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Report of the Terrestrial Bodies Science Working Group

Volume V. Mars

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National Aeronautics and
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OVERLEAF: Mars—The Mystique Is Gone, but the Mysteries Remain

Mars is the most fully explored planet outside the Earth–Moon system. Three US flybys, three orbiters and two landers have produced a wealth of information about Mars' atmosphere, geology, geophysics and chemistry. Biology remains a prominent question. The diversity of Mars is one of the continuing reasons for continued exploration.
(Picture taken on approach to Mars. Shown are the four gigantic volcanoes of the Tharsis Montes and the enormous system of canyons, the Valles Marineris. Viking photograph 169C25, JPL photograph P-16725)

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PREFACE

This volume is one of a nine-volume series documenting the work of the NASA-sponsored Terrestrial Bodies Science Working Group in developing plans for the exploration of Mercury, Venus, the Moon, Mars, asteroids, Galilean satellites, and comets during the period 1980-1990. Principal recommendations and conclusions are contained in Volume I (Executive Summary); reports and working papers of the study subgroups are presented in Volumes II-IX.

This volume is the report of the Mars subgroup, whose members and contributors are H. Masursky (chairman), A. L. Albee, G. Briggs, M. B. Duke, J. W. Schopf, L. Soderblom, C. Sonett, I. Stewart, J. Trombka, and J. Wood.

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SECTION I

STATE OF OUR KNOWLEDGE

Telescopic observations of Mars have fascinated man for centuries by showing Earth-like seasonal changes, the annual growth and retreat of its polar caps, a myriad of clouds of various colors, shapes, sizes, and other phenomena, both real and imagined, that have been interpreted by various workers as suggestive of the presence of a Martian biota. As we have begun to explore Mars with unmanned spacecraft, many similarities to our terrestrial environment have emerged but major differences are also apparent. Mars is geologically more primitive and biologically less hospitable than was once supposed. The atmosphere, primarily CO_2, has a surface pressure less than 1% of that on Earth; the seasonal polar caps are frozen CO_2, overlying and extending far beyond the permanent water ice caps; the annual seasonal changes episodically result in intense global dust storms; the average temperature, a few meters below the surface, is 50°C below the triple point of water.

Remarkably, however, Mars appears to be much like the Earth in other characteristics. Although geologically primitive, it is far more Earth-like than the other terrestrial planets that we have thus far explored. Its general level of internal evolution, as manifested in volcanic forms, has apparently extended over several billion years -- the Moon and probably Mercury record much shorter earlier histories. Mars is the only other planet of our solar system that has a transparent atmosphere with surface temperature conditions in the range of stability of complex organic compounds. As a consequence, it is a logical target for the search for life.

A. GLOBAL PROPERTIES AND SURFACE CHARACTERISTICS

Information about the magnetic field of Mars from Mariner 4 suggests the presence of a bow shock and is consistent with an upper limit for the Martian dipole moment 3×10^{-4} times that of the Earth. These data suggest that the interaction of Mars with the solar wind could be Venus-like (i.e., an absence of a magnetosphere and the solar wind pressure is balanced by the ionosphere). Alternatively, Soviet data are interpreted to imply an intrinsic Martian field which is deformed and modulated by the solar wind. The calculated dipole moment is 2.5×10^{22} gauss-cm^3, consistent with the upper limit derived from the Mariner data.

The density of Mars is relatively low (3.9 gm cm^{-3}) compared to the other terrestrial planets. Its dynamical flattening is in reasonable agreement with the observed optical flattening; the difference can be explained either by a relatively thick equatorial crust or by the strength of the interior. Analysis of gravity and figure data indicates that the planet is largely isostatically compensated except for a large positive gravity anomaly in the Tharsis region. To date no seismic information about internal structure is available, but it seems probable that Mars is seismically less active than the Earth. The figure of the planet is markedly nonspherical, with large differences in radius north to south and around the equator. Such differences are related to the presence of lava-covered high plateaus that reach a height of 11 km above the mean geoid (the 4th order, 4th-degree spherical harmonic figure based on the 6.1-mb surface) and on which occur large shield volcanoes as much as 27 km high. The shield shape of these volcanoes and the flow shapes and patterns resemble those of basaltic composition on the Earth and Moon. The lava plains have lobate flow fronts that resemble those in the lunar maria which are basaltic in composition also. The lowest point on Mars lies within Hellas, a large impact basin in the southern hemisphere.

The surface of the planet Mars is composed of several geologic provinces. The predominant subdivision occurs between two hemispheres separated roughly on a great circle inclined about 20 deg to the equator. South of this boundary the most widespread unit is an ancient cratered terrain containing an intensely degraded population of large (20- to 100-km diameter) craters with smooth floors and intercrater plains. North of the boundary the most extensive unit consists of plains, some with volcanic ridges and domes, with varying populations of small (1- to 10-km) craters. Although the relative ages of the major units have been defined, absolute ages are currently in dispute.

In comparison to the Moon or Mercury, the morphology of the Martian surface is more diverse and complex. Some of these features include: two forms of polar deposits (one, a massive blanket several hundred meters thick with eroded, depressed hollows, the other consisting of a series of many alternating light and dark layers each a few tens-of-meters thick); extensive fields of sand dunes; permanent ice caps composed of water ice; enormous "shield volcanoes," hundreds of kilometers in diameter and tens of kilometers in height (and many smaller, associated volcanic constructs); ancient subdued volcanic centers hundreds of kilometers in diameter, scattered throughout the cratered terrain; complex series of erosional channels, canyons, and collapsed terrain, downcut into both of the widespread units; myriads of fine, dendritic channels found in the ancient cratered terrain between the equator and ~20°S latitude; and complex regional fault zones, of various ages and directions, which extend halfway around the planet.

Large-scale surface albedo features change with time, and orbital imaging suggests that these changes are the result of ongoing wind action. Ground-based observations show that the light and dark albedo features have different reflectance spectra. Current interpretation of these spectral data suggest that oxidized, hydrated weathering products are responsible for the majority of the features in the bright areas with some apparently less-weathered basaltic material in the dark areas.

Measurements of the elemental composition of soil in two widely separated sites have yielded similar results: iron, calcium, aluminum, silicon and sulfur are major elements and titanium is present in minor quantities. This composition has been interpreted as nontronite, an iron-rich montmorillonitic clay that on Earth is a common weathering product of basaltic lava flows. The loose surface soil contains 3 to 7% of highly magnetic mineral, possibly maghemite or magnetite. The present data do not place strong constraints on suggested models for Martian mineralogic and lithologic composition.

Experiments intended to test for biological activity in the soils at two locations have yielded inconclusive results. However, the experiments have demonstrated that the soil is chemically active and strongly oxidizing, possibly as a result of complex photochemical reactions between relatively unweathered surface materials and water molecules. Analyses of numerous soil samples, including samples acquired from locations under rocks (and thus shielded from solar radiation), have indicated that organic molecules are not detectable (at the parts per billion level) at the two sites tested. Although the existence of an indigenous Martian biota has not been ruled out by these experiments, neither is it indicated; further studies are in progress.

B. ATMOSPHERE

The atmosphere of Mars, the mean pressure of which is about 6 mb, is predominantly CO_2 (95%) with about 0.02% oxygen, 2.5% nitrogen and 2% argon. The $^{36}Ar/^{40}Ar$ ratio is about 1:3000, about one-tenth of the terrestrial value. The abundance of ^{36}Ar per unit mass of the entire planet is about one-hundredth that of the Earth, and neon and krypton, though less well measured, are apparently depleted to a similar degree. Isotopic studies of carbon and oxygen show like depletions. The isotopic composition of carbon and oxygen is like that on Earth but ^{15}N is enriched by about 75%. The amount of atmosphere degassed by Mars, as implied by the noble gas abundance, is many times that presently observed. The explanation for the isotopic composition of the atmosphere may call for large amounts of water originally.

The pressure of the Martian atmosphere is seasonally variable by about 25% as a result of condensation of the polar caps. Substantial wind velocities are implied by the observed eolian activity, which includes the periodic occurrence of global dust storms, principally near perihelion, and of more frequent, smaller, local storms. Velocities up to ~60 m/s have been inferred from the motions of discrete clouds measured by Viking. Direct measurements of wind velocities near the surface have been made during the northern summer when winds are relatively calm; the highest velocities measured to date are 16 m/sec. At one surface site, diurnal and semidiurnal pressure oscillations have been measured and are ascribed to solar tides. Large-scale topography plays an important role in the dynamics of the atmosphere. The amount of water in the atmosphere varies with both season and location and ~100 precipitable microns of water vapor has been measured near the summer residual polar cap at 75°N. Condensation of the water to form hazes and discrete water ice crystal clouds is common, and some condensation onto the surface overnight may occur in places. Clouds and hazes believed to be composed of CO_2 have also been observed. Suspended aerosols are common and must play an important role in heating the atmosphere.

An efficient recombination mechanism, thought to involve either water vapor or the planet's surface as a catalyst, prevents the buildup of the photolysis products of CO_2, CO and O_2 which have been detected spectroscopically in the lower atmospheres at levels of a few tenths of a percent. Ozone abundance is variable up to (60 μ-atm) and is intimately related to water vapor and temperature. H, OH, HO_2 and H_2O_2 are inferred in trace amounts from the presence of H_2O. In the upper atmosphere, H, O, and CO have been observed also in small amounts; the atmosphere is largely undissociated up to the exobase above 200 km. CO_2^+ has been detected in the ionosphere, but the major ion is thought to be O_2^+, with trace amounts of O^+ and CO^+. Exospheric temperatures seem unusually low, apparently in the range 200 to 440 K.

SECTION II

MARS SCIENCE OBJECTIVES

The study of Mars should lead us toward major new insights into the processes by which planets accreted from the condensing solar nebula: the effects of initial temperatures, pressures, and compositions on the subsequent internal evolution of the planet; the time history of internal activity that led to the evolution of its current internal structure, surface features, and the atmosphere; the degree to which impact of meteoritic (or asteroidal or cometary) material may have determined planetary composition and crustal structure; the interaction of solar and galactic radiation with the atmosphere and surface materials of the planet and their role in determining atmospheric evolution; the history and dynamics of the atmosphere and hydrosphere and their interrelationship with surface and internal processes of the planet; and, if a Martian biota is now extant (or has existed in the geologic past), the nature of its biology, origin and evolutionary history. In this endeavor we can learn by direct study of the planet and its materials, by comparison to the Earth, Moon, Venus and other planets, and by laboratory studies that tie together observation and theory.

A. PRINCIPAL QUESTIONS

Some questions that must be addressed through these studies are:

(1) What is the chemical composition of the planet? How does that relate to the location of Mars in the evolving solar system? What were the heat sources that provided the energy for internal activity and differentiation?

(2) What is the current internal structure of the planet? What are the compositions and masses of the Martian core, mantle, and crust? What is the present heat flow? Is the magnetic field related to an internal dynamo? What is the current and past seismicity of the planet? What can be said about the history of Mars' moons?

(3) What is the history of crustal evolution, including volcanic activity? What are the compositions of crustal rocks? How thoroughly outgassed is Mars? What are the controlling oxidation/reduction reactions in the Martian interior and how have they affected the composition of crustal materials?

(4) What is the origin of the principal landforms of the planet? What are the relative ages of surface features? What are the relative roles of volcanism and tectonic processes on the surficial features of the planet? Has water erosion, mass wasting or erosion by wind-blown dust been the chief erosive agent modifying the surface? What is the past history of these processes?

(5) What is the origin, evolution, structure, and dynamical state of the Martian atmosphere? Are primordial gases retained, or are all gases derived from volcanic or interior outgassing? How are volatile materials distributed among the crust, regolith, poles, or atmosphere? Have substantial amounts of volatiles been lost from the planet? What are the controlling factors for atmospheric dynamics, including wind patterns, dust storms, polar hood growth and recession, and cloud formation? Are there records of greatly differing atmospheric compositions, pressures, or dynamics in the past?

(6) What is the history of meteoritic influx on the Martian surface? What differences occurred in the influx rates over the history of the planet? Is the composition of Martian meteorites different from those impacting the Earth? What is the relationship of Mars' moons to the planet, to asteroids or meteorites?

(7) What chemical and physical processes determine the composition of the boundary layer between the lithosphere and atmosphere? What parts do meteorite impact, pyroclastic volcanism and eolian erosion play in the generation of the regolith? What are the types and rates of mechanical and chemical weathering processes active at the surface. Do they vary in different locations; have they been different in the past? What is the fate of organic compounds on the Martian surface?

(8) What are the environments in which a Martian biota may have existed in the past or exists today? What organic compounds are stable in these environments? Are organic compounds produced or destroyed by abiogenic means? Are there viable organisms on Mars? Were there any in the past? If so, what are or were their characteristics?

B. MAJOR AREAS OF INVESTIGATION

Although the present state of the investigation of Mars is so advanced that highly detailed questions can be asked about the planet, it remains desirable to maintain a broad view. Thus groups of broad, basic questions are outlined below; it is clear that the answers to such questions will not be acquired as the result of any one spacecraft -- use of various technologies including orbiters, hard landers, mobile laboratories and spacecraft for sample return will be required.

1. Planetary Mass Distribution and Figure

The mass distribution and figure of a planet are fundamental properties determined by the nature of its origin and by its composition and evolution. Information about the structure, dynamics and strength of the interior and about the thickness and strength of the crust may be derived from accurate determinations of the gravitational field and figure of Mars. Improved data require a high-inclination, low-altitude circular orbit. The planetary figure can be determined with substantially higher accuracy and spatial resolution by the acquisition of orbital radar altimetry data. Altimetry is also required for the detailed analysis of gravity data in terms of Bouguer maps and density distributions.

2. Internal Structure

Gravity field data suggest that Mars probably has a core/mantle internal structure; it is thus of fundamental importance to determine the size, density and phase of the interior zones. Direct information about these properties can be achieved through analysis of seismic waves that have passed through the deep interior and analysis of free oscillations set up by strong marsquakes or large impacts. Such resonant vibrations provide a measure of the Q of Mars which is determined by the physical state of its interior. The establishment of a planet-wide network of suitably spaced seismometers is a major goal in the continued exploration of Mars. For the measurement of free oscillations, seismometers with a broad frequency response are required.

Demonstration that the magnetic field of Mars is due to an internal dynamo would indicate that the planet possesses a convecting iron core. The spin rate of Mars is sufficient to provide the required Coriolis forces for a dynamo, but the observed magnetic field could be explained as well by solar wind induction in the ionosphere. An orbiting magnetometer, preferably with low periapsis and supplemented by a plasma probe, would be an important aid in understanding the origin of the field. A surface network of magnetometers, in addition to other uses, would contribute significantly to understanding this phenomenon.

3. Crustal Composition and Bulk Composition

Study of the composition of surface rocks and soil on Mars is complicated by the variety of physical and chemical processes that have shaped the surface. The composition of the surface materials places certain types of constraints on the interior; geophysical data (gravity, seismic data) will define the volume and the physical state of crustal, mantle and core materials. Heat flow data will place limits on the content of radioactivity of the planet. Certain elemental or isotopic ratios, relatively unaffected by planetary differentiation, are determined by the original condensed planetary composition.

Determination of the chemical composition of the crust and mantle depends principally on samples and their mineralogical textures, chemistry, and isotopic properties. Through these analyses, the history of the rocks through volcanic, metamorphic, sedimentary impact and weathering processes can be studied. These types of investigations can best be done on samples returned from the planet for study on Earth. However, reconnaissance chemical and mineralogical data obtained by orbital γ-ray, infrared reflection spectroscopy and multispectral imaging are essential in selecting the most promising sample return sites. Furthermore, orbital chemical and mineralogical data can be obtained at resolutions that are good enough to distinguish regional geochemical trends and thus provide a basis for extrapolation of sample data planet-wide. However, the prevalence of surface dust and chemical weathering may degrade the interpretability of remote surface chemistry observations.

In order to fill the gap between the broad capabilities of orbital mapping and the local data obtained from sample studies, and to eliminate much of the interference from surface dust, surface chemical investigations should be made. Besides the techniques usable from orbit, which also can be applied at the surface, in situ compositional analysis could provide broader chemical coverage through proton-alpha scattering spectrometry, X-ray fluorescence, and X-ray diffraction. The in situ analysis has very much higher spatial resolution than the orbital data (individual rocks can be analyzed), but probably is not possible on a truly global scale. This work can provide enough detail to delineate those areas that would most profitably be sampled. Mobile surface vehicles can provide a mechanism for extending data into wider and less accessible areas.

Heat flow determinations are critical to understanding the radioactivity of the planet and its thermal history. They must be obtained on a planet-wide basis. Two techniques are promising, but not proved. The first, using orbital microwave radiometry, is hampered by near-surface structural complexities. The second, using surface probes, may be limited by instrumental and emplacement problems. Drills mounted on soft landers have been used successfully by the Russians to return lunar samples and may be applicable to heat-flow probe emplacement.

4. Crustal Evolution

Mars' relatively complex evolution is reflected in the nature of its crust, which is partly primitive and partly of more recent origin. To understand the surface of Mars, information about the bulk properties of the planet is required, and some of the areas of interest have been discussed previously. Another important area, atmospheric evolution, is discussed below. Here, attention is turned to direct investigations of the Martian surface by photogeology and petrology.

Images are essential for the proper interpretation of landforms, stratigraphic relationships and lithologic types. Viking orbital imaging has improved that available from Mariner 9, but very little data will be acquired at resolutions better than 40 meters/pixel. It is difficult to relate orbital images to pictures obtained at the surface. In order to provide the proper geologic context for selected sites (e.g., sample return landing sites or surface traverses), improvements of resolution (1-meter resolution, highly desirable; 5-10 meters a great improvement) are required. Multispectral images can provide compositional (mineralogical) data as well as surface morphology.

The mapping of Martian petrology is essential to the determination of the local and regional geologic history of the crust. Whereas returned sample studies provide basic data for interpreting origin, temperatures and pressures of formation and modification of rocks, and absolute ages, mapping provides information on the sequence of geologic events and the volumetric relations of various rock types. If rock types can be characterized by any set of observable parameters, those parameters may be extendable from orbital observations or by in situ measurements.

Petrologists use petrographic microscopy, along with chemical and mineralogical analysis as a principal tool for the determination of surface lithologies. Petrographic studies would be central to the studies of returned samples, which would attempt to characterize, analyze, and interpret the origin of the rocks collected. If planetary landers are able to extend geochemical data more broadly on the planet, so also they can extend lithologic interpretation through microscopic capability. A polarizing microscope with resolution of approximately 20 micrometers would be highly desirable for in situ analysis. Although this is substantially poorer than that obtainable in the laboratory, it would be suitable as a surface mapping tool.

The surface of Mars has an unexpectedly complicated chemical reactivity. The complete understanding of the interaction of the soil and the Martian atmosphere, which may be crucial in deciphering the evolution of the atmosphere, may be possible only if certain measurements are performed in situ. This would be the case if a steady state supported by radiation effects was maintained that was unrecoverable when samples were collected for return. The Viking chemistry capability has demonstrated that certain experiments are feasible; however, it remains to be demonstrated that the techniques have the required selectivity and sensitivity to be useful as mineralogical or surface-activated chemical analysis tools. X-ray diffraction also may be a useful surface analytical technique; however, complexities of sample preparation must be solved and adequate analytical precision must be demonstrated.

5. Atmospheric Evolution

Evidence diagnostic of the origin and evolution of the atmosphere is contained in the inventory of volatiles. Part of this inventory is inaccessible, trapped in polar deposits, in permafrost, and bound in the regolith, but an important part remains in the atmosphere and is directly measurable. The mix of volatiles in the planet as a whole probably reflects the composition and temperature of the solar nebula from which Mars condensed. Certain aspects of this mix remain in the atmosphere: for example, the rare gases. The amount of these volatiles relative to the mass of the planet depends on the intensity of early outgassing (controlled by the rate and conditions of accretion); on the subsequent addition of radiogenic volatiles, such as ^{40}Ar (depending on the thermal history and differentiation of the interior); and on escape processes, which are commonly mass-selective among isotopes. Detailed measurement of volatile abundances and isotopic ratios in greater detail than accomplished by Viking will provide a data base against which (in conjunction with similar data for the Earth and ultimately Venus and the outer planets) theories of planetary formation and evolution can be tested. The volatile content of the regolith must also be studied to elucidate the past and present mechanisms for exchange of volatiles between atmosphere and regolith.

The more recent history of the atmosphere has left its mark in the geological record. The abundant evidence of water erosion points to the existence of a more massive, moisture-bearing state of the atmosphere, and the layered polar deposits suggest that this state and the present one may have alternated regularly, at least during relatively recent times. We need to understand the mechanism producing the alternation and long-term changes, which have important implications for the questions of life on Mars as well as for planetological evolution.

As compared to the Earth, the present atmosphere of Mars represents only a minor portion of the volatiles that have probably been outgassed from Mars and which, at some time, resided in the atmosphere. An adequate understanding of the evolution of Mars requires that the atmospheric evolution and its present state be understood in detail. Areas open to observational attack include the following:

a. Atmospheric Composition. The abundance of the noble gases and of the various isotopes of certain gases yield important insight into the total outgassing of the planet. Accurate measurements of the abundance of neon, krypton and xenon require a relatively high-precision mass spectrometer with an improved chemical enrichment capability. Accurate measurements of isotope ratios can be achieved using mass spectrometers on entry vehicles or on low-altitude orbiters.

b. Atmospheric Escape. The escape of gases from the planet affects the evolution of the atmosphere as well as its present state.

The escape of H can be studied by Lyman-alpha photometry. Ionic recombination mechanism studies require ion mass spectrometer and Langmuir probe measurements at the base of the exosphere. Solar wind ablation analyses require field and particle measurements at all altitudes down to the main ionospheric region.

Exospheric temperature and thermospheric composition can be measured from a low-periapsis (sterilized if required) orbiter directly by mass spectrometer. From a higher circular orbit, limb-scanning UV spectrometry can measure temperature and the abundance of monatomic oxygen; other species of interest are more difficult because of the very rich spectrum originating from CO_2 itself. The remote-sensing optical technique, however, provides much better global coverage.

c. Stability of the Current Atmosphere. Outstanding compositional questions now concern chemically active minor species, their role in the catalysis of the recombination of CO_2, and their relationship to the possible existence of Martian organisms. Attempts to explain the stability of the CO_2 atmosphere by gas-phase catalysis have involved either very vigorous downward mixing of oxygen to prevent the copious production of O_2 in the stratosphere, or a very moist troposphere to promote the destruction of this O_2 by formation and photodissociation of H_2O_2. Since the vertical distribution of "odd oxygen" is sensitive to the vigor of mixing, the critical experiment is the simultaneous measurement of the vertical profiles of O_3 and H_2O.

The H_2O and O_3 altitude profiles can both be measured in thermal emission by limb-scanning IR radiometry; O_3 can also be measured in absorption by limb-scanning UV photometry, but this method is susceptible to obscuration by aerosols. Nadir-viewing UV spectroscopy, which measures the altitude distribution of O_3 on Earth, is not applicable to Mars because of the much smaller optical depth of O_3.

Information on the turbopause altitude and on mechanical coupling between the thermosphere and lower atmosphere can be provided by measurements of the concentrations of some or all of O, CO, N_2 and Ar in the thermosphere, and by simultaneous measurement of thermospheric and lower-atmosphere temperature profiles.

Wave propagation is best studied by limb-scanning IR radiometry to measure the lower-atmosphere temperature profile, and by mass-spectrometer measurements of compositional inhomogeneities in the thermosphere.

d. Dynamical State. The Martian atmosphere is manifestly dynamic, as shown by the occurrence of dust storms, light and dark surface streaks, dune fields, the geological evidence of eolian sedimentation and erosion, and the presence of "weather" systems. The theoretical challenge is to apply an understanding of atmospheric dynamics derived from the Earth's atmosphere to that of a very different planet.

The phenomena that must be further studied and understood are of both global (e.g., the seasonal transfer of volatiles from one pole to the other, the growth and diminution of the perihelic planet and sporadic small dust storms, the growth and recession of the polar hoods), and local scale (e.g., diurnal wind patterns, ice fogs, fronts, lee-wave clouds). Extensive measurements of the pressure-temperature field is required as a function of position, local time, and season, as are cloud images and surface meteorological stations measuring temperature, pressure, winds, and the aerosol burden. In addition, dynamic coupling of the upper and lower atmospheres must be explored.

The pressure/temperature field can be measured by nadir-viewing IR radiometry of the 15-μm band of CO_2. Cloud and dust-storm studies require targetted orbital visual imaging, and also temperature (IR) and scattering (UV) measurements. Meteorological stations are required on any lander. Imaging studies of seasonal and secular changes in the polar regions must be continued, and the water-erosion phase or phases must be dated. Understanding of the cyclic characteristics of the atmosphere is especially important to the extrapolation of existing conditions and processes (such as escape mechanisms) backward through time.

e. Volatile Inventory. Most of the volatiles degassed from Mars must now reside in the remnant polar caps, as subsurface permafrost, or trapped in the regolith as ices or as weathering products. It is important in understanding the evolution of the atmosphere and the crust to determine how the volatile inventory is divided between these sinks at present and in the past.

If the remnant polar caps (which consist primarily of water ice) are thin, then orbital gamma-ray spectroscopy or *in situ* examination by a mobile laboratory might provide the desired measurements. If orbital observations indicate the presence of more than a few tens of gram/cm^2 of ice, then other methods of measurement will be needed. Moreover, the presence of frozen water, permafrost and water in the Martian soil and subjacent rocks is believed to account for a significant fraction of the total inventory of degassed water.

Although volatiles condensed on or just under the surface can be detected both by direct chemical measurements from orbit and at the surface, water or ice occurring at greater depth would require other means of detection. Several of these means depend on an electrical response or echo from the subsurface strata. Water in amounts greater than one or two monolayers has an important effect on the electrical properties of porous or granular material because it is a highly polar molecule (ice has a dielectric constant $\epsilon \sim 100$ and a dc resistivity, $\rho \sim 10^7$ ohm-m as compared to $\epsilon \sim 8$ and $\rho \sim 10^{12}$ ohm-m for a typical silicate). At temperatures of the Martian regolith, measurements of the soil electrical properties at frequencies below the relaxation frequency of ice ($\sim 10^4$ Hz) could provide important information about the abundance of water in the regolith. For permafrost electrical conductivity equal to that of sea water, the skin depth is about 5 m for frequency of 10^3 Hz. Using conventional magnetometers (~Hz) the skin depth increases to 0.2 km. The skin depth is approximately the thickness of the thinnest layer that could be detected. Thus, buried ice may be detectable by coherent, long wavelength, synthetic aperture radar (such as was flown on Apollo 16) or by using radio frequencies with a transmitter-receiver combination, one or the other being placed on a rover. Resolution is a function of frequency and area illuminated; the surface radio frequency and orbital radio frequency differ, depending partially on the subsurface structure.

The use of a passive system employing magnetometers has the advantage of employing the natural background electromagnetic spectrum to excite the subsurface strata. This advantage is mitigated if the "forcing" field is poorly known. Also, the frequencies commonly used have an upper limit of a few hertz. Therefore, deeper strata can be detected but at the expense of nearer subsurface resolution.

These methods can be complemented by electric field measurements which can enhance substantially the analysis of electrical data.

The presence of ice or volatiles in the regolith could be determined by measuring the electrical properties of the soil by suitably emplaced electrodes and associated instrumentation on hard-landing or soft-landing spacecraft. Measurements of dc resistivity as a function of temperature could be made by a penetrator experiment. Determinations of resistivity as a function of frequency for various depths (accomplished by varying the electrode separation) could be made by a mobile laboratory. Both types of data would characterize the abundance of ice in the soil.

Another approach capable of measuring the presence of absorbed water and chemically bound water is the use of a differential scanning calorimeter, which provides an accurate measurement of the temperature of a soil sample as that sample is progressively heated. This experiment is best suited to a soft-landing spacecraft.

SECTION III

MISSION OBJECTIVES

To accomplish the science objectives discussed in the previous section and to answer the important scientific questions about Mars require an exploration program with four types of measurements:

(1) Orbital science: Many different observations from orbiting spacecraft (i.e., imaging, spectral mapping, γ-ray mapping, gravity, magnetic, aeronomy, etc.) attacking a variety of global, whole-body, surface, and atmospheric science questions.

(2) Network science: Systematic measurement (e.g., seismic, meteorologic, chemical, imaging, heat flow, and water detection) for a long time at several points widely distributed over the planet.

(3) Mobile-lab surface science: Detailed and complex investigations (i.e., surface properties and chemistry and mineralogy of soil, atmospheric chemistry and isotopic composition, biologic experiments, soil mechanics, etc.) at a number of surface locations within a limited area of mobility.

(4) Sample return: The return of rationally selected samples from a carefully chosen limited area (implying limited mobility for sample selection).

Three clearly defined phases can be identified for continued exploration of Mars. The first of these involves the Viking Extended Mission. The four spacecraft currently deployed should be utilized to the fullest possible extent and analysis of data obtained must be vigorously pursued to provide information on which subsequent missions can be effectively based. One or two Martian years of observations, especially through a perihelic dust storm, and low periapsis altitudes for the orbiters, will yield a rich return.

The second phase of exploration involves GEM (Global-Environment Mission). This mission is designed to look both at planet-wide phenomena and local heterogeneity.

The third phase envisioned is the MSSR (Mars Surface Sample Return Mission). This mission will permit the application of the powerful tools available in Earth-based laboratories to investigate both the planetological and biological history of Mars.

A. SYNOPSIS OF PROPOSED MISSIONS

To answer the range of planetological questions that can now be posed about Mars in the context of our present understanding of Earth and the other planets, a post-Viking exploration program requires four types of approaches:

(1) Whole-planet mapping: A comprehensive mapping of the surface morphological, lithological and chemical provinces of the planet, its gravity and magnetic fields and other whole body problems, using orbiting spacecraft. These data are necessary to provide the context for surface measurements and will allow detailed observations from surface stations to be extended with confidence to answer planetwide questions.

(2) Network science: Geophysical measurements (e.g., seismic study of interior structure, heat flow to bound the thermal state, and meteorological stations) uniquely require the establishment of a network of stations that operate over an extended period of time. It presently appears that such a network can best be emplaced by penetrators or rough landers.

(3) Surface science: Detailed investigation at the Martian surface can provide fundamental data on the interaction of the surface and atmosphere, properties of surface materials, stratigraphic investigations of depositional history, atmospheric composition and evolution, and biological questions. With surface mobility, these data can extend data obtainable from returned samples to otherwise unreachable localities and can provide surface data for correlation with orbital mapping.

(4) Sample analysis: Sample return for analysis on Earth represents the best way to obtain many types of petrological, chemical, isotopic, biological and physical data from Mars. The return of unsterilized Martian materials can uniquely provide data on the absolute chronology of Martian rock units, on detailed detection and characterization of Martian life, on surface-atmosphere interaction processes and rates, and on the composition and evolution of Mars' crust and mantle. A sample return must provide rationally chosen samples from carefully selected areas (with limited mobility for sample selection).

Data from all of the above approaches must be synthesized to answer planetological questions. Opportunities to combine the objectives in single missions should be studied carefully. We have identified two principal missions that we believe are feasible and would be highly productive:

(1) Global-environmental mission (GEM): This mission would consist of an orbital science package capable of whole-planet coverage, a penetrator network (6-12 penetrators) for geophysical and geochemical studies, and soft-landed stations, including surface mobility, to extend the surface

investigations done by Viking. Such a mission would provide unique global and environmental data and would prepare for subsequent sample return missions.

(2) Mars Surface Sample Return (MSSR): Sample return missions should be a principal long-term objective of Mars exploration. Such missions may also carry surface science experiments. Surface mobility would benefit from the development of GEM capability; however, many new systems and capabilities (low-thrust propulsion to augment landed science and returned sample payload) would also be required. Quarantine control for protection of Earth from back-contamination levies severe constraints and requires early definition. The missions must make optimum use of data derived from previous missions.

The scientific objectives of these missions are discussed in greater detail in the following sections.

B. ORBITAL SCIENCE

1. Geoscience (Geology and Geochemistry)

a. Global Elemental Composition and Mineralogy.

1) Remote-Geochemical Techniques. Elemental composition mapping can be performed for a variety of important elements at Mars. Mapping of the naturally radioactive elements K, Th and U is relatively uncomplicated since the gamma rays are produced directly by the elements and no modeling assumptions concerning excitation are needed to infer elemental concentrations. Knowledge of atmospheric column density to ~10% is required to correct for atmospheric absorption. A particularly significant result of this class of measurements is the K/U ratio, which is related to the degree of planet-wide differentiation and the enhancement or depletion of volatile elements during and since planet formation.

Another set of elements can be detected through neutron capture and scattering interactions with atmospheric and surface material. These include O, Fe, Si, Mg, H, Al, Ti, S and possibly C and Gd, in approximate order of detectability. Qualitative analysis of these elements is relatively straightforward since these elements produce characteristic spectral signatures which can be unraveled using procedures and calibration data developed for Apollo orbital gamma-ray analysis. Quantitative analysis is more complex even for relative abundance values since the excitation depends on the neutron energy spectrum, which can be modified by the atmosphere and hydrogen concentrations. Indirect evidence allowing the determination of the neutron spectrum is provided by the ratio of intensities in emission lines (e.g., Fe or Si) produced by thermal and fast neutron interactions. It is believed that a direct measurement of neutron flux and fast to thermal ratio at the orbiter would greatly ease modeling of this effect. Neutron detectors of the proper type exist and are not believed to be a major technological driver for this experiment. In addition, the neutron measurements themselves are very useful for detection of hydrogen. The direct gamma-ray detection of H through 2.2-MeV capture γ line only allows detection of H at depths of 10 cm, while the existence of H at greater depths (few meters) can be inferred from its effect on the ratio of fast to thermal neutrons, since H increases the thermal component. Secondly, the presence of rare earths (e.g., as in lunar KREEP rich rocks) tends to decrease the thermal neutron flux in a dramatic way. Since the presence of both hydrogen and rare earths would combine to decrease total flux in both fast and thermal neutrons, knowledge of the neutron flux at the orbiter will allow the disentangling of these effects.

2) Spectral Reflectance Techniques. Analysis of the spectral characteristics of reflected solar radiation to infer mineralogical and compositional information about planetary surfaces has been developed as a useful remote sensing tool over the past few years. Generally, compositional information comes from three basic features in reflectance spectra: (1) charge transition bands due to transitions in the d-shell electrons of transition metal ions in crystal lattices (the best known of these are the bands near 1.0 μm and 2.0 μm due to Fe^{2+} in pyroxenes); (2) charge transfer bands where electrons are exchanged among ions in a material (generally less diagnostic of detailed mineralogy than transition bands but frequently useful in determining concentrations of transition metal ions or oxidation state); and (3) vibrational bands: usually due to H_2O, OH, SO_4, CO_3 in minerals (analogous to molecular absorption bands in the infrared spectra of gases and relatively sharp and diagnostic when present). Mars appears from ground-based spectra to exhibit all of these classes of spectral features and is thus a promising target for the application of these techniques.

Ideally, one would want a perfect reflectance spectroscopy experiment to yield full spectra at about 1% spectral resolution ($\Delta\lambda/\lambda$) for each spatial resolution element on a planet's surface. In practice, telemetry and data handling constraints along with instrumental considerations tend to yield a series of compromises where spatial resolution is traded off against spectral resolution. One end member of this sequence is obviously the monochromatic image where spatial resolution totally dominates instrument requirements. The other end of the sequence is a very high-resolution spectrum of an entire planet, as frequently acquired in ground-based work. In terms of spacecraft experiments, two complementary approaches have been developed: multispectral imaging and reflectance spectroscopy. In application on a spacecraft the two experiments work together: multispectral imaging provides broad-coverage, high-spatial-resolution maps of areas having similar spectral properties at a number of carefully chosen wavelengths; reflectance spectra taken at several points within each of these units are used to characterize the unit in terms of its mineralogy. If the bands in the multispectral experiment have been chosen to separate the major spectral classes on a given planet's surface, the combination with the reflectance spectra can provide essentially the same information as the ideal experiment.

a) Multispectral Imaging. Multispectral imaging uses monochromatic images taken at several wavelengths to provide information on the spatial distribution of spectral properties within a given scene in addition to traditional photogeological and morphological information. The technique, which requires high photometric accuracy and broad spectral range for greatest efficiency, involves taking a number of images in different spectral bandpasses and then recombining the data to display spectral variations. In a framing camera approach this is accomplished by taking successive images through a set of filters. In line-scan approaches, images in several wavelengths can be built up simultaneously. Several display formats can be used, including (1) spectral ratios, where two images are ratioed and enhanced to display the variation in reflectance at the two wavelengths, (2) color ratio composites, where three or more spectral ratio images are used to control the intensity of red, green and blue light to produce a color product where the color shade is related to spectral properties, and (3) digital maps, where units having similar spectral properties are identified by a classification scheme and a resultant map of "spectral units" is produced.

For Mars, a wide spectral range such as provided by CCD or silicon vidicon systems is highly desirable since the known color contrasts on Mars are strongest beyond the range of Se-S vidicons ($\lambda > \sim.7\mu$).

b) Reflectance Spectroscopy. The presence and abundance of many minerals, including those known through previous ground-based and spacecraft observations to be present in the Martian surface, can be determined with about 1-km spatial resolution using the technique of reflectance spectroscopy. Geochemical surface units can be defined and their extent mapped by using a reflectance spectrometer operating in the spectral range 0.30 - 4.5 μm with about 400 parallel operating spectral channels. Many geochemically interesting minerals such as pyroxene, olivine, plagioclase, iron oxides, water ice, carbon dioxide ice, carbonates and sulphates have several types of electronic and/or molecular absorptions which are often diagnostic of the species and composition of the mineral and sometimes of the relative abundance of several minerals. The CO_2 and H_2O molecular and Fe^{3+} electronic absorption and particle scattering in the Martian atmosphere would slightly complicate interpretation of spectra. Available flux levels should allow photometric precision of 0.1 to 0.5% and spatial resolution of 1 km.

b. Global Geomorphology.

1) Imaging Systems. A pair of cameras should be used to extend the photographic data acquired by Viking orbiters. As photographs have been acquired by successive spacecraft observations of Mars (including Mariners 4, 6, 7, and 9 and Vikings 1 and 2) it has become apparent that significant new information has become available with increasing resolution.

It has been difficult to correlate 100-meter/TV line pair orbital images with the complex detail shown in the lander images. Increasing the resolution to 1 meter would almost certainly reveal abundant new information on geologic and geochemical processes. The new high-resolution imaging system should try to be upgraded to 1 meter per TV line; a minimum increase is 5 to 10 meters/TV line. This increase may be possible by combining Viking and Voyager imaging system components. The other essential use for the very high-resolution system will be to examine landing sites and plan traverses for the possible rover spacecraft. Traverse planning will include selecting sites where measurements of compositions will be made in order to correlate surface geochemical measurements with orbital geochemistry.

A low-resolution camera is essential to observe larger areas of the planet, to establish a new geodetic control network, and to observe time-variable features such as surface frost and atmospheric phenomena.

c. Global Geophysics.

1) Magnetic Fields. Mars' magnetosphere is relatively unexplored but we know that the global magnetic field forming the background fabric for the magnetosphere is far weaker than that of the Earth. Consequently, the bow shock wave is so close to the planet that the post-shocked solar wind may be in direct physical contact with the ionosphere. If so, some or even all of the magnetospheric field may be due to induction by the solar wind electric field. If the field were induced this would have two principal results. First, a dynamo source would be ruled out. External induction of the magnetic field also provides an important and novel mechanism for "erosion" of the Martian atmosphere. Any atmospheric constituent which is ionized by charge exchange, photoionization, or photodissociative ionization will be subject to acceleration by the solar wind electric field. Details of these processes are obscure but could be important over geological time. An important test for the source of the Martian magnetic field comes from testing the magnetospheric field as to whether it is primarily poloidal (dynamo) or toroidal (induced).

A low-altitude orbit is needed for a magnetometer experiment. The reason is that if the field is induced, the current system closes from the solar wind through the ionosphere. Therefore, the satellite should make close contact with the ionosphere. A complementary plasma probe would permit details of the solar wind interaction to be determined with more confidence. Also a plasma probe may aid in separation of the direct and Peelerson currents in the ionosphere.

To understand details of the solar wind interaction ideally requires a reference subsatellite in the solar wind upstream of Mars. Such a satellite will necessarily spend some time downstream; this can be an advantage for mapping the total magnetospheric magnetic field and the flow field downstream of Mars.

Because the magnetosphere is weak, and especially if it is induced, it represents a new physical regime. For a successful study a reference subsatellite is required; otherwise processes arising in the solar wind and which "drive" the magnetosphere cannot easily be separated from those generated internally in the magnetosphere.

A magnetospheric mapping magnetometer is also required in order to provide information on the "forcing" field at the surface of Mars. This is essential information if a network of surface magnetometers is used to investigate the subsurface electrical properties such as those produced by permafrost.

2) Heat Flow. Pending the further analysis of its potential, microwave radiometry may provide a significant means of evaluating the global heat flux from Mars. Such an experiment should be complementary to a suite of subsurface probes using penetrators. The penetrator heat flux technique is as uncertain as the microwave method. Even if the penetrator procedure is satisfactorily resolved, the potentially high degree of variability in measurements suggests strongly the need for intercomparison with orbital data, the latter representing a global average. On the other hand, the likely variability of subsurface measurements is in itself important as an expression of the planet's thermal heterogeneity.

3) Gravity and Altimetry. Determining the higher degree harmonics of the Mars gravitational field is an important geophysical objective, placing constraints on crustal thickness and strength. Doppler tracking of an orbiter can accomplish these goals; gravity gradiometer systems also show promise of being able to perform sensitive gravity surveys from orbit. Since gradiometry has better response to high spatial frequencies in the gravity field and doppler tracking to low frequencies, the two methods used together would in principle produce a superior survey.

Accurate altimetry is required to make maximum geophysical use of the data. Altimetry is used to correct the important effects of topography on the gravity field, allowing the effects due to density variations to be modeled. Radar altimeters can accomplish the altimetry requirement and also provide some information on surface roughness and electrical properties. Accurate altimetry and gravity data will also allow determination of the center-of-figure, center-of-mass offset.

Observations relating to the dynamical history of the Mars system can be accomplished by studies of Mars' moons, Phobos and Deimos. The dynamical history of these interesting satellites is still a subject of debate and, among other things, better determination of the secular acceleration of Phobos is needed. Determination of the masses of the satellites would be of great importance for these dynamical studies as well as being very interesting in their own right.

2. Meteorology

a. Global Atmospherics.

1) Atmospheric Composition. Simultaneous altitude profiles of H_2O, O_3, and temperature should be measured as functions of position and time (diurnal and seasonal). Such measurements can be obtained by

limb-scanning UV and IR techniques from a circular orbit. Measurements of the mixing ratios of CO and O_2 and of their long-term temporal variations (if any) are also needed. To obtain such measurements, an entry mass spectrometer is a minimum requirement; a lander mass spectrometer is preferable. These measurements can be readily extended to such other minor atmospheric constituents as odd nitrogen (NO, NO_2, HNO_3, etc.).

2) <u>Exospheric Temperature and Composition.</u> If quarantine requirements rule out a low-periapsis (200-km) orbiter carrying *in situ* instruments, then entry vehicles should carry neutral and ion mass spectrometers and, if possible, retarding potential analyzers and electron temperature probes. Long-term studies will require limbscanning orbiter airglow UV spectroscopy. The nature of escape processes occurring in upper reaches of the Martian atmosphere will be difficult to determine experimentally. Lyman-alpha photometry and a full complement of solar wind experiments are needed. The pressure-temperature field can be investigated by means of a nadir-viewing selective chopping IR radiometer, an instrument that should be included on any orbiter mission.

3) <u>Dynamics.</u> The nature of lower/upper atmosphere coupling on Mars is best inferred from temperature profiles, measurements possible with the selective chopping IR radiometer or with a limb-scanning IR radiometer of the Pioneer Venus type. The atmospheric aerosol burden can be determined by means of TV techniques on orbital (limb-scanning) and lander (extinction, terminator) vehicles. Dust storms and similar meteorological phenomena can be studied by global orbital imaging and lander imaging.

C. ORBITAL MISSION CONSIDERATIONS

1. Spacecraft Considerations

The geochemical and geological mapping experiments and some meteorological and geophysical experiments described above operate most efficiently in a nadir-pointing configuration. A stabilized, nadir-pointing spacecraft would provide the most favorable platform for these classes of measurement. Some atmospheric and meteorological experiments operate best in a limb-scanning mode, which could be achieved either by spacecraft maneuvers or by the addition of a limited scan platform capability. A Viking Orbiter-class spacecraft, with three-axis stabilization and a scan platform can also be operated to maintain a nadir-looking configuration, although this would require frequent scan platform motion. The Viking Orbiter approach would provide more flexibility for some limb-scanning experiments, but on balance we feel that most of the first-order objectives of a geochemical and geophysical survey would be best served by a nadir-looking approach. The LPO configuration has in fact been designed to maximize return from general planetary orbital surveys of this type.

A third possibility is a JOP-type dual-spin spin-stabilized spacecraft. Limb-scanning atmospheric experiments and solar wind interaction experiments benefit from a spinning spacecraft, and the nadir-viewing experiments can be accommodated on the despun section if the spin axis is suitably oriented.

2. Orbit Considerations

a. Geoscience Experiments.

1) <u>Geochemical and Geological Experiments.</u> The objectives of this class of experiments call for global mapping at moderate resolution. The resolution of the elemental analysis experiments (γ-ray and neutron) is determined by altitude, being approximately equal to the spacecraft altitude until this becomes comparable to or exceeds the planetary radius. On a planet other than Mars the optimum orbital altitude would be determined by the tradeoff between resolution on the one hand and data rate and integration time (sensitivity) on the other. On Mars the optimum is the lowest altitude compatible with the quarantine requirement; and a circular orbit is preferred to give uniform resolution. Multispectral imaging requirements for global mapping at the 1-km resolution level are met from such a low circular orbit if the orbit period and longitude phasing are chosen and adjusted to give complete surface coverage. Again, a circular orbit is desirable for the uniformity it brings. Neither of these classes of experiments depends critically on lighting conditions, except that the multispectral imaging objectives will not permit a Sun-synchronous, near-terminator orbit (closer than ~30 deg to terminator).

2) <u>Geophysical Experiments.</u> Mapping the magnetic field requires extensive variation in aerographic and Sun-planet coordinates and in altitude. This points not only to a near-Sun-synchronous orbit but also to an eccentric orbit, at least for part of the mission. Surface magnetometer data and/or a second spacecraft with a magnetometer are highly desirable for a complete understanding of the Martian environment.

Gravitational data can be obtained by doppler tracking of the spacecraft. Mapping of small gravity features is improved by low altitude orbits in general and complete coverage during the mission is required.

b. <u>Meteorology Experiments.</u> Those atmospheric experiments aimed at remote sensing of any part of the atmosphere benefit from a low-altitude orbit, which favors both spatial resolution when viewing the nadir and altitude resolution when limb-scanning. The limit is set by orbital lifetime constraints, and a circular orbit is favored. There is a strong requirement for complete local time coverage, and the precession of the orbit should be rapid enough to permit the decoupling of local time and seasonal changes.

A group of experiments would benefit greatly from an eccentric orbit, or at least an eccentric phase during part of the mission. These include _in situ_ measurements of the neutral upper atmosphere (at present, only possible with a sterilized orbiter), Lyman-alpha mapping of the hydrogen corona, and particularly, _in situ_ measurements of the solar-wind (atmosphere interaction region).

c. Surface Experiment Support. Measurements made at the surface help considerably in increasing the return from an orbiting spacecraft payload by providing both _in situ_ confirmation (ground truth) and refinement of surface conditions measured by orbital instruments as well as obtaining additional measurements to aid in reducing and interpreting orbital data.

Surface measurements of elemental and mineralogical composition and material and physical properties will greatly increase our confidence in orbital geochemical results. For instance, understanding of surface weathering processes can be crucial in interpreting reflectance spectroscopic results.

Measurements at the surface of X-ray, γ-ray and neutron fluxes, and of atmospheric scattered light contributing to the surface reflected light as seen by the orbiter, will be of considerable help in calibrating and reducing orbital geochemical data.

Meteorological measurements (pressure, temperature, velocity) help calibrate and improve the usefulness of orbital meteorological experiments and also help refine estimates of atmospheric column density, important in calibrating the high-energy geochemical data.

Measurements from the surface of the aerosol burden will greatly assist the interpretation of orbital limb-scanning experiments, particularly in the UV. They will also contribute to the atmospheric corrections needed for orbital elemental analyses.

D. NETWORK SURFACE SCIENCE

Investigations at widely separated and different sites on Mars require the deployment of instruments at diverse regions. The primary spacecraft candidate to accomplish the network science objectives is the penetrator. This vehicle consists of a missile-like body that strikes the planetary surface at high velocities and splits in two, allowing a nose section to penetrate into the planet a distance of several meters. The advantages include its access to the subsurface, the large number that can be deployed, and the advanced stage of initial development. Disadvantages include limited payload capacity, low data rates and storage, extremely high decelerations, and restricted physical dimensions.

An alternate concept for a network science vehicle is the rough lander. This vehicle remains at the surface after landing and has a considerable capability for deployment of subsystems. Its payload is greater than that of a penetrator. Its advantages over a penetrator as a delivery vehicle derived from its ability to carry heavier, less rugged instruments such as a mass spectrometer; from its deployment abilities, including the raising of imaging devices and meteorological instruments from the ground and the deployment of analytical instruments away from the RTG; and from its superior telecommunications subsystem. Its disadvantages appear to include the difficulty of deploying a sensitive seismometer and any kind of heat flow experiment, the smaller number of stations (due to larger bulk) in a network, and the fact that it cannot perform geochemical analyses of rocks or sediments beneath a wind-deposited overburden. These disadvantages may derive more from lack of study of implementation aspects of rough landers than from inherent problems in the spacecraft concept.

A geophysical network is required for experiments needing similar measurements at widely dispersed sites. In some cases simultaneity of measurement is also required, for example: seismometry, magnetometry, and meteorology. Imaging, heat flow measurements, chemical analyses and water detection can make important use of dispersed sites because of Mars' demonstrated surface inhomogeneity, but simultaneity is at most a secondary requirement. The accumulation of the very diverse data needs of the different experiments will require a major hardware and mission design effort.

1. Seismology

A minimum Martian seismic experiment would consist of a single three-axis instrument with the greatest possible sensitivity. Coupling should be maximized; based on the present level of instrument/spacecraft development, this suggests that penetrators would be the most appropriate vehicles. Much more comprehensive experiments can be performed by deploying a network. Widely dispersed coverage is required for deep refraction and shadowing studies. The necessary number of emplacements can only be determined on the basis of model studies which, so far, have not been carried out. Based upon lunar experience, four instruments nonoptimally placed would not be sufficient and would produce limited results. Even on the basis of geometrical optics and ray tracing, the spherical geometry of Mars suggests that 6 to 12 instruments would probably be required to completely cover the planet. A larger number of instruments gives greater statistical assurance that regional heterogeneity will not mask the subsurface structure. A large number would also permit the placing of some seismometers in regions of possible seismic interest, such as the isostatically uncompensated Tharsis plateau.

The seismometers themselves should be much more sensitive than the Viking instruments, approaching, if possible, the levels of the Apollo Lunar Surface Experiment Package instruments.

2. Magnetometry

A single surface magnetometer experiment would determine the equivalent centered dipole of Mars. Additional magnetometers at other distant sites would (a) test the validity of the centered dipole model, (b) provide inferrential data on higher-order moments of the field, and (c) address the question of local and/or regional "fossil" magnetism.

Much more extensive magnetic experiments become possible if the external forcing field is known. This field is seated in the magnetosphere, which is itself influenced by the solar wind. If the forcing field is known, a surface network of magnetometers can be used to sound the vertical and horizontal structure of the bulk electrical conductivity in the interior of the planet. This might reveal the presence of a conducting permafrost layer, or even a metallized core. Knowledge of the magnetosphere forcing field will require at least an orbiting magnetometer to map and monitor the magnetosphere, and perhaps also a second orbiting magnetometer in the free-streaming solar wind.

The network should contain as many instruments as possible to best resolve the structure of the induced internal current system. The instruments should be capable of measuring fluctuating fields of strengths of up to 100-200 γ, with an accuracy of 1%, over a bandwidth of order 1 Hz.

A key requirement for a magnetometer network with the intrinsic capability of electromagnetic sounding is a data base which is carefully designed to meet requirements for Fourier analysis. A principal requirement is a continuous bit stream without significant data gaps. A second requirement is that data filtering observe the Nyquist limit so that aliasing does occur. The magnetic characteristics of the other penetrator instruments must be well known.

The supporting orbiter m. netometer should be carried on a low circular orbit. This instrument would of course provide data on the solar wind/atmosphere interaction, which is of great interest in other contexts.

3. Heat Flow Measurements

The basic objective requires deep implantation of probes to get below the diurnal and annual waves. At least some of a dispersed network of penetrators might achieve this. Serious identified but unresolved problems are the thermal transient due to implantation and thermal contamination by the RTG. Further study is needed to decide if thermal sensor deployment into the surrounding soil is required.

A single heat flow measurement could lead to serious misunderstanding of the global pattern of heat flow on Mars. Therefore, the maximum possible number of probes should be flown. Enough sensors should be emplaced to allow measurement at thermally quiet sites (optimizing the global heat flow aspect) as well as ones to define thermal anomalies (with their attendant implications for geology and planetary history). Clearly, the more deployed sites, the better will be the measurement of the global heat flux.

4. Meteorology

Individual surface meteorological stations provide invaluable data on local conditions, including diurnal and seasonal variations. A network of such stations allows a much deeper understanding of these phenomena, including the elucidation of latitudinal and topographical influences. In addition, and from a widely disposed network of measurements, the purely local boundary-layer effects can be removed, yielding the forcing function for the gross circulation of the atmosphere.

5. Surface Imagery

Surface imaging of the Martian terrain at highly diverse sites, ranging from volcanic terrains to canyons and polar deposits, is very important for understanding of the geology and the surface evolution of the planet. Cameras attached to the afterbody of penetrators or situated in rough landers can characterize geomorphology, surface environmental properties, and aeolian and atmosphere processes.

CCD arrays and/or small facsimile cameras can be shock-hardened (to 20,000 g) and used for these purposes. A limitation of the penetrator imaging is the camera elevation. The field of view of a camera from a low (10-20 cm) surface elevation would be small. Although these would provide excellent local imagery, regional or panoramic coverage would be limited.

6. Geochemistry

Chemical analysis of the Martian crustal material at eight or more sites can provide important data in helping to determine the composition of the Martian crust. Geochemical data can be related to geologic processes and help answer the questions related to volatile budget of the planet. Penetrators may be emplaced in the crustal material beneath the regolith and below the surface soil layer. Thus _in situ_ sampling of the material at some depth may provide chemical data on unaltered crustal material. It can determine water abundance below the surface and establish if indeed a permafrost layer exists on Mars.

The elemental abundances can best be accomplished by a combination alpha, proton and X-ray analysis. With these three modes all major elements (except hydrogen) and many of the minor and trace elements can be measured. An instrument to carry out such measurements can be miniaturized to fit the penetrator environment and can be shock-hardened to about 3500-g levels. Some parts of these instruments have already been tested to such levels.

An γ-ray spectrometer to measure especially Th, U, O, K and H can be a valuable addition. However, γ-ray measurements are more difficult than the alpha, proton and X-ray measurements because of shielding requirements against the γ-rays emitted by the RTG.

To eliminate the effects of the alteration or contamination of the soil layer around the penetrator, it is important to acquire samples from beyond this zone. A simple drill and sample acquisition system has been designed to fit into the penetrator and it appears to be quite feasible.

7. Water Detection

Measurements of soil moisture below the surface and the amounts of free and bound water are very important for understanding the volatile balance and geochemical and weathering processes and the assessment of the biological environment of the planet. Penetrators provide an excellent way of sampling the subsurface.

A P_2O_5 electrolytic hygrometer has been tested for shock and penetrator environment, and it is feasible. Other detectors, such as solid-polymer electrolytic types, may also be usable for free-water detection. Detection of bound-water and its abundance are important goals, but their feasibility remains to be dèmonstrated.

E. MOBILE LABORATORY/SURFACE SCIENCE

1. Biology/Soil Chemistry

As a result of Viking analyses, the problems of biology and surface chemistry have become thoroughly interconnected. It has become increasingly apparent that some material present in Martian surface samples is chemically highly reactive; whether this material is biological in nature or whether it is solely inorganic (with observed "biologic-like" reactions being a product of exotic surface chemistry) remains to be established. In both nature and degree, the activity of the Martian soil differs from any known sterile, terrestrial analog.

Viking performed three life-detection experiments, each designed to detect the presence of a different type of biochemical reaction. In two experiments, results indicated the presence of an oxidant; the third experiment demonstrated the presence of a reducing agent. Separate analyses showed that the soil samples studied contained no detectable organic compounds (at the parts per billion level). These results do not fit any patterns familiar from terrestrial experience. The reactions observed may be solely of inorganic nature, possibly involving peroxides, superoxides, etc., and their interaction with water. If so, the Martian soil differs in interesting and fundamentally important aspects from all samples of similar material previously studied (i.e., those from the Moon and Earth). It also remains conceivable that the samples studied, and/or material that occurs elsewhere on the Martian surface, could harbor indigenous life forms, biologic systems that probably are different in important biochemical characteristics from terrestrial organisms. Thus, at present, the question of whether life now exists on Mars (or has there existed in the past) remains unanswered. Future missions to Mars should continue to accumulate chemical, atmospheric and other environmental data that are relevant to the possible existence and detection of Martian life.

One potentially promising approach to the *in situ* investigation of "organic nature" on Mars is by use of an "integrated chemistry" instrument. Such an instrument, highly flexible in capability, would be designed to perform a considerable number of different chemical and/or biochemical reactions using a common, highly sensitive detector (a gas chromatograph/mass spectrometer). The instrument would constitute a versatile *in situ* "laboratory" and would contain a large number of individual cells into which various reagents could be added to soil samples. The gas chromatograph-mass spectrometer would monitor the gaseous products resulting from inorganic chemical and/or metabolic reactions and the chambers could be monitored periodically, over a long period of time, or could be used to measure results of single chemical events. Experiments would be temperature-programmed and the instrument designed to achieve maximum flexibility in experimental procedure. Such a "laboratory," providing significant new data regarding the chemistry and/or biochemistry of the Martian soil, would be of importance for use on a roving vehicle: it could be used to investigate habitats ("oases") more hospitable to biological activity than those sampled by Viking. Coupled with data provided by lander imagery, such a "roving laboratory" could provide information invaluable for proper selection of chemically and/or biochemically active samples to be returned to Earth in a follow-on MSSR mission.

2. Geology and Geochemistry

An appropriate set of surface experiments would include high-resolution multispectral imaging, an alpha-proton-X-ray spectrometer, an X-ray diffractometer and an active seismic capability. An important facility would be a device to break rocks or to provide samples by drilling them for the elemental and mineralogic composition analyzers. For the analysis of the soil material where weathering is expected, an important instrument, complementary to the diffractometer, is a differential thermal analysis device and a scanning calorimeter or slow pyrolysis mass spectrometer able to identify trace minerals, that would be essentially invisible to the diffractometer, by means of the detection of hydrate phase changes. A Mars rover, by virtue of its mobility, could use these geological, geophysical and geochemical techniques to study in the vicinity of its landing site and along selected traverses. Particularly valuable would be study of sequences of rock like those exposed in the polar regions and in the canyon-lands to establish time and local area variability.

Imaging data would be used to make detailed observations of the local physiography and microscopic examinations vital to the selection of samples for analysis by other onboard experiments. Spectral data, indicative of various minerals, could also be used for comparison with orbital reflectance spectroscopic experiments. Rover mobility would be used to map important features and to systematically select samples.

3. Geophysics/Seismology

The use of mobile laboratories to acquire seismic data does not represent an optimum match of technologies. However, in view of the fundamental importance of the measurements (and the failure of the Viking instrument) the potential seismological capability of any soft-landing spacecraft must be fully used. The disadvantage of rover spacecraft is that only relatively few instruments can be operated and an optimum network cannot be established. Potential advantages, compared to multiple hard landing probes, of a soft-landing spacecraft with mobility are (1) the weight and dimensions of the instrument are less restricted so that a better frequency response, and perhaps sensitivity, can be achieved, and (2) an active experiment to study the regolith can be contemplated. Apollo demonstrated that surface deployment works well. An updated and comparably sized seismometer would have a sensitivity two orders of magnitude greater than the Viking instrument -- a sensitivity that Viking results suggest is both necessary and usable. Use of displacement rather than velocity sensors would lead to a substantially broadened frequency response so that the low-frequency free oscillations of the planetary surface induced by a large earthquake (magnitude 6 or greater) could be measured to characterize the interior structure of Mars. Thus even one well-instrumented soft lander would be capable of providing information about the Martian interior. The frequency of occurrence of magnitude 6 earthquakes is presently unknown, however, and the network approach (even using narrow-frequency-response hard-landed seismometers) may be better.

Experience with the Viking II spacecraft has shown that vibration interference from other experiments and from spacecraft motion due to wind needs to be reduced. For a mobile lander the deployment of the instrument on the surface when the vehicle is stationary would be a first step. Under ideal circumstances seismometers would be deployed as part of one or more autonomous geophysics stations that would operate independent of the roving lander. Some separation of stations could in principle be achieved by deploying one station near the landing site and another near the end of the planned traverse. Autonomous geophysics stations should be deployed in sites selected for minimal wind noise and good surface coupling. Given an appropriate timing synchronization the stations could be used for active seismic experiments in which the rover is used to create a small seismic disturbance at one or more points near the station. Information about the thickness of the regolith would be of great value. Thickness of near-surface units might be obtained also, e.g., the thickness of intercrater plains or that of the northern plains basalt flows, both overlying the heavily cratered terrain.

4. Subsurface Temperatures

A measurement that sets fundamental constraints on models of the thermal evolution of a planet is the heat flow from the interior to the surface. In practice, even on the Earth, such measurements are subject to unusual difficulties, and any attempt to measure heat flow remotely must be recognized as a high risk experiment. Thus, the subsurface temperature gradient will be disturbed by the emplacement of sensors, and the measurement of thermal conductivity is subject to errors arising from unseen blocks and voids in the material. However, Apollo has demonstrated that remote heat flow measurements can be made. The seasonal temperature wave penetrates for more than a meter, and unknowable temporal changes of surface albedo can lead to changes in temperature gradient for greater distances, dependent upon the time scale of such a change. Although subsurface temperature measurements would likely cast as much light on problems such as these (interesting in themselves) as on the rate of interior heat flow, this is an important experiment. The measurements must be made over a time comparable to half a Martian year and will thus necessarily function as part of the deployable geophysics station if part of a rover mission.

5. Meteorology

Any soft-landing spacecraft should extend Viking meteorological observations to as many additional sites as possible, preferably by means of deployable geophysics stations. The measured parameters should include, along with pressure, temperature, wind velocity and direction, humidity in order to better understand the diurnal and seasonal water vapor cycle and to provide information about surface vapor pressure to correlate with orbital measurements (which only determine total column abundances). For meteorological purposes the lander sites would ideally be at different latitudes from those already sampled or, in conjunction with the current Viking sites, should establish a triangular network of ~1000-km side for simultaneous pressure measurements to adequately define the regional meteorology. Three stations could determine the pressure gradient and thereby allow the geostrophic wind at the top of the boundary layer (2- to 3-km altitude) to be inferred.

The rover imaging system can be used as an important source of meteorological data about atmospheric optical depths as a function of time, clouds, eolian activity and night fogs (for this purpose a light should be provided). The mobility of the rover can be used to investigate the effects of local topography on temperatures, pressures and winds which are, in regions of major relief, of first importance.

6. Volatile Inventory

A soft-landing spacecraft can make a variety of measurements pertinent to the investigation of the evolution of the Martian atmosphere. Some of these measurements have already been discussed: active seismometry (regolith depth), calorimetry (adsorbed volatiles and chemically bound water), subsurface temperature measurements, temporal variations of humidity and nighttime images (fogs indicative of atmosphere/surface water exchange). Other important determinations include the refinement of noble gas abundance measurements and the measurement of near-surface electrical conductivity.

One technique to measure the latter properties involves the establishment of a base radio transmitter on the surface working at frequencies of 1 - 30 mhz and the reception of signals by a receiver on a mobile vehicle. The interference pattern established by the direct wave and the wave that passes through the surface characterizes the electrical properties of the regolith and can be used to assess the amount of water in the soil (there was none present in the case of the Moon). This technique is applicable to the Mars rover (and should be evaluated) but is expected to be operationally complex for an automated vehicle. A simpler approach would be to measure the soil conductivity directly by means of electrodes emplaced in the soil.

F. SURFACE MISSION CONSIDERATIONS

The geochemical orbiter would first support the lander/rover then be freed to map as much of the planet as possible with geochemical and geophysical sensors (gamma-ray spectrometers, infrared/visible mapper and spectrometer, microwave radiometer, magnetometer, UV spectrometer, radar altimeter, and S-band transponder to map the gravity field and high-resolution cameras to map and to select and certify traverse routes).

The lander on entry would measure the atmosphere witn ion and neutral mass spectrometers, retarding potential analyzer and pressure and temperature sensors and accelerometer.

The mobile lander could deploy a geophysical station at the beginning and end of the traverse, including a seismometer, magnetometer, heat flow sensor and meteorology station. The mobile lander could carry an X-ray fluorescence device, X-ray diffractometer, alpha backscatter, gamma-ray spectrometer, and differential thermal analyzer and scanning calorimeter. These devices should allow determination of elemental abundances, mineralogic composition of rocks and minerals, clay, hydrates or other evaporatives, and solid volatiles. Multispectral images with an auxiliary microscope would allow determination of textures and grain size and sorting of and possible composition of rocks and sediments.

G. SAMPLE RETURN

A well-planned and flexible mission directed at sample return would provide a wide diversity of information to a broad spectrum of science disciplines. The Space Science Board of the National Academy of Sciences recommended in 1974 that "Mars Surface-Sample Return (MSSR) be adopted as a long-term goal and that an early start be made on research and development into a verifiable system of sample isolation." We strongly support this position.

Sample studies are uniquely capable of providing an absolute chronology for the planet, and will be required for characterization of Martian life, for providing detailed petrographic evidence bearing on the nature of the condensing solar nebula, the extent of and time scales for chemical differentiation of the planet, and the nature of chemical and physical processes that have shaped its surface. Studies of samples returned to the Earth are unique in that they (1) can be performed by a wide variety of scientists with state-of-the-art technology at the time of the sample return, unconstrained by weight or volume limitations (the sensitivity, precision, and scope of laboratory analysis are constantly improving at a high rate); (2) permit iterative, imaginative experiments, designed rapidly based on unexpected results; (3) allow separation and concentration of phases, based on the specific properties of the sample; (4) permit many different analyses on the same sample; and (5) permit the deferral of experiments if better analytical technology or understanding is necessary. The flexibility and confidence in laboratory sample analysis is large due to high analytical precision and because of greater control of experimental parameters. Care must be taken, however, to preserve evidence of chemistry and components that may depend on *in situ* conditions.

The following general areas of research on returned Martian samples are anticipated:

1. Mineralogy/Petrology/Geochemistry

Studies of the mineralogy, mineral chemistry, textures, and bulk chemical composition are necessary to define the physical and chemical history of rocks and their degradation products. Evidence for processes ranging from crustal formation to chemical weathering at the surface can be addressed through these studies. These are especially necessary where rocks have experienced sequences of events which can be distinguished only through detailed comparison of textural properties, mineral compositions, and the distribution of elements within the rocks.

2. Trace Element Chemistry

A wide variety of signatures has been identified among trace elements which are tracers for geochemical processes. Analyses of siderophile, chalcophile, lithophile, and volatile elements in groups or as pairs yield evidence on, among other things, the nature of the bulk starting material for planetary differentiation, the degree of differentiation, the planetary heat sources, the temperatures and pressures of internal processes, and the nature of meteoritic material impacting the planet. These data must be interpreted in conjunction with petrologic data to unravel the complex evolutionary history of planetary surface materials.

3. Isotopic Studies

Precise isotopic analyses, which can be only accomplished in terrestrial laboratories, are used to study a wide variety of chronologic and geochemical problems. Long-lived radioactive species (U-Th-Pb, K-Ar, Rb-Sr, Nd-Sm) are used to obtain isotopic ages for rocks which will provide the only means of establishing an absolute chronology of the planet. The stable isotopes (O, Si, C, S) provide a number of very powerful geochemical tracers that can be used with chronological data to give information on past states of the interior of the planet as well as more recent surface processes. Anomalies left by the decay of extinct short-lived radioactive isotopes can provide evidence for pre-accretion conditions and time scales.

4. Noble Gas Studies

Analyses for He, Ne, Ar, Kr, Xe and their isotopes are essential for understanding the differentiation history of the planet, its interaction with cosmic radiation, and the evolution of the atmosphere. These analyses on Mars surface materials with complex petrologic histories provide powerful tools for understanding the evolution of the planet's surface and interior. Xe isotopes are perhaps the most versatile, as the isotopic patterns may be affected by extinct short-lived isotopes, fission of long-lived and extinct isotopes of U and Pu, and mixing effects of various reservoirs of gas. Other noble gas studies must be done *in situ* to allow sufficient enrichment so that measurements can be made.

5. Physical Properties

Rocks will be examined for evidence of remanent magnetization related to the past history of the magnetic field, and for a variety of physical properties, such as density, porosity, thermal conductivity, and seismic wave velocities that are essential to complement the geophysical measurements that will be made from orbit and from surface stations to map the planet's internal structure. The physical properties of surface materials must also be understood in order to determine their capacity to adsorb and release gases and the rates of interchange with the atmosphere.

6. Biological Studies

The study of returned Martian samples provides an excellent opportunity for the detection of evidence of Martian life and, if detected, an unparalleled opportunity for its characterization. Unless unusual precautions are taken, it seems probable that any organisms included with the returned sample would be killed by exposure to the high pressure, high water content and high oxygen content of the terrestrial atmosphere. The most promising life detection "experiments" would therefore appear to be those based on chemistry and morphology (e.g., organic chemical studies of returned samples and "micropaleontologic-like" studies of samples stained with dyes reactive with carbon compounds) or on morphology alone (as in micropaleontologic studies of mineralogically replaced microorganisms) rather than those based on growth or metabolism. Nevertheless, such growth ("microbiological") experiments should certainly be carried out on representative aliquots of the returned materials. Such growth studies must obviously be predicated on the assumption that the sample is returned in an unsterilized condition; if sterilized, the sample must be in a condition such that the morphology and chemistry of the contained organisms are not altered beyond recognition (for the "micro-paleontologic-like" studies). Protection of the integrity of the information contained in the returned sample, both geochemical and, potentially, biological, requires that sterilization (by whatever method) be avoided. Finally, if living systems (viable, dormant, recently dead or fossil) are detected in the returned sample, a concerted, and presumably long-term, effort will be required to characterize fully the Martian biosphere in order to understand ultimately the nature of its origin, evolution and present composition and distribution.

7. General Considerations

Although essential to understanding the planet, sample studies alone are not sufficient, especially with respect to understanding the internal structure and dynamics of the planet.

Whereas direct studies of Martian samples is a principal objective of the MSSR, the availability of samples will spawn a new set of investigations to be carried out on analog materials, such as experimental petrological and mineralogical studies which will attempt to reconstruct internal conditions from which endogenic rocks formed, laboratory studies of the effects of meteoritic impact on Martian surface materials, and chemical reactions of Martian surface materials. The additional orbital entry and lander science will need to be fitted into new models which will describe the origin and history of the planet and compare its behavior to that of other planets and the Earth.

The optimization of data from returned samples depends on a broad sampling of the planet. Several important geologic units can be sampled with a few well chosen and accurately placed landing sites at the boundaries between major units. These sites should be chosen to utilize natural processes, such as meteorite impacts, landslides, or eolian and aqueous erosion and deposition, to obtain the widest diversity of samples in the vicinity of the landing sites. Although several missions would most likely be needed to provide coverage of all important planet-wide units, even a single successful mission could add significantly to our understanding of Mars.

The total amount of material required to characterize and permit detailed study of an individual rock or soil sample varies, but a few grams can be used effectively. Thus a sample collection strategy which maximizes the number of samples in the range of 0.5 to 10 gm maximizes the information content by making comparative studies possible. Samples from the surface and subsurface environments should be collected and documented and packaged to maintain their integrity during return.

Sample selection capability superior to that of Viking is essential for a MSSR. Viking data suggest that a variety of rock types exist within a few hundred meters at each of the landing sites. The Viking sampling arm can reach a large number of rocks that are too large to fit its analytical instruments, so that a chipper or drill may be essential for sample return. The abundance of subcentimeter fragments in the soil (which have been very important in the lunar samples) needs to be investigated further and a device to collect this kind of material included. Additional design effort is needed to evaluate these new sampling procedures to optimally use a core drill and rock chipper which might substantially enhance the ability to collect diverse samples.

By defining the landing sites to be highly selective and near boundaries of major units, the chance of obtaining more than one rock type at the landing site is increased. The probability of obtaining diverse materials would increase further if surface mobility were available. The data obtained should include that which is necessary to document the sample and to provide information pertinent to its integrity during return to Earth (pressure, temperature and contained volatiles). It is essential to conduct tests for biological activity so that back-contamination control procedures can be optimized.

Containment of the Martian samples for return will be important both from the point of view of physical sciences and back-contamination control. In general, the returning samples should be kept under Mars environmental temperature and pressure conditions. The most serious period of potential gas leakage into containers will occur when the sample canisters are inserted into the Earth's atmosphere. To prevent sample degradation, leak rates of 10^{-9} to 10^{-10} ccHe/sec STP are required; the attainment of such a seal involves significant technological problems, as it must be done by remote control. A complete containment and contamination control system must be designed and certified, including all aspects of sample acquisition and sealing, environmental monitoring during return, design of quarantine and sample handling facilities at Earth, and development of the technical and management team to carry out the containment program. Experience in the lunar program suggests that this part of the mission has a long lead time and requires immediate attention.

Two or three sample return missions will not constitute the ultimate in Martian exploration. The areal coverage of MSSR would be limited, although the sample data would enhance the ability to extend global data, such as orbital γ-ray and other remote sensing measurements, with much greater confidence to other regions of the planet. On the other hand, global remote sensing measurements such as those provided by the intermediate polar orbiter and lander (GEM) mission will help define the number of landing sites necessary to adequately sample Mars. Special environments, such as the polar regions, would provide attractive sites for sample return missions.

H. SAMPLE RETURN MISSION CONSIDERATIONS

The Mars sample return mission will be the most technologically ambitious planetary mission to be carried out during the next decade and will require careful cooperative analysis between scientists and engineers to obtain maximum scientific return consistent with mission constraints. All of the areas discussed below must be studied carefully at an early stage of planning.

1. Mission Profile

Several options for transportation systems to return samples may be available in the late 1980's. Ballistic systems that are feasible include direct Mars entry/orbital Mars entry options, direct Earth return/Mars orbital rendezvous return options, and direct Earth entry/Earth orbital capture options. The 1988 opportunity has the lowest energy requirements and provides the most flexibility in mission weight tradeoffs. Each option must be evaluated in terms of weight limitations, mission reliability, and quarantine constraints. In the late 1980's, the availability of low-thrust propulsion systems may greatly affect the details of the mission profile. The obvious advantages of increased Mars science that should result from larger payloads demand that serious attention be given to the development of low-thrust propulsion options.

2. Site Selection

The quality of scientific information obtainable from a sample return mission is crucially dependent on the proper selection of locations for sampling. Several factors are important in this regard, including the precision with which sites can be selected from prior data, the precision with which identified sites can be reached, and the mobility available on the planet's surface. Limited mobility and flexibility of sampling capabilities are minimal requirements for MSSR. Prior experience with development of mobility options for previous Mars missions may be critical to developing more sophisticated mobility options for MSSR.

3. Quarantine System

The problem of protecting Earth from back-contamination places severe constraints on mission design for MSSR. Problems range from the legal framework for sample entry to Earth to detailed engineering requirements for contaminant and sample handling systems. In order that these constraints do not raise barriers to the orderly progress of mission development, they require early definition and research and development effort.

4. "Add-On" Science

The landing of a highly complex spacecraft on Mars provides the opportunity to do other types of experiments that require the delivery of equipment to the planet's surface. The types of instruments defined by the sections on network and surface science are possible candidates. The timing of MSSR would allow further development of instruments planned for earlier missions. Such instruments could continue to operate beyond the time of departure of the sample return vehicle. Concepts for these instruments should be studied; however, they should not conflict with the prime objective of returning samples from Mars.

SECTION IV

EXPLORATION STRATEGY

The exploration strategy for Mars in the period 1980-1990 must be guided by the science objectives, technical feasibility, and a logical progression of missions. Furthermore, it must fit into a balanced and coherent program for the exploration of the planets and other terrestrial bodies of the solar system.

Important scientific questions have been posed and the necessary measurements have been identified in the previous sections. The problem of how these measurements can be integrated into a mission sequence needs to be addressed here.

The post-Viking Mars exploration program requires four types of measurements.

(1) Orbital Science: Many different observations from orbiting spacecraft (e.g., imaging, spectral mapping, γ-ray mapping, gravity, magnetic, etc.) attacking a range of global, whole-body, surface, and atmospheric science.

(2) Network Science: Systematic measurement (e.g., seismic, meteorologic, chemical, imaging, heat flow, and water detection) for a long time at several points widely distributed over the planet.

(3) Mobile-Lab Surface Science: Quite detailed and complex investigations (surface properties and chemistry and mineralogy of soil, atmospheric chemistry and isotopic composition, biologic experiments, solid mechanics, etc.) at a number of surface locations along a traverse by a surface rover.

(4) Sample Return: The return of rationally chosen samples from a carefully chosen area(s) (with limited mobility for sample selection) for detailed chemical, biological, physical, geological, chronological studies.

This sequence represents a logical progression in the exploration of the planet. First the global characteristics of the surface, atmosphere, and whole-body properties are measured from the orbit.

Second, instruments are deployed at six to eight sites for local geologic and geochemical investigations of the diverse terrains and to establish a network necessary for the studies of the internal structure and the atmospheric dynamic. A surface rover mission can carry out sophisticated laboratory investigations of surface chemistry, mineralogy, atmospheric composition and biology along a traverse.

The sample return mission, which represents a very important milestone in Mars exploration requires most extensive technological development. It is important that it is planned with the knowledge of the previous missions.

Proper scientific and cost-effective accomplishment of these four types of mission objectives requires a careful assessment and combinations of the objectives.

The most complete and vigorous Mars strategy for the eighties responds to Viking's success with a dual mission involving 1984 launches of a Mars Polar Orbiter with penetrators (GEM=MPOx) and a surface rover.

SECTION V

SUPPORTING RESEARCH AND TECHNOLOGY REQUIREMENTS

The recommended strategy for a 1984 Mars mission (GEM) including orbital, network and rover science requires that planning efforts be started immediately in order to make most intelligent and cost-effective use of this opportunity. The Mars surface sample return (MSSR) mission to be flown at a later date also requires certain study efforts to be started immediately. Thus, SRT requirements for both of these missions are discussed below. Many of the developments required are necessary for other terrestrial bodies and may be discussed in more detail elsewhere in the report (e.g., penetrators and propulsion systems).

A. PROPULSION SYSTEMS

The size of sample that can be acquired from the MSSR mission is greatly determined by the nature of the propulsion system available at the time of the launch of the mission. The sample size, in turn, will determine the variety of different materials that can be returned. Finally, the scientific return from such a mission is significantly affected by the numbers of different soil samples and rock types returned for analysis. Thus, vigorous work on alternate systems that will enable the return of large samples needs to be started as soon as possible. Examples of such systems are SAIL and SEP.

B. MISSION OPTIONS

A variety of mission options for both the Global - Environmental Mission (GEM) and MSSR have been studied. The various concepts differ in complexity, risks, and contaminative control. Tradeoffs between engineering, science, contamination and quarantine will have to be made in order to insure accomplishing the best science within the mission budget. Briefly, we here indicate some of the considerations that may be necessary.

1. GEM

In terms of the orbital science, the lowest possible altitude consistent with quarantine constraints and long-term orbit stability should be selected. Global coverage required for orbital science and the servicing of the landed surface science systems has to be studied in terms of choice of landing sites and orbital inclination and altitude.

2. MSSR

A number of mission profiles have been studied. Each of these differs in complexity, risks, and capability in terms of landed weight, ease of control of back-contamination, and other factors. The best option will maximize the probability of successfully accomplishing mission science requirements. The types of mission options studied have included direct return and Mars orbital rendezvous transfers as the Mars-Earth mode, and direct entry or capture in Earth orbit as Earth return options.

C. LANDING ACCURACY

The accuracy with which a chosen landing site can be reached and the ability to avoid hazards will govern the site selection and strategy and the requirements for the lander portion of both missions. As some of the more interesting scientific sites are apparently too dangerous to land at using present techniques, improvement in accuracy and hazard avoidance will significantly increase the number of potential landing sites that can be selected.

D. SURFACE SAMPLING SYSTEM

Concepts should be developed for making sampling systems (such as the Viking sample arm) more versatile. Candidates include items such as a rock chipper and a short core drilling device which could be used as a soil or rock bore. A rock crusher is not as important for sample return but is desirable for in situ analysis and for discrimination between rocks and soil clods. The extended flexibility of sampling will be important for sample return as well as future planetary landers.

E. SAMPLE SEALING, CONTAINMENT AND MONITORING

Vacuum seals of 10^{-10} ccHe/sec STP are obtainable routinely in a controlled situation on Earth. The design of a sample cannister that can be sealed remotely at that level requires development of new concepts. Maintenance of the cannister at Mars-ambient pressure and temperature and the monitoring of internal conditions, while also meeting requirements of sturdiness, will be significant challenges. Preparation of containers that do not build up internal atmospheres through outgassing is required.

F. RECEIVING LABORATORY -- CONTAINMENT AND QUARANTINE PROTOCOLS

The concept definition/verification of this entire system requires early work. The requirement to maintain systems at Mars-ambient temperature is a major difference with respect to previously developed technology for containment of biological or radioactive materials.

G. DATA FOR LANDING SITE SELECTION

Thorough evaluation of orbital imagery obtained by Mariner and Viking is necessary to provide the best basis for selection of landing sites and for establishing a framework for interpretation of sample data.

H. LABORATORY ANALYSES

The amount of Martian material returned will be small compared with that returned from the Moon, but it will be even more complicated mineralogically. Under these conditions, high-sensitivity experiments on small subsamples will be required. Developments supported by the lunar program have revolutionized surface analysis and high-precision mass spectrometry techniques, among others, which are now being applied in many areas of science and technology. Similar developments and wide applications of new techniques are major objectives of a supporting research program for MSSR.

I. RADIATION ACTIVATION AND RTG BACKGROUND

Radioisotope thermoelectric generators (RTG) will be used extensively as power sources for the penetrators, hard landers, soft landers, and rovers being considered for Martian missions. These RTG's emit both gamma rays and neutrons. The γ-ray flux can significantly interfere with a number of particle, X-ray and γ-ray detectors. In some cases these γ-ray fluxes may completely overwhelm the detector in the energy region of interest. A second and perhaps more important effect is the activation of the spacecraft and instruments due to the continuous neutron emission from the RTG during trans-Martian flight, orbital flight and lander operation. These problems must be considered in detail for they will greatly affect the selection of instruments to be included aboard various portions of the GEM and MSSR missions.

J. COSMIC RAY BACKGROUND EFFECTS

A special problem for orbital X-ray and γ-ray instruments may be attributed to primary and secondary neutrons produced in the spacecraft environment and Martian atmosphere and surface that will activate the detectors and produce false elemental signatures. Continuing research is required to delineate the magnitude and spectral distribution of this background so that spectral data can be corrected for this effect.

K. INSTRUMENTATION DEVELOPMENT

In this section instrument development requirements for orbiters, penetrators, and landers (both hard and soft) will be considered. The whole problem of instrument survival under the various environmental and/or impact conditions is generally applicable, and studies need to be pursued for all instruments to be considered for flight. The problems of being prepared to fly instruments which will lead to significant scientific return for both GEM and MSSR will require the possible development of a larger group of instruments that can be accommodated during the mission. But until the mission profile is finalized, a final selection of such instruments cannot be accomplished. Instrument design requirements and interface problems will greatly affect the spacecraft and mission design. These developments must proceed in parallel. Thus a number of instruments will have to be developed which may never fly during these missions.

1. Network Science

a. Delivery System. A rigorous program has to be pursued to determine the optimum way of delivering the network systems.

b. Seismic Experiment. A minimum experiment would be a three-axis instrument with maximized coupling. Although further studies are needed, it is felt that a network of 6 to 12 instruments would be required to completely cover the planet. The seismometer to be developed should be much more sensitive than the Viking; it should probably be more comparable to the Apollo instruments.

c. Magnetics. A network of instruments is required to best resolve the structure of the induced current system. Individual instruments must be capable of measuring fluctuating fields of strength up to 100-200γ with a 1% accuracy over a bandwidth of order 1 Hz. Specifications regarding permissible levels of magnetic interference from the other instruments and required levels of magnetic cleanliness must be defined.

d. Heat Flow. Deep implantation of probes to get below the diurnal and annual heat waves is required. RTG thermal contamination requires that further study be carried to determine the feasibility of these types of measurements.

e. Meteorology. The development of small stations to provide data on local conditions (including diurnal and seasonal variations) is required.

f. Surface imagery. It is believed that CCD arrays and/or small facsimile cameras can be developed for this purpose.

g. Elemental Analysis. A number of techniques provide potential means for elemental analysis. For penetrators, a combination of alpha proton backscatter and X-ray fluorescence shows greatest promise. Problems of sample acquisition must be solved before such techniques can be used. Passive gamma-ray techniques should be considered, although they may suffer from significant interference from the RTG system. The interference produced by RTG on the alpha proton-X-ray system must also be studied. On hard landers, the problem of sample acquisition and RTG interference can more easily be overcome. This will require the development of deployment systems. Another system for elemental analysis, using neutron-gamma ray methods, can be considered for hard landers. This technique also requires further development for application to the Martian network science program.

h. Water Detection. Such instruments as the P_2O_5 electrolytic hygrometer need to be further developed for application to this program.

2. Orbital Science

a. Elemental Composition. The experience gained from the orbital geochemistry package for Apollo has shown the importance of utilizing high-energy resolution γ-ray spectrometers. This is particularly true for Mars because of atmospheric interference effects. Thus continued development of intrinsic-germanium, passively cooled detectors is required. In terms of subsurface and surface water detection and monitoring for the gamma-ray spectrometer, neutron detectors capable of measuring thermal, epithermal and fast neutron fluxes are required.

b. Mineralogy. Earth-based studies and measurements obtained on such missions as Viking and Apollo have indicated the importance of multispectral imaging and reflectance spectroscopy for characterizing units on planetary surfaces. Both instrument development and theoretical studies must be pursued in order to achieve optimum information from such measurements.

c. Orbital Imagery. Much experience has been gained in acquiring photographic data from Mariner and Viking. This experience must now be used in designing optimum high-resolution and low-resolution photographic systems for forthcoming Mars missions.

d. Magnetics. A magnetospheric mapping magnetometer is needed for the orbital portion of the mission. The major problems to be considered are the orbital parameters (e.g., inclination and altitudes). These studies must proceed in order to best design the mission profile.

e. Atmosphere. Atmospheric measurements have been included on many planetary missions; thus the major effort in this area is the determination of the optimum mix of instruments appropriate to the specific mission.

f. Heat Flow. Further studies are required to ascertain the potential of utilizing microwave radiometry for mapping the global heat flux of Mars.

g. Gravity and Altimetry. These techniques have been used on many planetary missions. The major problems to be studied involve the design of the mission so as to define the best orbital profile in order to obtain optimum scientific results. Specifically, altimeters should be studied and developed.

3. Soft Lander and Rover

Many of the instruments described for use in the penetrators and landers can be applied to the soft landers also. The requirements for development will therefore not be repeated in this section. Furthermore, instruments developed for such missions as Viking and Apollo will be applicable to this program.

a. Organic/Inorganic Analysis System. The design of this system strongly depends on the better understanding of results obtained during the Viking mission. It is believed that an "integrated chemistry instrument" capable of performing chemical and/or biochemical reactions as measured using a common, highly sensitive detector (gas chromatograph-mass spectrometer) can be developed. This program should be vigorously pursued.

b. Mineralogy and Petrology. The Viking results indicated the necessity of performing *in situ* mineralogical analyses. Such analyses might be carried out utilizing an X-ray diffraction system. The possibility of combining X-ray fluorescence techniques with a diffractometer has been considered and should be under continuing study. Sample preparation and pattern interpretation are also major problem areas in this research. Thus strong emphasis in the research program should be placed on understanding and overcoming these problems. It is felt that, although there have been less than encouraging results on the use of microscopes for *in situ* petrography, the current availability of high-quality technology and of microprocessors suggests that this technique should be further investigated.

L. END-TO-END DATA PROCESSING

In planetary exploration programs with multiple systems such as that here outlined, the problems of data accumulation, processing, transmission, analysis and distribution can become complex and expensive. It is suggested that the overall data system be studied in detail, from the accumulation of data at the point of measurement to the dissemination of the analyzed data to various investigators. Software engineering studies prior to the development of hardware may greatly simplify the system. After such a study, more intelligent tradeoffs (e.g., between onboard processing and ground-based processing) could be defined.

The use of distributed intelligence systems utilizing microprocessors could greatly ease the problems of experiment design, integration and analysis. This type of work should continue to be encouraged.

M. GROUND-BASED STUDIES

IR and radar observation of Mars should be continued. These ground-based studies permit the test of possible flight instruments and the acquisition of navigational data that will be needed for the design of the GEM and MSSR program.

SECTION VI

TBSWG STATEMENT ON 1980's MARS STRATEGY

The Terrestrial Bodies Science Working Group (TBSWG) recommends a vigorous and systematic program of exploration of the terrestrial bodies for the decade of the eighties. The recommended program begins with FY'78 new starts for Lunar Polar Orbiter (LPO), and for a Jupiter Orbiter and Probe (JOP) with satellite-intensive science. The rest of the program involves the reconnaissance of bodies not previously studied by spacecraft (comets and asteroids), the exploration of bodies previously reconnoitered (Mercury and the Galilean satellites), and the intensive study of bodies previously explored (the Moon, Venus and Mars).

In evaluating a Mars strategy following the Viking successes, TBSWG finds that there are four categories of mission objectives whose accomplishment is necessary for a comprehensive advance in our understanding of Mars (including its interior, surface characteristics, processes and history, atmosphere, origin and evolution, and its potential as a habitat for life past or present):

<u>Type 1 - Orbital Science</u>: Many different observations from orbiting spacecraft (e.g., imaging, spectral mapping, γ-ray mapping, aeronomy, gravity, magnetic, etc.) attacking a range of global, whole-body, surface, and atmospheric science questions.

<u>Type 2 - Network Science</u>: Systematic, long-duration observations (e.g., seismic, meteorologic, chemical, imaging, heat flow, water detection, magnetic, etc.) at several points widely distributed over the planet.

<u>Type 3 - Mobile-Laboratory Surface Science</u>: Quite detailed and complex investigations (e.g., chemistry and mineralogy of sequences of rocks and surficial material, atmospheric chemistry and isotopic composition, biologic experiments, geophysical experiments, surface properties and soil mechanics) at a number of surface locations within a limited mobility range.

<u>Type 4 - Sample Return Science</u>: The return of rationally chosen samples from carefully chosen areas (with mobility and analytical capability for sample selection and acquisition) for detailed chemical, biological, physical, geological, and chronological studies.

Type 1 (orbital) objectives can best be met by an orbiter in a polar, low-altitude circular orbit. Type 2 (network) objectives can best be met by a carefully dispersed set of penetrators or rough landers. Type 3 (mobile-lab) objectives can be met by a reinstrumented Viking lander with limited mobility or a special rover mission. Type 4 (sample return) objectives require multiple samples selected by landers with adequate manipulative capability and mobility.

The most complete and vigorous Mars strategy for the eighties responds to Viking's success with a dual mission involving 1981 launches of a Viking-based Mars Polar Orbiter with Penetrators (MPOp) and a mobile Viking III. This combined mission will provide broad scientific advances, share technical development, and institute cost savings over two separate missions through its backup/complementary rather than backup/redundant approach. TBSWG would enthusiastically support such a mission, provided it does not jeopardize other elements of our recommended Terrestrial Bodies Program, specifically the fiscal 1978 new starts for LPO and a satellite-intensive JOP.

If the extraordinary commitment of resources required by such a mission cannot be made, then TBSWG finds that the next launch to Mars should be a MPOp mission. This will accomplish broad-ranging global studies of the physics, chemistry, and geology of Mars, and it will be the most meaningful follow-on to Vikings I and II It will set the stage scientifically well in advance for the Mars Surface Sample Return (MSSR) mission, as required for the optimization of MSSR. In addition, it accomplishes the network science objectives at a logical point in the overall program.

It is TBSWG's judgment that meeting the objectives of either of the above alternatives for a 1981 Mars mission will require immediate and substantial effort in funding, organization and development. TBSWG is strongly committed to a complete and balanced program for the terrestrial bodies in the eighties. We believe that the success of Viking provides impetus to, and should generate the resources for, the vigorous exploration of Mars within this program, but we do not believe that terrestrial bodies science will be well served if this Martian effort delays or curtails the rest of our recommended program.