Mars Science Goals, Objectives, Investigations, and Priorities: 2008

Mars Exploration Program Analysis Group (MEPAG)

September 15, 2008

Prepared by the MEPAG Goals Committee:

Jeffrey R. Johnson, Chair, United States Geological Survey (jrjohnson@usgs.gov)

Representing Goal I
Jan Amend, Washington University (amend@levee.wustl.edu)
Andrew Steele, Carnegie Institute of Washington (steelie@mac.com)
Representing Goal II
Steve Bougher, University of Michigan (bougher@engin.umich.edu)
Scot Rafkin, Southwest Research Institute (rafkin@boulder.swri.edu)
Paul Withers, Boston University (withers@bu.edu)
Representing Goal III
Jeffrey Plescia, Applied Physics Laboratory (jeffrey.plescia@jhuapl.edu)
Victoria Hamilton, Southwest Research Institute (hamilton@boulder.swri.edu)
Representing Goal IV
Abhi Tripathi, Johnson Space Center (abhishek.b.tripathi@nasa.gov)
Jennifer Heldmann, Ames Research Center (jheldmann@mail.arc,nasa,gov)

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 over the past few years 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-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[5]). 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 making progress in all three sciences 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 understand 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

---

[1] MEPAG (2001), Scientific Goals, Objectives, Investigations, and Priorities, in <u>Science Planning for Exploring Mars</u>, JPL Publication 01-7, p. 9-38. Available on the web at http://mepag.jpl.nasa.gov/reports/index.html.

[2] MEPAG (2004), Scientific Goals, Objectives, Investigations, and Priorities: 2003, G. J. Taylor, ed., 23 p. white paper posted 07-16-04 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.jpl.nasa.gov/reports/index.html.

[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.jpl.nasa.gov/reports/index.html.

[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.jpl.nasa.gov/reports/index.html.

[5] 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.jpl.nasa.gov/reports/index.html.

affect our analysis of habitability issues and ultimately improve the effectiveness of the Mars Exploration Program.

Each Goal includes two or 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 12 objectives, nine of which are scientific in nature, and three of which relate to reducing the risk of mission operations.

A series of investigations that collectively would achieve each objective is also identified. While some investigations can be achieved with a single measurement, others will 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 can 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 Scout 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 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 will require decades and it is possible that many investigations are so complex that they may 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 will 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 requires 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 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 may 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, and will be addressed by MEPAG science analysis groups in the near future.

Notes relating to this version of the Goals Document

This present version of the Goals Document incorporates changes made by the MEPAG Goals Committee and based on comments from the broader science community. The Goals Committee provided comments and suggested revisions using inputs from discussions held with the Mars community at the 7th International Conference on Mars in July 2007. The Mars community was then given the opportunity to comment on the draft revision from late August to late September, 2007. The Goals Committee then prepared a second revision that was circulated to the MEPAG Executive Committee in December 2007. This revision was then discussed at the 18th MEPAG meeting in February 2008, and the final version was posted in September, 2008 as part of the 19th MEPAG meeting.

Goal IV (Preparation for Human Exploration) was revised in 2005 with the assistance of a MEPAG-chartered Mars Human Precursor Science Steering Group (SSG) in order to update the 2001 and 2004 versions of the Goals Document regarding the schedule and engineering implementation options for human missions to Mars. With the exception of moving former Goal II, Objective C ("Characterize the State and Processes of the Martian Atmosphere of Critical Importance for the Safe Operation of Spacecraft"), to Goal IV, Objective C, additional revision of Goal IV has been deferred until additional studies currently underway by the Mars Architecture Working Group are completed in 2008. Note also that changes to Goal I recommended at the above meetings have not been implemented owing to turnover in the Goal I representatives on the Goals Committee in mid-2008. These changes will be implemented in the subsequent revision to the Goals Document in 2009.

I. GOAL: DETERMINE IF LIFE EVER AROSE ON MARS

Determining if life ever arose on Mars is a challenging goal. The prime focus of this goal is to determine if life is or was present on Mars. If life exists or existed, another focus is to understand the systems that support or supported it. Finally, if life never existed yet conditions appear to have been suitable for formation and/or maintenance of life, a focus would then be to understand why evidence of life was not found. A comprehensive conclusion about the question of life on Mars will necessitate understanding the planetary evolution of Mars and whether Mars is or could have been habitable, and will need to be based in multi-disciplinary scientific exploration at scales ranging from planetary to microscopic. The strategy we have adopted to pursue this goal has two sequential components: assess the habitability of Mars (which needs to be undertaken environment by environment); and, test for prebiotic processes, past life, or present life in environments that can be shown to have high habitability potential. These constitute two scientific objectives: "assess habitability" (A) and "test for life" (C). A critical means to achieve both objectives is to characterize Martian carbon chemistry and carbon cycling. Consequently, the science associated with carbon chemistry is so fundamental to the overall life goal that we have established it as a third primary science objective, "follow the carbon" (B). To some degree, these scientific objectives can be addressed simultaneously, as each requires basic knowledge of the distributions of water and carbon on Mars and an understanding of the processes that govern their interactions. Clearly, these objectives overlap, but are considered separately.

In order to prioritize the objectives and investigations, we need to be specific about the prioritization criteria. In broad perspective, Objectives A ("assess habitability") and B ("follow the carbon") are the critical steps in narrowing the search space to allow Objective C to be addressed. Objective C ("test for life") is synonymous with Goal I and is a long-term objective. We need to know where to look for life before making a serious attempt at testing for life. At the same time, Objectives A and B are fundamentally important even without searching for life directly; they help us understand the role planetary evolution plays in creating conditions in which life might have arisen, whether it arose or not. Thus, objectives A, B, and C, in this order, form a logical exploration sequence. Note that research goals and technology development plans must incorporate both short- and long-term scientific objectives. The rigorous development of instrumentation and flight technologies is required to meet these objectives. Relevant tests would identify, characterize, and curate laboratory samples from relevant environments as part of ongoing efforts to improve detection limits.

A. Objective: Assess the past and present habitability of Mars (investigations listed in priority order)

As used in this document, the term "habitability" refers to the potential to support life of any form. Although Objective A is considered at a planetary scale, we know from our experience on Earth that we should expect that different micro-environments on Mars will have different potential for habitability. It will not be possible to make measurements of one environment and assume that they apply to another. In order to address the overall goal of determining if life ever arose on Mars, the most relevant life detection investigations would be those carried out in

environments that have high potential for habitability. Thus, understanding habitability in space and time is an important first order objective.

Arguably, until we discover an extant Martian life form and measure its life processes, there is no way to know definitively which combination of factors must simultaneously be present to constitute a Martian habitat. Until then, "habitability" will need to describe the potential of an environment to sustain life and will therefore be based on our understandings of habitable niches on Earth or plausible extrapolations. Current thinking is that at a minimum, the following four conditions need to be satisfied in order for an environment to have high potential for habitability:

- The presence of liquid water. As we currently understand life, water is an essential requirement. Its identification and mapping (particularly in the subsurface, where most of Mars' water is thought to reside, but also as ephemeral water and hydrous mineral phases) must be accomplished on a global, regional and local basis using established measurement techniques.
- The presence of the key elements that provide the raw materials to build cells.
- A source of energy to support life.
- The absence or protection from hazards detrimental to sustaining life (e.g., radiation).

Finally, environments with potential for habitability are assumed to have unequal potential to preserve the evidence in geological samples. There needs to be an understanding of these effects in order to understand the significance of many types of life-related investigations.

1. Investigation: Establish the current distribution of water in all its forms on Mars.

Water on Mars is thought to be present in a variety of forms and occur in many locations, ranging from trace amounts of vapor in the atmosphere to substantial reservoirs of liquid, ice and hydrous minerals that may be present on or the below the surface. The presence of abundant water is supported by its existence in the Martian perennial polar caps, the geomorphic evidence suggestive of present-day ground ice and past fluvial discharges, and by the Mars Odyssey GRS detection of abundant hydrogen (which is interpreted to occur as water ice and/or hydrous minerals) within the upper meter of the surface across much of the planet. To investigate current habitability, the identity of the highest priority H2O targets, and the depth and geographic distribution of their most accessible occurrences, must be known with sufficient precision to guide subsequent investigations. To understand the conditions that gave rise to these potential habitats it is also desirable to characterize their geologic and climatic context. The highest priority H2O targets for the identification of potential habitats are: (1) liquid water -- which may be present as pockets of brine in the near-subsurface, in association with potential geothermally active regions (such as Tharsis and Elysium), as super-cooled thin films within the lower cryosphere, and beneath the cryosphere as confined, unconfined, or perched aquifers. (2) Massive ground ice – which may exist in a complex stratigraphy beneath the northern plains and the floors of Hellas, Argyre, and Valles Marineris (based on a the presumption of a Noachian ocean), the geomorphic evidence for extensive and repeated flooding by Hesperian-age outflow channel activity. These ground ice location may preserve evidence of former life. and. (3) The polar layered deposits – whose strata may preserve evidence of climatically-responsive biological activity (at the poles and elsewhere on the planet) and whose ice-rich environment

may allow for the episodic or persistent occurrences of liquid water associated with climate change, local geothermal activity and the presence of basal lakes.

2. Investigation: Determine the geological history of water on Mars, and model the processes that have caused water to move from one reservoir to another.

In order to assess past habitability, we need to start with an understanding, at global scale, of the abundance, form, and distribution of water in Mars' geologic past. A first-order hypothesis to be tested is whether Mars was at one time warmer and wetter than it is now. This could be done, in part, through investigation of geological deposits that have been affected by hydrological processes, and, in part, through construction of carefully conceived models. One key step would be to characterize the regional and global sedimentary stratigraphy of Mars. It is entirely possible that Mars had life early in its history, but that life is now extinct.

3. Investigation: Identify and characterize phases containing C, H, O, N, P and S, including minerals, ices, and gases, and the fluxes of these elements between phases.

Assessing the availability and distribution of biologically important elements and the phases in which they are contained, would allow a greater assessment of both habitability and the potential for life to have arisen. Detailed investigations for carbon are the primary focus of Objective B and therefore will not be further discussed here. Nitrogen, phosphorous and sulfur are critical elements for life on Earth and the phases containing these elements and fluxes of these elements may reflect biological processes and the availability of these elements for life. They are often intimately associated with carbon and their distribution is commonly controlled by water and oxidation states, so interpreting these elemental cycles in terms of C, H, and O is extremely valuable to understanding habitability. The redox chemistry of S is of interest, because of its known role in some microbial metabolic strategies in terrestrial organisms and the abundance of sulfate on the surface of Mars.

4. Investigation: Determine the array of potential energy sources available on Mars to sustain biological processes.

This investigation would allow identification of the potential of Mars to have harbored or continue to harbor life. Biological systems require energy. Therefore, measurement of the availability of potential energy sources is a critical component of habitability, and understanding how life might use them is a critical component of designing scientifically robust life detection experiments. Sources of energy that should be measured may include chemical redox, pH gradients, geothermal heat, radioactivity, incident radiation (sunlight), and atmospheric processes.

B. Objective: Characterize Carbon Cycling in its Geochemical Context (investigations listed in priority order)

Carbon is the basic building block of life on Earth and it is assumed to be the building block of life on Mars (if life exists/existed). Understanding how carbon has been distributed on Mars through time, including now, is critical for understanding where to look for life on Mars, how

life might have evolved on Mars, and how life might have originated on Mars. In addition, there may be aspects of the carbon cycle that reveal the existence of life (extant or extinct), and results are likely to strongly influence approaches to searching for other biosignatures. Thus, characterization of the carbon cycle is critical to determining if life ever arose on Mars.

Understanding the origin of organic carbon is particularly important and sources on Mars could be from several reservoirs that are summarized in Table 2. Once organic carbon is discovered, a major challenge will be in constraining the source and distribution of that organic carbon. Terrestrial contamination is a significant concern, because of the need to avoid false identification of organic carbon or specific organic molecules on Mars. In addition, meteoritic delivery of organic carbon to the surface of Mars and abiotic organic synthesis processes could produce measurable organic carbon concentrations.

We assume that extraterrestrial life would be based on carbon chemistry (Committee on the Limits of Organic Life in Planetary Systems, Committee on the Origins and Evolution of Life, National Research Council, 116 p., 2007). Although this assumption may subsequently need to be revised, we would not know where else to begin in designing investigations of possible extraterrestrial life. If anomalous measurements indicate the presence of non-carbon based macromolecules associated with some form of life-like processes then further experiments could be designed to address this problem.

Table 2. Possible sources of organic carbon that need to be distinguished in Martian samples.

Source of Carbon	Carbon compounds (examples/comments)
Prebiotic/protobiotic molecules from meteoritic / cometary influx	Amino acids, purines and pyrimidines, polycyclic aromatic hydrocarbons, chain hydrocarbons, fatty acids, carbohydrates, sugars and sugar derivatives.
Prebiotic/protobiotic molecules from abiotic process on Mars	Amino acids, purines and pyrimidines, polycyclic aromatic hydrocarbons, chain hydrocarbons, fatty acids, carbohydrates, sugars and sugar derivatives.
Terrestrial contaminating organics	Condensation products derived from rocket exhaust, lubricants, plasticizers, atmospheric contaminants
Terrestrial contaminating organisms	Whole cells, cell components (LPS, DNA, proteins, cytochromes)
Terrestrial organisms	Organisms not present on the craft measuring them, but had been previously transferred from Earth by either meteorite impact or contamination of previous spacecraft. Target molecules could include individual genes, membrane constituents, specific enzymes, and co-enzymes that would be expected to be over expressed or adapted in Martian conditions.
Terrestrial-like organisms – evolved on Mars	Organisms that utilize terrestrial like biochemistries and have evolved on Mars. Target molecules could include individual genes, membrane constituents, specific enzymes, and co-enzymes that would be expected to be over expressed or adapted in Martian conditions, or organisms using metabolisms that would not be present on a space craft contaminant such as methanogens, psychrophiles endolithic survival mechanisms.
Non-terrestrial-like organisms	Utilizes an array of molecules for information storage, information transfer, compartmentalization and enzymatic activity that differ from those used by extant terrestrial life. Examples would be the use of novel amino acids and nucleotides or the use of novel nitrogen utilization strategies.
Fossil biomarkers	Detection of established terrestrial fossil biomarkers such as hopanes, archaeal lipids and steranes, for the detection of the diagenetic remains of terrestrial based life.

Note this table lists all possibilities without designating the likelihood that a particular category exists.

1. Investigation: Determine the distribution and composition of organic carbon on Mars.

The spatial distribution and composition of organic carbon have not been characterized, but are instrumental in understanding the biological potential of Mars. (Methane and other simple reduced carbon molecules are included as "organic carbon" in this context.) Abiotic synthesis of organics, delivery of organics to Mars via meteorites, and possible biological production of organics must all be evaluated in the context of carbon cycling on Mars. Characterizing the molecular and isotopic composition of organic carbon would be essential for determining the origin of the organics shown in Table 2, which includes the types of organic materials that need to be detected and deconvolved from each other. Investigations require sufficient spacecraft cleaning and verification to minimize the likelihood of contamination, in addition to careful planning of specific methods to identify and exclude forward contamination at the experiment level. Example measurements include analysis of the concentration and isotopic composition of organic carbon, characterization of the molecular structure of organic carbon, or identifying and monitoring reduced carbon (e.g., methane) fluxes.

2. Investigation: Characterize the distribution and composition of inorganic carbon reservoirs on Mars through time.

Transformations of carbon between inorganic and organic carbon reservoirs are a characteristic of life. Evaluating carbon reservoirs and the fluxes between them would be critical to understanding both the modern and geological evolution of carbon availability, and the inorganic carbon reservoirs are an important link in the cycle. The distribution of these reservoirs could also reveal critical habitability information because they can record climate variations. Potential measurements include continued searching for carbonate minerals from orbit, in situ, and in returned samples, characterizing CO_2 fluxes on various time scales globally and locally, and measuring the isotopic composition of any inorganic reservoir.

3. Investigation: Characterize links between C and H, O, N, P, and S.

The carbon cycle is intimately linked to H, O, N, P, and S, particularly in the presence of life. Identifying connections among the geological cycles of these elements will substantially aid interpretations of the carbon cycle and may provide indicators that can be used to interpret biological potential. Potential measurements include mineralogical characterization of samples containing C, N, P, or S, isotopic and oxidation state characterization of S-containing phases, and identification of reactions involving any of these elements.

4. Investigation: Characterize the preservation of reduced compounds on the near-surface through time.

The surface of Mars is oxidizing, but the composition and properties of the responsible oxidant(s) are unknown. Characterizing the reactivity of the near-surface of Mars, including atmospheric (e.g., electrical discharges) and radiation processes as well as chemical processes

with depth in the regolith3 and within weathered rocks is critical to interpreting the paucity or possible absence of organic carbon on the surface of Mars. Understanding the oxidation chemistry and the processes controlling its variations will aid in predicting subsurface habitability, considering that surface organic compounds likely have been highly degraded by oxidation reactions and ionizing radiation from space. Potential measurements include identifying the species and concentrations of the oxidants, characterizing the processes forming and destroying them, and characterizing concentrations and fluxes of redox sensitive gases in the lower atmosphere.

C. Objective: Assess whether life is or was present on Mars (investigations listed in priority order)

This objective reflects several of NASA's chief exploration goals. As mentioned earlier, the need to prevent false positives or negatives, and develop technology and experimental protocols, makes Objective C ("test for life") a long-term goal. Objectives A ("assess habitability") and B ("follow the carbon") are the critical steps in narrowing the search space to allow Objective C to be addressed. Furthermore, Objective C itself does not halt upon a positive or negative answer. In the eventuality of a positive answer, the next step would be to characterize whatever life form is discovered, and then its origins and reason for surviving on Mars. In the case of a negative answer, further characterization of why life did not begin on Mars would become a priority and in itself help us to understand more about life on Earth.

Determining whether life ever existed on Mars is a scientifically exciting and challenging endeavor. The following investigations would look for biosignatures, which are defined as results that REQUIRE the presence or past presence of life. Commonly, multiple observations in a context are required to identify biosignatures, and multiple scales of observation are very important. Four investigations of features currently recognized as biosignatures are listed here.

Investigation 1 (Characterize complex organics) is considered to be the highest priority. Investigation 1 and some measurements to address Investigation 4 would require sufficient spacecraft cleaning and verification to avoid likelihood of contamination, in addition to careful planning of specific methods to identify and exclude forward contamination at the experiment level. Investigations 2 and 3, which depend on the spatial distribution of signatures, are less sensitive to contamination and might be more practical to pursue first. Remote sensing techniques addressing investigation 4 also would have much lower to no contamination issues. Investigations 1-4 are largely in situ investigations that would be best conducted in those habitable environments identified in A1.

A notional fifth investigation concept consists of suites of observations based on correlations in biological indicators, which by themselves are only suggestive for life and only in combination can provide a true biosignature. It seems likely that many of the combinations of measurements have yet to be identified, and it is expected that innovative proposals for suites of observations will be put forth to evaluate the past or present presence of life.

---

[3] Regolith. As used in this document, a general term referring to the mantle of fragmental, unconsolidated to partially cohesive material, of any origin (*in situ*, residual, or transported) that nearly everywhere underlies the surface of Mars (after Glossary of Geology).

1. Investigation: Characterize complex organics.

The identification of complex organics that can only be produced biologically is a very strong biosignature, if forward contamination by terrestrial organics can be excluded. Measurements for this investigation must include appropriate methods to identify and exclude forward contamination as a source of the target materials. To this end, new techniques and instruments must be developed for cleaning and monitoring of spacecraft contamination. Instruments must be developed to include procedural blanks to allow accurate calibration measurements by that instrument. This entails that the critical path of contamination, i.e., the path the sample takes to the instrument, be cleaned to a level below the detection limit of the instrument. Example measurements might include characterization of organics such as DNA, nucleotides, chlorophyll, etc. for extant life; hopanes, steranes, isoprenoids, etc. for fossil life; or cumulative properties and/or distributions of organics such as homochirality.

2. Investigation: Characterize the spatial distribution of chemical and/or isotopic signatures.

The spatial distribution of chemical or isotopic variations can be a biosignature, if the distribution is inconsistent with abiotic processes. Example measurements might include imaging of the distribution of organics on a surface or in minerals; identifying correlations among isotopic values and elemental concentrations that reflect biological processes; or the presence of reduced and oxidized gas phases in disequilibrium.

3. Investigation: Characterize the morphology or morphological distribution of mineralogical signatures.

Sedimentary and weathered rocks can preserve biosignatures in the distribution of grains and minerals or in the morphology of biologically produced minerals. Example measurements might include micron to nanometer imaging and chemical analysis of crystals or morphological characterization of sedimentary lamination to regional or global scale characterization of sedimentary stratigraphy.

4. Investigation: Identify temporal chemical variations requiring life.

Extant life may be active, producing observable changes in chemistry over the time scale in which a lander experiment may be functional. Monitoring systems that may harbor life is an excellent way to identify the presence of life. However, possible abiotic reactions need to be thoroughly understood and forward contamination needs to be identified or excluded. It is critical that measurements which are subject to contamination include appropriate methods to identify and exclude forward contamination as a source of the signatures being monitored. Example measurements might include monitoring the flux of gases thought to be biologically produced; monitoring oxidative changes in a way that excludes abiotic reactions; or performing experiments to look for metabolic processes.

II. GOAL: 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.

A. Objective: Characterize Mars' Atmosphere, Present Climate, and Climate Processes Under Current Orbital Configuration (investigations in priority order)

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 CO_2, H_2O 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 is needed for a proper characterization of the present day climate of Mars.

1. Investigation: 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 will 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.

2. Investigation: 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.

B. Objective: Characterize Mars' Recent Climate History and Climate Processes Under Different Orbital Configurations (investigations in priority order)

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.

1. Investigation: 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.

2. Investigation: 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.

3. Investigation: 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.

C. Objective: Characterize Mars' Ancient Climate and Climate Processes (investigations in priority order)

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.

1. Investigation: 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 is 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.

2. Investigation: 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.

III. GOAL: 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).

A. Objective: Determine the nature and evolution of the geologic processes that have created and modified the Martian crust (investigations in priority order)

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.

1. Investigation: 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 can not be detected in remote observation.

2. Investigation: 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.

3. Investigation: 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.

4. Investigation: 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.

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

Understanding the 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 (100's of meters to kilometers), detailed geologic and topographic mapping (including impact mapping/studies), and determination of the compositions of major geologic units. A long-term, continuously active seismic network composed of multiple stations would be required to 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.

B. Objective: Characterize the structure, composition, dynamics, and evolution of Mars' interior (investigations in priority order).

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 for understanding the origin and evolution of Mars, its surface evolution, and the release of water and atmospheric gasses. 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 would require seismology (e.g., passive and active experiments and understanding of the seismic state of the planet), heat flow, and gravity data.

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.

C. Objective: Understand the origin, evolution, composition and structure of Phobos and Deimos (investigations in priority order).

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 thee satellites 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.

IV. GOAL: PREPARE FOR HUMAN EXPLORATION

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 future human and robotic exploration of Mars. Goal IV of the MEPAG document differs from the previous Goals in that it addresses science and engineering questions specific to increasing the safety, decreasing the cost, and increasing the productivity of human crews on Mars. To address these issues this section describes both the data sets that are to be collected and analyzed (Objective A), and the demonstrations of critical technologies that must be validated in the Martian environment (Objective B). Finally, Objective C highlights mission critical atmospheric measurements that would reduce mission risk and enhance overall science return, benefiting all future missions to the planet (both robotic and human). No attempt has been made to prioritize these risk mitigation and engineering related measurements since all are important.

The 2004 National Vision for Space Exploration provides guidance for a broad range of human and robotic missions to the moon, Mars and destinations beyond. Robotic missions serve as one component of a "system of systems", the sum of which work together to accomplish the goals of implementing a safe, sustained, and affordable robotic and human program to explore and extend human presence across the solar system and beyond. One of the Vision's main points is to conduct robotic exploration of Mars to prepare for human exploration, and NASA has adopted a "level zero" requirement to "conduct robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to support future human exploration activities." Specifically, robotic precursor missions would be used in part to acquire and analyze data for the purpose of reducing cost and risk of future human exploration missions, would perform technology and flight system demonstrations for the purpose of reducing cost and risk of future human exploration missions, and would deploy infrastructure to support future human exploration activities.

As part of the momentum associated with the 2004 National Vision for Space Exploration, in 2004-2005 MEPAG undertook a major reassessment of the issues associated with preparing for the human exploration of Mars. This work is summarized in the following two documents, which represent analyses of Goal IV Objective A, and Goal IV Objective B, respectively. The logic associated with the investigations and measurements is described in these reports.

Beaty, D.W., Snook, K., Allen, C.C., Eppler, D., Farrell, W.M., Heldmann, J., Metzger, P., Peach, L., Wagner, S.A., and Zeitlin, C., (2005). An Analysis of the Precursor Measurements of Mars Needed to Reduce the Risk of the First Human Missions to Mars. Unpublished white paper, 77 p, posted June 2005 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.jpl.nasa.gov/reports/index.html.

Hinners, N.W., Braun, R.D., Joosten, K.B., Kohlhase, C.E., and Powell, R.W., (2005), Report of the MEPAG Mars Human Precursor Science Steering Group Technology Demonstration and Infrastructure Emplacement (TI) Sub-Group, 24 p. document posted July, 2005 by

the Mars Exploration Program Analysis Group (MEPAG) at
http://mepag.jpl.nasa.gov/reports/index.html.

A. Objective. Obtain knowledge of Mars sufficient to design and implement a human mission with acceptable cost, risk and performance.[4]

Investigations #1A-1D are judged to be of indistinguishable high priority.

1A. Investigation. Characterize the particulates that could be transported to hardware and infrastructure through the air (including both 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 is required.

Measurements

a. A complete analysis, consisting of shape and size distribution, mineralogy, electrical and thermal conductivity, triboelectric and photoemission properties, and chemistry (especially chemistry of relevance to predicting corrosion effects), of samples of regolith from a depth as large as might be affected by human surface operations.

> *Note #1: For sites where air-borne dust naturally settles, a bulk regolith sample would be sufficient—analysis of a separate sample of dust filtered from the atmosphere is desirable, but not required.*
> *Note #2: Obtaining a broad range of measurements on the same sample would be considerably more valuable than a few measurements on each of several samples (this naturally lends itself to sample return).*
> *Note #3: There is not consensus on adding magnetic properties to the list of measurements.*

b. Characterize at least one regolith deposit with fidelity sufficient to establish credible engineering simulation labs and/or software codes on Earth to solve engineering problems related to differential settlement of the regolith, and plume/regolith interactions (see Note #4).

For one site on Mars (see Note #5), measure the following properties of the regolith as a function of depth to 1 meter:

Particle shape and size distribution
Ice content and composition to within 5% by mass
Regolith density to within 0.1 g/cm^3
Gas permeability in the range 1 to 300 Darcy with a factor of three accuracy
Presence of significant heterogeneities or subsurface features of layering

---

[4] General Notes:

- *Except as noted, investigations are listed in priority order. Within each investigation, measurements are listed in priority order.*
- *Prioritization Criteria:*
  - *Magnitude of effect of precursor information on reduction of risk and/or cost of a human mission to Mars.*
  - *Perceived degree of viability and cost of available mitigation options.*
  - *Potential to obtain minimum necessary information in a less expensive way than by flying a mission to Mars.*
- *Assumptions:*
  - *The first human mission includes a landed human element.*
  - *The possibilities of "short-stay" (~30 sols) and "long-stay" (~300 sols) are both under consideration, so the precursor program needs to support both.*

An index of shear strength

Flow Rate Index test or other standard flow index measurement

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

c. The same measurements as above on a sample of air-borne dust collected during a major dust storm.

d. Subsets of the complete analysis described above, and measured at different locations on Mars (see Note #2). For individual measurements, priorities are:

shape and size distribution and mineralogy

electrical

chemistry

Note #4. Because there is a large engineering lead-time required to solve the geotechnical problems, these data must be obtained early in the precursor program.

Note #5. These measurements should be made in a competent regolith deposit as opposed to loose drift material (cohesionless sand dunes), as landing is expected to attempt to avoid the looser material. Also, if mission planners would select high latitude polar deposits for a human landing site, geotechnical data would be required from a representative location of those deposits. These measurements should include polarity and magnitude of charge on individual dust particles suspended in the atmosphere and concentration of free atmospheric ions with positive and negative polarities. Measurement should be taken during the day in calm conditions representative of nominal Extra Vehicular Activity (EVA) excursions.

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

Measurements:

a. Measure velocity (v), pressure (P), temperature (T) and density (ρ) in the upper, middle and lower atmosphere during EDL. Obtain as many profiles at various times and locations as possible (requested for all landed missions). Sample rate should be high enough (~100 Hz) to quantify turbulent layers. Specific direct or derived measurements would include:

- Density from 120 km to surface ranging from high altitude values of 10^{-9} to near-surface values of 10^{-1} kg/m^3, dρ = 1% of local ambient
- Pressure from 120 km to surface ranging from high altitude values of 10^{-7} to near-surface values of 15 mb, dP= 1% of local ambient
- Temperature 60-300 K, dT = 0.5K
- Directional Wind Velocity, 1-50 m/sec, dv = 1 m/s

Particular emphasis on measurements between 0-20 km to quantify boundary layer wind and turbulence and 30-60 km where vehicle dynamic pressure is largest.

b. Monitor surface/near-surface velocity (v(z)), pressure (P), temperature (T(z)), and density (ρ) as a function of time. Quantify the nature of the surface heating driver and associated boundary layer turbulence at altitudes above station. Data defines the initial conditions for high altitude modeling. Obtain data from as many locations as possible (requested for all landed missions). Surface/near surface packages should measure directly:Pressure, at surface, 0.005 mb to 15 mb, dP = 2 microbar, full diurnal sampling, rate= >10 Hz

- Velocity, at surface, 0.05-50 m/sec, dv = 0.05 m/s, horizontal and vertical, full diurnal sampling, rate= 10 Hz
- Air temperature, at surface, 150-300 K, dt = 0.04K, full diurnal sampling, rate= 10 Hz
- Ground temperature 150-300 K, dt = 1K, full diurnal sampling, rate= 1 Hz
- Air temperature profile, 0-5km, <1km resolution, 150-300K, dt=2K, full diurnal sampling, rate=1 Hz

- Velocity profile, 0-5km, <1km resolution, 1-50 m/sec, dv=1 ms/, horizontal and vertical, full diurnal sampling, rate=1 Hz
- Opacity, visible, depth 0.2-10, dtau = 0.1, once every 10 min

c. Make long-term (>> 1 Martian year) remote sensing observations of the weather (atmospheric state and variations) from orbit, including a direct or derived measurement of:
- Aeolian, cloud, and fog event frequency, size, distribution as a function of time.
- Vertical temperature profiles from 0-120 km with better than 1 km resolution between 0-20 km, 1-3 km resolution between 20-60 km, 3 km resolution > 60 km and with global coverage over the course of a sol, all local times *[Development work required for T from surface to 20 km]*.
- Vertical density/pressure profiles from 0-120 km with better than 1 km resolution between 0-20 km, 1-3 km resolution between 20-60 km, 3 km resolution > 60 km and with global coverage over the course of a sol, all local times *[Development work required for ρ from surface to 20 km]*.

3-D winds as a function of altitude, from 0-60 km with better than 1 km resolution below 20 km, and 1-3 km resolution between 20-60 km, and with global coverage over the course of a sol, all local times *[Development work required at all altitudes for an independent means to derive V, with special emphasis from surface to 20 km]*.
> Note particular emphasis on measurements between 0-20 km to quantify boundary layer wind and turbulence and 30-60 km where vehicle dynamic pressure is large.

d. At time of human EDL and TAO, deploy ascent/descent probes into atmosphere to measure pressure, temperature and velocity just prior to human descent at scales listed in 1Ba.

Note #6: 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.

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

Measurements:

a. Determine if extant life is widely present in the Martian near-surface regolith, and if the air-borne dust is a mechanism for its transport. If life is present, assess whether it is a biohazard. For both assessments, the required measurements are the tests described in the Draft Test Protocol.

Note #7: To achieve the necessary confidence, this would require sample return and analyses in terrestrial laboratories.

Note #8: The samples could be collected from any site on Mars that is subjected to wind-blown dust.

Note #9: At any site where dust from the atmosphere is deposited on the surface, a regolith sample collected from the upper surface would be sufficient--it is not necessary to filter dust from the atmosphere.

b. At the site of the planned first human landing, conduct biologic assays using *in situ* methods, with measurements and instruments designed using the results of all prior investigations. All of the geological materials with which the humans and/or the flight elements that would be returning to Earth come into contact need to be sampled and analyzed.

Note #10: It is recommended that a decision on whether human landing sites after the first one would require a lander with biological screening abilities be deferred until after Measurement a has been completed.

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

Measurement Options:

a. Perform measurements within the top few meters of the regolith in a location within the near-equatorial region (approximately ±30°) that the Mars Odyssey mission indicates is a local maximum in hydrogen content, to determine: (i) concentration of water released upon regolith heating, (ii) composition and concentration of other associated volatiles released with water, and (iii) three-dimensional distribution of measurements i & ii within a 100 meter x 100 meter local region. This option would include water contained in hydrous minerals, as adsorbed water, and in any other form it might be present in the regolith.   Either unconsolidated or loosely consolidated regolith is a focus of current attention because of the need to minimize mining engineering, but outcrops of rock containing hydrous minerals may also be a valuable possibility if they are sufficiently friable.

b. Perform measurements to (i) identify and determine the depth, thickness, and concentration of water in subsurface ice deposits to a few meters depth at approximately 40° to 55° latitude, (ii) determine the demarcation profile/latitude where near-surface subsurface ice formation does and does not occur.

c. Perform measurements in the polar region (70º to 90º) to determine the depth, thickness, and concentration of near-surface water/ice.

Measurements for water at other locations and depths are not precluded but would require further scientific measurements and/or analysis to warrant consideration. This option would specifically include accessing a deep aquifer.

The following investigations are listed in descending priority order.

2. Investigation. Determine the possible toxic effects of Martian dust on humans.

Measurements:

a. For at least one site, assay for chemicals with known toxic effect on humans. Of particular importance are oxidizing species (e.g., CrVI). (May require Mars Sample Return (MSR)).

b. Fully characterize soluble ion distributions, reactions that occur upon humidification and released volatiles from a surface sample and sample of regolith from a depth as large as might be affected by human surface operations.

c. Analyze the shapes of Martian dust grains sufficient to assess their possible impact on human soft tissue (especially eyes and lungs).

d. Determine if Martian regolith elicits a toxic response in an animal species that are surrogates for humans.

3. Investigation. Assess atmospheric electricity conditions that may affect TAO and human occupation.

Measurements:

a. Basic measurements:

    DC E-fields: 0-80 kV/m, dV=1 V, bandwidth 0-10 Hz, rate = 20 Hz

    AC E-fields: 10 uV/m – 10 V/m, Frequency Coverage 10 Hz-200 MHz, rate = 20 Hz, with time domain sampling capability

    Atmospheric Conductivity: 10^{-15} to 10^{-10} S/m, ds= 10% of local ambient value

    Ground Conductivity: $>10^{-13}$ S/m, ds= 10% of local ambient value

    Grain charge: $>10^{-17}$ C

    Grain radius: 1-100 μm Combine with surface meteorological measurements to correlate electric forces and their causative meteorological source for more than 1 Martian year, both in dust devils and large dust storms. Combine requirements for 1Bb with 3a above.

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

Measurements:

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

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

Measurements:

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

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

Measurements:

a. Determine vertical variation 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}.
b. Determine variation in *in-situ* internal angle of friction for dust dunes and dust pockets to within 1°.
c. Determine regolith cohesion for rocky areas, dust dunes and in dust pockets to within 0.1 kN m^{-2}.
d. Imaging to Mars Reconnaissance Orbiter High Resolution Imaging Science Experiment (MRO HiRISE) standards (30 cm/px) for selected potential landing sites.

For basic design of mobility systems, the following measurements would be needed (not just at the dust pockets and dunes, but also on the consolidated regolith surfaces where we might do most of the driving): (i) rolling resistance (the torque that regolith applies to a rolling wheel while driving), (ii) traction test (torque required to spin a wheel while the rover is held stationary), and (iii) shape/size of the resulting wheel ruts while driving normally.
Note #11: These three things would probably be measured routinely on all Mars rovers.
Note #12: ISRU excavation could require hauling larger loads (regolith/ice payload) than what we have ever hauled in the past. Therefore they would need these data to properly design wheels and chases (e.g., rover and large structure mobility systems), avoiding energy-wasteful designs or risk of getting bogged down.

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

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

Table 1. Summary of Location Considerations for high-priority human Precursor Investigations.

Investigation	Needed once at Mars	Measurements at multiple sites	Measurements over time	Measurement at the human site
1Aa-b. Basic dust/regolith properties	X	?		
1Ac. Airborne dust in dust storms	X			
1B. Atmospheric variations		X	X	
1Ca. Biohazard - dust	X			
1Cb. Biohazard - site specific				X
1D. Water for ISRU		X		X
2. Dust toxicology	X			
3. Atmospheric electricity		X	X	
4. Forward Planetary Protection	X		X	?
5. Ionizing radiation	X		X	
6. Terrain trafficability	X	?		?
7. Dust storms	X		X	

B. Objective. Conduct risk and/or cost reduction technology and infrastructure (T/I) demonstrations in transit to, at, or on the surface of Mars.

Technology validation on Mars flight missions and infrastructure emplacements are needed to reduce the risk and associated uncertainty inherent in new, unproven technologies and to reduce the cost of human Mars exploration. These demonstrations were chosen for Mars robotic flight missions based upon: (a) their high degree of interaction with the Mars environment, (b) their anticipated large leverage on human Mars mission architecture feasibility, and (c) uncertainty of whether Earth, Earth-orbit or lunar testing would supply sufficient data to reduce risk and cost, or increase performance of these systems.

Prioritization Criteria

The following criteria were used, assuming a series of robotic flight missions preceding the first human mission, to establish the priority of importance, when the validation should be done and whether or not the validation must be done on a Mars mission:

Priority: The anticipated magnitude of the risk and/or cost reduction of human missions to Mars.

Timing: The likely timing of the technology flight mission needed relative to the first human mission:

>Early: to influence architecture decisions (14 to 20 years prior)
>Mid: to influence mission and flight system design decisions (8 to 12 years prior)
>Late: to influence operability decisions (4 to 6 years prior)

Venue: Some technology validations could be accomplished less expensively and more comprehensively on other than Mars missions. Required technologies were therefore grouped according to whether they could best be performed (in decreasing order of cost) :

>a, At or in transit to/from Mars
>b. On the Moon
>c. In Earth orbit
>d. On Earth

Only those technology and infrastructure items requiring demonstration at Mars, 3a, are listed below as candidates for Mars human precursor missions. Those not requiring development and demonstration on Mars missions, 3b,c and d, are prioritized and described in the associated white paper. Additionally, a set of suggested near-term systems studies has been defined which will, when completed, enable refined definition and prioritization.

The following is a prioritized grouping 1 through 3; there is no sub-prioritization within the groups.

1A. Demonstration. Conduct a series of three aerocapture flight demonstrations:

70° sphere cone shape (robotic scale) to demonstrate aerocapture at Mars (Early).
New entry vehicle configuration suitable for human exploration (robotic scale) aerocapture at Mars (Mid).
New entry vehicle configuration suitable for human exploration (larger scale, end-to-end mission sequence) aerocapture at Mars (Late).

A primary challenge of flight missions to Mars is decelerating the incoming spacecraft. There are four primary options:

>Chemical propulsion
>Aerobraking
>Direct entry
>Aerocapture

Given the expected mass of proposed human missions, the estimated required mass of propellant to use Option #1 is large—this could lead to severe cost and operational problems. Aerobraking (Option #2) is the approach in which multiple orbits are used, extending over months, to gradually lower the apoapsis as was done on the Mars Global Surveyor (MGS) and Odyssey missions. The disadvantage of using this for human missions is that it takes considerable time, which is likely to be incompatible with other constraints on the proposed human mission. Direct entry (Option #3), as used by Pathfinder and Mars Exploration Rover (MER) missions, is at the extreme variation of aeroassist in which entry capsules are decelerated to the point of parachute deployment. However, the "g" forces involved in direct entry are excessive relative to human tolerance. Aerocapture (Option #4) is an intermediate form of aeroassist in which the vehicle is captured into low Mars orbit on the first atmospheric pass. Aerocapture requires accurate navigation, attitude control, and an effective aeroshape design. It is thought that it would take three successful flight missions to demonstrate this technology to a level of confidence that one would be prepared to use it on a human mission.

1B. Demonstration. Conduct a series of three in-situ resource utilization technology demonstrations:

(1) ISRU Atmospheric Processing (Early)
    1. Demonstrate acquisition and separation of atmospheric resources for life support and propulsion/fuel cell power systems. Demonstrate production and storage of critical mission consumables (oxygen, fuel, life support gases, etc.).
    2. Preliminary Experiment Requirements: Mass <25 kg; Power <50 W; Production rate >20 gm/day O_2 or O_2 fuel.
    3. Duration > 30 sols.

(2) ISRU Regolith-Water Processing (Early)
    1. Perform excavation of Mars regolith down to 2 meters and demonstrate regolith handling and transport capabilities to regolith processing unit. Perform *in situ* measurements to support design of robotic and human scale excavation systems. Perform regolith processing to extract and separate water from the regolith in multiple batches to obtain TBD ml of water. Perform *in situ* measurements of the water and volatiles released during processing. Perform processing on the water to produce oxygen, hydrogen, and methane.
    2. Requirement for mobility is dependant on results from '07 Phoenix and '09 Mars Science Laboratory (MSL) missions.
    3. Preliminary Experiment Requirements: Mass <30 kg; Power <50 W; Production rate >10 cm^3/day of water.
    4. Duration >15 sols.

(3) ISRU Human-Scale Application Dress Rehearsal (Late)
    1. The primary purpose of this demonstration would be to "buy down" risk by operating a complete end-to-end ISRU system (1/20 scale, duration 80 sols) culminating in a significant application such as producing propellants for a Mars Hopper, and the subsequent operation of the Hopper. An additional goal would be to make a first attempt to gather and utilize regolith for construction purposes, (e.g., radiation shielding, at a

       small scale). This would be closely coupled to excavation, material transport, and beneficiation techniques derived from Regolith-Water Processing demonstration.
2. Perform in conjunction with other human mission subsystems if possible, e.g., power system, fuel cell power system, oxygen/methane propulsion, landing hazard avoidance.
3. Preliminary Requirements: 0.25 to 0.05 kg of O_2-fuel/hr, Power 200 to 400 W.
4. Duration 80 sols min.

It is not yet known when, if at all, ISRU would be a part of human missions to Mars. However, *if ISRU is to be fully assessed,* these demonstrations are considered to be required (i.e., they are considered necessary to reach a decision to proceed or not with ISRU and constitute yes/no gates). These demonstrations would need to be carried out in parallel with Goal IVA Investigation #1D, which relates to discovery and characterization of the water deposits.

Currently there are no criteria for where human exploration would occur on Mars. If ISRU is a potentially enabling factor in affordability or safety, then resource location and feasibility would be a driver in site selection. Alternatively, if a negative decision regarding ISRU were to be made on the basis of relative cost or risk alternatives, then these demonstrations become moot.

In addition to the exploration-related questions in Goal IVA-1D, the practicalities of implementing ISRU are serially dependent upon two fundamental factors: 1). Is the potential resource "economically" accessible, meaning can enough be procured at acceptable cost, to more than offset the cost of bringing it from Earth? 2). Can sufficient supplies of the end-product be produced, stored and transferred with low risk? The most obvious uses of *in situ* resources are those that focus on obtaining resources that, if they have to be launched from Earth, are large mass, thus cost, drivers. Typically water, oxygen and fuels would be leading candidates for ISRU. Water has immediate use as such for crew life support and hygiene. It also would serve as a source for hydrogen and oxygen. The atmosphere of Mars contains carbon dioxide, traces of water vapor, and inert gases (useful for diluting atmospheric oxygen). The carbon dioxide could be a source of oxygen and could be reacted with hydrogen to make fuel.

1C. Demonstration. Demonstrate an end-to-end system for soft, pinpoint Mars landing with 10 m to 100 m accuracy using systems characteristics that are representative of Mars human exploration systems. (Mid)

Pinpoint landing systems for human exploration vehicles would be required for two reasons: first, safety and secondly, risk mitigation. It is likely that pre-positioned supplies and emergency abort systems would be located on Mars prior to arrival of humans. Landing near such assets would increase the likelihood of successfully accessing such in an emergency and would enhance mission efficiency in non-emergency situations. Second, it is likely that a site selected for human exploration would be selected because there is a specific science objective to be accomplished. If prepositioned assets could be sufficiently localized that landing in proximity would increase the probability of successful science accomplishment.

2A. Demonstration. Demonstrate continuous and redundant *in situ* communications/navigation infrastructure (Early). Deploy in full-up Precursor Test Mission (Late).

Mission safety and effectiveness would require the development of high band-width continuous and redundant communications. This support for human mission could be met, for example, by a pair of longitudinally-offset areostationary relay satellites.

2B. Demonstration. Investigate long-term material degradation over times comparable to human mission operations. (Mid)

Our current state of knowledge of the Mars environment is inadequate to confidently design essential space systems to be used on the Martian surface. These include EVA suits, habitats and ancillary systems, including mobility.

It would be essential to verify the capability of materials under consideration for Mars surface operations to tolerate long-term exposure (years) to Mars environmental phenomena using coupon, component, subsystem and system level tests on Mars. Phenomena include: radiation; temperature extremes and cycles; wind; atmosphere chemical and electromagnetic properties; regolith and dust chemical, mechanical, and electromagnetic properties; and Mars biology (if any). An LDEF (Long Duration Exposure Facility) should be considered (implied return of test samples).

3. Demonstration. Develop and demonstrate accurate, robust and autonomous Mars approach navigation. (Mid)

This is a mission safety item. It would provide a backup/replacement to Deep Space Network based terminal navigation for a mission time-critical event (e.g., Mars Orbit Insertion (MOI) or aerocapture).

C. Objective. Characterize the State and Processes of the Martian Atmosphere of Critical Importance for the Safe Operation of Both Robotic and Human Spacecraft (*not in priority order*).

This objective focuses on atmospheric processes of importance for the safe implementation of all spacecraft missions. These investigations would yield the critical information necessary to improve the likelihood of successful execution of missions in the Martian environment. Investigations would seek to characterize the atmosphere from the surface to 400 km altitude to support spacecraft landing, flight, aerocapture, aerobraking, long-term orbital stability, targeting of observations from orbit, and mission planning. Every effort should be made to accommodate instruments that would address these investigations on each spacecraft bound for Mars.

1. Investigation: Understand the thermal and dynamical behavior of the planetary boundary layer.
The lowest portion (<5km) of the atmosphere can be highly turbulent. Horizontal and vertical winds in this region represent a significant risk to spacecraft EDL and the operation of aerial platforms (e.g., balloons and aeroplanes). Turbulence also transports heat, so would also be a concern for thermal design. The turbulence is driven by thermal contrasts between the surface and the atmosphere, and mechanical interactions between the mean wind and the rough planetary surface. This investigation is designed to probe the connections between surface temperature,

the modification of surface and air temperatures by aerosol radiative heating, and the dynamical and thermal state of the lower atmosphere.

2. Investigation: Understand and monitor the behavior of the lower atmosphere (0-80km) on synoptic scales.

Mars exhibits significant seasonal and dramatic, episodic changes in the state of the atmosphere. Of great concern to the operation of surface and near-surface spacecraft, and for aerobraking, aerocapture, or aeropass maneuvers, is the onset of regional and global dust storms. Atmospheric dust loading and sedimentation modulates available solar energy at the surface and perturbs the density profile. The mechanisms of storm development are unknown at this time, and thus current models cannot predict them. Prediction would require significant additional study of these events, while early observation would enable mission engineers to prepare for the effects storms may have on mission activities. It is critical for support of Mars missions that continuously-operational, meteorological assets be maintained in Martian orbit to improve our understanding of the processes so that we could better predict atmospheric conditions at the time a spacecraft arrives and to make observations near the time of entry.

3. Investigation: Determine the atmospheric mass density and its variation over the 80 to 200 km altitude range.

Aerobraking, aerocapture, and aeropass operations use the atmosphere as a brake. These operations are safest when the drag imparted by the atmosphere can be accurately estimated ahead of time. Unfortunately, the Martian atmosphere exhibits substantial variations in density at a given geometric height due to the influence of the diurnal cycle, seasonal cycle, large-scale atmospheric circulation, and the propagation of waves. Mapping and understanding the processes responsible for the density variations in the upper atmosphere would be critical to high-precision spacecraft trajectory planning. For example, techniques for measuring and predicting the mass density on time scales of hours to days are key requirements for aerobraking. This information would also be important for mission planning (e.g., estimating the amount of fuel needed throughout mission life).

4. Investigation: Determine the atmospheric mass density and its variations at altitudes above 200 km.

Knowledge of mass density variations at high altitudes is important for precision targeting of orbital observations and for achieving long-term orbital stability required to meet planetary protection constraints.

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 is 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-present). Although as of 2008 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.