Part 2:

Scientific Goals, Objectives, Investigations, and Priorities

by the Mars Exploration
Payload Assessment Group

Chair: Ron Greeley

This document is the result of a series of meetings and workshops (Table 1) collectively involving more than 110 individuals from the Mars community with representatives from universities, research centers and organizations, industry, and international partners for Mars exploration. Although the effort was focused through activities of the *Mars Exploration Payload Analysis Group (MEPAG,* chaired by R. Greeley), participation has been much wider, as indicated in Appendix 2, and builds on the work of the *Mars Expeditions Science Group* led by D. McCleese.

Initial discussions and earlier drafts of this document were centered on Mars Program goals related to *Life, Climate, and Resources,* with the crosscutting theme of "follow the water." It generally has been recognized that geological sciences and investigations that would lead to exploration by humans were incorporated in the "Resources" goal. The consensus reached in August 2000 was that the program **goals** should be recast as *Life, Climate, Geology, and Preparation (for Human Exploration),* with "water" remaining a crosscutting theme.

Table 1. Meetings and workshops used to develop the scientific goals, objectives, investigations, and measurements for Mars exploration.

Group	Date	# of participants
MAST	11–12 Jan. 2000	5
MEPAG/MPRG	22–24 Feb. 2000	101
MAST	6 Jun. 2000	8
MAST	weekly/semi-monthly telecons	3-6
MEPAG	8-10 Aug. 2000	49
MAST	1 Nov. 2000	12
MEPAG	15-17 Nov. 2000	65

MAST (*Mars Ad hoc Science Team)*
MEPAG *(Mars Exploration Payload Analysis group)*
MPRG (*Mars Peer Review Group;* one-time meeting)

The **objectives**, **investigations,** and **measurements** needed for the exploration of Mars have been formulated and prioritized by subgroups of participants focused on the four principal exploration goals. Individuals were free to participate in more than one group during workshops and there were intergroup critiques of the objectives, investigations, and measurements, the results of which are reflected here.

Within each objective, the investigations are listed in priority order as determined within each discipline. There was no attempt to synthesize the overall set of investigations, but it was recognized that synergy among the various goals and objectives could alter the priorities in an overall strategy. Completion of all the investigations will require decades of effort. It is recognized that many investigations will never be truly complete (even if they have a high priority) and that evaluations of missions should be based on how well the investigations are addressed. While priorities should influence the sequence in which the investigations are conducted, it is not intended that they be done serially, as many other factors come into play in the overall Mars Program. An evaluation of the *technology development* needed to conduct each measurement is given as "none," "some," or "much."

I. GOAL: DETERMINE IF LIFE EVER AROSE ON MARS

Objectives A and B are regarded as co-priorities and should be addressed in parallel. Although the investigations and measurements within these objectives are generally ordered by progression from orbital science to surface exploration to sample return, orbital missions should be interleaved synergistically with in situ science and sample return to optimize selection of landing sites and samples for study.

A. Objective: Determine if life exists today.

1. Investigation: **Map the 3-dimensional distribution of water in all its forms.** Zones of liquid water in the subsurface provide the most likely environments for extant life on Mars. In the absence of life, such environments could also sustain prebiotic chemistry of interest for understanding the origin of life on Earth. **Requires global remote sensing of water in all its forms to identify the locations, phases, and, if possible, temporal (seasonal) changes in near-surface water budgets.**

Measurements

a. Global search and mapping of water to 10 km depth at a horizontal spatial resolution of 100 m and a vertical resolution of 10 m for the upper 500 m and a few hundred meters below that depth; must be able to distinguish CO_2 clathrate, ice, and liquid water. *Technology development needed: Modest.*

2. Investigation: **Carry out in situ exploration of areas suspected of harboring liquid water.** Results will be used to validate remote sensing observations and to explore for life or prebiotic chemistry. **Requires subsurface drilling, in situ instrumentation to detect water in all its forms (inclusive of microenvironments; e.g., brine films), CO_2 clathrate, and to analyze rocks, soils, and ices for organic compounds or to detect life.**

Measurements

a. For at least 20 stations at 4 targeted sites (based on remote sensing), conduct in situ geophysical and chemical (e.g., "sniffers") searches for subsurface water and other volatiles (e.g., carbon dioxide and reduced gases like methane and ammonia) over km^2 surface areas. *Technology development needed: Some.*

Note: The following two investigations (b and c) could be done in parallel.

b. For at least 3 targeted sites, drill initially to 2 m depth and later to 100s of meters and conduct experiments to detect thin films (~50 μm) of water and major and trace volatiles in ices (e.g., carbon dioxide reduced gases such as methane and ammonia) in surface and subsurface soils and atmospheric measurements of trace gases. *Technology development needed: Much (subsurface drilling).*

c. For at least 3 targeted sites, drill initially to 2 m depth and later to 100s of meters and search for biogenic elements (e.g., C, H, N, O, P and S) and their oxidation states, organic compounds (e.g., amino acids, proteins, carbohydrates, lipids, nucleic acids, etc.) and chirality. *Technology development needed: Much (subsurface drilling to 10 m and deeper; in situ detection of organics).*

3. Investigation: **Explore high-priority candidate sites (i.e., those that provide access to near-surface liquid water) for evidence of extant (active or dormant) life forms.** Although the means for in situ life detection is poorly defined, basic measurements are likely to include both in situ analysis and laboratory-based analysis of pristine (uncontaminated or unaltered) samples to search for organic and inorganic biosignatures, metabolic activity, isotopic fractionation, disequilibrium chemistry, etc. **Requires in situ life detection experiments on subsurface materials and laboratory analysis of returned core samples**.

Measurements

Note: 3a. could be done in conjunction with 2b and 2c.

a. In situ experiments for at least 3 targeted sites to detect extant or dormant life in soils and ices; could include the search for complex organic compounds at a ppb detection limit (e.g., amino acids, proteins, carbohydrates, lipids, nucleic acids, etc.), chirality, fluorescent staining and microscopy for specific biomolecules, metabolic products, methods for nucleic acid amplification, and, potentially, culture-based methods to detect growth and metabolism, etc. Methods should include a means for the detection of false positives (i.e., for assessing forward contamination). *Technology development needed: Much.*

b. Sample return (0.5–1.0 kg each from 3 diverse sites) for laboratory-based life detection experiments, such as advanced GC-MS analysis of powdered rocks, microscopy (e.g., light, fluorescent and laser confocal, TEM, SEM, X-ray tomography, laser Raman imaging, etc.) of rock surfaces and interiors to explore for chemical (isotopic, trace elemental, etc.), morphological and mineralogical biosignatures and methods to search for metabolic activity, disequilibrium chemistry, etc. *Technology development needed: Modest for measurement technologies; much for sample containment assurance.*

4. Investigation: **Determine the array of potential energy sources available on Mars to sustain biological processes.** Biological systems require energy that could come from a variety of sources and use a wide variety of transudation mechanisms.

Potential sources include chemical redox, pH gradients, geothermal heat, radioactivity, and incident radiation (sunlight). **Requires orbital mapping, in situ investigations, and sample return.**

Measurements

a. Remote sensing to map biogenic elements (e.g., C, H, N, O, P, and S) and their oxidation states, transition metals, and aqueous minerals [including carbonates, fixed inorganic nitrogen, phosphates, sulfates, halides, metallic oxides (e.g., hematite) and sulfides, clays, etc.]. Need coverage at all high priority sites (5% of planet's surface) that show geomorphic evidence for prolonged hydrological activity. Local coverage of all high-priority sites at a minimum spatial resolution of 100 m (mineral mapping) and a few km (for elemental mapping) at a spectral resolution of 2.5 nm over the range 1.0–5.0 microns. *Technology development needed: Some for halides and metal oxides; Much for elements.*

b. Thermal infrared remote sensing to search for local geothermal "hot-spots" in the shallow crust at a spatial resolution of 100 m. *Technology development needed: None.*

c. Remote sensing to search for point-source concentrations of volatiles (e.g., gas-emitting vents, or "fumeroles") using near and mid-IR spectroscopy at a spatial resolution of a few km. *Technology development needed: Some.*

d. In situ investigations to search for biogenic elements (e.g., C, H, N, O, P, and S) and their oxidation states, transition metals, and aqueous minerals [including carbonates, fixed inorganic nitrogen, phosphates, sulfates, halides, metallic oxides (e.g., hematite) and sulfides, clays, etc.] and evidence of chemical disequilibrium, including gradients and redox chemistry, pH, temperature, radiation, etc. *Technology development needed: Modest.*

e. In situ investigations to explore for specific classes of organic molecules (derivatives of chromophores, including porphyrins and their precursors, pyroles) that are known to be important for energy-transduction in living systems on Earth. *Technology development needed: Modest.*

f. Returned samples (minimum of 0.5–1.0 kg from each of 3 diverse sites) for mineralogical and geochemical characterization (potential analyses include X-ray diffraction, X-ray tomography, X-ray fluorescence, ICP-MS, etc). *Technology development needed: Much.*

5. Investigation: **Determine the nature and inventory of organic carbon in representative soils and ices of the Martian crust.** Carbon is a fundamental building block for life. It may exist within soils and ices in a variety of biotic and abiotic forms. Its distribution would exert a primary control on where and how life could develop. **Requires in situ exploration and sample return.**

Measurements

a. In situ analysis of surface and subsurface (to a few meters depth) soils and ices to search for organic compounds (e.g., amino acids, proteins, carbohydrates, lipids, nucleic acids, etc.) and their concentration gradients, and to detect seasonal fluxes in carbon dioxide and reduced gases (e.g., methane, ammonia, etc.). *Technology development needed: Much (in situ organics detection; Much for subsurface drilling).*

b. Returned samples (0.5–1.0 kg from each of 3 diverse sites) to analyze soil and rock cores for organic compounds, including molecular structures, stable isotope compositions (e.g., C, H, N, O, P and S) and their oxidation states. Must also apply methods for assessing sample containment assurance and for detecting false positives (i.e., forward contamination). *Technology development needed: Much.*

6. Investigation: **Determine the distribution of oxidants and their correlation with organics.** Results from Viking suggest that unknown oxidation processes in Martian soils are responsible for the selective destruction of organic compounds. The distribution of oxidants on Mars is likely to have been a controlling factor in determining where, when, and how life might have developed. **Requires instrumentation for determining the elemental chemistry and mineralogy of surface and subsurface samples.**

Measurements

a. In situ experiments at one well-targeted, low-latitude site and 1.0-meter depth to determine gradients in the concentration of electrochemically active species (e.g., oxygen and hydrogen) at ppm concentrations and susceptibility of metallic and organic compounds to oxidation and to determine the spatial and depth distribution of specific classes of oxidizing compounds (e.g., peroxides, etc.). *Technology development needed: Modest.*

B. Objective: Determine if life existed on Mars in the *past*.

1. Investigation: **Determine the locations of sedimentary deposits formed by ancient and recent surface and subsurface hydrological processes.** Such deposits provide the best repositories for preserving a fossil record of ancient Martian life. **Requires global mapping of geomorphology and mineralogy, followed by in situ "ground truth" of mineralogy and geochemistry for remote sensing and to assist the selection of landing sites and samples for return to Earth.**

Measurements

a. Global remote sensing in the visible at 15 m spatial resolution to search for geomorphic features (e.g., paleolake basin shoreline deposits, fluvial-deltaic deposits, hydrothermal spring mounds, etc.) indicative of aqueous sedimentary processes. *Technology development needed: None.*

b. Global mapping in the mid-IR (wavelength range: 5–14 µm) at 100 m resolution; targeted at 40 m spatial resolution hyperspectral mapping (1–5 µm, 2.5 nm spectral resolution of aqueous sedimentary deposits (e.g., those targeted at lower resolution based on geomorphic and mineralogical evidence for prolonged aqueous sedimentary processes) to explore for aqueous mineralogies [e.g., carbonates, fixed inorganic nitrogen, phosphate, silica, metallic oxides (e.g., hematite) and sulfides, sulfates, borates, halides, clays, etc.] that are potential repositories for fossil biosignatures. High-spatial-resolution mapping (100 m) in thermal IR to explore for near-surface hydrothermal systems. *Technology development needed: Some.*

c. In situ measurements (e.g., laser Raman, infrared spectroscopy, X-ray diffraction, X-ray fluorescence, etc.) to determine the mineralogy and geochemistry of potential aqueous materials, such as carbonates, fixed inorganic nitrogen, phosphates, silica, sulfates, halides, borates, metallic oxides (e.g., hematite) and sulfides, clays, etc., including hydrous weathering products formed by interactions of primary lithologies with water, conducted at a minimum of 3 diverse sites for obtaining ground truth to calibrate orbital IR measurements. *Technology development needed: Modest.*

2. Investigation: **Search for Martian fossils (morphological and chemical biosignatures of ancient life).** Life can leave a variety of biosignatures in water-deposited rocks. Based on studies of the fossil record on Earth, certain environments and types of deposits provide favorable settings for the preservation of fossil biosignatures. These include environments where fine-grained, clay-rich deposits form in lakes and streams, or where minerals precipitate rapidly from water in the presence of organisms. Locating the most favorable deposits for preserving fossil biosignatures requires remote sensing, in situ analysis, and targeted sample returns.

Measurements

a. Global remote sensing at 15 m spatial resolution in the visible to search for geomorphic features (e.g., paleolake basin and shoreline deposits, fluvial-deltaic deposits, hydrothermal spring mounds, etc.) and in the mid- and near-IR to explore for minerals [e.g., carbonates, fixed inorganic nitrogen, phosphates, silica, sulfates, halides, borates, metallic oxides (e.g., hematite) and sulfides, clays, etc.] indicative of aqueous sedimentary processes. *Technology development needed: Some.*

b. In situ analyses of aqueous sedimentary lithologies (e.g., using laser Raman spectroscopy, infrared-spectroscopy, X-ray diffraction/fluorescence, etc.) conducted at a minimum of 3 well-characterized and diverse sites to determine the mineralogies (e.g., aqueous minerals, reduced phases, biominerals, etc.), macro- and micro-scale rock textures and carbon compounds (e.g., total carbon content, the presence of particulate kerogen or more volatile hydrocarbons, etc.) in aqueous sediments (e.g., siliciclastics, carbonates, evaporites, etc.) and to explore for potential biosignatures (e.g., chemofossils, biosedimentary structures, etc.) preserved in sedimentary rocks. *Technology development needed: Some.*

c. Return of targeted samples (0.5–1.0 kg) from each of 3 sites "certified" to be of aqueous sedimentary origin) for detailed microscopic (e.g., light, fluorescence, and laser confocal microscopy; TEM; SEM; X-ray tomography; laser Raman imaging, etc.), geochemical analysis (e.g., isotopic, trace element), mineralogical characterization (e.g., using laser Raman mapping spectroscopy, X-ray diffraction/X-ray fluorescence, etc.), and organic analysis (e.g., gas chromatography-mass spectrometry; laser desorption spectroscopy, etc.) and to search for fossil biosignatures (e.g., organic-walled microfossils or their mineralized replacements, chemofossils (e.g., organic biomarker compounds, isotopic and trace element signatures) and biominerals). *Technology development needed: Much (sample return); Modest (instrumentation).*

<u>3. Investigation:</u> **Determine the timing and duration of hydrologic activity.** To assess the potential for the origin and evolution of life on Mars during the planet's history, knowledge is needed for when, where, and how long liquid water environments were present at the surface and in the subsurface. This requires the development of stratigraphic (age) frameworks for deposits based on remote sensing, in situ measurements, and samples returned from key sites for radiometric.

Measurements

a. In situ (using mobile platforms and subsurface drills) exploration for aqueous minerals [e.g., carbonates, fixed inorganic nitrogen, phosphates, silica, metallic oxides (e.g., hematite) and sulfides, sulfates, borates, halides, clays, etc.], water-formed geomorphic features (e.g., paleolake basin and shoreline deposits, fluvial-deltaic deposits, hydrothermal spring mounds, etc.) and diagnostic meso-scale sedimentary structures (e.g., planar cross bedding, oscillation ripples, mudcracks, teepee structures, various biogenic sedimentary structures, etc.) indicative of hydrologic activity. These detailed investigations should be conducted for at least 6 diverse units. *Technology development needed: Modest (rover development); None (instrumentation); Much (preparing for human exploration).*

b. Returned samples from at least 6 units suitable for establishing valid radiometric dates to calibrate the geologic timescale for Mars. Integrated petrographic and geochemical analyses for understanding initial isotopic ratios and the effects of shock metamorphism and weathering processes on the reliability of age dates. Note: Sampling strategies could include sites where diverse lithologies and units could be sampled at a single site. If overlapped with human exploration, initial sample analysis might be done at Mars. *Technology development needed: Modest (rover development); None (instrumentation); Much (preparing for human exploration).*

C. Objective: Assess the extent of *prebiotic organic chemical evolution*.

<u>1. Investigation:</u> **Search for complex organic molecules in rocks and soils.** The steps in prebiotic chemistry that lead to life on Earth are unknown. On Earth, the record of those early events has been largely destroyed by plate tectonics and weathering. If life arose on Mars, it probably would have consumed and transformed much of the original organic inventory present. However, if life did not arise, the record of prebiotic chemistry that developed in an Earth-like setting on early Mars is considered fundamentally important for developing the understanding of the chemical steps that preceded the appearance of life on Earth. Because Mars apparently lacks plate tectonics, it might provide an unrivaled record of early prebiotic chemical events in an Earth-like setting. The exploration for prebiotic chemistry ultimately requires a different approach than the search for the extant biochemistry. The search for prebiotic chemistry requires studies of modern aqueous environments (e.g., groundwater, ice-brine transitions, hydrothermal systems, etc.) and the record of aqueous paleoenvironments preserved in ancient sedimentary rocks. Targets for in situ studies must be first identified by remote sensing based on geomorphology and mineralogy (see I.A.1) and then mobile platforms (rovers) used to determine mineralogy, geochemistry, organic chemistry, and returned samples.

Measurements

a. In situ/mobile platforms deployed to at least 3 well-characterized and diverse sites to assess the mineralogy (e.g., using laser Raman mapping spectroscopy, X-ray diffraction/X-ray fluorescence, etc.), geochemistry (e.g., alpha proton or mass spectrometer methods for elemental and isotopic compositions) and organic materials (e.g., gas chromatography-mass spectrometry; laser desorption spectroscopy, etc.). *Technology development needed: Modest (rover development); Some (in situ instrumentation).*

b. Return samples from at least 6 units suitable for radiometric dating to calibrate the geologic timescale of Mars. Integrated petrographic and geochemical analyses for understanding initial isotopic ratios and the effects of shock metamorphism and weathering on age date reliability. Measurement of other volatile components (e.g., D/H) to calibrate volatile history. *Technology development needed: Much (sample return); Some (lab instrumentation).*

2. Investigation: **Determine the changes in crustal and atmospheric inventories of carbon through time.** Changes in the atmospheric and crustal carbon inventories over geologic time would have greatly affected the prebiotic chemistry and climate of the Martian surface and, hence, the potential for life to develop. The detailed history of the carbon cycle will require intensive sample analysis of a wide range of rock types and ages. This objective parallels investigation I.A.5. (determine the crustal inventory of carbon) but seeks to integrate that information over time. Thus, the objective is posed in a historical way that will require a stratigraphic (temporal) framework for sampling (established through detailed geological mapping from orbit), in situ drilling and samples returned to Earth for detailed chemical analysis of carbon compounds, and radiometric dating of samples.

Measurements

a. Global remote sensing in the near-infrared at ~40 m spatial resolution to map mineralogy. *Technology development needed: Modest.*

b. Returned samples (0.5–1.0 kg) from at least 6 well-dated, temporally diverse sites for both organic and inorganic carbon analysis [e.g., ratios of carbon isotopes, simple inorganic (e.g., bound volatiles like CO, CO_2, CH_4, etc.) and analysis of complex organic compounds (e.g., amino acids, proteins, carbohydrates, lipids, nucleic acids, etc.)] preserved in rocks, soils, and ices. *Technology development needed: Much.*

c. Returned samples from at least 6 temporally diverse units to establish radiometric dates to calibrate the geologic timescale. *Technology development needed: Much. [Note: In this context, technology (instrumentation) developments for precise in situ dating on Mars could mitigate the need for returned samples.]*

II. GOAL: DETERMINE CLIMATE ON MARS

A. Objective: Characterize Mars' present climate and climate processes (investigations in priority order)

***1. Investigation:* Determine the processes controlling the present distributions of water, carbon dioxide, and dust.** Understanding the factors that control the annual variations of volatiles and dust is necessary to determine to what extent today's processes have controlled climate change in the past. **Requires global mapping and then landed observations on daily and seasonal timescales.**

Measurements (a, b, and c concurrently)

a. Global mapping with sufficient temporal resolution **(*define*)** to characterize seasonal variations of dust, water vapor, carbon dioxide, and temperature requires *daily* global coverage of the planet with *horizontal resolutions* equal to, or better than, 5 degrees latitude and 30 degrees longitude. Some sampling of *diurnal* variations (e.g., day-night contrasts) is required to understand aliasing of longer-term measurements. Water vapor, dust extinction, and meteorological measurements taken *concurrently* (within one hour of one another). Vertical measurements are required with *half-scale height* resolution (< 5 km) over the following height ranges:

- Water vapor: 0–40 km with sensitivities of 3–30% in mixing ratios over that range for reasonable water amounts (e.g., 5–10 precipitable microns column amounts)
- Dust and water ice cloud extinction: 0–60 km with ± 10% in extinction
- Temperature/pressure: 0–80 km with typically 1–2 K precision and pressure registration to ± 1%

- Surface pressure: Required precision is a few percent for seasonal variations, < 1 % relative precision for dynamical (weather) variations
- Energy balance: Albedo and thermal irradiance measurements adequate to compute surface net heat balance (and equivalent carbon dioxide flux) to ± 20% over representative regions of the permanent and seasonal polar caps.

Technology development needed: Modest.

b. Estimate water vapor flux, requiring in situ daily, diurnally resolved measurements of near-surface water vapor concentration over (latitudinally dependent) seasonal timescales (e.g., 60 sols in polar regions; 1 Mars year at nonpolar latitudes). Measurements needed at low, mid, and high latitudes and in a variety of terrain (not necessarily concurrently): low and high thermal inertia regions, off and on the residual north polar cap. Measurements from a site with subliming seasonal frost also desired. *Technology development needed: Some.*

c. In situ measurements of adsorbed and solid water and carbon dioxide in the soil concurrent with the measurements described in (a) and (b) above to depths of a few cm at multiple times per day. Ice abundance measurements should cover the range from 0.01 to 1.0 g cm^3 with 10% accuracy. Adsorbed H_2O measurements should cover the range from 10^{-4} g/g to 10^{-2} g/g with 10% accuracy. Measurements of adsorbed CO_2 should cover the range from 10^{-5}g/g to 10^{-3}g/g with 20% accuracy. Measurements adsorbed H_2O and CO_2 and water ice should also be conducted to depths of ~1 meter, but do not require diurnal or even seasonal temporal resolution. *Technology development needed: Some.*

d. Detect near-surface (< 100 m) and deep (100 m–5 km) liquid water; global mapping at scales of 10° longitude by 30° latitude. Determine depths to ± 10 m for near-surface water, ± 100 m at greater depth. *Technology development needed: Much.*

e. Detect subsurface ice with precisions of 100–200 m as deep as 5 km, at horizontal scales of a few hundred kilometers. *Technology development needed: Much.*

f. In situ meteorological measurements:

- *Seasonal monitoring*: Hourly measurements of temperature, pressure, and atmospheric column dust opacity from 16 or more globally distributed sites for one Mars year.
- *Weather monitoring*: Diurnally resolved (e.g., hourly) measurements of pressure, wind speed and direction, temperature, and optical depths from sites at high, middle, and low latitudes, in both hemispheres, for a Mars year or longer. (At polar sites, winter measurements are not required, but are desirable.)
- *Boundary layer processes*: High-frequency measurements (comparable to, or better than, 1 sec sampling) of near-surface wind, temperature, and water vapor concentration for representative portions (~ 15 minute sampling

intervals) of diurnal cycle (e.g., pre-dawn, mid-morning, mid-afternoon and post-sunset). Needed for representative sites at low, mid, and high latitudes; low and high thermal inertia nonpolar sites; one site dominated by local topography (e.g., canyon or edge of layered terrain). Vertical temperature profiling (1–3 levels minimum) highly desired through first few meters.

Technology development needed: Some.

g. Returned samples to study the physical, chemical, and geological properties of rocks and soils and their interaction with the atmosphere and hydrosphere. Samples taken from 1 m depth soil and of rock weathering rinds; samples needed from one representative low-latitude site (0 to 30°), and one high-latitude site (60–90°). *Technology development needed: Much.*

2. *Investigation:* ***Determine the present-day stable isotopic and noble gas composition of the present-day bulk atmosphere.*** These provide quantitative constraints on the evolution of atmospheric composition and on the source and sinks of the major gas inventories.

Measurements

a. In situ, high-precision measurements of atmospheric isotopic composition at one site. ± 5 per mil for 18-O/16-O, 17-O/16-O, 13-C/12-C; ± 250 per mil for D/H, anywhere on the planet. *Technology development needed: Much.*

b. Sample return of pristine atmospheric samples for measurement of key elements such as 40-Ar and 129-Xe. *Technology development needed: Much.*

3. *Investigation:* ***Determine long-term trends in the present climate.*** This determination will test to what degree the Martian climate is changing today.

Measurements

a. Extension of the orbital and lander measurements of (A1) to multiple Mars years. *Technology development needed: Much.*

b. Long-term (at least 10 years), in situ monitoring of key atmospheric variables (e.g., pressure, temperature, dust opacity, water) at globally representative sites (network science) for at least 12 sites. *Technology development needed: Much.*

4. *Investigation:* ***Determine the rates of escape of key species from the Martian atmosphere, and their correlation with solar variability and lower atmosphere phenomenon (e.g., dust storms).*** **Requires global orbiter observations of species (particularly H, O, CO, CO_2, and key isotopes) in the upper atmosphere, and monitoring their variability over multiple Martian years.**

Measurements

a. Map from orbit the 3-D distribution of key atmospheric neutral and charged species such as H, O, CO, CO_2, and key isotopes. *Technology development needed: None.*

b. Measure from orbit the variations of key atmospheric neutral and charged species (H, O, CO, CO_2, and key isotopes) over seasonal cycles, through dust storm events, and over the solar cycle. *Technology development needed: None.*

<u>5. *Investigation:*</u> *Search for micro-climates.* Detection of exceptionally or recently wet or warm locales and areas of significant change in surface accumulations of volatiles or dust would identify sites for in situ exploration. Requires global search for sites based on topography or changes in volatile distributions and surface properties (e.g., temperature or albedo).

Measurements

a. Detect hot spots (e.g., surface geothermal activity) at spatial resolution of <100 m. *Technology development needed: Some.*

b. Detect local concentrations of water vapor, particularly within the lowest 1–3 km the atmosphere at spatial resolution <100 m. Regions repeatedly surveyed during spring and summer seasons. *Technology development needed: Some.*

<u>6. *Investigation:*</u> *Determine the production and reaction rates of key photochemical species (O_3, H_2O_2, CO, OH, etc.) and their interaction with surface materials.*

Measurements

a. Measure species in the atmosphere with sensitivities of 10^9 cm=3 as a function of insolation. *Technology development needed: Some.*

b. Measure and identify surface complexes or chemabsorbed species on a representative sample **(sample return or in situ ?)** of surface materials (primary and secondary materials). *Technology development needed: Much.*

B. Objective: Characterize Mars' ancient climate and climate processes (investigations in priority order)

<u>1. *Investigation:*</u> *Find physical and chemical records of past climates.* These provide the basis for understanding the extent and timing (e.g., gradual change or abrupt transition) of past climates on Mars. **Requires: remote sensing of stratigraphy and aqueous weathering products, landed exploration, and returned samples.**

Measurements

a. Remote sensing of 100s of target sites in the visible at 15 cm/pixel or better to characterize fine-scale layers in sedimentary deposits. The interpretation of high-resolution data requires lower-resolution context images. *Technology development needed: Some.*

b. Hyperspectral orbital remote sensing at resolutions of 20–50 m/pixel to search for and characterize aqueous alteration and deposition products such as carbonates, hydrates, and evaporites. *Technology development needed: Some.*

c. In situ exploration of layered deposits to characterize the physical structure of layers the chemistry, trace elements, isotopic (especially H, N, and O), mineralogy, and petrology for two regions (polar and nonpolar) on the planet, at multiple stratigraphic locations at each site. *Technology development needed: Much.*

d. Returned samples of soils, rocks, atmosphere, and trapped gasses/ices to measure the chemistry, mineralogy, and ages. A single sample is a major advance, but multiple samples spanning a range of ages is highly desirable. *Technology development needed: Much.*

2. *Investigation:* ***Characterize history of stratigraphic records of climate change at the polar layered deposits, the residual ice caps.*** The polar regions suggest repeated geologically recent climate change. A key to understanding their histories is relative dating of polar layering and volatile reservoirs. **Requires orbital, in situ observations and returned samples.**

Measurements

a. Orbital or aerial platform remote sensing of 100s of sites in the visible at 15 cm/pixel or better to characterize fine-scale layers in both north and south polar layered deposits. *Technology development needed: Some.*

b. Hyperspectral orbital remote sensing at resolutions of 20–50 m/pixel to search for and characterize physical properties, composition and morphology, volatile composition of north and south polar deposits. If NIR spectra are used, the coverage should extend to 4 microns. *Technology development needed: Some.*

c. In situ, local exploration of layered deposits in north and south polar regions to characterize the physical structure of layers, volatile content, chemical and isotopic (especially H, N, and O) variations. Measurements should be conducted at multiple stratigraphic locations at each site. *Technology development needed: Much.*

d. Returned samples of polar layered deposits that preserve fine-scale stratigraphy, ices, and trapped gasses, and enable measurements of chemistry, mineralogy, and determination of ages. Multiple samples spanning a range of ages are desirable to search for episodic volcanic activity, major impact events, or large-scale environmental variability due to changes in Mars' orbital and axial elements. *Technology development needed: Much.*

III. GOAL: DETERMINE THE EVOLUTION OF THE SURFACE AND INTERIOR OF MARS ("Geology")

A. Objective: Determine the nature and sequence of the various geologic processes (volcanism, impact, sedimentation, alteration etc.) that have created and modified the Martian crust and surface (investigations in priority order)

1. Investigation:* *Determine the present state, distribution, and cycling of water on Mars. Water is arguably the most important geologic material that influences most geological processes, including the formation of sedimentary, igneous and metamorphic rocks, the weathering of geological materials, and deformation of the lithosphere. **Requires global observations using geophysical sounding and neutron spectroscopy, coupled with measurements from landers, rovers, and the subsurface.**

Measurements

a. Global search for water to a depth of several kilometers at spatial scales of ~ 100 m and to a depth resolution of 100 m. *Technology development needed: Some.*

b. Aerial platform remote sensing to search for subsurface water to a depth of 500 m at a depth resolution of 10 m and a spatial resolution of 100 m. *Technology development needed: Some.*

c. Acquire vertical profiles of the distribution of subsurface liquid water and ice at several sites where water is likely from the sounding measurements in (a) and (b). *Technology development needed: Much.*

d. In situ drilling to liquid water or ice to depths up to a kilometer for at least one site and to depths of several hundred meters for several sites with down-hole instruments to determine elemental abundances, mineralogy of volatile and other phases, including ices. *Technology development needed: Much.*

e. Identify and measure the abundance of water-bearing minerals for several diverse sites of different ages. *Technology development needed: Much.*

2. Investigation:* *Evaluate sedimentary processes and their evolution 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. Eolian sediments record a combination of globally averaged and locally derived fine-grained sediments and weathering products. Sediments are also likely past or present aquifers. **Requires knowledge of the age, sequence, lithology, and composition of sedimentary rocks (including chemical deposits), as well as the rates, durations, environmental conditions, and mechanics of weathering, cementation, and transport processes.**

Measurements

a. Global stereo imaging with at least 10 m/pixel resolution and contiguous regional coverage of at least 1 percent of the planet at better than 1 m/pixel. *Technology development needed: None.*

b. Global orbital remote sensing with access to the entire planet at 30 m/pixel in the visible to reflected infrared (0.4 to 5 micrometers) with a spectral resolution of 10 cm^{-1}. *Technology development needed: Some.*

c. In situ measurements, including traverses across sedimentary units of different ages for several sites to determine physical properties of rocks and fines and their chemistry, mineralogy, lithology, and petrology. Characterization should be sufficient to identify the rock types, their mode of deposition and degree of alteration. *Technology development needed: Some.*

d. Returned samples for detailed characterization from at least several sites containing water-lain sediments, for which *valid* surface ages can be obtained in order to constrain the sedimentary record. *Technology development needed: Much.*

e. Drilling to 1 km at one site and to ~100 m at several sites to determine the physical properties of rocks and fines and their chemistry, mineralogy, and petrology. *Technology development needed: Much.*

3. *Investigation:* ***Calibrate the cratering record and absolute ages for Mars.*** The evolution of the surface, interior, and surface of Mars, as well as possible evolution of life, must be placed in an absolute timescale, which is presently lacking for Mars. **Requires absolute ages on returned rock (not soil) samples of known crater ages.**

Measurements

a. Returned samples of volcanic rocks whose cratering age dates the same event as its radiometric age from at least two key sites, chosen to resolve uncertainties in crater ages (one focusing on early to mid Mars history and one relatively young). *Technology development needed: Much.*

b. Measurement of current impact flux from seismic network and an infrasonic network operating for 1 Mars year, using 12 stations arrayed in triangular groups of 3 spaced 100–200 km apart. *Technology development needed: Much.*

c. Measurement of the current impact flux from by orbital detection of ionospheric perturbations induced by meteorite entry. *Technology development needed: Much.*

4. *<u>Investigation:</u>* *Evaluate igneous processes and their evolution through time, including the present*. This study includes volcanic outgassing and volatile evolution. 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 for the search for life. **Requires global imaging, geologic mapping, techniques for distinguishing igneous and sedimentary rocks, evaluation of current activity from seismic monitoring, and returned samples.**

Measurements

a. Orbital remote sensing, including stereo, in the visible (better than 1 m/pixel with ~10 m/pixel context images as listed above in III.A.2.a) and hyperspectral data of 30 m/pixel spatial resolution for key igneous regions of Mars (~20 % of surface). *Technology development needed: Some.*

b. In situ measurements from the surface for at least several volcanic sites to determine chemistry, mineralogy, and petrology. Characterization should be sufficient to identify the rock types and will require a payload with significantly more capability than Athena. *Technology development needed: Some.*

c. Global seismic monitoring of potential volcanic activity using an array of broad-band (0.05 to 50 Hz) seismometers (12 stations in groups of three with an internal spacing of 100–200 km) distributed globally. *Technology development needed: Some.*

d. Returned samples of a variety of igneous rocks from at least two sites of different ages and types for geochemical, isotopic, mineralogical, and petrographic analysis to understand the chemistry and physical process in the magma source regions and how they have changed with time. *Technology development needed: Much.*

e. Search for thermal anomalies at a horizontal resolution of tens of meters. *Technology development needed: Some.*

5. *<u>Investigation:</u>* *Characterize surface-atmosphere interactions on Mars, including polar, eolian, chemical, weathering, and mass-wasting processes.* Interest here is in processes that have operated for the last million years as recorded in the upper 1 m to 1 km of geological materials. Understanding present geologic, hydrologic, and atmospheric processes is the key to understanding past environments and possible locations for near-surface water. Knowing the 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. **Requires orbital remote sensing of surface and subsurface,**

and in situ measurements of sediments and atmospheric boundary layer processes.

Measurements

a. Orbital remote sensing, including stereo, in the visible (better than 1 m/pixel with 10 m/pixel context), and hyperspectral (30 m/pixel) for key terrains (a total of ~ 20 % of the surface). *Technology development needed: None.*

b. Global SAR mapping of subsurface structures (below surficial materials) at depths up to several meters at spatial resolutions of 100 m/pixel. *Technology development needed: Some.*

c. In situ analysis of sediment grain size distribution, textures, composition, and mineralogy of the regolith and characterization of the weathering rind on rocks at several sites. *Technology development needed: Some.*

d. Network of at least 16 stations to monitor weather (temperature, pressure, wind velocity, and strength) with concurrent visual observations from the surface and from orbit. Mission lifetime of 3 Mars years to determine seasonal and internal variations. *Technology development needed: None.*

e. A diverse set of returned samples, including soil profiles, duricrust and rock, from several sites (for detailed mineralogy of weathered products, isotopic fractionation, nature of weathering rinds, if any, and so on). *Technology development needed: Much.*

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 place constraints on the distribution of subsurface aquifers, and aid interpretation of past igneous and sedimentary processes. **Requires remote sensing and geophysical sounding from orbiters and surface systems, geologic mapping, in situ analysis of mineralogy and composition of surface material, returned samples, and seismic monitoring.**

Measurements

a. Global remote sensing, including stereo, in the visible (better than 1 m/pixel with 10 m/pixel context), and hyperspectral (30 m/pixel). *Technology development needed: None.*

b. SAR mapping of subsurface structure to depths up to several meters and at 100 m spatial resolution. *Technology development needed: Some.*

c. In situ measurements of physical properties of rocks and fines for chemistry, mineralogy, petrology at several sites of diverse ages and types. *Technology development needed: None.*

d. Long-term (at least 1 Mars year) global seismic measurements using an array of broad-band (0.01 to 20 Hz) seismometers (at least 12 stations distributed in groups of at least 3, with internal spacing of 100–200 km). *Technology development needed: None.*

e. Returned samples of igneous rocks from several diverse units of different ages for detailed physical, chemical, and geologic analyses. *Technology development needed: Much.*

f. Global gravity survey to precision of 10 mgal spatial (wavelength) resolution of 175 km. This will require precision tracking at low (~200 km) altitude and application of drag compensation techniques. *Technology development needed: Some.*

g. Drilling to 1 km at one site and to ~100 m at several sites to determine the physical properties of rocks and fines and their chemistry, mineralogy, and petrology. *Technology development needed: Much.*

h. Active seismic reflection and refraction measurements to delineate the third dimension, density, and physical properties of the crust and geological units. *Technology development needed: Some.*

i. Regional gravity surveys to precision of <1 mgal over spatial scales of tens of meters for understanding the local third dimensional geometry of the crust and geological units. *Technology development needed: Some.*

7. *Investigation:* *Document the tectonic history of the Martian crust, including present activity.* Understanding of the temporal evolution of internal processes 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. **Requires geologic mapping using global topographic data combined with high-resolution images, magnetic and gravity data, and seismic monitoring.**

Measurements

a. Global remote sensing, including stereo, in the visible (better than 1 m/pixel with 10 m/pixel context), and hyperspectral (30 m/pixel). *Technology development needed: None.*

b. Global magnetic measurements (spacing better than 50 km) to an accuracy of better than 0.5 nT at an altitude no greater than 100–120 km. *Technology development needed: Some.*

c. Regional magnetic surveys in regions with substantial anomalies using aerial platforms at altitudes of 1–5 km. *Technology development needed: Much.*

d. Global gravity survey to precision of 10 mgal spatial (wavelength) resolution of 175 km. This will require precision tracking at low (~200 km) altitude and application of drag compensation techniques. *Technology development needed: Some.*

e. Regional gravity surveys to precision of <1 mgal over spatial scales of tens of meters for understanding the geometry of structural features with depth. *Technology development needed: Some.*

f. Active seismic reflection and refraction measurements to delineate the geometry (with depth) of structures and tectonic features and regions. *Technology development needed: Some.*

g. Measure crustal in situ stress and strain in drill holes using well pressurization, bore hole break outs, and down hole, well logging measurement techniques. *Technology development needed: Much.*

8. Investigation: ***Evaluate the distribution and intensity of impact and volcanic 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 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. **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.**

Measurements

a. Global and detailed imaging to search for and characterize candidate volcanic and impact crater locations, including volcanoes with channels systems, and impact crater walls and central uplifts. *Technology development needed: None.*

b. In situ measurements, including traverses across hydrothermal systems present at the surface or exposed by impacts, or other erosional processes with capabilities similar to those listed under III.A.2.c. *Technology development needed: Some.*

c. Returned samples covering the range of available lithologies from at least several sites ranging from very recent to very old. *Technology development needed: Much.*

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

1. *Investigation:* *Characterize the configuration of Mars' interior.* This is needed to understand the origin and thermal evolution of Mars and the relationships to surface evolution and release of water and atmospheric gasses. **Requires orbital and lander data.**

Measurements

a. Global gravity survey to 10 mgal precision and 175 km spatial resolution. *Technology development needed: Some.*

b. Global magnetic measurements spaced <50 km to an accuracy of 0.5 nT or better at an altitude <100-120 km. *Technology development needed: Some.*

c. Concurrent measurement of rotational dynamics from at least two landers to a precision better than 10 cm. *Technology development needed: None.*

d. Global seismic monitoring using an array of very broad-band (DC to 10 Hz) seismometers (at least 12 stations in groups of 3 with internal spacing of 100–200 km) operating for 1 Mars year. *Technology development needed: Some.*

e. Returned samples of a variety of fresh volcanic rocks from several diverse sites, including those where rocks excavated from deep within the crust by large impacts are available for sampling. *Technology development needed: Much.*

2. *Investigation:* *Determine the history of the magnetic field.* Evidence that Mars had a magnetic field early in its history has important implications for the retention of its early atmosphere and for the shielding of the surface from incoming radiation and the possible evolution of life. **Requires orbiter in eccentric orbit or low-altitude platform.**

Measurements

a. Global magnetic measurements (spacing < 50 km) to an accuracy of better than 0.5 nT from an altitude <100–120 km. *Technology development needed: Some.*

b. Regional magnetic surveys in areas with a large remanent signature using aerial platforms at altitudes of 1–5 km. *Technology development needed: Some.*

c. Samples of a variety of volcanic rocks of different ages from different sites, the sampling being performed such that knowledge of the orientation of the samples is preserved. *Technology development needed: Much.*

d. Long-term (at least 1 Mars year) global seismic measurements using an array of broad-band (0.01 to 20 Hz) seismometers (at least 12 stations distributed in groups of at least 3, with internal spacing of 100–200 km). *Technology development needed: Much.*

3. *Investigation:* *Determine the chemical and thermal evolution of the planet.* Knowledge of the thermal evolution places constraints on the composition, quantity, and rate of release of volatiles (water and atmospheric gasses) to the surface. **Requires measurements from orbiter and lander.**

Measurements

a. Global gravity survey to 10 mgal precision and 175 km spatial resolution. *Technology development needed: Some.*

b. Global magnetic measurements spaced <50 km to an accuracy of 0.5 nT or better at an altitude <100–120 km. *Technology development needed: Some.*

c. Concurrent measurement of rotational dynamics from at least two landers to a precision better than 10 cm. *Technology development needed: None.*

d. Global seismic monitoring using an array of very broad-band (DC to 10 Hz) seismometers (at least 12 stations in groups of 3 with internal spacing of 100–200 km) operating for 1 Mars year. *Technology development needed: Some.*

e. In situ heat flow measurements to a precision of 5 mW/m^2 for at least 3 sites representing highland crust, lowlands, and recent volcanism. *Technology development needed: Much.*

f. Returned samples of a diverse array of igneous rocks of different ages. *Technology development needed: Much.*

GOAL IV: PREPARE FOR HUMAN EXPLORATION

A. Objective: Acquire Martian environmental data sets (priority order of investigations under review)

1. Investigation: Determine the radiation environment at the Martian surface and the shielding properties of the Martian 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, and the backscatter effects of the regolith. **Requires simultaneous monitoring of the radiation in Mars' orbit and at the surface, including the ability to determine the directionality of the neutrons at the surface.**

Measurements

a. Measure charged particle spectra, at the surface and in orbit, accumulated absorbed dose and dose rate in tissue as a function of time over time, particularly at solar maximum and solar minimum. *Technology development needed: Some.*

b. Determine the radiation quality factor, determine the energy deposition spectrum from 0.1 keV/µm to 1500 keV/µm, and separate the contributions of protons, neutrons, and HZE particles to these quantities. *Technology development needed: None.*

c. Measure neutron energy spectrum from 100 keV to 50 MeV or above. The ability to obtain information on the source of the neutrons (depth in soil, atmosphere) is a strongly desirable feature and therefore provisions for assessing direction of incidence of the neutrons are required. *Technology development needed: Some.*

d. Simultaneous surface and orbital measurements are required to determine the shielding component of the atmosphere. *Technology development needed: Some.*

e. Simultaneously measure the atmospheric pressure at the surface of Mars and the atmospheric dust loading. *Technology development needed: Some.*

f. Measure the natural radioactivity of the planet's surface materials (soil and rocks). *Technology development needed: None.*

2. Investigation: ***Characterize the chemical and biological properties of the soil and dust.*** Toxicity and reactivity needed to develop hazard mitigation strategies to ensure safety of human explorers on the Martian surface. Requires in situ experiments. If in situ experiments cannot achieve adequate levels of risk characterization, returned samples will be required. The requirements can and may have to be met through sample studies on Earth. Earth sample return provides significant benefits to HEDS technology development programs.

Measurements

a. In situ determination of the toxic trace elements and mineral species including, but not limited to, As, Be, Cd, Cl, F, and Pb. *Technology development needed: Some.*

b. Determine the toxic and genotoxic potential of dust and soil to biological cell analogs (enzymes, lipids, nucleic acids, etc.), to identify reactivity of quasi-cellular systems from which the potential for acute toxicity for human explorers could be inferred. *Technology development needed: Some.*

c. Determine the chemical reactivities with a sensitivity of ppm (of particular interest are changes in the reactivities upon heating, with exposure to humidity, and with emphasis on the identification and volatility of the gases evolved) and up to a maximum depth of 150 cm. Understand the solubility in water of Martian soil (total weight loss after water is equilibrated with the soil), the before and after composition of the soil, and the composition of the aqueous phase in equilibrium with Martian soil. *Technology development needed: Much.*

d. Determine the depth of the superoxidation zone at several locations. *Technology development needed: Much.*

e. In situ sensors or analytical tools to determine the content of carbon and complex organic compounds in wind-blown dust, surface soil, and materials from secluded environments to a sensitivity of 10 ppm. *Technology development needed: Much.*

f. Biohazard assessment. *Technology development needed: Much.*

g. Determine physical properties (size, shape, hardness, adhesion) of representative dust samples: *Technology development needed: Some.*

3. Investigation: ***Understand the distribution of accessible water in soils, regolith, and Martian groundwater systems.*** Water is a principal resource to humans. **Requires geophysical investigations, subsurface drilling, and in situ sample analysis.**

Measurements

a. Map the Martian subsurface for ice and liquid water reservoirs. *Technology development needed: Much.*

b. Measure the vertical distribution (and ultimately comprehensive 3-dimensional subsurface maps) of permafrost, water ice and liquid water with a vertical resolution of ~ 10 m at selected sites. *Technology development needed: Much.*

c. Determine the adsorbed and bound water content of soil samples from several provenances (air-borne dust, surface fines, sand dunes) with precision of ± 10% down to levels of 0.1%. Determine the release temperature of water over the range 0ºC–600ºC. *Technology development needed: Much.*

4. Investigation: ***Measure atmospheric parameters and variations that affect atmospheric flight.*** Pressure and density versus altitude, temporal and spatial variations. **Requires instrumented aeroentry shells or aerostats.**

Measurements

a. Measure and record pressure versus altitude, and temperature for all Mars entry vehicles during the E/D/L phase of the mission. *Technology development needed: Some.*

b. Measure basic surface meteorology: temperature, pressure, wind speed and direction at different sites. *Technology development needed: Some.*

c. Monitor global weather patterns from orbit. *Technology development needed: None.*

d. Measure the frequency and magnitude of dust storms at selected surface locations; characterize the processes active in these storms in terms of the associated wind speeds, pressure changes, atmospheric dust loading. *Technology development needed: None.*

e. Detect local atmospheric vorticity in terms of frequency of local "dust devil" development, quantity of dust lofted, associated wind speeds, and pressure differentials. *Technology development needed: None.*

***5. Investigation:* Determine electrical effects in the atmosphere**. Needed to understand the role of electrical discharge, electrostatic effects, etc., in atmospheric processes, including dust-raising and potential hazards to surface operations**. Requires experiments on a lander.**

Measurements

a. Measure the electrical properties of dust in the atmosphere and observe the consequences of dust electrification. *Technology development needed: Much.*

b. Determine the atmospheric electrification due to turbulent motion in dust clouds and dust storms; determine the population of atmospheric ions and whether there is a diurnal variation; determine what types of discharges occur on Mars. *Technology development needed: Much.*

c. Determine the electrostatic charge state (magnitude, sign, and longevity of charges) for both aerosols and soil particles up to 100 microns. *Technology development needed: Much.*

d. Determine Paschen curves (electrical breakdown in gases) for Mars as a function of temperature, pressure, wind, dust load in atmosphere, and season for meteorological use and as a tool for designing and safeguarding equipment for Mars exploration. *Technology development needed: Some.*

***6. Investigation:* Measure the engineering properties of the Martian surface.** Soil and surface engineering data (bearing strength, angle of repose, geoelectric properties, etc.) **Requires in situ measurements at selected sites.**

Measurements

a. Measure soil bearing strength and surface penetration resistance. *Technology development needed: None.*

b. Measure soil cohesion and angle of repose. *Technology development needed: None.*

c. Measure soil magnetic and electrostatic properties (adhesion potential, strength of adhesion, and character of the charge). *Technology development needed: Some.*

d. Measure surface temperature and touch temperature of surface features. *Technology development needed: None.*

e. Measure surface heat capacity. *Technology development needed: None.*

f. Measure surface albedo. *Technology development needed: None.*

g. Measure surface thermal conductivity/insulation properties. *Technology development needed: Some.*

h. Determine the particle size and distribution, in the range 0.01 to 10.0 microns (0.01 to about 10 cm surface depth), with higher emphasis on particles much smaller than 1.0 micron. *Technology development needed: Some.*

i. Determine the total columnar suspended load of dust in the atmosphere. *Technology development needed: Some.*

j. Measure average surface sink temperature. *Technology development needed: Some.*

k. Determine soil and dust chemical composition. *Technology development needed: Some.*

l. Measure the conductivity, resistivity, dielectric constant, and piezoelectric properties of the subsurface to a depth of 10 m as a function of latitude, time of year, and geological environment. *Technology development needed: Some.*

m. Measure subsurface distribution of ground ice. *Technology development needed: Some.*

7. Investigation: ***Determine the radiation shielding properties of the Martian regolith.*** Soil and dust from the Martian surface offer a readily available source of shielding material for surface crews. The thickness of the required regolith cover will depend upon the measured shielding properties. **Requires an understanding of the regolith composition, a lander with the ability to bury sensors at various depths up to a few meters. Some of the in situ measured properties may be verified with a returned sample.**

Measurements

Determine the radiation shielding characteristics of Martian regolith as a function of cover depth. Radiation sensors would be placed under various depth of regolith cover, and their readings correlated with an unburied sensor. *Technology development needed: Much.*

8. Investigation: ***Measure the ability of Martian soil to support plant life.*** Determine the ability of the indigenous soil to support life, such as plant growth, for future human missions. **Requires in situ measurements and process verification.**

Measurements

Conduct in situ process verification of plant growth experiment through full plant growth, seed and re-germination cycle. *Technology development needed: Much.*

9. Investigation: ***Characterize the topography, engineering properties, and other environmental characteristics of candidate outpost sites.*** Site certification for human outposts requires a set of data about the specific site that can best be performed by surface investigations. Specific measurements are listed in other investigations.

10. Investigation: ***Determine the fate of typical effluents from human activities (gases, biological materials) in the Martian surface environment.***

Measurements

a. Determine the rate of reaction of typical materials exposed to the Martian environment. *Technology development needed: Much.*

b. Monitor the rate of dispersion of analog materials in the Martian environment. *Technology development needed: Much.*

B. Objective: Conduct in situ engineering science demonstrations (priority order of investigations under review)

1. Investigation: ***Demonstrate terminal phase hazard avoidance and precision landing.*** Necessary to decrease the risks associated with soft landing, and to enable pinpoint landing. **Requires flight demonstration during terminal descent phase.**

Measurements

a. Demonstrate terrain recognition systems (e.g., LIDAR)

b. Utilize hazard avoidance algorithms during terminal descent.

c. Demonstrate controlled terminal descent and soft landing.

<u>2. Investigation:</u> Demonstrate 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 performance and landing precision. **Requires wind tunnel testing and flight demonstration during aeroentry phase of the mission.**

Measurements

a. Flight test slender body, mid L/D (0.4–0.8) aeroentry shapes.

b. Achieve and verify an actual horizontal position error at parachute deployment of ±10 km or less. This value includes an entry aero-maneuvering control error goal of ±2 km error, the Mars approach phase navigation error, map tie errors, parachute deployment variables, etc.

c. Use approach navigation that provides control of the flight path angle at the defined entry interface to ±0.5 deg or less and pre-entry knowledge of ±0.1 deg or less.

d. provide control to remain well within the expected control authority of the entry aero-maneuvering system and the knowledge is needed to provide initiation of the entry aero-maneuvering system IMU.

e. The ability to obtain this approach navigation performance with radio navigation depends on selection of a low-latitude landing site location (latitude between 30 deg N and 30 deg S). High-latitude sites would require optical approach navigation.

f. Reconstruct the entry trajectory (after the fact) to an accuracy of ±1 km or better to provide verification of the entry aero-maneuvering system performance.

g. Demonstrate aerocapture maneuver in the Martian atmosphere at speeds within the envelope for human missions (5.7–8.7 km/sec in reference mission).

h. Collect vehicle attitude, trajectory, guidance and control system performance data, and free stream conditions for entire aeropass (atmospheric entry through heat shield ejection).

i. Collect heatshield performance for use in CO_2 chemistry model validation, predictions of aerothermal loads and thermal protection system response.

j. Collect temperatures at selected points within and on heat shield.

k. Collect pressure at selected points on the body.

l. Validation of flight trajectory determination vs. prediction, including aerodynamic predictions and atmospheric modeling.

m. Analysis of the performance of the guidance and control system, including sensors, attitude control system, and CPU.

<u>3. Investigation:</u> Demonstrate high-Mach parachute deployment and performance. Higher-ballistic-coefficient entry vehicles will be result from flying more massive landers. This will result in higher parachute deploy speeds, which are beyond the qualification of current parachute systems. **Requires high-altitude Earth-based testing and flight demonstration during Mars entry phase.**

Measurements

a. Demonstrate and qualify parachute deploy in an expanded velocity regime (up to M=3.0).

b. Demonstrate parachute deploy characteristics in the flow field trailing a mid-L/D aeroentry vehicle.

<u>4. Investigation:</u> Demonstrate in situ propellant (methane, oxygen) production (ISPP) and in-situ consumables production (ISCP) (fuel cell reagents, oxygen, water, buffer gases). 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 use of end products**. Requires process verification with in situ experiments.**

Measurements

a. Demonstrate the intake and adsorption of carbon dioxide from the Martian atmosphere.

b. Demonstrate thermal management concepts of heat transfer between the components of the ISPP plant as well as to the outside environment.

c. Monitor the performance degradation characteristics of advanced solar array and radiator concepts operated in the actual Mars environment.

d. Evaluate the functionality of electrostatically removing accumulated dust off the solar array.

e. Understand the characteristics of zirconia cells to generate propellant-grade oxygen.

f. Demonstrate "end-to-end" system-level operation of ISPP and ISCP processes, including acquisition of resources, chemical processing, storage of products, and demonstration-level use of the products.

g. Demonstrate ISCP, such as buffer gas (nitrogen and argon) or water extraction.

5. Investigation: ***Access and extract water from the atmosphere, soils, regolith, and Martian groundwater systems.*** Water is a principal resource. Requires in situ operations to determine hydrologic characteristics of aquifers and aquicludes. **Requires subsurface drilling.**

Measurements

a. Demonstrate autonomous drilling operations on the Martian surface.

b. Demonstrate progressively deeper drilling, beginning with pilot drill demonstrations to tens of meters, and concluding with depths corresponding to subsurface aquifers.

c. Demonstrate extraction of water from subsurface aquifers.

d. Demonstrate the extraction of water from Martian permafrost layers.

e. Demonstrate the ability to extract potentially useful quantities of water from the atmosphere.

f. Demonstrate the extraction of water from Martian regolith (hydrated minerals).

6. Investigation: ***Demonstrate deep drilling.*** The Martian subsurface will provide access to potential resources (e.g., water) as well as providing access to valuable scientific samples. **Requires landed demonstration.**

Measurements

a. Demonstrate autonomous drilling operations on the Martian surface.

b. Demonstrate progressively deeper drilling, beginning with pilot drill demonstrations to 10's of meters, and concluding with depths corresponding to subsurface aquifers.

C. Objective: Emplace infrastructure for (future) missions (priority order of investigations under review)

1. High-capacity power systems to support ISPP activities in support of robotic sample return missions and eventual human support.

Performance Targets

a. 300 watts per kilogram solar power generation.

b. Megawatt-class surface nuclear power.

c. Megawatt-class space solar power arrays.

<u>*2. Communication infrastructure*</u> to support robotic missions with high data rates or a need for more continuous communications, and eventual human support.

Performance Targets

a. 1 Mb/sec bandwidth at maximum Earth-Mars distance.

b. 99% (TBD) communications link availability, other than during superior conjunction.

<u>*3. Navigation infrastructure*</u> to support precision landings for robotic or human missions.

Performance Targets

a. Provide navigation infrastructure that will support arriving Mars spacecraft multi-point tracking and nav state determination.

b. Provide navigation infrastructure that will support determination of surface spacecraft location to (TBD) meters.