynthesis). Chemosynthetic metabolism extracts energy from chemical reactions that are thermodynamically favored to proceed even in the absence of life. Life distinguishes itself in these reactions by speed (catalysis 10^6-fold or greater, in many terrestrial examples) and selectivity (as expressed in kinetic isotope effects and, sometimes, stereoselectivity). Catalytic speed may be evident in progress toward equilibrium in chemical reactions that are abiotically sluggish under ambient conditions, concentration or depletion of specific elements or chemical species, or strong chemical gradients or zonation (including in redox and pH). The latter can sometimes be recorded in biomineralization, which may be an important class of evidence for ancient systems. Selectivity may be evident in isotopic fractionation between candidate substrate and product pairs (noting that abiotic processes may also fractionate), or in deposition of structurally or chemically distinctive mineral forms. Where possible, chemical information (e.g., analysis of potential metabolic product/reactant pairs) should be coupled with isotopic and other information, to capture combined evidence of life's catalytic and selective effects. An important aspect of the metabolic class of biosignatures is that, unlike biomolecular markers, life's role in imposing an imprint on the environment is simply catalytic. Hence, special allowance need not be made, in this category, for "alternative" or exotic biochemical machineries – it is the reactants and products of catalyzed reactions (and the imprints of speed and selectivity thereon) that constitute the biosignature, and not the catalyst (organism) itself.

3. Physical structures. Life imposes organization and order on its physical environment at many levels, from the structure and sub-structures within a cell to community-level structures formed by trillions of individuals (e.g., microbialites and microbial fabrics). The structural components, cells, colonies, biofilms, mats and extracellular polymeric substances (EPS), may be preserved in fossilized form in a number of ways. Cells may leave organic walled impressions, mineral-coated or impregnated structures, or empty casts in a mineral precipitate. Biofilms and mats may also be preserved as organic impressions in sediments or mineralized structures.

Cells walls can be preserved as organic impressions in fine-grained, anaerobic sediments. This kind of preservation can be aided by the fixation of metals, such as Fe, on cell envelopes, which may retard lysis. The most common form of preservation of microbial structures is mineral-assisted fossilization. In this process, minerals bind to the organic surfaces of the cells and/or their polymers in a passive reaction resulting in encrustation or permeation of the organic structure. The microbial surfaces and exopolymers therefore act as "mineralizing templates." Depending upon the availability of the minerals in solution, the microorganisms may be completely entombed in a mineral precipitate. Many mineral phases can bind to microbial cell walls including silica, carbonates (Ca, MgCa, Fe, Mn), metal oxides/hydroxides (Fe/Mn and magnetite), sulfates (Ca, Sr, Ba, Fe), sulfides (Fe, Ni, Pb, Zn, CuFe), phosphates (Ca), clays, and zeolites. In anaerobic environments, the macromolecules can be entombed within the mineral precipitate. However, in order for the fossilised cells or cell comunities to be preserved in the rock record, the mineral-coated or permeated microbial structure needs to become encased in a mineral cement or by fine-grained sediments. Here, further diagenetic changes may take place, including changes in mineralogy (e.g. transformation of oxyhydroxides to oxides), replacement (complete or partial) of one mineral by another (e.g., silicification of carbonate mineralized remains), or dissolution. The final mineral or sediment-encased microbial fossils may exhibit different morphological preservation modes.

On a cautionary note, abiological mineral precipitates can be notoriously confused with fossilized microorganisms. Many minerals, for instance silica, may form simple spherical, oval, elongated and even twisted morphologies.

The problem of contamination

Any of the classes of biosignature evidence that might be sought in our investigations is potentially subject to contamination. However, this is perhaps most critical for the "biochemical" class, where any of a broad range of organic contaminants have potential to be introduced by the spacecraft itself. Investigations targeting biochemicals must therefore include appropriate controls against terrestrial contamination. To this end, new techniques and instruments are presently being developed for cleaning and monitoring of spacecraft contamination. In searching for life on Mars, sample handling and analytical procedures must include procedural blanks that allow for the tracking and quantification of contamination introduced by the spacecraft and its processes, for any analytes that might serve as evidence of life. Planning along these lines should also address the potential that the aging of a spacecraft, or its exposure to different environments, could alter its potential to introduce contamination over the course of a mission.

Preservation of features related to assessing habitability or biosignatures

Once an organism or community dies, its imprint on the environment, in any of the classes of features described above, begins to fade. Preservation/degradation of the different types of biosignatures is controlled by the combination of biological, chemical and physical factors, and a combination that would best preserve one class of features may not be favorable for another. *Characterization of the environmental features and processes on Mars that preserve specific lines of biosignature evidence is a critical prerequisite in the search for life.* Along with an assessment of relative habitability, assessment of preservation potential should serve as a key criterion in selecting sites for life detection missions. It should not, however, have high priority as a *stand-alone* enterprise, since life detection is the ultimate and highest priority objective of Goal I.

It will be important to consider an environment's potential to preserve evidence in each of the three categories of biosignatures. Often, preservation within the biochemical category is given the most attention, because such molecules (in undegraded form) may present the most diagnostic evidence of life, but may also be among the most labile forms of evidence. However, obtaining clear evidence of life on Mars would likely require multiple biosignatures in different categories. Thus, recognizing physical structures in context, identifying associated biominerals, and finding the chemical and isotopic imprints of metabolism would be no less important. Investigations of ancient communities on Earth might provide a preliminary guide for understanding preservation potential on Mars. However, it should be noted that the differing histories and surface environments of those two worlds may translate into quite significant differences in the processes that degrade or preserve specific lines of evidence. For example, metamorphic alteration represents a major destructive mechanism for biosignatures from early Earth environments, while radiation and oxidation may present the greater challenge to biosignatures on Mars.

Preservation of biochemicals

Organic molecules in sediments are rapidly degraded in natural environments by a number of chemical and biological processes during early diagenesis and rock lithification, as well as during low temperature burial metamorphism to high temperature metamorphism (on Mars this will be equated with impact shock and/or volcanism). Chemical and radiolytic degradation on the surface of Mars would include the effects of UV and ionizing radiation, radionuclide decay, oxidation in the presence of liquid water and certain minerals, such as Fe(III), and exposure to oxidants, such as H_2O_2. Furthermore, in the presence of liquid water, racemization of chiral organic molecules could occur within a couple of million years. The ideal locality for searching for biomolecules on Mars would therefore be in the subsurface in materials that have not been exposed to liquid water since their burial and preservation. Molecules that have a greater chance of long-term preservation are those that have undergone restructuring to become resistant cross-linked aliphatic or aromatic macromolecules and that have been preserved by association with certain lithologies and minerals, such as clays, silica, sulfates, carbonates, and ices. The isotopic composition of organic compounds is relatively stable, to the extent that basic molecular skeletons are preserved. On Earth, the effect of thermal metamorphism on organic matter is to degrade it chemically, typically forming isotopically lighter volatile species and isotopically heavier residual refractory solids.

Preservation of physical structures

On Earth, long-term preservation of physical microbial structures depends upon several factors, in particular the following. (1) The rapid burial of organic structures in anaerobic conditions by fine-grained impermeable siliceous sediments, such as clays, where they are protected from oxidizing fluids. This preserves the structures as flattened organic compressions between sediment layers. (2) Replacement or coating by a wide range of minerals. It must be noted that different microorganisms have different susceptibilities for mineral fossilization and those that are particularly delicate may not fossilize at all; thus, the microfossils preserved in a rock will not necessarily represent the original microbial community.

The preservation of larger scale biological constructs (such as biolaminated deposits or stromatolites) is aided by the association with sediments and carbonate precipitation. Such physical biosignatures may be mechanically destroyed by erosion (including impact erosion). As mineralogical structures, they can be corroded, for instance by acidic ground waters if they have a carbonate composition. The complicated post-diagenetic history of aqueous alteration of the sediments at Meridiani Planum is illustrative of the processes that could have affected potential Martian microbial structures. Changes to the rock encasing the physical structures brought about by different types of metamorphism (shock, thermal), will induce gradual destruction of the structures depending upon the degree of metamorphism. For example, Early Archaean terrestrial rocks that have undergone little more than burial metamorphism (prehnite-pumpellyite to lowermost greenschist facies) contain well preserved physical biosignatures. In the long term, because the degradation of organic biosignatures over time is inevitable, physical biosignatures have a greater chance of preservation than complex organic markers.

Preservation of biominerals

The range of minerals passively formed as a result of microbial metabolism is very large. As with fossilized microbial structures (as above), the preservation of biominerals will depend on the history of alteration (metamorphic, chemical, physical) of the rock after formation.

References

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GOAL II: UNDERSTANDING THE PROCESSES AND HISTORY OF CLIMATE ON MARS

The fundamental scientific questions that underlie this goal are how the climate of Mars has evolved over time to reach its current state, and what processes have operated to produce this evolution. These scientific questions are in accord with several key science objectives found in the NASA Solar System Exploration Roadmap (2003). Mars climate can be defined as the mean state and variability of its atmosphere and exchangeable volatile reservoirs (near the surface) evaluated from diurnal to geologic time scales. The climate history of Mars can be divided into three distinct epochs: (i) Present, operating under the current obliquity; (ii) Recent past, operating under similar pressures and temperatures but over a range of orbital variations (primarily obliquity); and (iii) Ancient, when the pressure and temperature may have been substantially higher than at present and liquid water may have been stable on the surface. An understanding of Mars climatic evolution rests upon gaining a full understanding of the fundamental processes governing its climate system, and thus upon obtaining detailed observations of the current (observable) system. Goal II also is in line with the recommendation of the Solar System Exploration Survey [2002], which calls out the explicit need for Mars upper atmosphere measurements to characterize current volatile escape rates for application to climate evolution studies. Each Objective below corresponds to a different climate epoch and are given in priority order. Objective A is focused on the present state of the entire atmospheric system (from the surface-atmosphere boundary to the exosphere). It would form the baseline for interpreting past climates of Mars. Objective B is focused on specific investigations that would provide information on the recent period of climate history driven primarily by obliquity changes. Objective C is focused on the ancient climate history, when Mars may have been warmer, wetter and more habitable than today.

Objective A.: Characterize Mars' Atmosphere, Present Climate, and Climate Processes Under Current Orbital Configuration

Our understanding of the composition and dynamics of the present Martian atmosphere is the basis for understanding past climates on Mars. Investigations of the upper and lower atmosphere plus the surface and near-surface reservoirs of CO2, H2O and dust would be essential because they are integral parts of an interconnected system. Measurements of both atmospheric regions and the reservoir exchange region of the regolith would enable us to explore different suites of processes that play unique roles in understanding the Martian climate and its evolution. In short, a ground-to-exosphere approach to monitoring the Martian atmospheric structure and dynamics would be needed for a proper characterization of the present day climate of Mars.

<u>1. Investigation:</u> Determine the processes controlling the present distributions of water, carbon dioxide, and dust by determining the short- and long-term trends (daily, seasonal and solar cycle) in the present climate. Determine the present state of the upper atmosphere (neutral/plasma) structure and dynamics; quantify the processes that link the Mars lower and upper atmospheres.

To understand the present climate system, from the surface to the exosphere, would require long-term (multi-year) continuous global monitoring from both landed and orbital platforms.

Understanding the factors that control the annual variations of volatiles and dust is necessary to determine to what extent processes operating today have controlled climate change in the past.

(i) Lower atmosphere climate and processes
In situ measurements are uniquely suited to measure locally near-surface water vapor, winds, heat, momentum, and mass fluxes, and other variables that control the exchange of volatiles and dust between the surface and atmosphere. In situ measurements could be obtained by stationary landed observatories (individual or networked), mobile platforms (e.g., rovers), and aerial platforms (e.g., balloons). Each of these platforms could provide unique measurements critical to a complete understanding of the climate system. In situ measurements could also provide calibration and validation for complementary measurements retrieved from orbit.

Orbital missions could provide information on the global and vertical structure of the atmosphere, direct measurement of winds, and information on the spatial distribution of aerosols, water vapor, clouds (both water and CO_2) and potentially other important trace species. This information leads to the elucidation of the local- through global-scale processes that operate to maintain the climate and transport volatiles and dust. The global meteorological, radiative, and mass balance observations gathered from these platforms on daily- to decade-long timescales would establish the magnitude of inter-annual variability, aid in the identification of the responsible mechanisms, and demonstrate whether there are any long-term trends in the present climate system. Specifically, these measurements would provide a means to characterize the annual variations and cycling of volatiles, condensates, and dust. These observations would also assist in identifying the causes of the north/south asymmetry in the nature of the polar caps, and the physical characteristics of the layered deposits. Ultimately, these data would serve as the foundation for the development of more realistic models to assess the effects of various external forcing-factors (such as obliquity and increased atmospheric pressure) on the climate of Mars.

(ii) Upper atmosphere climate and processes
Orbiter missions would also be needed to investigate the mean state and variability of the neutral and plasma environment above ~80 km. These data would improve our understanding of the coupling of the lower and upper atmospheres, and characterize the regions of the upper atmosphere that interact with the solar wind. Also, the global characterization of the present lower and upper atmosphere structure and dynamics would be required over various timescales (daily, seasonal, and solar cycle) in order to properly interpret volatile escape measurements and the subsequent volatile evolution model results. This objective reemphasizes the need for a ground-to-exosphere approach to monitoring of the Martian atmospheric structure and dynamics.

(iii) Planetary boundary layer: heat, momentum and mass exchange
Thermal variation between the surface and the atmosphere combined with mechanical interactions between the wind and surface roughness element drives turbulence. The links between surface and air temperature (via aerosol radiative heating) and the thermodynamic state of the lower atmosphere would be studied under this investigation. Turbulence and heat transport in the lowest portion (<5km) of the atmosphere would also be a concern for thermal design of spacecraft.

<u>2. Investigation:</u> Determine the production/loss, reaction rates, and global 3-dimensional distributions of key photochemical species (e.g., O_3, H_2O, CO, OH, CH_4, SO_2), the electric

field and key electrochemical species (e.g., H^2O_2), and the interaction of these chemical species with surface materials.

This investigation would necessarily involve study of both the lower and upper atmosphere. Surface sinks and sources and lower atmospheric distribution would be required to interpret atmospheric escape rates and upper atmosphere aeronomic processes. Current multi-dimensional photochemical models predict global distributions of these species. Such models require validation to confirm key reactions and rates and the role of dynamics in the transport of these constituents. There is, however, considerable uncertainty in the surface fluxes of major species. In particular, the absolute abundance and the corresponding spatial/temporal variability of CH_4 are uncertain, but have important implications for Mars biological or non-biological processes (see section I.B). In addition, electro-chemical effects may be important for production of certain species (e.g., H_2O_2) and promoting surface-atmosphere reactions, but confirmation is needed. This investigation would require global orbiter observations of neutral and ion species, temperatures, and winds in the lower and upper atmospheres, and the systematic monitoring of these atmospheric fields over multiple Mars years to capture inter-annual variability induced by the solar cycle, seasons, and dust storms.

3. Investigation: Understand how volatiles and dust exchange between surface and atmospheric reservoirs, including the mass and energy balance. Determine how this exchange has affected the present distribution of surface and subsurface ice as well as the Polar Layered Deposits (PLD).

The current Martian seasonal cycle is dominated by condensation and evaporation of 1/3 of the carbon dioxide atmosphere into the seasonal caps. Both dust and water ice are entrained in this seasonal wave and may be incorporated into more permanent icy deposits. Mechanisms of deposition (“snow”, direct condensation) as well as evolution and densification of deposits bear directly on the stability, evaporation and venting of those deposits in spring. The onset of sporadic, planet-encircling dust events coincides with the retreat of the south seasonal cap, but their timing and causes are still not well understood. Exposure of permanent water ice deposits in the north drives the water cycle and exchange with the atmosphere. Transport of dust and water in and out of the polar regions are seasonally, annually, and decadally variable, requiring long-term monitoring. Large scale sub-surface ice deposits exist at high latitudes in both hemispheres and may buffer long-term surface-atmosphere exchange. This investigation would require measurement of both mass and energy balances of volatiles and dust within the permanent and seasonal volatile reservoirs: polar layered deposits, buried ice rich soils, seasonal ice deposits and the atmosphere. Assessment of net accumulation or loss of the residual ice deposits and mass, density and volume of the seasonal ice as function of location and time are important components of this investigation.

4. Investigation: Search for microclimates.

Detection of exceptionally or recently wet or warm locales, exceptionally cold localities, and areas of significant change in surface accumulations of volatiles or dust would identify sites for in situ exploration. This would require a global search for sites based on local surface properties (e.g., geomorphic evidence, topography, thermal properties, albedo) or changes in volatile (especially H_2O) distributions.

Objective B.: Characterize Mars' Recent Climate History and Climate Processes Under Different Orbital Configurations

Understanding the climate and climate processes of Mars under past, but geologically recent, orbital configurations would require interdisciplinary study of the Martian surface and atmosphere. The investigations described below focus on quantitative measurements (concentrations and isotopic compositions) of important gases in the atmosphere and trapped in surface materials. It also would require the study of geologic materials to search for the record of past climates. The most likely location of a preserved record of recent Mars climate history is contained within the north and south polar deposits and circumpolar materials. The polar layered deposits and residual ice caps may reflect the last few hundred thousand to few million years, while terrain softening, periglacial features, and glacial deposits at mid- to equatorial-latitudes may reflect recent high obliquity cycles within the last few million years.

<u>1. Investigation:</u> Determine how the stable isotopic, noble gas, and trace gas composition of the Martian atmosphere has evolved over obliquity cycles to its present state.

This investigation would require knowledge of the composition of the atmosphere at various times within recent climate history to provide quantitative constraints on the evolution of atmospheric composition and on the sources and sinks of the major gas inventories. It is important to understand the temporal and spatial variability of atmospheric composition. In situ or returned sample high precision isotopic measurements of the present atmosphere, and analogous measurements of trapped guesses within polar layered deposits or other gas-preserving ices, would be required.

<u>2. Investigation:</u> Determine the chronology, including absolute ages, of compositional variability, and determine the record of recent climatic change that are expressed in the stratigraphy of the PLD.

The presence of extensive layered deposits suggests that the climate of Mars has undergone frequent and geologically recent change. A key to understanding the climatic and geologic record preserved in these deposits is to determine the environmental conditions and processes that were necessary to produce them. Specific examples of the type of information these deposits may preserve include a stratigraphic record of volatile mass balance; insolation variations; atmospheric composition; dust storm, volcanic and impact activity; cosmic dust; catastrophic floods; solar luminosity (extracted by comparisons with terrestrial ice cores); supernovae and perhaps even a record of microbial life. Clues to climate evolution are recorded in the stratigraphy and physical and chemical properties of the layers. Keys to understanding the climatic and geologic record preserved in these deposits are to determine the relative and absolute ages of the layers, their thickness, extent and continuity, and their petrologic/geochemical characteristics (including both isotopic and chemical composition). Addressing this investigation would require high-resolution imaging, in situ and remote sensing measurements of stratigraphy and layer properties, and absolute ages determined either in situ or from returned samples.

<u>3. Investigation:</u> Relate low latitude terrain softening and periglacial features to past climate eras.

Recent high resolution imaging has shown numerous examples of flow-like features on the slopes of Tharsis volcanoes and in other lower-latitude regions. These features, interpreted to be glacial and peri-glacial, may be related to ground ice accumulation in past obliquity extremes. This investigation would link observed deposits to past orbital conditions primarily through models and age dating and additional investigations in Goal III.A.

Objective C.: Characterize Mars' Ancient Climate and Climate Processes

Understanding the ancient climate and climate processes on Mars requires interdisciplinary study of the Martian surface and atmosphere. There is great uncertainty about the composition and state (pressure and temperature) of the ancient atmosphere and its ability to support liquid water on the surface. The investigations described below would focus on the study of atmospheric escape processes and the study of geologic features and geochemical signatures. Understanding atmospheric loss processes enable extrapolation backwards in time to better estimate the atmospheric conditions present during the ancient climate regime and better understand the evolution of the ancient climate to its present day condition. Observations of present geomorphology and geochemistry record the integrated climate history of Mars from ancient times to present. The atmospheric and geologic record must be used synergistically to decode a self-consistent picture of the ancient climate and climate evolution of Mars.

<u>1. Investigation:</u> Determine the rates of escape of key species from the Martian atmosphere, their correlation with seasonal and solar variability, the influence of remnant crustal magnetic fields, and their connection with lower atmosphere phenomenon (e.g., dust storms). From these observations, quantify the relative importance of processes that control the solar wind interaction with the Mars upper atmosphere in order to establish the magnitude of associated volatile escape rates.

These measurements would provide crucial constraints to atmospheric evolution models that extrapolate these rates to determine past climates. This investigation would require global orbiter observations of neutral and plasma species, crustal magnetic fields, temperatures, and winds in the extended upper atmosphere. The systematic monitoring of these fields over multiple Mars years would be needed to capture the inter-annual variability induced by the solar cycle, seasons, and dust storms. This investigation also would require more thorough and higher-resolution measurements of crustal magnetic fields.

<u>2. Investigation:</u> Find physical and chemical records of past climates.

This investigation would center on finding geomorphic and chemical evidence of past climates or of prior environmental events or conditions that may have perturbed the local or global climate in unexpected ways (e.g., the former presence of an ocean or seas or of global magnetic fields, large impacts, episodic volcanism or outflow channel activity). These would provide the basis for understanding the extent, duration (e.g., gradual change or abrupt transition), and timing of past climates on Mars. This investigation would require, for example, determining sedimentary stratigraphy and the distribution of aqueous weathering products. Specific investigations are further elaborated in Goal III.A.

3. Investigation: Determine how the stable isotopic, noble gas, and trace gas composition of the Martian atmosphere has evolved through time from the ancient climate state.

These provide quantitative constraints on the initial atmospheric inventory of gases that are needed to determine the evolution of atmospheric composition to its present state. It would require high-precision dating and isotopic measurements of Martian meteorites and returned samples.

GOAL III: DETERMINE THE EVOLUTION OF THE SURFACE AND INTERIOR OF MARS

Insight into the composition, structure, and history of Mars is fundamental to understanding the solar system as a whole, as well as providing insight into the history and processes of our own planet. There are compelling scientific motivations for the study of the surface and interior of the planet in its own right. The geology of Mars sheds light on virtually every aspect of the study of conditions potentially conducive to the origin and persistence of life on that planet, and the study of the interior provides important clues about a wide range of topics, such as geothermal energy, the early environment, and sources of volatiles.

A critical aspect of Mars is the evidence for the presence and activity of liquid water on or near the surface over an extended period of time. This has enormous geological implications affecting, for example, erosion, weathering, heat flow, and the possibility of life (which can, in turn, have significant effects on geological processes).

Objective A.: Determine the nature and evolution of the geologic processes that have created and modified the Martian crust

The Martian crust contains the record of all the processes that shaped it, from initial differentiation and volcanism, to modification by impact, wind, and water. Understanding that record would help us understand the early environment (as reflected, for example, in the alteration mineralogy), the total inventory and role of water, regions likely to have been habitable, processes involved in surface-atmosphere interactions, and the planet's thermal history. Many of the listed investigations are interrelated and could be addressed by common data sets and/or methodologies. In many cases, the reasons for separating some subjects into different investigations have to do with issues of scale (both vertical and lateral) or geologic/geophysical process. For the purposes of Goal III, "regolith" refers to the upper few meters to hundreds of meters of the Martian surface; greater depths are treated as part of the crust.

<u>1. Investigation:</u> Determine the formation and modification processes of the major geologic units and surface regolith as reflected in their primary and alteration mineralogies.

The regolith is a filter through which we view most of the Martian surface by remote sensing. In addition, it may provide a valuable record of the history of surface conditions and processes. Understanding Mars' geologic/environmental history, including regolith formation and modification, requires quantitative measurement of mineralogy and chemistry. Identification of alteration processes requires characterization of both unaltered and altered rock. There have been considerable advances in the understanding of surface mineralogy based on remote sensing and limited in situ observations. Orbital remote sensing with high spatial and spectral resolution has demonstrated the ability to correlate mineralogy with specific geologic units. However, calibration of the orbital data with in situ direct determination of mineralogy is critical, both to ensure the interpretations based on orbital data are correct and to understand those species that either have limited spatial extent or concentration or which cannot be detected in remote observation.

<u>2. Investigation:</u> Evaluate volcanic, fluvial/laucustrine, hydrothermal, and polar erosion and sedimentation processes that modified the Martian landscape over time.

Sediments and sedimentary rocks formed in and near fluvial, laucustrine, or other deposition regimes are the most likely materials to preserve traces of prebiotic compounds and evidence of life. Sediments and sedimentary rocks record the history of aqeuous processes. Aeolian sediments record a combination of globally averaged and locally derived fine-grained sediments and weathering products. Pyroclastic deposits record a style of volcanism that commonly involves interactions with or compositions containing relatively abundant volatiles. Understanding this wide variety of sedimentary processes requires knowledge of the ages, sequences, and mineralogies of sedimentary rocks; as well as the rates, durations, environmental conditions, and mechanics of weathering, cementation, and transport.

<u>3. Investigation:</u> Constrain the absolute ages of major Martian crustal geologic processes, including sedimentation, diagenesis, volcanism/plutonism, regolith formation, hydrothermal alteration, weathering, and the cratering rate.

The evolution of the interior and surface, as well as the possible evolution of life, must be placed in an absolute timescale, which is presently lacking for Mars. Without an understanding of the absolute timing of events, the potential for current geologic/biologic activity remains unknown. Developing this chronology requires determining the absolute ages of crystallization or impact metamorphism of individual units with known crater frequencies. This would allow calibration of Martian cratering rates and interpretations of absolute ages of geologic units. This investigation could be approached with both in situ and returned sample analysis, although with different precision.

<u>4. Investigation:</u> Hydrothermal environments.

Hydrothermal environments provide a potentially unique environmental niche in which life may presently exist, or in which life may have existed in the past. It is also an important indicator of past volcanic and thermal activity. Should life (extant or extinct) be found in such an environment, it would serve as a possible basis for understanding the earliest evolution of life on the Earth. Hydrothermal systems may also play an important role in the chemical and isotopic evolution of the atmosphere and the formation of the regolith, and may record the histories of these events. The search for active hydrothermal systems would require high spatial resolution thermal data; the search for active or past hydrothermal systems might be conducted by searching for high-temperature alteration minerals or those associated with those environments, such as amorphous silica.

<u>5. Investigation:</u> Evaluate igneous processes and their evolution through time.

This investigation includes the broad range of igneous processes such as the mineralogy and petrology of the rocks as well as, for example, volcanic outgassing and volatile evolution. In addition to dramatically shaping the surface of the planet, volcanic processes are the primary mechanism for release of water and atmospheric gasses. Sites of present day volcanism, if any, might be prime sites to investigate. Understanding primary lithologies also is a key to interpreting alteration processes that have produced secondary mineralogies.

6. Investigation: Characterize surface-atmosphere interactions on Mars, as recorded by aeolian, glacial/periglacial, fluvial, chemical and mechanical erosion, cratering and other processes.

The focus of this investigation would be on the processes that have operated within the recent past. Studying surficial features resulting from recent hydrologic, glacial/periglacial, cratering, and atmospheric processes, as well as those associated with chemical and physical erosion, contributes to our understanding of which features may (or may not) indicate possible locations for near-surface water and helps us interpret features formed in past environments. Integrating information about the morphology, chemistry and mineralogy of surface deposits is essential for understanding alteration processes. It would require orbital and surface-based remote sensing of the surface (microns to centimeters) and direct measurements of sediments and atmospheric boundary layer processes.

7. Investigation: Determine the present activity, tectonic history, and large-scale vertical and horizontal structure of the crust. This includes, for example, the structure and origin of hemispheric dichotomy.

Understanding the natural seismicity, tectonic record, and the structures within the crust over large vertical and horizontal scales is crucial for understanding the geologic history as well as the temporal evolution of internal processes. This, in turn, places constraints on release of volatiles from differentiation and volcanic activity and the effect of tectonic structures (faults and fractures in particular) on subsurface hydrology. Determining these structures would require gravity data, deep subsurface sounding (100s of meters to kilometers), detailed geologic and topographic mapping (including impact mapping/studies), and determination of the compositions of major geologic units. Because the present level of seismicity on Mars is essentially unknown, a single, well-coupled seismic station would be of great value as a "pathfinder" for a full network, providing distance to and level of seismicity, and character of seismic signals and noise in this unexplored environment. The accurate localization of marsquakes in space and time provided by a long-term, continuously active seismic network composed of multiple stations would be required to fully understand the distribution and intensity of current tectonic activity.

8. Investigation: Determine the present state, 3-dimensional distribution, and cycling of water on Mars including the cryosphere and possible deep aquifers.

Water is an important geologic agent on Mars, influencing most geological processes including the formation of sedimentary, igneous and metamorphic rocks, the weathering of geological materials, and deformation of the lithosphere. Determining the distribution of water in its various phases and in different locations would require global observations using various types of subsurface sounding techniques and remote sensing, coupled with detailed local and regional sounding and measurements.

9. Investigation: Determine the nature of crustal magnetization and its origin.

The magnetization of the Martian crust is only poorly understood from Mars Global Surveyor magnetometer data, but is intimately related to the geothermal history of the planet. Addressing this problem would require high-resolution (spatial and field strength) mapping of the magnetic field and determining of the crustal mineralogy (particularly the magnetic carries), geothermal gradient, and magnetization of geologic units.

10. Investigation: Evaluate the effect of large-scale impacts on the evolution of the Martian crust.

Impacts are one of the most important of the processes shaping the crust and surface of Mars. A detailed understanding of effects of impact events (e.g., those producing quasi-circular depressions and basins) on the structural, topographic and thermal history of Mars is a prerequisite for any broad understanding of the history of the crust and lithosphere. Understanding impact effects would require geologic mapping using global topographic data combined with high-resolution images and remote sensing data.

Objective B.: Characterize the structure, composition, dynamics, and evolution of Mars' interior.

Investigating the internal dynamics and structure of Mars would contribute to understanding the bulk chemical composition of the planet, the evolution of its crust, mantle, and core, its thermal evolution, the origin of its magnetic field, and the nature and origin of the geologic units. These are fundamental aspects of Mars that form the basis of comparative planetology.

1. Investigation: Characterize the structure and dynamics of the interior.

Understanding the structure and dynamical processes of the mantle and core is fundamental to understanding the origin and evolution of Mars, its surface evolution, and the release of water and atmospheric gases. For example, the thickness of the crust and the size of the core provide strong constraints on the bulk composition of the planet, its thermal history, and the manner in which it differentiated. This investigation requires seismology (e.g., passive and active experiments and understanding of the seismic state of the planet), heat flow, gravity data, precision tracking for rotational dynamics, and electromagnetic sounding. Because accurate localization of seismic activity is necessary to fully address all objectives, at least four stations operating simultaneously for a full Mars year are required. However, progress in this investigation could be made with a single station. There are a number of techniques available for using single-station seismic, heat flow, and precision tracking data to obtain key information on interior structure and processes. Interpretation of such data depends on models and assumptions, and the results would be biased toward a single region of the planet. But given the nearly complete lack of data on the Martian interior, results from a single station would represent a significant advance.

2. Investigation: Determine the origin and history of the magnetic field.

Evidence that Mars had a magnetic field early in its history has important implications for its formation and early evolution, as well as for the retention of an early atmosphere and for the shielding of the surface from incoming radiation. The collection of high-precision, high-resolution global, regional, and local magnetic measurements, calibration of the ages of surfaces, and measurements of the magnetic properties of samples would now be required.

3. Investigation: Determine the chemical and thermal evolution of the planet.

Knowledge of the chemical and thermal evolution places constraints on the composition, quantity, and rate of release of volatiles (water and atmospheric gasses) to the surface. This investigation would require measurements of the internal structure, thermal state, surface composition and mineralogy, and geologic relationships. These data could be obtained through analysis of the seismic velocity profile, heat flow measurements, and study of the mineralogy and geochemistry of xenoliths in volcanic and plutonic rocks.

Objective C.: Understand the origin, evolution, composition and structure of Phobos and Deimos.

1. Investigation: Determine the origin of Phobos and Deimos.

These two satellites may represent captured asteroids, pieces of the Martian crust ejected during large basin formation, or residual accretionary debris. Understanding their origin would allow an understanding of the extent to which they represent pieces of Mars.

2. Investigation: Determine the composition of Phobos and Deimos.

Understanding the chemical and mineralogic composition of the satellites will would provide insight into their origin. Analysis of surface materials might also indicate whether the satellites preserve materials ejected from the surface of Mars. Such analyses would also shed light on processes of space weathering in the Martian environment. Understanding the pristine chemistry and mineralogy would require analysis of material unaffected by space weathering; this, in turn, would require the collection and analysis of subsurface materials.

3. Investigation: Understand the internal structure of Phobos and Deimos.

Determining the internal structure of these bodies would provide information on their origin, formation and evolution. They might be rubble piles or rocks bodies with a surface regolith. Determining their internal structure would require an active seismic experiment as they are unlikely to exhibit endogenic seismic activity.

GOAL IV: PREPARE FOR HUMAN EXPLORATION

Introduction

Goal IV refers to the use of robotic flight missions (to Mars) to prepare for the first potential human missions (or set of missions) to Mars. Robotic missions serve as logical precursors to eventual human exploration of space. In the same way that the Lunar Orbiters, Ranger and Surveyor landers paved the way for the Apollo Moon landings, a series of robotic Mars Exploration Program missions is charting the course for potential future robotic-assisted human exploration of Mars.

It is obvious that preparing for the human exploration of Mars would involve precursor activities in several venues, including on Earth (e.g., in laboratories, in computers, and in field analogs), in low Earth orbit (including the International Space Station), and probably on nearby celestial objects such as the Moon and asteroids. Although all are important, the scope of this document is limited to precursor activity related to the Mars flight program. Connectivity between all of these precursor activities needs to be maintained separately.

History of Goal IV Revisions

This 2013 revision is based on analysis conducted by the joint MEPAG-SBAG (Small Bodies Assessment Group) Precursor Strategy Analysis Group (P-SAG 2012). The P-SAG was chartered to update and prioritize what measurements are needed before the first human missions to the Martian system (as described in DRA 5.0). The P-SAG was also asked to consider implementation options and priorities as well as technology needs (which are not appropriate for inclusion in the MEPAG Goals document). The P-SAG report provides additional measurement details beyond those described here.

- Note that the P-SAG measurements relevant to human missions to Phobos/Deimos are not described here. Check the SBAG website for details (http://www.lpi.usra.edu/sbag/).

The 2010 revision of Goal IV was based on analysis conducted over a period of about four months between 2009-2010 by a committee lead by Lim et al. (see Goal IV text in the 2010 version of the Goals document). It considered both (1) new scientific and exploration data about Mars and (2) planning information related to the Design Reference Architecture (DRA) 5.0 document (Drake, 2009), released in late 2009. A considerable number of experts were consulted in the process of revising recommended investigations and priorities.

- Objective A, which is organized into a prioritized list of investigations, was updated. This structure is parallel to that of the objectives in Goals I, II, and III.
- Former Objective B was removed because it was inconsistent with the overall structure and purpose of the MEPAG Goals Document.
- Former Objective C, which relates to a set of atmospheric measurements, was merged with Investigation IVA. There was previously an unnecessarily high degree of overlap between the two.

A major revision of Goal IV was completed in 2005 (following the 2004 National Vision for Space Exploration and subsequent planning activities). The revision effort included the formation of two parallel MEPAG study teams, Beaty et al., 2005 and Hinners et al., 2005. Each prepared reports that became the foundations for Goal IV Objective A (a prioritized listing of the investigations and measurements necessary to safely and effectively carry out the first human mission to Mars), and Goal IV Objective B (a roadmap that demonstrated the technologies on the critical path to the first human mission), respectively. Established more recently, Objective C (critical atmospheric measurements that would reduce mission risk and enhance overall science return) was derived from an objective that was originally part of Goal II, but which seemed better suited for inclusion under the purview of Goal IV.

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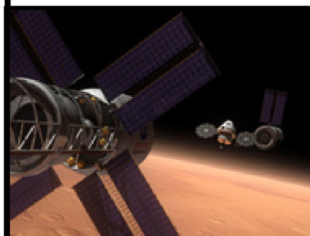
Committee on Precursor Measurements Necessary to Support Human Operations on the Surface of Mars (2002), Safe on Mars Precursor Measurements Necessary to Support Human Operations on the Martian Surface, NATIONAL ACADEMY PRESS, Washington, D.C.

P-SAG (2012) Analysis of Strategic Knowledge Gaps Associated with Potential Human Missions to the Martian System: Final report of the Precursor Strategy Analysis Group (P-SAG), D.W. Beaty and M.H. Carr (co-chairs) + 25 co-authors, sponsored by MEPAG/SBAG, 72 pp., posted July 2012, by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.jpl.nasa.gov/reports/.

Timing and Priorities

The P-SAG (2012) was asked to consider preparation for all potential human missions to the martian system, including missions to Mars orbit, Phobos and/or Deimos, and the Martian surface (Figure IV-1 and Table IV-2).

Figure IV-1: Types of human missions to the Martian system. The missions appear in time sequence from left to right. Note that the Goal IV- and Goal IV– P/D missions are optional.

Goal IV-	Goal IV- P/D	Goal IV	Goal IV+
			
Human missions to Mars orbit as a precursor to Mars surface missions (optional).	Human missions to Phobos and/or Deimos as a precursor to Mars surface missions (optional).	Human missions to the Martian surface.	Sustained human presence on Mars. Follows Mars surface missions.

Human missions to Phobos and/or Deimos are not described in this document; these are the purview of the Small Bodies Analysis Group (SBAG).

Goal IV, human missions to the Martian surface, was divided into 2 phases to aid in the setting of priorities. "Goal IV Early" consists of the information needed to define the overall mission architecture[9] for the mission or set of missions to the Martian surface. "Goal IV Late" consists of information needed to actually design systems to get to and operate on the Martian surface.

The criteria used to set priorities within the P-SAG report were based on the ability of each Gap-filling activity (GFA) to address the issues related to increasing safety, decreasing cost, and increasing the performance of human missions to Mars. The criteria are listed in Table IV-1.

Table IV-1: Prioritization criteria used by P-SAG (2012).

Priority	Definition
High	Recognized as enabling a critical need or mitigating high risk items
Medium	Enables important but not critical need or mitigates moderate risk items

[9] "Architecture" as used here means defining at a high level how the missions will be structured. For example, as a mission to the Martian surface go into Mars orbit 1st or does it enter directly into the Martian atmosphere are on approach? Do we get into Mars orbit propulsively or using a combination of propulsion and aerocapture? Note these kinds of questions need to be answered before we can design the systems we will use on the missions. This is one reason why Goal IV Early is higher priority than Goal IV Late.

Low	Enhances mission or mitigates lower risk items

Table IV-2 Partial listing of P-SAG Strategic Knowledge Gaps and Gap-filling Activities. This table focuses on the Gap-filling Activities (GFAs, equivalent to measurements) to be performed at Mars from P-SAG (2012). See the full P-SAG report and associated matrix for details, including technology demonstrations and investigations not needing Mars flight opportunities, at http://mepag.jpl.nasa.gov/reports/.

Investi-gation	Priority	SKG	Gap filling activity (GFA)
1A	Highest	A1. Upper Atmosphere	A1-1. Global temperature field.
1A	Highest		A1-2. Global aerosol profiles and properties
1A	High		A1-3. Global winds and wind profiles
3A	Medium	A3. Orbital Particulates	A3-1. Orbital particulate environment
1A	High	B1. Lower Atmosphere	B1-1. Dust Climatology
1A	Highest		B1-2. Global surface pressure; local weather
1A	High		B1-3. Surface winds
1A	Medium		B1-4. EDL profiles
4A	Low		B1-5. Atmospheric Electricity conditions
1B	Highest	B2. Back Contamination	B2-1. Biohazards
3B	Medium	B3. Crew Health & Performance	B3-1. Neutrons with directionality
3B	Medium		B3-2. Simultaneous spectra of solar energetic particles in space and in the surface.
3B	Medium		B3-4. Spectra of galactic cosmic rays on surface.
3C	Medium		B3-5. Toxicity of dust to crew
4A	Low	B4. Dust Effects on Surface Systems	B4-1. Electricity
2A	High		B4-2. Dust physical, chemical and electrical properties
3D	Medium		B4-3. Regolith physical properties and structure
1B 2B	High	B5. Forward Contamination	B5-1. Identify and map special regions
2A	High	B6. Atmospheric ISRU	B6-1. Dust physical, chemical and electrical properties
2A	Low		B6-2. Dust column abundances
4B	Low		B6-3. Trace gas abundances
3D	Medium	B7. Landing Site and Hazards	B7-1. Regolith physical properties and structure
3E	Medium		B7-2. Landing site selection
3E	Low		B7-3. Trafficability
5	High	D1. Water Resources	D1-3. Hydrated mineral compositions
5	High		D1-4. Hydrated mineral occurrences
5	Medium		D1-5. Shallow water ice composition and properties
5	Medium		D1-6. Shallow water ice occurrences

The human mission types were assumed to follow a defined order, with missions to Mars orbit or Phobos/Deimos optionally happening before missions to the Martian surface. Sustained human presence was assumed to happen long after the first missions to the Martian surface. Therefore, in setting the priorities in this document, timing also was considered (in addition to the P-SAG priorities) to set the 5 priority levels of Investigations used in this section of this document. Table IV–3 shows the mapping of the P-SAG priorities and timing into the priorities in this document. GFAs needed earlier occur at higher priority than those needed later. All of the items related to Goal IV+ occur at priority 5 due to the late nature of the need for this information.

Table IV-3: Investigation priority levels mapped to Timing and Priority for individual Gap-filling Activities. The numbers in the table relate to the 5 Investigations in Objective A, which follows.

Priority: / Timing	High	Medium	Low
IV-	1	3	4
IV Early	1	3	4
IV Late	2	3	4
IV+	5	5	5

Note that in this document assignment of a specific “Investigation” to a priority level is based on the highest priority Gap-Filling Activity within that Investigation. No attempt was made to order investigations within each priority level; for instance, Investigations 1A and 1B are judged to be of indistinguishable highest priority.

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

<u>1A. Investigation</u>: Determine the aspects of the atmospheric state that affect aerocapture, Entry Design and Landing (EDL) and launch from the surface of Mars. This includes the variability on diurnal, seasonal and inter-annual scales from ground to >80 km in both ambient and various dust storm conditions. The observations are to directly support engineering design and also to assist in numerical model validation, especially the confidence level of the tail of dispersions (>99%).

Atmospheric precursor data requested in Investigation 1A would reduce the risk of loss of crew and loss of mission primarily by reducing the risk during EDL. This data would also reduce the risk during aerocapture and launch from Mars. The level of acceptable risk is much lower for manned missions than robotic landers and significant additional atmospheric measurements would be required to support the engineering design and modeling fidelity necessary to reduce the risk. Thus the Investigation 1A observations would be mission-enabling. The combination of mission-enabling observations and a reduction in the risk of loss of crew yields a high priority for the investigation.

The measurements listed in Investigation 1A are designed to fulfill the needs of the consulted EDL engineers; in particular, those working on design studies for human class (~40t) landing systems for Mars. The observations are designed to both directly support engineering studies and to validate atmospheric numerical models. The latter are essential to help characterize the potential dispersion of parameters. Existing recent observations fulfill some of the measurement requirements, but are currently insufficient to provide the necessary fidelity for the engineering modeling. The current orbital record is not yet long enough and fails to provide good coverage at a range of local times. The surface observations are both too short and only exist at four locations.

The global nature of the measurements (spatially and temporally) is driven by two factors. First, global coverage avoids having to limit site selection due to lack of observations. Local time coverage may allow access to sites otherwise deemed dangerous when conditions are safe. Secondly, it provides context for weather prediction during critical events. Atmospheric temperatures (measurements “a” and “f” below) would provide the density information necessary to determine entry trajectories, atmospheric heating, and deceleration rates. The aerosol information (measurement “b” below) is primarily necessary to understand and model the performance of guidance systems (especially optical systems). Surface pressure (measurement “c” below) directly controls the total atmospheric mass and thus the altitude of critical events during EDL. The dust activity climatology (measurement “d” below) is primarily designed to understand the statistical frequency of events and their expected durations (to determine the necessary margins for waiting them out in orbit or on the surface). A better understanding of winds (measurement “e” below) would help allow pinpoint landing of surface systems.

Assumptions:

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 that would 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 instrumenting entry vehicles would be required.

Priority	GFA	Gap-Filling Activity needed measurements
Highest	A1-1	a. Make long-term (> 5 Martian year) observations of the global atmospheric temperature field (both the climatology and the weather variability) at all local times from the surface to an altitude >80 km. The global coverage would need observations with a vertical resolution ≤ 5 km as well as observations with a horizontal resolution of ≤ 10 km (the horizontal and vertical resolutions do not need to be met by the same observation).
Highest	A1-2	b. Make global measurements of the vertical profile of aerosols (dust and water ice) at all local times between the surface and >60 km with a vertical resolution ≤ 5 km. These observations should include the optical properties, particle sizes and number densities.
Highest	B1-2	c. Monitor surface pressure in diverse locales over multiple Martian years to characterize the seasonal cycle, the diurnal cycle (including tidal phenomena) and to quantify the weather perturbations (especially due to dust storms). The selected locations are designed to validate global model extrapolations of surface pressure. The measurements would need to be continuous with a full diurnal sampling rate > 0.01 Hz and a precision of 10^{-2} Pa. Surface meteorological packages (including temperature, surface winds and relative humidity) and upward looking remote sounding instruments (high vertical resolution temperature and aerosol profiles below ~10 km) would be necessary to validate model boundary schemes.
High	B1-1	d. Globally monitor the dust and aerosol activity, especially large dust events, to create a long term dust activity climatology (> 10 Martian years).
High	A1-3 B1-3	e. Make long-term (> 5 Martian year) observations of global winds and wind direction with a precision ≤ 3 m/s at all local times from 15 km to an altitude > 60 km. The global coverage would need observations with a vertical resolution of ≤ 5 km and a horizontal resolution of ≤ 300 km. Simultaneous with the global wind observations, profile the near-surface winds (< 15 km) with a precision ≤ 2 m/s in representative regions (plains, up/down windo of topography, canyons). The boundary layer winds would need a vertical resolution of ≤ 1 km and a horizontal resolution of ≤ 100 m. The surface winds would be needed on an hourly basis throughout the diurnal cycle. During the daytime (when there is a strongly convective mixed layer), high frequency wind sampling would be necessary.
Medium	B1-4	f. Occasional temperature or density profiles with vertical resolutions < 1 km between the surface and 20 km are also necessary.

<u>1B. Investigation</u>: Determine if the Martian environments to be contacted by humans are free, to within acceptable risk standards, of biohazards that might have adverse effects on the crew that might be directly exposed while on Mars, and on other terrestrial species if uncontained Martian material would be returned to Earth. Note that determining that a landing site and associated operational scenario would be sufficiently safe is not the same as proving that life does not exist anywhere on Mars.

The measurements described in Investigation 1B would aid in reducing risks associated with back planetary protection to acceptable, as-yet undefined, standards as they pertain to: 1) the human flight crew, 2) the general public, and 3) terrestrial species in general. The risks in question relate to the return of uncontained Martian material, such as regolith and dust, that would certainly be on the outside of the ascent vehicle, within the cabin, or even within the astronauts' bodies when the crew leaves Mars. As shown by our experience with Apollo, when the crews open the seals to their landed systems to carry out EVA explorations, it is impossible to avoid getting dust on the outsides of the spacesuits as well as into the living quarters. For robotic sample return missions, a step called "breaking the chain of contact" is necessary to avoid these kinds of problems, but for a crewed mission, this prevention currently is not thought to be possible. Because it would not be possible to prevent human contact with the dust, it is necessary to determine in advance whether or not that dust is biologically hazardous. The action of returning the astronauts to Earth at the end of the mission, along with any associated uncontained Martian material, could pose a low but as-yet undefined risk to the Earth's ecosystem. For this reason, the impact of the data from this investigation on mission design has been rated high (mission enabling) and the impact of the data on risk reduction has also been rated high (public safety), for a combined priority rating of high.

Priority	GFA	Gap-Filling Activity needed measurements
Highest	B2-1	a. Determine if extant life is widely present in the Martian near-surface regolith, and if the air-borne dust is a mechanism for its transport. If life is present, assess whether it is a biohazard. For both assessments, a preliminary description of the required measurements is described in the MSR Draft Test Protocol (Rummel et al., 2002). This test protocol would need to be regularly updated in the future in response to instrumentation advances and a better understandings of Mars and of life itself.
High	B5-1	b. Determine the distribution of Martian special regions (see also Investigation IV-2B below), as these may be "oases" for Martian life. If there is a desire for a human mission to approach one of these potential oases, either the mission would need to be designed with special protections, or the potential hazard would need to be assessed in advance.

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<u>2A. Investigation</u>: Characterize the particulates that could be transported to hardware and infrastructure through the air (including natural aeolian dust and other materials 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 would be required.

Mars is a dry, dusty place. Past experience with surface operations on the Moon illuminated that that it would be difficult, if not impossible, to prevent dust from getting into different parts of a landed system on Mars. On the Moon, there were three primary anthropogenic dust-raising mechanisms (ranked according to increased importance): astronaut walking, rover wheels spinning up dust, and landing and takeoff of spacecraft. On Mars, there are also winds, which are capable of raising and transporting dust.

We need to understand the potential impacts of dust on the surface system. There are at least three potential deleterious effects that need to be understood: 1) effects of dust on seals, especially seals that need to be opened and then reestablished, 2) effect of dust on the electrical properties of the surfaces on which it would accumulate (for example, the effect of dust on circuit boards), and 3) the corrosive chemical effects of Martian dust on different kinds of materials. Note that for the purpose of this investigation, we distinguish between the direct effects of Martian dust on human beings (Investigation #3C below) and the effect of dust on the engineering system that would keep the humans on Mars alive and productive. Significant data about dust properties, dust accumulation rates, and effects on mechanical surface systems on Mars have been obtained from MER (Opportunity and Spirit) and Phoenix, thus the impact of additional measurements of these properties are now ranked lower than in previous versions of this document. However, additional measurements of these properties at other sites would help to understand the range of conditions expected and might still have an impact on mission design.

This investigation requires collecting enough data about the Martian dust to be able to create a large quantity of a Martian dust simulant that could be used in engineering laboratories on Earth. These data would be best obtained by analysis of a returned sample.

Priority	GFA	Gap-Filling Activity needed measurements
High	B4-2 B6-1	a. A complete analysis of regolith and surface aeolian fines (dust), consisting of shape and size distribution, density, shear strength, ice content and composition, mineralogy, electrical and thermal conductivity, triboelectric and photoemission properties, and chemistry (especially chemistry of relevance to predicting corrosion effects), of samples of regolith from a depth as large as might be affected by human surface operations.
Low	B4-2 B6-1	b. Repeat the above measurements at a second site in different geologic terrain. Note this is not seen as a mandatory investigation/measurement.
Low	B6-2	c. Determine the column abundance and size-frequency distribution, resolved at less than scale height, of dust particles in the Martian atmosphere.

<u>2B. Investigation</u>: Determine the Martian environmental niches that meet the definition (as defined by COSPAR) of "Special Region.[10]" It is necessary to consider both naturally occurring special regions and those that might be induced by the (human-related) missions envisioned. Evaluate the vulnerability of any special regions identified to terrestrial biological contamination, and the rates and scales of the Martian processes that would allow for the potential transport of viable terrestrial organisms to these special regions.

The measurements described in this investigation relate to characterizing "Special Regions" on the Martian surface, either extant or possibly induced by a human mission. One of the major mission objectives of the proposed human mission would be to determine if and how life arose naturally on Mars. Therefore, data that contributes to the understanding of the location of extant Special Regions where Martian life could exist is considered of the highest priority (mission enabling). This mission objective could be compromised, however, by inducing a Special Region through the engineering aspects and biological inputs innate to a human mission. Evaluating the extent of this potential compromise would require data from the measurements described below.

Priority	GFA	Gap-Filling Activity needed measurements
High	B5-1	a. Map the distribution of naturally occurring surface special regions as defined by COSPAR[5]. One key investigation strategy is change detection.

<u>3A. Investigation:</u> Determine the orbital particulate environment in high Mars orbit that may impact the delivery of cargo and crew to the Martian system.

There may be a dust ring between Phobos and Deimos located in and around the equatorial plane of Mars. Knowledge of the presence of these particulates and their size frequency distribution would help mission architecture planning and engineering designs for cargo and human missions to Mars orbit.

Priority	GFA	Gap-Filling Activity needed measurements
Medium	A3-1	a. Spatial variation in size-frequency distribution of Phobos/Deimos ejecta particles in Mars orbit

<u>3B. Investigation:</u> 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.

Risks to astronauts from radiation in space have been characterized for decades. Outside the protection of Earth's magnetic field and atmosphere, the ever-present flux of galactic cosmic rays (GCRs) poses a long-term cancer risk. The particle energies in GCRs are so powerful that

[10] A Special Region is defined as "a region within which terrestrial organisms are likely to propagate, or a region which is interpreted to have a high potential for the existence of extant Martian life. As of 2010, no Special Regions had definitively been identified, however as of this writing, HiRISE has only covered 1% of the Martian surface. It is presumed that the policy of protecting special regions from terrestrial contamination would continue into the era of human exploration.

using shielding mechanisms as a mitigation would be possible but impractical in most situations. Superimposed on the continual GCR background are solar energetic particles (SEPs), generated episodically by a component of solar activity known as coronal mass ejections (CMEs). SEPs are composed primarily of protons, generally lower in energy than GCRs, and possess much higher number fluxes. An individual SEP event could be fatal to a crewmember if a crewmember is caught unprotected. Given the energy distribution and fluxes of typical SEP events, the use of shielding to mitigate their impact is feasible but shielded areas might be limited in size due to mass constraints. Hence, avoiding SEP exposures would rely primarily on gaining an understanding of space weather, with predictive and monitoring capabilities for CMEs and the SEPs that commonly accompany them. By having such knowledge, precautionary measures and appropriate actions could be taken.

The central issue with radiation exposure on Mars involves validating radiation transport codes and other tools designed to simulate and predict the biological relevancy of being exposed to radiation on Martian surface by taking into account all of the major variables. On Earth, the relatively thick Earth atmosphere combined with a sizeable, global magnetic field effectively shields humanity from the direct exposure to SEP events and substantially reduces GCR fluxes. Conversely, the Martian atmosphere is geometrically thinner and of lower density than Earth's, and lacks adequate global, intrinsic magnetic field, thus posing a higher risk to radiation exposure.

As energetic particles dissipate energy into the Martian atmosphere and regolith, they would also produce a host of secondary particles. These include neutrons, which can be highly biologically effective and therefore contribute a significant share of the dose equivalent. Radiation dose is expected to vary not only with solar activity and GCR levels, but also with topography and regolith composition. Although GCR energies cause the majority of these particles to pass through the atmosphere, many SEP events most likely deposit the bulk of their energy towards the atmosphere with a significant production of biologically relevant secondaries. Of these, the efficiency for the production of secondary neutrons is currently uncertain. Thus, GCRs and SEPs are fairly distinct in terms of the physics of their interaction with the atmosphere. During future missions, SEP intensities would most likely be forecasted and detected from the vantage point of space or Earth. Models and tools must account for the details of SEP energy deposition into the atmosphere to assess the impact of these events on the surface of Mars. Hence, successful development of these tools would require simultaneous, accurate measurements of the radiation field both above the atmosphere and on the surface, such that the inputs and resulting outputs of the model system are fully constrained.

MSL is carrying the Radiation Assessment Detector (RAD), designed to assess radiation hazards from both neutrons and energetic charged particles on the surface of Mars. MSL will provide ground-truth measurements of the radiation environment on the surface of Mars, for both GCR and the SEP events, which it will observe over the course of the MSL mission (nominally 2 Earth years). These measurements will be useful in providing necessary boundary conditions to constrain radiation exposure models primarily for GCRs, whose input flux, energy spectra, and variations are approximately uniform over much of the length of the solar system, but have never been measured on the Martian surface. MSL will also characterize the contribution to the surface radiation environment of the SEP events that it samples; however, due to the highly variable spectral, spatial, and temporal properties of SEPs, the properties of the radiation input at the top of the atmosphere will be far less well understood. Thus measurements on MSL will likely satisfy the listed measurement goals “a” and “b” below for GCRs only. The impact of SEPs will not be fully characterized by MSL, either due to solar variability (few or no significant CMEs during the mission) or more importantly, a lack of an orbital reference to compare the measured inputs and outputs from the Martian atmosphere (measurement goal “c” below).

Priority	GFA	Gap-Filling Activity needed measurements
Medium	B3-4	a. Identification of charged particles at the surface from hydrogen to iron and measure particle energies from 10 MeV/nuc to 400 MeV/nuc along with LET measurement during solar min.
Medium	B3-1	b. Measurement of neutrons with directionality. Energy range from $\leq$10 keV to $\geq$100 MeV.
Medium	B3-2	c. Simultaneous with surface measurements, a detector should be placed in orbit to measure energy spectra in solar energetic particle events.

3C. Investigation: Determine the possible toxic effects of Martian dust on humans.

A discussion about the importance of the potential toxic effects of Martian surface materials is detailed in the NRC report, “Safe on Mars” (2002), by the Committee on Precursor Measurements Necessary to Support Human Operations on the Surface of Mars. They considered the presence and distribution of Cr(VI), commonly called “hexavalent cromium,” especially important to understand because it is a strong human carcinogen. None of the past missions to Mars have carried instrumentation capable of measuring this species. Also discussed in the report are other potential cancer-causing compounds, many of which are still of concern due to lack of sufficient data. Potential chronic effects like lung injury in the form of silicosis must also be studied in greater detail, preferably with a returned sample. Collection of data related to the measurements listed above was considered of highest priority from a risk perspective because the risk of insufficient data connects directly to the probability of loss of crew. In terms of impact on design, it was of comparatively less importance given the fact that EVA systems, as well as dust mitigation protocols and design features, would already be significant, driven by other environmental challenges and forward and back contamination protocols.

Priority	GFA	Gap-Filling Activity needed measurements
Medium	B3-5	a. Assay for chemicals with known toxic effect on humans. Of particular importance are oxidizing species (e.g., Cr(VI)) associated with dust-sized particles. Might require a sample returned to Earth as previous assays have not been conclusive enough to retire risk.
Medium	B3-5	b. Fully characterize soluble ion distributions, reactions that occur upon humidification and released volatiles from a surface sample and sample of regolith of similar depth might be affected by human surface operations. Previous robotic assays (Phoenix) have not been conclusive enough to significantly mitigate this risk.
Medium	B3-5	c. Analyze the shapes of Martian dust grains with a grain size distribution (1 to 500 microns) sufficient to assess their possible impact on human soft tissue (especially eyes and lungs).

<u>3D. Investigation</u>: Characterize the properties of the Martian regolith sufficiently to design systems that will land, work properly, and survive on the Martian surface. Analytic fidelity sufficient to establish credible engineering simulation labs and/or performance prediction/design codes on Earth would be required.

Landing and working on Mars means interacting with the Martian surface, which is mostly regolith. Therefore it is important to understand the properties of the Martian regolith in order to design and operate systems on Mars. The main interactions include landing, roving, and siting habitats and other facilities. In addition, it may be desirable to excavate regolith materials, both to establish foundations for facilities and as an in situ resource.

Landing on Mars with human-scale systems will likely include rocket propulsion to slow the vehicle down for landing. Blast ejecta from descent engines could exceed the bearing capacity of soils, as demonstrated on the Phoenix and MSL missions. This can lead to excavation of holes under the landers as well as the ejection of materials that potentially damage other systems at the landing site.

Both landing and the construction of habitats and other facilities will require a surface with sufficient bearing strength to handle the load placed on the surface. In addition, excavation to establish foundations or to provide protection from the surface environment by, for example, burying habitats beneath the regolith to provide protection from radiation, will require understanding subsurface structure of the regolith in order to design and operate systems capable of excavating and using the regolith materials.

The regolith is also a potential resource. In bulk form it could be used to cover habitats as radiation shielding. It could also be used has a source material for extraction of water or other useful materials.

Priority	GFA	Gap-Filling Activity needed measurements
Medium	B7-1	a. Regolith physical properties and structure, including surface bearing strength; presence of significant heterogeneities or subsurface features of layering; and an index of shear strength.
Medium	B4-3 B7-1	b. Regolith particle shape and size distribution, as well as Flow Rate Index test or other standard flow index measurement on the regolith materials.
Medium	B7-1	c. Gas permeability of the regolith in the range 1 to 300 Darcy with a factor of three accuracy.
Medium	B4-3 B7-1	d. Determine the chemistry and mineralogy of the regolith, including ice contents.

<u>3E. Investigation</u>: Assess landing site-related hazards, including those related both to safe landing and safe operations within the possible area to be accessed by elements of a human mission.

A successful human surface mission would need to land safely at a site of significant scientific interest, and in terrain that would allow the astronauts to move about the site as part of their exploration activity. We know from experience with site selection for past robotic landers/rovers that sites with some of the most interesting scientific attributes also tend to have more difficult and risky terrain. Correctly understanding the trade-off between landing site hazards and expected scientific return for a crewed mission would be fundamental to realizing the full potential of sending humans to Mars. Landing site-related hazards can be grouped into two categories: 1) hazards related to landing safely, and 2) hazards related to the various movements at the Martian surface needed to achieve a mission's objectives. Hazards in both areas would be capable of causing mission-ending failures. In the case of safe landing, we know from experience with prior Mars landers that the following four factors are particularly relevant: the size and concentration of surface rocks, terrain slopes, and the concentration of dust. The specific safety thresholds for these parameters would depend on the specific design of the mission (for example, ground clearance provided by landing legs), but we know from prior experience that these factors have to be considered carefully for all landed missions at Mars.

In order for landed human missions to achieve their objectives, movement across the Martian surface would be required. This might manifest itself in establishing and maintaining necessary surface infrastructure, or in accessing specific scientific targets. Thus, trafficability hazards need to be considered. In the case of MER, both Spirit and Opportunity became embedded in soft soil while driving. Opportunity was able to extricate itself and continue driving, but Spirit was not. Other trafficability hazards include rock fields and steep slopes. Although the operation of the MER rovers has significantly improved our general understanding of the issues related to trafficability on the Martian surface, such assessements would need to be made on a site-by-site basis given the range of mobile elements associated with a human mission.

Priority	**GFA**	**Gap-Filling Activity needed measurements**
Medium	B7-2	a. Imaging of selected potential landing sites to sufficient resolution to detect and characterize hazards to both landing and trafficability at the scale of the relevant landed systems.
Low	B7-3	b. Determine traction/cohesion in Martian regolith throughout planned landing sites; where possible, feed findings into surface asset design requirements.
Low	B7-3	c. Determine vertical variation of *in situ* regolith density within the upper 30 cm for rocky areas, on dust dunes, and in dust pockets to within 0.1 g cm^3.

<u>4A. Investigation</u>: Assess atmospheric electricity conditions that might affect Mars Take-off, Ascent, and Orbit-Insertion (MTAO) and human occupation.

Atmospheric electricity has posed a hazard to aircraft and space launch systems on Earth, and might pose similar danger on Mars. One notable incident was the lightning strike that hit the Apollo 12 mission during the ascent phase, causing the flight computer in the spacecraft to reset. Far from a random event, the strike was likely triggered by the presence of the vehicle itself, combined with its electrically conducted exhaust plume that provided a low resistance path to the ground. Future explorers on Mars might face similar risks during MTAO after the completion of their mission due to charge suspended in the atmosphere by local, regional or global dust activity. The amount of charge contained in these events, their spatial and temporal variations, and discharge mechanisms remain largely unknown. Surface measurements of electrodynamic phenomena within the atmosphere (i.e., below the ionosphere) could reveal whether or not charge buildup is sufficient for large scale discharges, such as those that affected Apollo 12.

Electrified dust and discharge processes might also represent a hazard during surface operations, which might effect everything from static-discharge sensitive equipment to communications. Unknown frictional charging interactions ("triboelectricity") between EVA suits, rovers, and habitats might also come into play. Understanding the ground and atmospheric conductivity, combined with the electrical properties of dust, would help to constrain the magnitude of these risks.

Priority	GFA	Gap-Filling Activity needed measurements
Low	B1-5 B4-1	a. Measure the magnitude and dynamics of any quasi-DC electric fields that may be present in the atmosphere as a result of dust transport or other processes, with a dynamic range of 5 V/m-80 kV/m, with a resolution ΔV=1V, over a bandwidth of DC-10 Hz (measurement rate = 20 Hz)
Low	B1-5 B4-1	b. Determine if higher frequency (AC) electric fields are present between the surface and the ionosphere, over a dynamic range of 10 uV/m – 10 V/m, over the frequency band 10 Hz-200 MHz. Power levels in this band should be measured at a minimum rate of 20 Hz and also include time domain sampling capability.
Low	B1-5 B4-1	c. Determine the electrical conductivity of the Martian atmosphere, covering a range of at least 10^{-15} to 10^{-10} S/m, at a resolution ΔS= 10% of the local ambient value.
Low	B4-1	d. Determine the electrical conductivity of the ground, measuring at least 10^{-13} S/m or more, at a resolution ΔS of 10% of the local ambient value
Low	B1-5 B4-1	e. Determine the charge on individual dust grains equal to a value of 10^{-17} C or greater, for grains with a radius between 1-100 μm
Low	B1-5	f. Combine the characterization of atmospheric electricity with surface meteorological and dust measurements to correlate electric forces and their causative meteorological source for more than 1 Martian year, both in dust devils and large dust storms

4B. Investigation: Understand trace gas abundances and their potential to interfere with atmospheric ISRU processing.

The resources to support a human stay at the Martian surface would be C, O, and H for both life support and ascent propellant (see DRA 5.0). Key trades include quantifying the mass, power, and risk associated with the equipment necessary to acquire and process these three commodities from Martian resources compared to the mass, power, and risk of simply delivering them from Earth. One of the outcomes of the DRA 5.0 analysis was that in the case of C and O, the chemical pathways and processing equipment required to obtain these commodities from the Martian CO_2 atmosphere were so well understood and mechanically simple that it became logical to plan to acquire them via ISRU. Carbon and oxygen acquired via ISRU could be used to supply breathing oxygen for the crew.

However, we do not understand in sufficient detail the properties of atmospheric constituents near the surface to determine the adverse effects on ISRU atmospheric processing system life and performance within acceptable risk for human missions. Dust is a concern for all surface systems, as described in Investigation 2A. Trace gas abundances and their potential to interfere with atmospheric ISRU processing are not completely understood, so measurement of the trace gas composition of the Martian atmosphere are desired. Because the Martian atmosphere is well-mixed, it is close enough to isochemical that only a single advance measurement would be needed. The SAM instrument on MSL has sufficient capability to make this measurement.

Priority	GFA	Gap-Filling Activity needed measurements
Low	B6-3	a. Measure the trace gas composition of the martian atmosphere with sufficient resolution and accuracy to detemine the potential effects on atmospheric ISRU.

<u>Assumptions:</u>
Perchlorate was considered as a possible oxidant for producing ascent fuel, but a) a more readily form of oxidant exists from the Martian atmosphere (O_2 extracted from CO_2) and b) there is no known method for clearly distinguishing perchlorate from orbit, thus no measurements of perchlorate are called for at this time.

<u>5. Investigation</u>: Characterize potential key resources to support In Situ Resource Utilization (ISRU) for eventual human missions.

As stated above, the resources to support a human stay at the Martian surface would be C, O, and H for both life support and ascent propellant (see DRA 5.0). Key trades include quantifying the mass, power, and risk associated with the equipment necessary to acquire and process these commodities from Martian resources compared to the mass, power, and risk of simply delivering them from Earth.

In the case of hydrogen (or equivalently, water), ISRU has the potential to have a substantial impact on mission affordability (particularly as related to the amount of mass to be delivered to the surface) especially for long-stay missions. Information gathered from MGS, Mars Odyssey, MEx, MER, Phoenix, MRO and telescopic observations have shown that H resources exist on Mars in at least three settings: hydrated minerals in rocks and soils, in ground ice, and in the atmosphere. This information has been of potential interest for ISRU. Nevertheless, it is unknown whether any of the resource deposits and the demands placed on the mission's processing system to extract the deposits would be compatible with the engineering, risk, and financial constraints of a human mission to Mars.

At this time it is not known where on Mars potential human exploration might occur, whether at multiple sites or repeated visits to the same site. However, a key implication is that delivery of high-mass ISRU processing equipment to a single site on Mars would likely cause future missions to return to the same site. Returning to a single site might not be in line with overall science objectives and this must be taken into account.

As is true of all extractive natural resources, determining whether a resource deposit is "ore" or "waste" cannot be determined without knowledge of *both* the resource and processing system. ISRU power estimates depend on mineral composition because of varying heating needs when extracting water from each mineral type. Therefore, deciding whether or not H-ISRU should be part of a future human mission scenario would require characterizing the candidate resource deposits on Mars and technology development work on Earth. The answer to this question could be best arrived at through two sequential phases: Reconnaissance-scale characterization sufficent to make prioritization decisions (Phase I) and a detailed site-specific characterization sufficient to plan for specific mission design (Phase II).

Hydrated minerals:
Numerous deposits of hydrated silicate and sulfate minerals have been identified on Mars from spectroscopic measurements [e.g., Bibring et al. 2005]. These deposits are attractive candidates for ISRU because: 1) they exist on the surface, thus their surface spatial distributions are easy to constrain using remote methods, 2) they exist in a variety of locations across the globe, thus provide many choices for mission landing sites, and 3) the low water activity in these minerals would preclude planetary protection issues. Limitations on existing measurements include: 1) uncertainty of volume abundance within the upper meter of the surface, 2) best available spatial resolution (~20 m/pixel) might not be sufficient for ISRU processing design, and 3) mechanical properties of H-bearing materials are not sufficiently constrained.

Subsurface ice:
Accessible, extractable hydrogen is likely at most high-latitude sites in the form of subsurface ice [Boynton et al., 2002; Feldman et al. 2002; Mitrofanov et al. 2002]. In addition, theoretical models can predict subsurface ice in some mid-latitude regions, particularly on poleward facing slopes [Aharonson and Schorghofer, 2006]. Indeed, ice at northern latitudes as low as 42° has been detected in fresh craters using high resolution imaging and spectroscopy. Based on observed sublimation rates and the color of these deposits, the ice is thought to be nearly pure with <1% debris concentration [Byrne et al. 2009]. Pure subsurface ice and other ice-cemented soil were also detected by the Phoenix mission [Smith et al., 2009]. Subsurface ice deposits have ISRU potential, but are ranked lower than deposits of hydrated minerals because: 1) low-latitude ice deposits are currently thought to exist only in glacial deposits that are associated with high elevations and difficult topography, and 2) mid-latitude deposits have substantial overburden that would make mining difficult (and in some cases are also in areas of difficult topography).

Additional reconnaissance would be required to better constrain the excavatibility, overburden, and mission power/volume needs associated with each of these H-resource types. In-situ measurements would be critical to confirming the resource abundance associated with excavatibility, depth, and power necessary for processing the H-resource(s) at the chosen landing site. Thus, the following proposed measurement specifications for the chosen landing site include both initial reconnaissance and follow-up in-situ measurements.

Priority	GFA	Gap-Filling Activity needed measurements
High	D1-3 D1-4	High spatial resolution maps (~2 m/pixel) of mineral composition and abundance. Verification of mineral volume abundance and physical properties within approximately the upper 3 meters of the surface. Mineral identification must also be verified. Measurement of the energy required to excavate/drill the H-bearing material. Measurement of the energy required to extract water from the H-bearing material.

Medium	D1-5 D1-6	High spatial resolution maps (~100 m/pixel) of subsurface ice depth and concentration within approximately the upper 3 meters of the surface. Verification of ice volume abundance and physical properties within approximately the upper 3 meters of the surface. Measurement of the energy required to excavate/drill the H-bearing material. Measurement of the energy required to extract water from the H-bearing material.

Note:
The 2m spatial resolution is based on the measurements for terrestrial mineral prospecting, which is achieved by using a combination of high-resolution (2.5 m/pixel) visible imagery, lower resolution multispectral imagery (15-90 m/pixel), and ore formation models. This spatial resolution might be achieved on Mars by using data from recent orbital sensors—combining the highest-resolution visible imagery (~50 cm/pixel) with the highest-resolution spectral data (~18 m/pixel) for specific areas or regions. When using this technique, one would need to assume similar surface textures/albedos between resolutions.

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V. CROSS-CUTTING STRATEGIES

Analysis of the above goals, objectives, and investigations has led to the formulation of several cross-cutting strategies that could be used to guide the present and future exploration of Mars. These include:

Follow the Water. In 2000-2001, at the time of the formation of MEPAG and the establishment of the first version of the Goals Document, it was recognized that water was a central aspect of many of the high-priority objectives and investigations in each of the four goals areas. MEPAG proposed the strategy of “follow the water” as a means of simultaneously approaching multiple objectives.

- For Goal I (Life), water (and in liquid form) is essential to life as we know it. Thus, finding past or present liquid water is our best starting point for the search for life.
- For Goal II (Climate), water is one of the keys to understanding the climate system in the form of the polar caps, the seasonal movement of water into the atmosphere, atmosphere-crust interactions associated with the circumpolar permafrost belts, the progressive loss of water and other molecules from the top of the atmosphere, etc.
- For Goal III (Geology), water plays a major role in many fundamental geologic processes that have formed and shaped the Martian crust, including volcanism, erosion, sedimentation, alteration/diagenesis, and glaciation.
- For Goal IV (Preparation for Humans), water would be a critical local resource needed for the support of human explorers.

This strategy served as a very important focal point of the Mars program through the missions Mars Global Surveyor (MGS) (1996-2006), Mars Odyssey (ODY) (2001-present), Mars Exploration Rovers (MER) (2003-present), Mars Reconnaissance Orbiter (MRO) (2005-present), and Phoenix (PHX) (2007-2008). Although as of 2013 we have not completed our analyses of water on Mars, it is generally considered that our discoveries to date are sufficient to no longer warrant water as a primary focal point for the program.

Understand Mars as a System. By the end of 2004, with extensive results from MGS, several years of data from ODY, and one year of data from the two MER rovers, it was recognized that Mars is significantly more diverse and complex than had been previously thought. Thus, achieving a full understanding of Mars would require understanding the primary components of the Martian system, and how they have interacted with each other during different epochs of Martian history. This strategy implies that we need to understand the diversity of Mars, how that diversity originated, and the interconnectivity of the different components.

Seek Habitable Environments. Upon recognition that Mars has a variety of different local environments, past and present, and that these environments have different potential for habitability, this cross-cutting strategy was proposed in 2008. Developing a quantitative understanding of that habitability potential would require investigations and measurements that span many of the aspects of Goals I, II, and III. In addition, although Goal I relates to indigenous habitability (and actual habitation), Goal IV relates to exogenous habitability (i.e., habitability by human explorers). Thus, this strategy applies to all four goal areas and is likely to become the primary focus of Mars exploration efforts in the coming decade.

Along these lines, the results from the Phoenix mission and the reported detection of variable amounts and spatial distribution of atmospheric methane might influence the long-term strategy of the MEP. Analyses of Phoenix data are altering interpretations of the physical and chemical conditions under which water, salts, and brines exist in the current polar environment. Understanding how these materials interact among the atmosphere, surface, and subsurface, particularly in the context of habitable environments, cuts across multiple objectives and investigations within each of the four goals.