Scientific Goals, Objectives, Investigations, and Priorities: 2004

MEPAG (Mars Exploration Program Analysis Group)

July 16, 2004

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MEPAG (2004), Scientific Goals, Objectives, Investigations, and Priorities: 2003. Unpublished document, http://mepag.jpl.nasa.gov/reports/index.html.

PREAMBLE

This document updates the goals for Mars exploration as reported in *Scientific Goals, Objectives, Investigations, and Priorities*, edited by R. Greeley under the auspices of the Mars Exploration Program Analysis Group (MEPAG), which was based on discussions in 2000 and then published in 2001. The original goals document has helped shape priorities for the exploration of Mars. Recent successful missions and analysis of data from them and previous missions have led to the need to update the goals and objectives of Mars exploration. These revisions are done in the context of the Mars program and its relationship to the solar system exploration program as described in two recent documents--the Solar System Exploration Roadmap published by the NASA Office of Space Sciences (Code S) and the report published by the NAS National Research Council on New Frontiers in the Solar System: An Integrated Exploration Strategy (the so-called Belton committee report). The plan is that MEPAG will update the goals approximately every two years, corresponding to each Mars launch opportunity. As with the 2001 version, the goals were revised with extensive participation from the community of scientists and engineers active in Mars exploration.

The MEPAG Chair and steering committee appointed a subcommittee of the Mars Exploration Program Analysis Group (MEPAG) to carry out the revisions. The goals committee met through weekly teleconferences from mid-January 2003 leading up to the MEPAG meeting held February 26-27, 2003, in Tempe, Arizona. The committee identified important potential revisions during this time period and outlined a series of issues to discuss at the Tempe MEPAG meeting. Over 100 Mars experts, in addition to program managers, attended (see Appendix A). Participants discussed goals revisions in four breakout groups, corresponding to the four major goals for Mars exploration. A primary objective of the meeting was to identify central issues and questions to discuss with the entire Mars exploration community through an online survey that the Geophysical Laboratory of the Carnegie Institution of Washington managed and co-sponsored.. Over 300 individuals participated in the survey. A draft report was then circulated via e-mail to the Mars Community and discussed in detail during the September 10-11 MEPAG meeting in Pasadena, California. Over 150 scientists attended the Pasadena meeting, in addition to program managers. A revised document was circulated to the community again in October 2004, which resulted in insightful comments from about 40 individuals. Revised versions were circulated among members of the Goals Committee and the MEPAG Executive Committee, and approved by the MEPAG Executive Committee on 26 February 2004. Thus, the updated goals outlined here represent the consensus view of a broad cross section of the Mars exploration community.

Prioritization

The four goals described below are ***not*** listed in priority order. Each is important and they are interrelated. All must be pursued aggressively to understand the entire complex Mars system and how it operated through time, and to prepare for human exploration of Mars. However, within each goal, the objectives and investigations ***are*** listed in priority order. Table 1 lists the prioritization criteria. There is an enormous diversity of opinion among individual scientists regarding these priorities, and this intellectual diversity is extremely healthy for the Mars

Exploration Program. However, to help guide implementation and planning, we have put a major effort into establishing consensus statements of priority within each goal area.

Table 1. Prioritization criteria

1	Degree of alignment with the high-level objectives of NASA and the Office of Space Science, such as the Solar System Exploration Roadmap (2003), as well as guidance from external groups, including the Solar System Decadal Survey (2002).
2	Expected scientific value, if completed successfully
3	The feasibility of implementing the necessary measurements (includes cost, risk, and technology readiness of missions and instruments)
4	Any logic associated with the need to have investigations done sequentially

The online survey was particularly useful in establishing these priorities. No attempt was made to weight the priorities, but it is clear that the highest priority objective or investigation is not ten times more important than the lowest one.

As noted in the first MEPAG goals report, completion of all the investigations will require decades of studying Mars. Many investigations may never be truly complete (even if they have a high priority). Thus, evaluations of prospective missions should be based on how well the investigations are addressed. While priorities should influence which investigations are conducted first, they should not necessarily be done serially, as many other factors come into play in the overall Mars Program. On the other hand, we have tried to identify cases where one investigation should be done before another. In such cases, the investigation that should be done first was given a higher priority, even if in the long run the second investigation will be more important.

Future Studies

Technology development. Even a cursory reading of the goals, objectives, and investigations outlined below will show that several crucial technical capabilities need to developed. The most important of these are: (1) *Access to all of Mars*--high and low latitudes, rough and smooth surfaces, low and high elevations, plus precision landing. (2) *Access to the subsurface*, from a meter to hundreds of meters, through a combination of drilling and geophysical sounding. (3) *Access to time varying phenomena*; hence we need to be able to make some measurements over a long period of time (at least a Martian year). This applies particularly to climate studies. (4) *Access to microscopic scales* by instruments capable of measuring chemical and isotopic compositions and determining mineralogy and the nature of mineral intergrowths. Orbital and landed packages can make many of the high priority measurements, but others absolutely require that samples be returned from Mars. There is a strong consensus on the need for sample return missions. 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 has the potential to revolutionize our view of Mars. A full discussion of these issues is beyond the scope of this document, but we anticipate that they will be addressed by MEPAG and other scientific advisory committees in the near future.

<u>Measurements</u>. In the previous edition of this document (MEPAG, 2001), the measurements that could contribute to each investigation are listed. Within each investigation, MEPAG chose not to place the measurements in priority order, in large part because of the difficulty of establishing systematic and impersonal criteria for doing so. In planning for the current revision of the "Goals" document, at the Sept. 2003 MEPAG meeting MEPAG adopted the position that any listing of measurements related to an investigation would be as examples only. It is not MEPAG's intent to discourage the innovation of the science community in developing additional measurements that can contribute to these investigations as science and technology evolve in the future. Scientists and engineers working with this document are specifically ENCOURAGED to apply their creativity to improved measurement approaches.

In addition, an aspect of the measurements that will contribute heavily to forward program planning is the precision, accuracy, and detection limits required to achieve the stated objectives.

These additions are planned for a future online addendum to this Scientific Goals, Objectives, Investigations, and Priorities: 2003 document. We anticipate that in the addendum the measurements will be listed as examples, not as specific requirements. The consensus view is that such detailed requirements ought to be defined by Science Definition Teams and Payload Science Integration Groups for program missions and by the Science Teams for Scout missions.

I. GOAL: DETERMINE IF LIFE EVER AROSE ON MARS

Determining if life ever arose on Mars is a challenging goal. The essence of this goal is to establish that life is or was present on Mars, ***or*** if life never was present to understand the reasons why Mars did not ever support its own biology. A comprehensive conclusion 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 aspects: 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 high-level scientific objectives. A critical means to achieve both of these 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. To some degree, these overarching 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 here.

To spur development of flight technologies required to achieve these objectives there must be an increase in the number of terrestrial ground truth tests for instrumentation on samples of relevance to Mars exploration. This aids the development of instrumentation directly while maintaining pressure to improve detection limits. In support of such tests, suites of highly characterized samples from relevant environments should be identified and curated for laboratory studies.

In order to prioritize the objectives and investigations described here, we need to be specific about the prioritzation criteria. In broad perspective, Objective C ("test for life") is 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. 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.

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 stated at a planetary scale, we know from our experience on Earth that we should expect that different 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 will 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 <u>definitively</u> which combination of factors must simultaneously be present to constitute a Martian habitat. Until then, "habitability" will need to describe the <u>potential</u> 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 three 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) can be pursued 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.

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. <u>Investigation:</u> 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 potential distributions, 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 the existence of the Martian perennial polar caps, the geomorphic evidence of present day ground ice and past fluvial discharges, and by the Mars Odyssey GRS detection of abundant hydrogen (as water ice and/or hydrous minerals) within the upper meter of the surface in both hemispheres, at mid-latitudes and above. To investigate current habitability, the identity of the highest priority H_2O targets, and the depth and geographic distribution of their most accessible occurrences, must be known with sufficient precision to guide the placement of 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 H_2O targets for the identification of potential habitats are: (1) liquid water -- which may be present in as pockets of brine in the near-subsurface, in association with geothermally active regions (such as Tharsis and Elysium), as super-cooled thin films within the lower cryosphere, and beneath the cryosphere as confined, unconfined, and perched aquifers. (2) Massive ground ice – which may preserve evidence of former life and exist in a complex stratigraphy beneath the northern plains and the floors of Hellas, Argyre, and Valles Marineris, an expectation based on the possible former existence of a Noachian ocean, and the geomorphic evidence for extensive and repeated flooding by Hesperian-age outflow channel activity. (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 result in episodic or persistent occurrences of liquid water associated with climate change, local geothermal activity and the presence of basal lakes.

2. **<u>Investigation:</u> 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 understanding at global scale the abundance, form, and distribution of water in Mars' geologic past. A first-order hypothesis to be tested is that Mars was at one time warmer and wetter than it is now. This can 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. It is entirely possible that Mars had life early in its history, but that life is now extinct.

3. **<u>Investigation:</u> 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 of biological important elements and the phases in which they are contained, will 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 expounded upon here. Nitrogen, phosphorous and sulfur are critical elements for life (as they are 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. <u>Investigation:</u> 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 is probably 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 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. Understanding the origin of organic carbon is as important as identifying it.

We assume that extraterrestrial life would be based on carbon chemistry. Although this assumption may subsequently need to be relaxed, 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 can 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, sugars and sugar derivatives.
Prebiotic/protobiotic molecules from abiotic process on Mars	Amino acids, purines and pyrimidines, polycyclic aromatic hydrocarbons, chain hydrocarbons, fatty acids, 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 like organisms – from Earth	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.

1. <u>Investigation:</u> 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 is 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 avoid 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. **<u>Investigation:</u> 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 among them is 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 can also reveal critical habitability information because they can record climate records. 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. **<u>Investigation:</u> 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. **<u>Investigation:</u> 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 regolith 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 if no organics are found on the surface. Potential measurements include identifying species and concentrations of 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, the Objective itself does not halt upon a positive or negative answer. In the eventuality of a positive answer there would be the need to characterize whatever life form is discovered, as well as its origins and reason for surviving on Mars. In the case of a negative answer, then further characterization of why life did not start 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 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 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 may be more practical to pursue first. Remote sensing techniques addressing investigation 4 also have much lower to no contamination issues. Investigations 1-4 are largely *in situ* investigations that are best conducted in those habitable environments identified in A1.

A 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 exciting proposals for suites of observations will be seriously considered in choosing investigations to evaluate the past or present presence of life.

1. <u>Investigation:</u> 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 instruments must be developed for cleaning and monitoring of space craft contamination. Instruments must be required to produce procedural blanks that allow accurate measurements by that instrument to be undertaken. 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 may 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. <u>Investigation:</u> 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 may 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. <u>Investigation</u>: 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 may include micron to nanometer imaging and chemical analysis of crystals or morphological characterization of sedimentary lamination.

4. <u>Investigation:</u> Identify temporal chemical variations requiring life.

Extant life may be active, producing observable temporal 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 capable of being contaminated include appropriate methods to identify and exclude forward contamination as a source of the signatures being monitored. Example measurements may 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 extremely important 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. 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 recent recommendation of the Solar System Exploration Survey [2002], which calls out the clear need for Mars upper atmosphere measurements to properly characterize current volatile escape rates. The Objectives below are given in priority order. Objective A is crucial to understanding the present state of the entire atmospheric system (from the surface-atmosphere boundary to the exosphere). It forms the baseline for interpreting past climate on Mars. Objective B focuses upon specific investigations that will measure key indicators of the past climate of Mars. Finally, Objective C highlights mission critical atmospheric measurements that will reduce mission risk and enhance overall science return, benefiting all future missions to the planet. No attempt has been made to prioritize these risk mitigation and engineering related measurements since all are important.

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

Our understanding of the composition and dynamics of the present Martian atmosphere is the basis for understanding past climate on Mars. Investigations of both the upper and lower atmosphere are essential because they are one large, interconnected system. Measurements of both atmospheric regions 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, requires 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

Landed missions can provide direct *in situ* measurements and are the best way to measure near-surface water vapor, winds, and other variables that control the exchange of volatiles and dust between the surface and atmosphere.

Orbital missions can 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, 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 will 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. These observations will 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. These data will 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 are also needed to investigate the mean state and variability of the neutral and plasma environment above ~80 km. These data will improve our understanding of the coupling of the Martian 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 is 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 reemphasizes the need for a ground-to-exosphere approach to monitoring the Martian atmospheric structure and dynamics.

2. Investigation: Search for micro-climates.

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 requires a global search for sites based on local surface properties (e.g., geomorphic evidence, topography, local thermal properties, albedo) or changes in volatile (especially H_2O) distributions.

3. Investigation: Determine the production/loss, reaction rates, and global 3-dimensional distributions of key photochemical species (O_3, H_2O_2, CO, OH, CH_4, SO_2, etc.), and their interaction with surface materials.

This investigation necessarily involves study of both the lower and upper atmosphere. Surface sinks and sources and lower atmospheric distributions are 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 over surface fluxes of major species. This investigation requires 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.

B. Objective : Characterize Mars' Ancient Climate and Climate Processes Through Study of the Geologic and Volatile Record of Climate Change (investigations in priority order)

Understanding the ancient climate and climate processes on Mars requires interdisciplinary study of the Martian surface and atmosphere. The investigations described below focus on quantitative measurements (concentrations and isotopic compositions) of important atmospheric gases in the atmosphere and trapped in surface materials. It also requires study of geologic features to search for the record of past climates.

1. Investigation: Determine the stable isotopic, noble gas, and trace gas composition of the present-day bulk atmosphere.

These 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. This investigation requires high-precision isotopic measurements of the atmosphere.

2. <u>Investigation:</u> **Determine the rates of escape of key species from the Martian atmosphere, their correlation with seasonal and solar variability, their modification by 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 will provide crucial constraints to atmospheric evolution models that extrapolate these rates to determine past climates. This investigation requires 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 requires more thorough and higher-resolution measurements of crustal magnetic fields.

3. <u>Investigation:</u> **Determine how the stable isotopic, noble gas, and trace gas composition of the Martian atmosphere has evolved through time.**

These provide quantitative constraints on the evolution of atmospheric composition and on the source and sinks of water and other major gas inventories. Requires high precision dating and isotopic measurements of Martian meteorites and returned samples, and high precision *in situ* measurements of samples on and beneath the surface (e.g.,polar layered-deposits or strata exposed in Valles Marineris).

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

This investigation centers 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, large impacts, episodic volcanism or outflow channel activity). These provide the basis for understanding the extent, duration (e.g., gradual change or abrupt transition), and timing of past climates on Mars. This investigation requires determining sedimentary stratigraphy and the distribution of aqueous weathering products.

5. <u>Investigation</u>**: Characterize the stratigraphic record of climate change preserved in polar layered deposits, residual ice caps, other climate-modulated deposits of H_2O, CO_2, and dust found elsewhere on the planet.**

The presence of extensive layered deposits at both polar and mid-latitude 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 (i) the relative and absolute ages of the layers, (ii) their thickness, extent and continuity, (iii) their petrologic/geochemical characteristics (including both isotopic and chemical composition), and (iv) 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. Addressing this investigation requires high-resolution imaging, *in situ* measurements of layer properties, and absolute ages determined either *in situ* or from returned samples.

C. Objective: Characterize the State and Processes of the Martian Atmosphere of Critical Importance for the Safe Operation of Spacecraft (no priority order).

This objective focuses on atmospheric processes of importance for the safe implementation of spacecraft missions. These investigations will yield the critical information necessary to improve the likelihood of successful execution of missions in the Martian environment. Investigations 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 address these investigations on each spacecraft bound for Mars.

1. <u>Investigation:</u> 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 Entry, Descent, and Landing (EDL) and the operation of aerial platforms (balloons and aeroplanes). The turbulence also transports heat, so is 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. <u>Investigation:</u> 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. The mechanisms of storm development are unknown at this time, and thus current models cannot predict them. Prediction will require much further study of these events, while early observation will greatly mitigate them. 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 can better predict atmospheric conditions at the time a spacecraft arrives and to make observations near the time of entry.

3. <u>Investigation:</u> 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 is 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 is also 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.**

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

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. Thus there are compelling scientific motivations for the study of the surface and interior of the planet in its own right. The recent heightened interest in the possibility of life on Mars provides additional emphasis for these investigations. Geology informs virtually every aspect of the study of conditions conducive to the origin and persistence of life, and the study of the interior provides important clues about a wide range of topics, including the early history of Mars, sources of volatiles, and geothermal energy.

The unique aspect of Mars, which in many ways make it appear more Earth-like and sets it apart from the other planet, is evidence of the presence and activity of liquid water at or near the surface. 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). Thus, an emphasis on water is a logical framework within which to explore the planet.

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

The Martian surface contains the record of all the processes that shaped it, from initial differentiation to volcanism, to modification by impact, wind, and water. Understanding that record will help us understand the total inventory and role of water on Mars, regions likely to have been habitable to life, the processes involved in surface-atmosphere interactions, and the thermal history of the planet.

1. **Investigation: Determine the present state, 3-dimensional distribution, and cycling of water on Mars.**

Water is an important geologic material 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 on Mars requires global observations using subsurface sounding and remote sensing, coupled with detailed local and regional sounding and measurements.

2. **Investigation: Evaluate fluvial, subaqueous, and subaerial sedimentary processes and their evolution** and distribution **through time, up to and including the present.**

Fluvial and lacustrine sediments are likely sites to detect traces of prebiotic compounds and evidence of life. Sediments also record the history of water processes on Mars. Polar layered terrains in particular may preserve a unique record of climate history. Eolian sediments record a combination of globally-averaged and locally-derived fine-grained sediments and weathering products. Understanding sedimentary processes requires knowledge of the age, sequence, lithology, and composition of sedimentary rocks (including chemical deposits, such as those observed at Meridiani); the rates, durations, environmental conditions, and mechanics of weathering, cementation, and transport processes; and the fluvial and lacustrine record preserved in the morphology of the surface and shallow subsurface.

3. **Investigation: Calibrate the cratering record and absolute ages for Mars.**

The evolution of the surface, interior, and surface of Mars, as well as the possible evolution of life, must be placed in an absolute timescale, which is presently lacking for Mars. Developing this chronology requires determining the absolute ages of geological units of known crater ages.

4. **Investigation: Evaluate igneous processes and their evolution through time, including the present**.

This investigation includes the broad range of igneous processes including, for example, volcanic outgassing and volatile evolution. In addition to dramatically molding the surface of the planet, volcanic processes are the primary mechanism for release of water and atmospheric gasses that support potential past and present life and human exploration. Sites of present day volcanism, if any, may be prime sites to investigate for life. This investigation requires global imaging, geologic mapping, techniques for distinguishing igneous and sedimentary rocks, evaluation of current activity.

5. **Investigation: Characterize surface-atmosphere interactions on Mars, including polar, eolian, chemical, weathering, and mass-wasting processes.**

The focus of this investigation is on processes that have operated for the last million years as recorded in the upper 1 m to 1 km of Mars. Understanding present geologic, hydrologic, and atmospheric processes is the key to understanding past environments and possible locations for near-surface water. Knowing the morphology, chemistry and mineralogy of both near surface rocks and alteration products is essential for calibrating remote sensing data. This study also has strong implications for resources and hazards for future human exploration. It requires orbital remote sensing of surface and subsurface, and direct measurements of sediments and atmospheric boundary layer processes.

6. **Investigation: Determine the large-scale vertical structure and chemical and mineralogical composition of the crust and its regional variations. This includes, for example, the structure and origin of hemispheric dichotomy.**

The vertical and global variation of rock properties and composition record formative events in the planet's early history constrain the distribution of subsurface aquifers, and aid interpretation of past igneous and sedimentary processes. Determining these structures requires global and local remote sensing and subsurface sounding, detailed geologic mapping, and determination of mineralogy and composition of surface material.

7. **Investigation: Document the tectonic history of the Martian crust, including present activity.**

Understanding the tectonic record 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. This investigation requires geologic mapping using global topographic data combined with high-resolution images, magnetic and gravity data, and seismic monitoring.

8. **Investigation: Evaluate the distribution and intensity of hydrothermal processes through time, up to and including the present.**

Hydrothermal systems are thought to be the connected with 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 Martian soil. Deposits from hydrothermal systems have the potential to record the history of the biosphere and crust-atmosphere interactions throughout Martian history. Assessing hydrothermal processes requires knowledge of the age and duration of the hydrothermal system, the heat source, and the isotopic and trace element chemistry and mineralogy of the materials deposited.

9. **Investigation: Determine the processes of regolith formation and subsequent modification, including weathering and diagenetic processes.**

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 regolith formation and modification requires quantitative measurement of mineralogy, chemistry, and physical parameters of the surface and shallow subsurface.

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

The magnetization of the Martian crust is poorly understood, but is intimately related to the igneous, thermal, tectonic and hydrologic history of the crust. Addressing this problem requires high-resolution mapping of the magnetic field and knowledge of the mineralogy and magnetization of the surface.

11. **Investigation: Evaluate the effect of impacts on the evolution of the Martian crust.**

Impact is arguably the most important of the processes shaping the crust and surface of Mars. A firm understanding of effects of impacts on the structural, topographic and thermal history is a prerequisite for any broad understanding of the Martian crust and surface. Understanding impact effects requires geologic mapping using global topographic data combined with high-resolution images and remote sensing.

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

Investigating the internal dynamics and structure of Mars contributes to understanding the bulk chemical composition of Mars, the evolution of its crust and mantle, and the origin of its magnetic field and the nature and origin of the minerals that record the field. These are fundamental aspects of Mars that for the basis of comparative planetology.

1. <u>Investigation:</u> Characterize the structure and dynamics of Mars' interior.
Understanding the structure and dynamical processes of the deep interior is fundamental for understanding the origin and evolution of Mars in general, and its surface evolution and the release of water and atmospheric gasses in particular. For example, the thickness of the crust and the size of the core provide strong constraints on the bulk composition of the planet and the manner in which it differentiated. This investigation requires mineralogic, isotopic, seismic, magnetic, gravity and heat flow data bearing directly and indirectly on interior structure and processes.

2. <u>Investigation:</u> 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 its early atmosphere and for the shielding of the surface from incoming radiation and the possible evolution of life. Requires high-precision, high-resolution global, regional, and local magnetic measurements, as well as mineralogic, isotopic, seismic, gravity and heat flow data bearing on interior structure and processes.

3. <u>Investigation:</u> 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 requires measurements of the internal structure, thermal state, surface composition and mineralogy, and geologic relationships.

4. <u>Investigation:</u> Study the structure, dynamics and composition of Phobos and Deimos as indicators of the formation and early evolution of Mars.
Dynamical arguments suggest that the origin of Phobos and Deimos are intimately connected with that of Mars itself. The dynamics of their orbits may provide constraints on the structure of Mars' interior and their composition may provide further clues to its evolution. This investigation is not aimed at detailed studies of Phobos and Deimos, but rather at using their properties to constrain the composition and evolution of Mars.

GOAL IV: 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 robotic Mars Exploration Program missions is charting the course for future human exploration of Mars. Goal IV of the MEPAG document differs from the previous Goals in that it addresses science 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 (Objective A), and the demonstrations of critical technologies that must be validated in the actual Martian environment (Objective B).

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 will be used in part to acquire measurement data for the purpose of reducing cost and risk of future human exploration missions, to perform technology and flight system demonstrations for the purpose of reducing cost and risk of future human exploration missions, and to deploy infrastructure to support future human exploration activities.

The Nation’s Vision for Space Exploration is focusing additional attention to future human exploration goals and the relationship between robotic and human exploration missions. It is expected that the issues described under this Goal will evolve over the coming months and years, and will expand upon the following objectives to include additional measurements, technology demonstrations and infrastructure requirements.

A. Objective: Acquire Martian environmental data sets (investigations listed in priority order)

Scientist-astronauts on the Martian surface will add a new dimension of discovery and exploration to a Mars science program. The safety and productivity of these human explorers requires an understanding of the hazards present in the Martian environment, and the design of systems to mitigate them. Quantitative models of the Martian atmosphere, surface, and subsurface will increase the safety of human missions, and help to identify resources that may greatly decrease the cost of human exploration.

1. <u>Investigation</u>: **Determine the ionizing radiation environment at the Martian surface and the shielding properties of the Martian soil and atmosphere.**

The propagation of high energy particles through the Martian atmosphere must be understood, and the measurement of secondary particles must be made at the surface to determine the buffering (or amplifying) effects of the Martian atmosphere, to understand the backscatter effects of the regolith, and to validate radiation transport models for the Martian atmosphere. Simultaneous monitoring of the ionizing radiation from Mars' orbit and at the surface to determine the shielding component of the atmosphere is desirable. Soil and dust from the Martian surface offer a readily available source of shielding material. The properties of the soil that contribute to its shielding effectiveness must be quantified to establish the transport of high-energy particles. UV is also a source of ionizing radiation and knowledge of the UV spectrum at the surface is required.

2. **<u>Investigation:</u> Determine the chemical and toxicological properties of Martian surface materials.**

Measurements related to toxicity and reactivity are needed to develop hazard mitigation strategies to ensure the safety of human explorers on the Martian surface. Surface materials include all soil, dust, ice, water or atmospheric aerosols that human explorers may come in contact with. Measurements require *in-situ* surface and subsurface sample analysis or return of environmentally preserved samples if *in-situ* measurement is not possible. Multiple sites should be sampled including designated human missions sites.

3. **<u>Investigation:</u> Measure atmospheric parameters and variations that affect atmospheric flight and surface systems.**

Upper level atmospheric parameters play a critical role in planning safe entry, descent, and landings for human missions. Knowledge of near-surface (boundary layer) properties is needed for safe design and operation of human surface systems.

4. **<u>Investigation:</u> Understand the characteristics, accessibility, and distribution of water resources in regolith, and Martian groundwater systems.**

Water is a principal resource to humans, and a critical element in surface operations. Measurements require geophysical investigations and *in-situ* sample analysis.

5. **<u>Investigation:</u> Measure the engineering properties of the Martian surface, and characterize topography, and other environment characteristics of candidate outpost sites.**

Soil and surface engineering data are needed to eliminate uncertainty in the design of landers, mobile systems, EVA suits and tools, and power and thermal systems. Also, site certification for human outposts requires a set of data about the specific site that can best be performed by surface investigations. Measurements require *in-situ* analysis at individual, specific sites.

6. **<u>Investigation:</u> Determine electrical effects in the atmosphere**.

Mixing dust and sand of various compositions and sizes has the potential to develop electric charge, and in “dust devils” and dust storms to create large electric fields. Electrostatic charging and associated electrical discharges pose possible hazards to surface operations through unanticipated arcing, dust adhesion, and radio frequency (RF) contamination (charge grain/antenna incidence). These effects become particularly significant in a low pressure (low Paschen breakdown) atmosphere.

B. Objective: Conduct in-situ engineering science demonstrations (investigations listed in priority order)

Technology validation and engineering science demonstrations are needed to reduce the risk inherent in new, unproven technologies. Demonstrating the performance of these technologies in the Martian environment prior to their use on human flights will reduce risk and improve confidence in mission safety. The investigations listed in this section were chosen because of their high degree of interaction with the Martian environment, and because of the uncertainty of whether analog testing would supply sufficient data to reduce risk and cost, or increase performance of these systems.

1. Investigation: Demonstrate terminal phase hazard avoidance and precision landing.
System testing is necessary to decrease the risks associated with soft landing, and to enable pinpoint landing. Validation requires flight demonstration during terminal descent phase.

2. Investigation: Demonstrate mid-range lift-to-drag (mid-L/D) aeroentry /aerocapture vehicle flight.
Mid-L/D (0.4-0.8) aeroentry shapes will be required as payload masses increase. Mid-L/D aeroassist increases landed vehicle payload performance and landing precision. Validation requires flight demonstration during aeroentry phase of the mission. Flight validation must be performed with a vehicle size that yields test results scalable to vehicle performance for a human mission.

3. Investigation: Demonstrate high-Mach deployable aerodecelerator performance.
Higher ballistic coefficient entry vehicles will result from flying more massive landers. This will result in higher parachute deployment speeds, which are beyond the qualification of current parachute systems. Validation requires flight demonstration during Mars entry phase.

4. Investigation: Demonstrate in-situ propellant (methane, oxygen) production (ISPP) and in-situ consumables production (ISCP) (fuel cell reagents, oxygen, water, buffer gasses).
The potential for Martian resources to be converted to useable products needs to be evaluated. Components that directly interact with the Martian environment should be evaluated in a relevant environment to determine their performance. End-to-end performance may be evaluated by acquisition of local resources, processing, storage, and potential use of end products. Validation requires process verification with experiments performed *in-situ* to reduce both engineering design uncertainties and the program risk of incorporating this technology into future robotic/human missions.

5. Investigation: Demonstrate in-situ water collection and conditioning using surface resources.
Water concentrations in the Mars surface regolith, and concepts to collect and separate the water, should be evaluated in a relevant environment to determine their performance. Hardware and investigation objectives can be performed separately or combined and integrated with other regolith characterization experiments. Validation requires process verification with *in-situ*

experiments to reduce both engineering design uncertainties and the program risk of incorporating this technology into future robotic/human missions**.**

6. <u>Investigation</u>: Demonstrate access to subsurface resources.

The Martian subsurface contains potential resources (e.g., water) as well as potentially important scientific samples. Drilling or other techniques for accessing the subsurface need to be developed. Validation requires *in-situ* demonstration.

7. <u>Investigation:</u> Demonstrate plant growth in the Martian environment.

Demonstrate the ability of the Martian environment (soil, solar flux, radiation, etc.) to support life, such as plant growth, to support future human missions. Validation requires *in-situ* measurements and process verification.