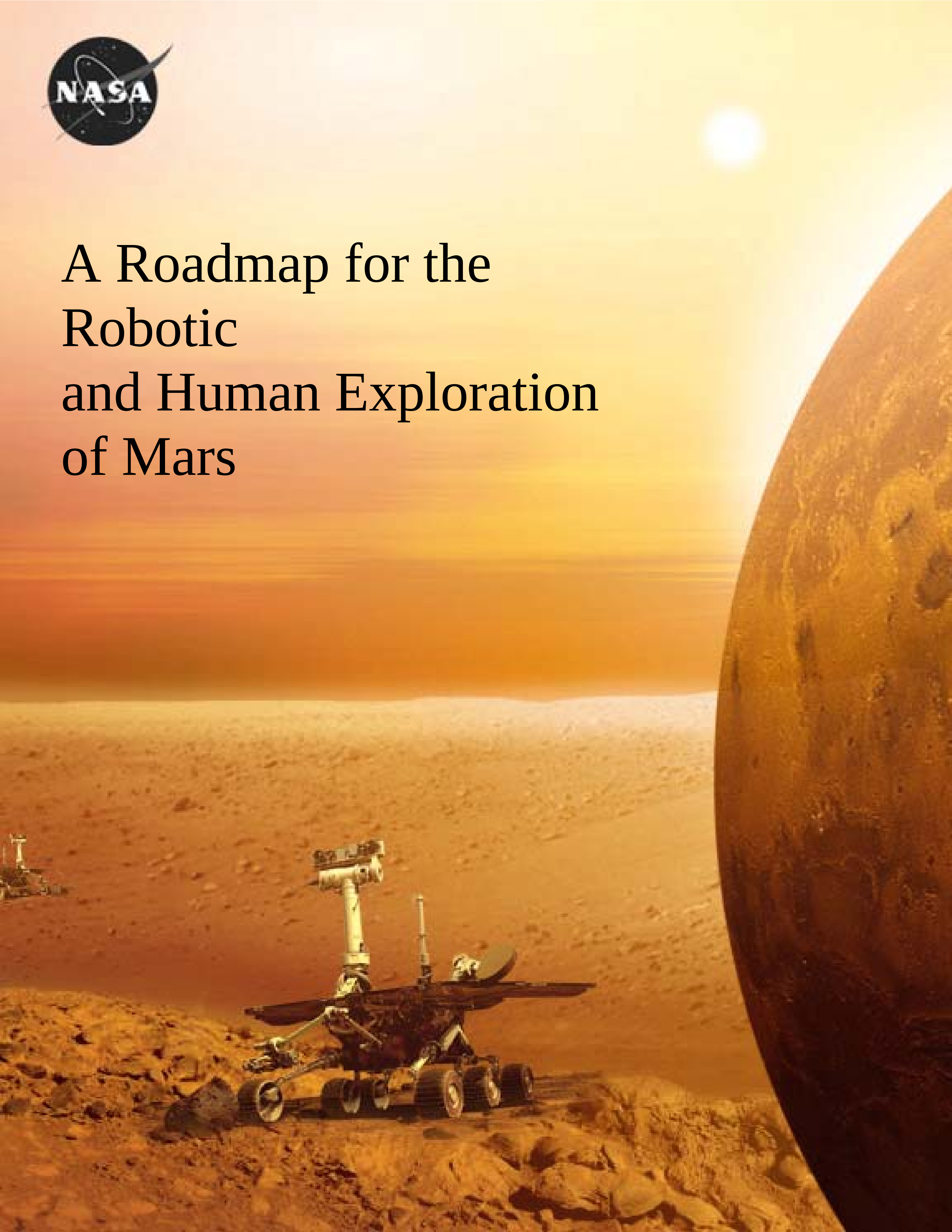
A Roadmap for the Robotic and Human Exploration of Mars



About the Roadmap

In December 2004, NASA established a number of strategic roadmap teams to provide guidance and priorities for achievement of the nation's space exploration objectives. This was partly in response to the Vision for Space Exploration, as well as to the Presidential Commission on Implementation of United States Space Exploration Policy (the "Aldridge Commission"). This is the report of the team chartered to study the robotic and human exploration of Mars.

The Mars Roadmap Committee met three times – in January, February, and March 2005. All of the strategic roadmap committees were requested by NASA to terminate their activities and provide their best-effort reports by May 2005; consequently, this document has not undergone the level of detailed editing, production, and printing that would normally have been expected. Nonetheless, the Committee feels that it has reached important conclusions about the priorities for the Mars exploration program, and has created a framework for the key decisions that will one day lead to human exploration of Mars. This document articulates those priorities and recommendations.

Mars Roadmap Committee

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Preface

NASA has been engaged in the scientific exploration of Mars for over forty years. During the past decade, six spacecraft - three NASA landers, two NASA orbiters, and one European orbiter - have begun to patch together the pieces of a wonderfully complex puzzle as they reveal the story of the Martian past and present. Yet we are still just in chapter one… even more riveting chapters will be read out by our robotic explorers in the next two decades.

The excitement of Mars exploration was elevated last year when the President laid out a new vision for integrated robotic and human exploration of the Moon, Mars, and beyond. Robotic science missions will extend our understanding of Mars while they lay the groundwork for human exploration - by making new discoveries, characterizing the environment, validating new capabilities, and emplacing the infrastructure that will enable safe and effective human missions.

This roadmap outlines how NASA can build on its existing robotic Mars Exploration Program to enable future human expeditions to Mars. Our existing science priorities are highly complementary to the requirements for early human exploration precursors, centered on the "Follow the Water" theme. Technology development for robotic exploration paves the way for larger-scale human missions in key areas. Augmentation of existing plans and investments with complementary measurements and technology developments represents a logical, systematic approach to implementing the Vision for Space Exploration.

Executive Summary

The Vision for Space Exploration provides new impetus and specific goals for the nation's Mars exploration program. These have been adopted as NASA's strategic objectives and constitute the charter of the Mars roadmap:

- Conduct robotic exploration of Mars
  - To search for evidence of life,
  - To understand the history of the solar system
  - To prepare for future human exploration.

- Conduct human expeditions to Mars
  - After acquiring adequate knowledge about the planet using robotic missions
  - After successfully demonstrating sustained human exploration missions to the Moon.

Observations

The development of the Vision for Space Exploration has added a new dimension to a vibrant and highly successful Mars exploration program. The existing scientific objectives of Mars exploration can be seen in light of a long-range future that will ultimately lead to human exploration of the planet, fulfilling a centuries-old dream of humankind. The goals of the present robotic Mars exploration program are well aligned with the needs of future human exploration and will enable the nation to make well-informed decisions regarding human mission capabilities, costs, risks, and priorities. New areas of emphasis should be added to the program, including:

- Precursor measurements to characterize and assess Mars' environment to ensure human safety
- Technologies responsive to the more demanding needs of human travel
- Engineering infrastructure required for human safety and mission success

Human exploration of the Moon can provide important opportunities to verify and validate systems and processes for human Mars exploration. Within a few decades, we will be prepared to undertake an integrated robotic and human exploration program for detailed study of the planet Mars, leading to a new understanding of the evolution of the solar system and the development and evolution of life.

A Phased Approach to Mars Exploration

Sustainable and effective exploration must be responsive to discoveries and resilient to unexpected changes. This has been one of the hallmarks of the highly successful robotic Mars program. The preceding years of Mars exploration position us to maintain that discovery-driven approach in the coming decades as we move toward more intensive robotic missions, human precursors, and eventually human exploration of Mars.

To facilitate program planning and development of a logical decision structure and investment portfolio, time phases of Mars exploration have been identified. The first phase (2005-2016) can be planned with some degree of specificity and serves as a near-term focus. Notional phases 2 through 4 can be defined now to provide context for goals and investments, but must remain discovery-driven and focused on key decisions. The detailed content of those later phases will be defined by and adjusted according to scientific findings, as well as by the pace of technology validation and by budgetary and programmatic factors.

<u>First Phase at a Glance</u>

The first phase of the roadmap extends from now (2005) through the recommended launch of the first Mars sample return mission in 2016. The primary scientific goals are the search for water and biosignatures. At the same time, those investigations will provide key information on the Mars environment that will enable decisions on human mission planning. Objectives of this period are:

Increase our understanding of Mars as a potential habitat for past and present life

- Continuation of orbital studies (MGS, Odyssey, Mars Express)
- Improved reconnaissance and site selection (Mars Recon. Orbiter)
- Water ground truth (Phoenix)
- Search for localized near-surface water and for minerals and organic compounds relevant to the search for life (Mars Science Lab)
- Launch the first Mars sample return

Pave the way for human exploration in later decades

- Architectural refinements and preliminary design of reference missions to identify architectural “swingers”
- First human precursor testbed to make environmental measurements crucial to human exploration
- Study and advance key capabilities (Entry/descent/landing, in situ resource utilization, nuclear power, etc.)
- Develop requirements flow-down for synergistic activities (lunar exploration, launch vehicles, ISS research)
- Study and down-select human exploration architectures

The Mars Science Lab (MSL) is the key mission that will establish the scientific and technical foundation for the future Mars exploration program, and is thus the single highest priority Mars exploration mission for the next 10 years. MSL will:

- Confirm and localize near-subsurface water
- Explore indications of habitability in selected environments
- Provide a comprehensive understanding of the Mars environment needed for future mission planning
- Enable informed strategic decisions on robotic science priorities and human mission architectures

MSL will demonstrate long-distance, long-duration, semi-autonomous mobility on Mars, which is a key to cost-effective future exploration. It will also utilize next-generation Entry/Descent/Landing (EDL) systems as a step toward higher-capability, human-scalable EDL.

The Committee strongly recommends that MSL should be launched no later than 2011 and preferably by 2009. Two MSL spacecraft should be launched to ensure mission success and maximize the science return. MSL is a key element of an exciting, engaging, scientifically productive robotic program leading to eventual human mission decisions.

Looking Beyond the First Phase

The subsequent phases of Mars exploration will be discovery-driven and will emphasize continued understanding of the planet and its habitability, as well as enabling well-informed decisions on future human exploration.

Phase 2: 2016 - 2025

- Continued robotic science, including analysis of the first returned Martian samples and *in situ* surface exploration
- Conduct scaleable validation tests of key capabilities (ISRU, EDL)
- Develop other major capabilities
- Establish required Earth-based facilities and infrastructure, including advanced Deep Space Network capability
- Validate human habitation and operations concepts on the Moon
- Select and validate Mars human exploration architecture
- Confirm the Mars human architecture in 2025

Phase 3: 2025 - 2035

- Emplace robotic outposts for scientific analysis and infrastructure, and verify performance of human support elements
- Build flight systems for human missions
- Demonstrate sustained human exploration on the Moon
- Conduct discovery-driven opportunistic science

Phase 4: 2035 – beyond

- Initiate human missions to Mars
- Explore Mars with a unified robotic and human system

Summary of Roadmap Achievements

The recommended phased approach to Mars exploration represents an exciting, affordable, and scientifically rewarding program that will address the key questions of planetary evolution, habitability, and life in the cosmos. At the same time it is a measured, decision-based structure that will enable the nation to make steady progress toward the long-range goal of human Mars exploration. The table below summarizes the key achievements that will be enabled by each phase of the roadmap.

Roadmap Goals	***Phase 1: 2005-2015***	***Phase 2: 2015-2025***	***Phase 3: 2025-2035***
Determine if Mars was Habitable and if Life Developed There	- Evidence of past water and aqueous processes - Habitable environments - Biosignatures	- Lab study of Mars samples - Subsurface exploration - Intensive search for life	- Intensive search for life - Discovery-driven opportunistic science
Understand the Climate of Mars	- History of water - Atmosphere chemistry and dynamics - Polar layered deposits	- Long-term climate change - Understand and predict Mars weather	- Discovery-driven opportunistic science
Understand the Geological Evolution of Mars	- High-res surface mapping - Global/local mineralogy - Surface-atmosphere interactions - Role of water	- *In situ* exploration of compelling sites - Lab study of Mars samples	- Discovery-driven opportunistic science
Prepare for Human Exploration	- Search for usable water - Environment, dust, surface characteristics - Atmosphere variability and models - Establish initial telecom infrastructure - Candidate architectures and key technologies	- Downselect architectures - Identify/explore candidate landing sites - Confirm resources - Biohazards, toxicity - Validate capabilities - Human habitation and exploration on Moon - Mars mission "dress rehearsal" - Confirm architecture	- Establish robotic outpost at preferred human site - Emplace infrastructure (Power, ISRU, comm., etc) - Develop key capabilities and build flight elements - Prepare for first human launch

Summary of Recommendations

The Mars Strategic Roadmap Committee makes the following recommendations:

<u>Scientific Recommendations</u>

- Build and fly two Mars Science Lab spacecraft
- Launch both MSL's *no later than* 2011, with a goal of launching one in 2009, and launch Mars Sample Return *no later than* 2016
- Incorporate the search for accessible water and development of water extraction techniques into Mars Exploration Program objectives
- Characterize the Mars atmosphere, both for scientific reasons and to aid in the design of EDL systems
- Upgrade our Mars science data archiving and access system to be ready for the data from future missions
- Structure an integrated program of robotic science missions and robotic human

precursor missions to achieve the desired measurements and capability advances

Programmatic Recommendations

- Develop standard product lines and reuse common products and designs whenever possible
- Expand the definition of Mars Scouts to embrace varied forms of implementation and program goals
- Build an industrial capability
- Forge partnerships with key academic units
- Increase the size of the community
- Include international components in the program
- Fully equip and utilize the International Space Station for human health research to enable human missions to Mars
- Perform system studies by industry and government and develop a Design Reference Mission to guide the human exploration plans
- Identify specific Mars mission requirements that can benefit from validation on the Moon, and levy those requirements on the human lunar exploration missions
- Form a "Super System Engineering" group to steer studies and investments

Technology/Capability Recommendations

Required:
- Hypersonic parachute to allow landing MSR-class assets at high elevations on Mars
- Human-scalable entry, descent, and landing systems capable of safely and precisely landing large masses in units of up to 40 MT
- Heavy-lift launch vehicle (~100 MT to LEO)
  - Validate on human lunar mission prior to first use for Mars
- Robust ~20-40 kW power plant for use on the surface of Mars
  - Total power required may be approx. 60-100 kW; use multiple units for flexibility and redundancy
  - Advanced high-efficiency radioisotope power is required for robotic missions
- Validation of capabilities needed for human expeditions, using appropriate venue
  - Strategically select opportunities to validate key capabilities in relevant environments
  - Includes Earth analog environments, ISS, Moon, and Mars (via robotic missions)

Possibly Required:
- ISRU for human consumables and propellant production
  - Downselect among candidate methods based on Mars environment knowledge (esp. presence of water), feasibility tests, and architecture studies
- Nuclear propulsion for Mars missions
  - If the cost benefit for Mars is established via trade studies, or if required by other overriding agency/national needs

Goals of Mars Science and Exploration

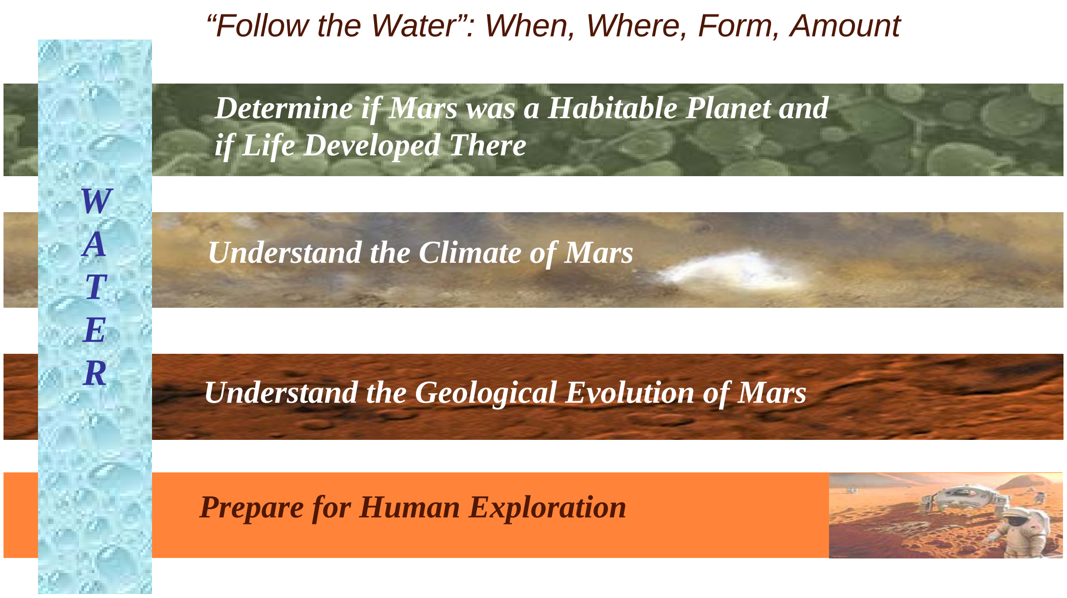
A fundamental question for humanity is whether life on Earth is unique or is abundant throughout the universe. Understanding the conditions (physical environment, energy sources, and crucial chemical components) required for life to emerge is central to this issue. The exploration of Mars offers one of the richest opportunities to address this question. The reason is fundamentally twofold. First, Mars has had a long, complicated geological evolution, with evidence for extended interaction of water with surface and subsurface materials. Second, water is believed to be a key ingredient for the development and evolution of life. We also note that understanding the evolution of Mars will undoubtedly increase our understanding of the evolution of planets, in general, and thus of the solar system.

Exploration of Mars will enable us to address questions that resonate across the scientific community and the public:

- How does life begin? What is the range of environments and chemistry that allow life to emerge and to be sustained?
- Is or was Mars a habitable planet?
- Did life develop on Mars, and if not, why not?
- What was the role of water in Mars' evolution and habitability?
- How will understanding the planetary-scale evolution of Mars contribute to a better understanding of the evolution of the solar system and planet Earth?

There is abundant evidence for interaction of liquid water and ice at the surface of Mars including dry river channel systems that cut across older terrains. Also, evidence of shorelines of past lakes and seas has been suggested by some researchers. Hydrated salts are found in association with layered deposits in the equatorial regions, including the evaporite deposits formed in shallow water and examined by the Opportunity rover in Meridiani Planum. Relatively young gullies emanating from canyon walls suggest that water existed very near the surface in geological time, at least ephemerally. Water ice is found exposed at the poles and buried under shallow soil deposits at high latitudes. Further, selected equatorial regions have enhanced water signatures associated with residual ice deposits or hydrated minerals. Finally, Martian meteorites provide a view of an early wet planet, with production of aqueous minerals, and tantalizing, but very controversial evidence for ancient life.

To answer the question of whether or not there is or was life on Mars requires a deep intellectual understanding of how the planet's interior, surface, and atmosphere have evolved and interacted over time, and the extent to which conditions were conducive to formation, evolution, and preservation of evidence for life. We need to understand if Mars ever possessed the essential chemical species (including water), the environmental conditions (e.g. temperature, radiation levels) and energy sources available in concert at the right time and place to support development, evolution, and sustenance of life. The scientific community has come to consensus that by understanding the history of water on Mars we can derive the greatest insight into the processes that have affected Mars' evolution and potential habitability; thus the Mars science strategy has come to be known as "Follow the Water". This strategy was established years before announcement of the Vision for Space Exploration, but it remains highly consistent with the goals articulated in the Vision and provides an excellent linkage between the goals of scientific understanding and preparation for human exploration.



In this section of the Roadmap Report we summarize what is currently known about Mars and its potential habitability, past and present. We provide a preview of robotic exploration and discovery missions through the next two decades that focus on developing the intellectual basis to understand the planet and whether or not life developed and evolved. We then consider how to further deepen this understanding as we transition from robotic to human expeditions to the red planet.

From Initial Reconnaissance to 2005
Water and the Evolution of Mars

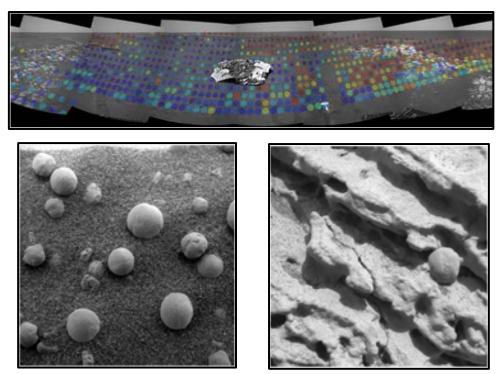
<u>Key Discoveries and Achievements:</u>

- Planetary spacecraft data and Mars meteorite studies have led to our emerging view of Mars as a water-rich planet
- Liquid water existed at and beneath the surface over most of geologic time
- Mars appears to have had the ingredients needed to develop and sustain life

The period from the first flyby reconnaissance of Mars, by Mariners 4, 6, and 7, to today, when the two Mars Exploration Rovers explore the surface in great detail as three active orbiters circle overhead, has revolutionized our understanding of the Red Planet and the role of water in its evolution. This understanding has been complemented and extended by study of approximately three dozen meteorites that have isotopic signatures indicative of a martian origin.

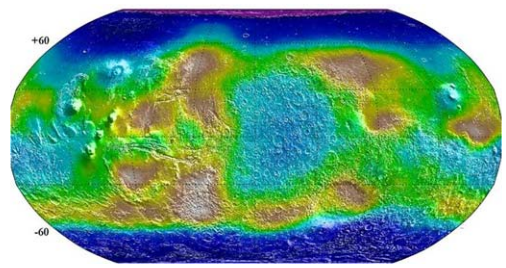
The emerging view of Mars is one of a planet with very active tectonic and volcanic evolution, particularly early in geologic time. An internal dynamo in a liquid core generated a magnetic field for approximately the first billion years of geologic time. The great Tharsis Plateau, a long-term locus of volcanic activity, formed early in time and massive volcanic emissions (water, carbon dioxide, and many other gases) from this and other volcanic systems caused greenhouse warming that raised surface temperatures. Fluvial channel systems formed during this period and open or ice-covered lakes and shallow seas may have existed at least on an ephemeral basis. As the rate of volcanism associated with the Tharsis Plateau and other magmatic centers declined, conditions grew colder because of the lack of supply of greenhouse gases, and surface water became less likely. In addition, analyses of Mars meteorites show that these materials are igneous rocks with an age range from 100 million to 4.5 billion years, supporting the idea that volcanism extended over most or all of geologic time. This indicates that, at least locally, conditions may have been warm enough, due to transient greenhouse warming and the presence of active hydrothermal systems, to allow liquid water to exist. This interpretation is bolstered by tantalizing evidence for on-going and occasional release of ground water from canyon walls. This evidence is in the form of morphologically fresh gully systems that extend downward from tops of cliffs and, in some cases, produce fan deposits that cover relatively recent wind blown dunes.

Recent results from the two Mars Exploration Rovers are also consistent with an extended presence of water and demonstrate its interaction with surface and near-surface materials. The first Mars Exploration Rover, Spirit, reached the Columbia Hills after traversing 157 sols across volcanic plains to find older rocks that have been altered by salty ground water. The second rover, Opportunity, traversing across the plains of Meridiani, found evidence for cross-bedded, hydrated sulfate evaporite deposits that formed in shallow, open water, with subsequent modification by corrosive ground waters. The deposits are at the top of a 300 m layer of sedimentary rock that covers the dissected, channeled cratered terrain. *This means that a water-rich environment existed at or near the surface* even after deposition of the 300 m section – that is, after burial of the channel systems within the cratered terrains.



Direct detection of aqueous processes by Opportunity

Mars Express OMEGA data show that hydrated sulfate deposits are found in abundance exclusively in association with layered deposits, including those in Meridiani Planum, and extensive deposits found within Valles Marineris. This result suggests that Mars, when wet, was dominated by acid-sulfate aqueous systems. The acidic conditions would have precluded formation of carbonate deposits. OMEGA data also show that clay minerals occur, but only in the older cratered terrains, consistent with a warm, wet early Mars. Finally, martian meteorites show evidence for magmatic fluids in their formation, as well as overprinting in the martian crust by circulating water-rich fluids. These materials also contain secondary minerals such as carbonates and sulfates formed in aqueous environments. The evidence in total from analyses of spaceborne and meteorite data shows that *Mars had and probably still has, to some extent, an active hydrological cycle and likely had environments in the near surface that were habitable by terrestrial standards.*



Concentrations of subsurface water detected by Mars Odyssey

Today, water on or near the surface is largely in the form of ice deposits in the permanent polar caps, shallowly buried ice deposits in the high latitudes, and hydrated minerals and perhaps residual ice deposits in the low latitudes. Mars undergoes orbital changes (akin to Earth's Milankovitch cycles) with major variations in obliquity, eccentricity, and the positions of the equinoxes over timescales ranging from ~100,000 to millions of years. These cycles have modulated the characteristics of the climate, including the atmospheric pressure and the ability of the atmosphere to transport water vapor and ice, carbon dioxide, and dust. The record of these cycles is within the hundreds of meters of layered polar deposits of dust and ice and the shallow water ice deposits beneath a thin cover of soil at high latitudes. Interestingly, these deposits may have supported the development of lenses or pockets of water during chaotic excursions of obliquity to values as high as 45 degrees that occur over approximately ten million year timescales.

The motivation for the current era of intensive Mars exploration arises from the mounting evidence for the presence of water, both as liquid and ice, on and beneath the surface throughout geologic time. In addition, martian meteorite ALH84001, a piece of the ancient cratered terrain, contains substantial evidence for modification by aqueous fluids, and morphologic evidence suggesting microfossils. The fossil evidence is highly controversial, but it has helped to energize both the science community and the public in exploring Mars to search for life. We note that the recent announcement of the presence of small amounts of methane in the martian atmosphere provides an additional piece of evidence that the planet is still active and/or may have extant life. Methane can be produced by cometary impact, by on-going volcanic emissions, and as a by-product of microbial metabolism. Methane is quickly destroyed by ultraviolet radiation in the martian atmosphere and thus demands an on-going source from the surface or subsurface. The methane evidence is also controversial and is being subjected to intense scrutiny by the science community.

Roadmap Phase 1: 2005-2016
Toward an Understanding of the Potential for Current and Past Life on Mars

Key Discoveries and Achievements

- Thousands of sites will be mapped from orbit and evaluated for habitability
- The modern climate and ancient hydrological processes will be characterized
- High-latitude soils and ices will be analyzed to determine current and past climatic conditions and to search for evidence of reduced carbon compounds
- High-priority sites will be studied in detail for evidence of accessible subsurface water and habitable environments
- A comprehensive understanding of Mars' environmental characteristics will enhance both our scientific foundation and our ability to plan future exploration

On ancient Mars, climate and surface conditions may have been favorable to the origin and evolution of life. The next step, beyond the missions already flown or still operating at Mars, is to search for past and present habitable environments. The MER Opportunity results suggest that such an environment may have existed long ago in Meridiani Planum. Perhaps Spirit will find that Gusev Crater was also once habitable. Future planet-wide searches will be conducted from orbit and on the surface in order to identify other habitable sites for in-depth study. Aqueously deposited sediments and surface alteration by water will be the primary subjects of this search, since it is in these sites on Earth where evidence of past life is found. *By finding these sites we will have identified locations on Mars where the potential is highest for finding evidence of past life.* Landed mobile missions will then examine these sites for evidence of biosignatures. Missions will be targeted not only will sites to temperate latitudes, but also to high latitude sites where surface or near-surface water ice may now be present.

In the coming decade, the investigations to be conducted at potentially habitable sites will include measurements of carbon chemistry in near-surface rocks and soil. Definitive mineralogy will also be critical, including identification of any evidence of formation or alteration by water. The tools for these investigations will be analytical instruments, under development for the past decade in universities and NASA centers, which begin to approximate the capabilities available in ground-based laboratories but which have size, mass, and power requirements consistent with robotic missions. These *in situ* studies will lay the scientific and technical groundwork for the return to Earth of martian samples taken from the highest priority sites, long considered a key to complete understanding of Mars and its potential as an abode for life.

Robotic Science Missions for the Coming Decade

Mars exploration begins a transition from reconnaissance from orbit and on the surface to studies that focus in great detail on martian phenomena and processes. Increasingly sophisticated and complex missions are required enabling measurements similar to those employed to better understand the Earth. Future measurements will be more like those used in Earth field geology and in laboratory analyses of samples collected in the field. Measurements from orbit will match the physical scale and precision of those currently being made by Earth satellites.

Using orbiters, landers, and rovers to carry sophisticated instruments, missions in the period from 2005-2015 will gather data to define in detail ancient habitats that might have supported the emergence and maintenance of life, search for the best locations to test for the presence of past and extant life, and conduct detailed analyses both *in situ* on Mars and with returned samples to understand if environmental conditions and chemistry were conducive to the emergence of life and to search for evidence of past and present life itself.

Mars Reconnaissance Orbiter. In the summer of 2005, the Mars Reconnaissance Orbiter will launch with a payload designed to characterize the atmospheric structure, map in detail numerous candidate sites that might preserve detailed evidence for aqueous processes (i.e., sites with high habitability potential), use of ground penetrating radar to map ground water and ice deposits, and continue investigation of the deep interior of Mars (i.e., through mapping the gravitational field). A primary objective is to provide detailed topographic maps, images, and mineralogical maps for up to 10,000 targets on the planet. These data will be of high enough spatial fidelity (30 cm/pixel imaging data and 18 m/pixel mineral maps from reflectance spectra) to "virtually" explore the geologic setting of these targets. Besides conducting scientific investigations with these data, numerous landing site analyses will be done to select the optimum sites for the subsequent Mars Science Laboratory Mission. The Mars Reconnaissance Orbiter will also provide four dimensional (location, altitude, time) maps of the atmosphere (temperature, pressure, water vapor, dust profiles) over a full martian year, observations that are crucial for understanding the current state of the atmosphere and resultant climatic conditions. The current atmosphere is a boundary condition for understanding earlier atmospheres and climate changes on the red planet.

Phoenix Lander/ Mars Scout. The Phoenix Lander will, during the summer of 2008, descend to the high northern latitudes, where water ice may be within 10 cm of the surface. A robotic arm and scoop will be used to excavate a trench and deliver soil and ice samples for detailed analyses of aqueous chemistry, mineralogy (including ices), and isotopic composition of evolved gases (including search for reduced carbon compounds). An imaging system will be used to map the landing site and investigate the evidence for periglacial (i.e., ice-related) processes. The imaging system will also track the opacity and color of the atmosphere while a LIDAR system maps aerosols and a meteorology package measures atmospheric pressure and temperature. Relative humidity will be determined, along with the isotopic composition of the atmosphere. The payload will also be used to search for trace amounts of methane in the atmosphere. Phoenix, the first

Scout Mission, is an example of discovery-driven science in that it was conceived, proposed, and selected after Odyssey observations demonstrated that water ice exists at high northern latitudes, covered by perhaps 10 to 20 cm of soil deposits. Phoenix will characterize the current atmospheric conditions at high northern latitudes, the nature of the ice deposits, and search for the presence of organic compounds.

Mars Science Laboratory. The cornerstone surface mission of the decade will launch in 2009 and/or 2011. The Mars Science Laboratory rover(s) will focus on traverses over its Mars year mission to explore a number of sites of interest and conduct initial measurements to define the extent to which Mars was or is habitable. Using an ensemble of remote sensing, arm-based contact sensors, and an analytical laboratory with elemental, mineralogical, and isotopic and molecular analysis capabilities, the mission will provide data to determine the aqueous history of the landing site and surrounding areas and search for and characterize reduced carbon compounds and other biochemically important compounds. In fact, this mission will begin the detailed search for biosignatures on Mars. Biosignatures are defined as characteristic "fingerprints" indicating that life exists or existed, including direct evidence in the form of recognizable life forms and an array of indirect evidence. For example, analyses of reduced carbon compounds will allow testing of biotic or prebiotic origins for these materials, since these two types of processes are likely to produce distinctly different compositional and isotopic signatures. Biotically produced methane may show isotopic signatures of metabolic processing, while the complex organic species produced by life may show distinct patterns in molecular weight or structure due to enzyme processing and other mechanisms. Fragile organic molecules from past biological activity on Mars are likely to have been substantially altered by chemically processes such as oxidation, but chemical patterns should still be retained. The Mars Science Laboratory payload is designed to find the rocks that maximize the probability of preserving biosignatures, acquire and prepare samples, and make initial measurements to search for the key elemental, mineralogical, and isotopic signatures indicative of life and its effect on the environment.

Future Mars Scouts. A hallmark of the Mars Exploration Program is the ability to respond to discoveries and make new measurements designed to better understand the evolution of Mars, its current and past habitability, and whether or not life developed and evolved. For example, the Phoenix Scout Mission was proposed in response to the discovery of shallow and accessible water ice deposits beneath a thin soil cover in the high northern latitudes. We fully expect to maintain program flexibility through continued Scout missions or their equivalents. The very nature of these missions precludes listing their foci and objectives in detail; nevertheless we expect that Scout missions will make important contributions to both fundamental Mars science as well as to preparation for human exploration.

Mars Environment Mission. Mitigation of engineering risks and science come together in the Mars Environment Mission. This will be a mission focused on scientific study of key environmental characteristics that will help to define the future human exploration architecture; thus it is an important precursor to human exploration. One option under consideration is an orbiter to enable thorough understanding and characterization of the martian atmosphere. Experience -- most recently demonstrated in the entry, descent and landing of the MER rovers -- has shown that knowledge of the Mars atmosphere is inadequate to confidently assure successful landing in all cases. Surface operations are also influenced by unpredictable weather; dust storms are one example. Measurements from orbit will monitor winds at low altitudes where landers are most vulnerable, characterize the variability of atmospheric density due to weather and season effects from the surface to 125 km, and monitor dust storms from local to global scales.

Other options for the first Mars Environmental Mission are a stationary lander to drill down to 10 meters or so in search of usable subsurface water, or a mobile lander to prospect for water/ice deposits over a broader region with shallow (~2-m) drilling. Either of these missions would be key to understanding the potential of water-based *in situ* resource utilization, which can have a dramatic effect on architecture selection and other capability investments. A decision should be made in about 2008 on which MEM mission to fly, so that launch can occur in 2013.

Mars Sample Return. The end of phase will see the launch of one of the most important robotic missions from the perspectives of both science and preparation for human exploration. For decades, the goal of returning samples from Mars has been considered one of the key missions in all of planetary science. Analyses of returned samples from a site selected using information obtained by preceding missions will allow the entire complement of sophisticated analytical tools available on Earth (and impossible to send in bulk to Mars) to be used to search for biosignatures and thus test for the presence life. Literally dozens of laboratory instruments, weighing thousands of tons, producing terabytes of data, will be used to unlock the history recorded in the returned martian materials. Further, as the first round-trip mission to Mars, and the first to launch from the martian surface, the sample return mission will directly connect robotic exploration to future human missions. The samples to be delivered to Earth will also be critical enablers for human exploration. Analyses of rocks and soils will allow the hazards (biological, chemical and mechanical) and utility of martian surface materials to be assessed. Mars sample return is a key to understanding critical

astronaut health issues that are likely to remain open until detailed analyses are performed on martian dust, soil, and rocks in laboratories on Earth.

Mission Summary

The table below depicts the recommended mission sequence for the coming decade, with options that can be selected based on budget and programmatic factors.

Opportunity	***Mission***
2005	Mars Reconnaissance Orbiter
2007	Phoenix lander (Mars Scout)
2009	Option 1: Mars Science Lab #1 Option 2: Mars Telecom Orbiter #1 plus Mars Scout
2011	Option 1: MSL #2, plus Mars Scout and/or MTO #1 Option 2: MSL #1 plus MSL #2
2013	Option 1: Mars Environment Mission #1 plus Mars Scout
2016	Mars Sample Return

Roadmap Phase 2: 2016-2025
Developing a Detailed Understanding of Habitability and Life

Key Discoveries and Achievements:

- Investigations will seek to confirm evidence of past life at ancient or modern habitable sites
- Martian samples will be studied in Earth laboratories to provide a definitive understanding of surface chemistry, climate history, and potential habitability
- Major water and ice deposits may be found, and key elements of *in situ* resource utilization systems will be tested.
- Detailed study of Mars' environmental characteristics will provide a window into the planet's past and to the possibilities for future human exploration

Having identified and investigated with analytical instruments one or more sites, tests will be performed for evidence of extinct organisms and present life, where appropriate. Detection and confirmation of even fossil life would be a discovery of profound importance that would alter our understanding of life on Earth and elsewhere in the cosmos. In the search for extant life, the demands of protecting martian organisms becomes paramount. In addition, this phase of exploration requires care to avoid false-positive detections of life. Consequently, technologies must be found to ensure that spacecraft and instruments are clean and sterile. The blunt tool of heat sterilization used by the Viking spacecraft is expensive and potential disabling for delicate electronics and mechanisms.

Astrobiologists are not of one mind on what measurements could provide definitive confirmation of life, past or present, Disagreement focuses on the matter that remains unresolved in the ongoing study of the martian meteorite ALH84001, namely the putative detection of microfossils in the meteorite that has not yet been proved beyond doubt. The interpretation of microfossils and associated biosignatures is a subject of intense debate, unresolved even with all the instruments and researchers available in laboratories world-wide. There are astrobiologists who argue that unambiguous *in situ* measurements can be made sufficient to prove the presence of fossil life. Others disagree, asserting that only through analyses in laboratories by experienced researchers can proof or refutation be obtained. At present, the Mars Program takes the matter as unresolved and plans for both investigations -- *in situ* to establish a preliminary detection and sample return for definitive answers.

By subjecting carefully selected samples to sophisticated analyses, the information embedded in a rock can extracted to trace the origins and history of the environment that it has experienced. The planetary science community thus ranks the return of samples from Mars as the highest priority for investigations in the next decade. Scientists seek to determine from returned samples their mineralogy, petrology, geochemistry, reduced carbon content and weathering histories, among many other characteristics commonly ascertained from Earth rocks and soil. Many of the most critical measurements required to unravel the evolution, history and current state of the martian surface ultimately depend upon complex instruments that occupy large laboratories; furthermore, many important measurements also require that samples undergo considerable preparation before being introduced into these laboratory instruments.

<u>Robotic Missions: Intensive Science and Preparation for Human Exploration</u>

Missions that follow sample return will employ advanced measurement technologies together with long lateral traverses and drilling to intermediate depth (3 to 10 m). The sites might be an "oases", localities where liquid water is or has been recently close to the surface. Drilling might be to depths of 10 meters or more, with down-hole measurements made to complement analyses of drill core samples. Such an Astrobiology Field Lab will provide perhaps our best opportunities to search a variety of environments for evidence of life.

A second major emphasis will be to search for and find accessible water deposits, perhaps as shallow ice or as liquid aquifers perched as "oases" above the deep water table. These water bodies may be sustained, for example, by continued magmatic activity at depth. These ices and aquifers will be examined for biosignatures. In addition water will be extracted from the deposits and perhaps utilized in prototypical ISRU experiments. A follow-on to the earlier Mars Environmental Mission may be a more sophisticated water extraction and processing experiment, which may even provide fuel to be used to launch another Mars sample back to Earth. This would amount to a full "dress rehearsal" of the key architectural elements required for a human landing and return, and would be an important factor in confirmation of the selected architecture and providing the required confidence to go forward with the human mission.

Roadmap Phases 3 and 4: 2025-2035 and Beyond
Preparing for and Implementing Human Expeditions

Key Discoveries and Achievements

- Robotic outposts will be established for extended scientific and environmental studies and preparation for human missions
- Human exploration of Mars will begin, representing one of the major scientific and engineering achievements in human history
- Humans and robots will form unified systems that will maximize detailed study and understanding of the evolution of Mars and life

In the coming decades, Mars orbital, *in situ*, and sample return studies are planned to achieve a comprehensive understanding of martian environmental characteristics and potential life. A likely evolution of the robotic program and a direct step toward human exploration is the establishment of a "robotic outpost". This is a localized collection of landed robotic assets that performs science and/or engineering tasks cooperatively, and may be an effective means of preparing for the arrival of human explorers. Cooperation may be directed by Earth-based controllers or autonomously. Tasks suitable for outposts will most often be those for which single independent robots cannot accomplish a task. We are confident that the scientific exploration of Mars will grow increasing challenging (in complexity or intricacy) such that some objectives will require cooperative engagement of robotic systems. An example is drilling to depths of 100 m and greater – a task that may be valuable for science and for access to resources needed to support human missions. In obviously challenging task, not only is the drilling itself mechanically sufficiently complex to require multiple robots but the analysis of samples for drill-operations and scientific purposes requires that numerous additional robotic skills be brought to bear.

Robotic outposts will be a powerful tool in the more advanced stages of the robotic exploration of Mars. Outposts are naturally a tool for the future because we must first locate and explore preliminarily sites that warrant devoting the significant amount resources required by outpost deployment. The discovery of an active hydrothermal vent on Mars would easily qualify as a site for follow-up and, potentially, the emplacement of an outpost. Deployment of infrastructure at the first human landing site is another likely role for robotic outposts. In fact, robotic outposts will be excellent candidate sites for landing humans because of the scientific opportunities there and the accumulated understanding of the site and its environment. Preparing a site for human explorers would involve erection and assurance of the habitat, deployment and test of an in situ resource utilization (ISRU) system, and deployment of a surface power system.

Robotic Outposts Supporting Human Exploration. The period from 2025 onward will focus on continued detailed scientific study of one or more key sites. Small outposts will be deployed for continued monitoring of the planet and its external and internal environments. Further, a primary outpost will be designated for a human landing, with robotic systems deployed to prepare the site. Deployment and assurance of infrastructure for humans (habitats, ISRU, power, power distribution) will likely be an enabling role for robotics.

Finally, we see the humans and robotic systems working together on Mars to continue to understand habitability and life on the red planet. In particular by this time period we should be able to characterize in detail how any martian life sustains or sustained itself, i.e., the ecological system. If the ingredients for life were or are present and life did not form and evolve, an equally challenging and important question is why not, with definite implications for formation and evolution of life on Earth.

Preparing for Human Exploration: Goals and Recommendations

Human exploration of Mars will be the culmination of a multi-decade program of discoveries and developments. But human exploration is decades away; our near-term goal must be to understand Mars and to enable sound strategic decisions that will create an affordable and sustainable architecture. Among the required elements that will lead to these decisions are:

- Architecture development and systems studies to identify and address the architectural swingers
- A flexible design reference mission to guide investments and decisions and provide the context for architecture assessment
- Articulation of an objective function by which candidate architectures will be compared and selected
- Knowledge of Mars resources and environment, and the effects on humans of Mars surface presence and interplanetary travel
- Understanding of human exploration in a planetary environment through extended human lunar missions
- A comprehensive capability development program using a variety of venues for validation

Overview of Key Goals and Challenges

Human exploration missions to Mars will require systems engineering and operational planning on a very large and perhaps unprecedented scale. The first step in the process is the selection of an overarching architecture that properly connects all the phases of the mission, beginning with launch from Earth and continuing through not only descent and landing on Mars and a surface mission of significant duration, but also ascent from the Mars surface and a safe return to the Earth. Over the past two decades, in various studies conducted by NASA and independent space groups, dozens of candidate architectures for human missions to Mars have been examined. But there exists no single architecture that represents a best baseline, or reference, mission for human exploration of Mars.

All candidate architectures require an enormous amount of mass to be placed in Earth orbit, at least 500 metric tons. All the architectures call for at least one precursor robotic cargo mission to land major infrastructure elements on the surface of Mars, and for this cargo mission to be followed by a pinpoint human landing in the immediate neighborhood of the landing site of the cargo mission. This is a huge delivery requirement, up by almost two orders of magnitude from the delivery capability of today's robotic Mars missions, and represents one of the major technological challenges of a human Mars mission.

Another feature common to all the Mars human mission architectures is the requirement for substantial power availability on the surface, both to support the deployment and maintenance of the infrastructure elements delivered by the cargo missions, and to sustain the human presence for any significant period of time.

All the architectures also assume that a long-term investigation program will eventually conclude that it is indeed safe to send human beings to Mars. At present human safety for such a mission has not yet been firmly established. To certify that the Mars environment itself is not harmful to humans, both in situ measurements by robotic spacecraft at Mars and the careful examination of samples brought back to the Earth from Mars are necessary.

Assumptions about in situ resource utilization (ISRU) are another major factor differentiating among the existing architectures. ISRU technology could be used to manufacture propellant for the Mars ascent vehicle, to produce water to sustain the crew, and to conduct other even more sophisticated tasks. However, ISRU technology is not yet mature. Before a human mission to Mars could include ISRU as a critical link in its architecture, the reliability of the ISRU processes would have to be demonstrated.

Strategy for Defining, Downselecting, and Confirming Mars Human Exploration Architecture

To determine the "best" architecture for a human mission to Mars requires the establishment of quantitative metrics, or at least evaluation criteria, relating such diverse attributes as human safety, mission risk/resiliency, system performance and robustness, technological readiness including development cost, schedule, and risk, science quality/quantity, and program policy. The single most important recommendation of the Mars roadmapping committee is the immediate establishment of a blue ribbon, multiyear, multidisciplinary, One NASA systems engineering team, whose primary function will be the development of these metrics and criteria to permit the comparative evaluation of the overall merit of the different possible architectures for a human mission to Mars. This recommendation, along with the other findings and recommendations resulting from the committee study, is presented in more detail in the subsequent paragraphs of this section of the report.

<u>Proposed program of NASA/industry studies</u>

An integrated "Super Systems Engineering" team should be formed immediately to guide decisions and investments for the integrated robotic-human Mars exploration program. This team should be multi-organizational in nature, including personnel within and external to NASA. Industry should also be heavily involved in the overall activity, both through broadbased systems engineering contracts and through more focused contracts emphasizing the key enabling systems This team should develop and assess candidate architectures and evaluation criteria for an integrated robotic and human Mars exploration program. The team should guide a series of joint NASA/industry studies which focus on architecture development and on study and downselection of key technology options. These studies should be initiated immediately so that there results can be available for the initial architecture downselection in 2008.

Reference human mission framework for capability needs assessment

A 2–4 year time period is required to perform thorough *preliminary design* level mission and flight system designs that are technically feasible. With these preliminary design efforts as a guide, prioritization will be possible among the many specific technologies that could be applicable to human Mars exploration. This effort will also allow requirements development for a Mars human exploration program to proceed and develop a technology development plan.

The initial focus of this team should be on the appropriate evaluation criteria against which to assess potential Mars exploration architectures. A multi-parameter evaluation scheme should be developed, with quantitative metrics if possible, that includes, but is not limited to, factors like human safety, mission resiliency, system performance and robustness, technology readiness, program policy, cost, schedule, and science quality/quantity must be developed. In addition, specific technology assessments should be undertaken in parallel.

Decision Strategy

The roadmap committee recommends the following timeline for key architectural decisions leading to human Mars exploration. This will take advantage of the scientific results of robotic missions, as well as capability development and validation of human operations on the Moon, and should be an affordable process that allows sufficient time for analysis and debate.

- Refine architectural and system studies and prepare a small set of *candidate architectures by 2008*
- Based on data from Mars robotic science and environmental measurements, select *preferred architecture(s) by 2015*
- Develop and test key capabilities, conduct further Mars science and precursor missions, and validate human exploration systems and concepts on the Moon to support *architecture confirmation by 2025*
- Begin emplacing long-lead infrastructure in a robotic outpost, continue capability development and sustained lunar exploration, verify readiness, and prepare to *launch the first crew to Mars by 2035-2040*

A number of technical factors will contribute to the design and final verification of the architecture. Among these key architectural decisions are:

- Select a new human Mars Design Reference Mission to guide capability investments and future mission planning
- Select lift capability of new heavy-lift launch system and determine timeframe of availability
- Identify and validate feasible means of safely landing large (~40 MT) mass elements on the surface of Mars

- Confirm the presence of usable subsurface water on Mars
- Identify the Mars mission elements for which validation on the Moon is critical
- Decide whether to proceed with fission reactor system for Mars surface power
- Determine the nature and degree of human health hazards likely to be encountered on Mars
- Determine need for high-efficiency in-space propulsion based on fission power
- Confirm the ability of humans to live and work safely in deep space long enough for transit to Mars, exploration of the planet, and return to Earth

An Integrated Robotic-Human Program: Role of Robotic Missions

Just as the robotic lunar missions of the 1960's were critical precursors to Apollo, robotic missions to Mars will lay the groundwork for sending humans to explore the Red Planet. Any national commitment to sending humans to Mars will depend critically on a robust program of robotic precursor missions that will enable good architectural decisions and maintain an acceptable level of risk to human explorers.

Robotic missions have already yielded a wealth of scientific data for reconnaissance, site selection, environmental characterization, surface operations planning, and resource mapping. They have laid the scientific foundation that will ultimately determine how and when, and perhaps whether, humans will travel to Mars, and what tasks they will accomplish when they get there. Mars Sample Return can be viewed as a clear tie point between the robotic science and human exploration program elements, since it will exercise all required elements of a round-trip mission and will help provide scientific and operational confidence in our exploration decisions.

The robotic exploration program's current mission plans focus on expanding our scientific knowledge of Mars in areas that are closely aligned with the needs of preparing for human exploration. The science priorities, such as the understanding the role of water in Mars' past and its current form and abundance, characterization of the regolith, and determining the biological potential of past or present Mars, are directly applicable. The science missions now planned will address many of the critical measurements needed for human exploration, including: toxicity and trafficability of the Martian surface; dust characteristics; potential biohazards from possible Martian life; atmospheric characterization for electrical properties; Martian meteorology and characterization of dust storms; and the existence, extent and location of water. MSL, AFL, and MSR will provide critical measurements in the characterization of possible organics; biohazard potential from extinct and/or extant life; radiation environments at the surface over time; meteorological data; lateral distribution of near surface water, dust mineralogy, adhesive properties, and toxicity; and surface soil variations by location. MRO, through high resolution imagery and moderate resolution sounding will globally extend previous measurements, identify and evaluate possible landing sites, identify location of resources and shallow subsurface features, and improve the understanding of the atmosphere.

Common threads link our scientific study of Mars with preparation for human exploration

	Scientific Imperative	*Human Preparation Imperative*	*Key Missions*
Search for Water	• Habitability • Geology/climate history	• ISRU method • Dramatic mass reduction	• Odyssey, Phoenix, Mars Science Lab, Mars Sample Return, Scouts • Mars Environ. Mission
Characterization of the Environment	• Planet evolution and processes	• Safety and productivity • Design of systems and habitats	• Mars Recon Orbiter, Mars Science Lab, Mars Sample Return, Scouts • Mars Environ. Mission
Search for Life	• Evolution of habitats • Origin, nature, prevalence of life	• Where and how to explore • Planetary protection	• Mars Sample Return, Astrobiology Field Lab, Mars Scouts

Mars Water and Human Exploration

The search for Mars water represents a key unifying theme that links robotic science and human preparation goals. Confirmation of accessible /usable water in the near sub-surface will open new architectural domains for future human Mars exploration. It can provide a source for both propellant production and human consumables, and can result in significant mass reduction and potential crew safety enhancements. While these benefits are clear, a negative result (absence of usable Martian water) will not invalidate human missions to Mars. Alternative pathways of resource utilization should be preserved until an informed decision can be made. Recommendations for near-term studies and missions are:

- Highest priority is Mars Science Lab to confirm and localize water in the near sub-surface
- Use search for accessible water as one of the architectural elements integrating the near-term science and human precursor missions
- Form a Science Study Group to suggest investigations and measurements (to be incorporated in science missions and dedicated Mars Environment Missions)

Key Capability Requirements

A large number of new capabilities and technologies will be required to enable advanced robotic exploration and eventually human exploration of Mars. The roadmap team has not attempted to specify each and every such development; clearly, that can only be done as a part of the detailed architecture and mission development and assessment that will continue throughout the decades. However, there are several capabilities that can be considered “architectural swingers”. These developments are considered so important that they will define the architecture and many other decisions will flow from them, and thus represent the top priorities for immediate study and development. Capabilities that are judged to be required include:

- A heavy-lift launch vehicle with lift capability to LEO of approximately 100 metric tons
- Advanced entry/descent/landing (EDL) technologies that will enable safe and precise landing of large robotic missions such as Mars sample return. This technology may also be suitable for landing elements of human infrastructure in a robotic outpost.
- Human-scalable EDL techniques capable of delivering about 40 metric tons safely and precisely to the surface.
- Systems for human life support, health, and safety during interplanetary travel and exploration of the surface of Mars. Development decisions will depend on research on the International Space Station as well as results from Mars robotic missions and human lunar missions.
- Power systems that will supply 60-100 kW on the Mars surface. This power level may be supplied by several units capable of 20-40 kW each to allow deployment flexibility. The roadmap team believes that fission power systems will be the most viable means of power generation for human exploration and thus advocates continued research and development of space nuclear power systems. Advanced radioisotope power will continue to be required for robotic missions.
- Advanced telecommunications and data networks on Earth, including an next-generation Deep Space Network

Several capabilities are judged to be possibly required, depending on the results of architecture studies and Mars robotic missions. These include:

- In situ resource utilization for production of propellant and human consumables, as well as for materials that may be used for construction or shielding on the surface. A key determinant of the value of ISRU is the availability of accessible subsurface water on Mars. In the view of the committee, water-based ISRU opens architectural pathways that may be of substantial benefit, and so the search for water is an important aspect of preparation for human exploration. Even if water is not available, however, ISRU may still be an important architectural element. Research into multiple types of ISRU should continue until enough is known to make a well-informed selection.
- High-efficiency interplanetary propulsion using nuclear power. The mass benefits of nuclear propulsion can be substantial, but its value must be assessed in the view of other parameters such as heavy-lift capability, ISRU, acceptable duration of human space travel and total mission, and other factors. Architectural studies should carefully consider the entire trade space before a judgment can be made on the need for nuclear propulsion.

Robotic Technology Leading to Human Missions

Technology on robotic science missions will lead the way to human-required technologies. Large-mass landing systems will be required to place humans on the surface. Entry, Descent and Landing technology investments will begin with precision entry and navigation with the Phoenix mission, and evolve through MSL and MSR where mass-to-the-surface will continue to increase, and pin-point landing will be achieved to access high-priority locations. Surface mobility technologies will evolve through increasingly autonomous robotic exploration of the Martian surface. Surface accessibility through mobility has rapidly advanced from the several-meter roving capability of Mars Pathfinder, to the several kilometer capability of Sprit and Opportunity, to the tens-of-kilometers planned for the MSL. MSR will be the first demonstration of a round-trip mission capability to Mars. While not directly scalable to human mission needs, MSR will serve as a "model" for patterning the following decade's sub-scale/scalable missions in advance of the first human mission. These missions will provide test-beds that will achieve critical technological hurdles before human landing.

NASA performed a study in 2004 to initially define precursor measurement and technology needs and priorities for human exploration of Mars. These initial studies yielded a series of measurement and technology gaps between human precursor requirements and the existing Mars Program portfolio. They provide a framework from which a more extensive series of study tasks should be undertaken. These new studies should define new potential human architectures, and the resulting measurement and technology pathways necessary to accomplish a human landing in the fourth decade.

Integration of robotic science mission plans and objectives, and human precursor requirements will lead to cross-program efficiencies and mutual benefit. NASA should focus the program through a coordinated management structure, such as a Mars "Super Systems Engineering" Group. Engineering-level determination of technology development and precursor mission requirements, acquisition, and partnering strategies, and near- and long-term architectures should feed into this steering group. NASA should initiate industry/government study tasks to help define the technology and mission compositions for human precursor missions and provide pathways for human architecture options.

Mars Environment Missions and Human Precursors

Initial studies mentioned above culminated in a strawman set of possible Mars Environment Missions (MEM) that also serve as precursors to human exploration. The extended studies are crucial to the definition of the first dedicated MEM mission. The Committee defined the following principles:

- Leverage the science mission portfolio to meet as many precursor measurement requirements as possible, without compromising the scientific integrity.
- Mission priorities must be set through community-wide studies, and should lead to human architecture supporting the first human landing in the century's fourth decade.

- The first testbed mission should be launched by 2013, and must concentrate on the "gap" requirements, by priority.
- Target a major subscale, but human-scalable, landing in the latter part of the next decade or early in the 3^{rd} decade (an excellent opportunity for a second sample return from a high-probability human landing site).
- The overall Mars program, with the core science, Scout and precursor elements, must support a human mission architecture validation by 2025. Prior to this decision point, selection of a human mission architecture should be made in the middle of the 2^{nd} decade to ensure that a sub-scale/scalable demonstration mission is conducted in the early in the 3rd decade.
- Joint industry/government studies must be conducted so that NASA can determine the construct of the first MEM mission. This decision must be made by 2008 to ensure a 2013 launch.

Initial infrastructure establishment with Mars Telecommunications Orbiter (MTO) is an important step toward future missions. Additional MTO missions, with advances through essential technology infusion, should be included in the program.

Test Venues: Verification and Validation

Technology advancement should be accomplished using cost-effective strategies across multiple test venues. Technology development activities should include: System studies and analyses, Earth-based testing and test-facility improvements, flight testing in the Earth's atmosphere, flight testing in Earth orbit or at the Moon, and human precursor investigations on flights to Mars. Earth test venues should lead the way and offer high data quantity and quality, a high-degree of test setup control, resilient data acquisition and return strategy, and reasonable test cost.

Unique Contributions of Lunar Missions

The Vision for Space Exploration clearly articulates the linkage of the Moon and Mars. Human exploration of the Moon is a step toward human exploration of Mars; likewise, human missions to Mars will only be undertaken after sustained lunar missions have provided validation of exploration systems and concepts. Exploration of the Moon will motivate advances in technology, operations concepts, program development and management, and engineering of large complex "systems of systems", all of which are key to human Mars missions. A number of specific technical contributions have been identified for which validation on the Moon may be important, including:

- Habitat design, construction, and operation
- Autonomy and human-robot interaction
- *In situ* resource utilization and launch from planetary surface
- Utilization of heavy-lift launch system for human missions
- Ascent from planetary surface and high-speed Earth entry of high-mass systems

Human Mars mission requirements should be derived and levied on lunar missions to ensure a unified exploration program in which the Moon is a platform to demonstrate "Mars-like" exploration systems and procedures. Architecture/system study results and initial human precursors will provide and validate requirements. NASA should strive to implement the lunar and Mars programs as an integrated endeavor to assure continuity and maximize value of common investments. Lunar exploration activities should be phased to provide maximum benefit to Mars architecture confirmation in ~2025

Required Infrastructure and Core Competencies

- The NASA workforce, infrastructure, and facilities must be energized and defined to meet the challenges of Mars exploration. A first step is to survey engineering talent and facilities to establish baseline and identify gaps. Strategic partnerships among government, industry, and academia will enable the nation to accomplish the required tasks most efficiently. In the view of the committee, key areas of emphasis for workforce include:
    - Systems engineering and mission planning
    - Robotics, mobility, instrument/system integration
    - Physiological research
    - Nuclear systems
    - Atmospheric entry and dynamics
    - Planetary science

Key areas of emphasis for facilities include:

- Atmospheric entry simulation and test
- Nuclear systems testing
- Mars simulation with realistic surface material/environmental properties
- Testing, simulation, and modeling of large-scale complex systems
- End-to-end ISRU system operations in a simulated Mars environment

NASA should begin immediately to ensure that these core competencies for Mars exploration are addressed.

What We Need to Know About Mars and the Interplanetary Medium

To make well-informed decisions about the feasibility, risks, timeline, and required developments that will lead to human exploration of Mars, we must acquire critical knowledge about the interplanetary medium and the Martian environment. The key measurements are those which cannot be made using any other test bed, but require robotic precursor missions. It cannot be stated categorically that all these measurements must be successfully accomplished prior to human arrival on Mars, as the acceptable risk for human Mars missions has not been addressed. However, it is important to understand how to mitigate as much risk as possible.

This committee reviewed the work of prior committees who have addressed the needs for robotic measurements on Mars prior to human arrival. Primarily two reports were reviewed. The first was the NRC Safe on Mars Report (NRC, 2002) which addressed hazards arising from exposure to the environment, including chemical and biological agents. The second and primary source of information was the report of the Measurements Subteam of the Mars Exploration Program Analysis Group (MEPAG) Mars Human Precursor Science Steering Group, Beaty et al. (2005) to analyze the kinds of measurements that robotic precursor missions could make that would have a significant effect on the cost and risk of the first human missions to Mars (MEPAG Goal IV). They considered Mars-related risks to the flight or surface systems in addition to environmental hazards to human and focused on design risk with recommendations for specific measurements to be made on robotic precursor missions. We highly recommend the reading of these reports as they address many interesting issues and contain much more detail than we have included here. Our discussions and recommendations borrow (and quote) heavily from the MEPAG report.

Interplanetary medium

The major risk during in-space transit is radiation. The interplanetary flux is fairly well characterized, although specific vehicle designs need to be developed to protect the crew against galactic cosmic radiation and infrequent but very intense solar particle events associated with solar storms. The roadmap team makes no recommendations for any additional robotic missions to characterize the radiation in the interplanetary medium.

Martian environment

Of interest here are environmental, physical, chemical, and biological issues that need to be well characterized prior to the first human mission to Mars. We are also concerned about what contamination may be transported to Mars and what may return with the vehicle and crew. Of high importance is confidence in the ability to land successfully on the Martian surface and lift off at the end of the mission. The following list of recommended measurements is roughly in order of priority.

- Perform sample measurements to characterize shape and size distribution, electrical and chemical properties of Martian dust. Perform *in situ* measurements of polarity and magnitude of charge of suspended particle both during quiescent periods and during dust storms. Include subsurface samples.

- Collect samples of air-borne dust to determine if life is present in the Martian near-surface soil and if it is a biohazard. Collect biological assays at the landing site reflecting all geological materials with which humans may come in contact as part of an MSR mission.

- Make basic measurements of atmospheric electricity. Also collect measurements of dust density from storms as a function of time at the surface for at least a Martian year. Use an orbiting weather station to monitor dust storm frequency, size and occurrence over a year, at varying altitudes if possible. Temperature measures should also be made as a function of time.

- Perform sample measurements to characterize toxicity of Martian dust. Assay for chemicals with known toxic effects on humans and assess possible impact on human tissue. Include subsurface samples at the landing site.

- Design *in situ* measurements, which, without contaminating the Martian environment, determine the fate of terrestrial organisms on Mars. Include measurements to determine such things as the rate of oxidation, the mechanisms and rate of dispersion, transport properties from into the Martian subsurface, and perhaps most importantly, if the terrestrial microbial life can survive and reproduce in the Martian environment. This almost certain terrestrial contamination, particularly if the effects cannot be well-characterized, makes finding indigenous life prior to human arrival a high priority to avoid the chance of a false positive.

- Measure mechanical and physical properties of the soil and ice/soil mixtures including variation with depth: (i) the cohesion, (ii) the soil density before and after volatiles are expelled thermally, (iii) an index test of shear strength, and (iv) the specific energy of boring.

- Make *in situ* measurements to determine the absorbed dose in a tissue-equivalent material on Mars at the expected or representative landing site and working area.

- Use orbiting satellites and in situ measurements to acquire accurate knowledge of the roughness, vertical terrain information including steepness, traction and cohesion in the Martian soil for the human mission landing site and expected area of operations during EVA.

It bears repeating that the reports mentioned earlier, particularly the full version of the MEPAG Goal IV recommendations (substantially quoted here) should be referenced for more detail and information.

Summary of Decadal Steps Toward Human Exploration

The following are a series of key achievements by decade for an integrated robotic-human Mars exploration program:

<u>2005-2016:</u>
- Follow the water: study geology, climate, habitability
- Characterize surface, dust, atmosphere
- Understand biological potential
- Identify accessible water
- Conduct physiological studies of human space flight and hazard mitigation
- Develop candidate architectures
- Emplace telecom network elements

- Develop key technologies such as EDL, ISRU, laser com
- Extensive field testing

<u>2016-2025:</u>
- Lab study of Mars samples
- Intensive search for life
- Subsurface exploration
- Understand potential Mars hazards - toxicity, biohazards,
- Scaleable demos of key capabilities (ISRU, EDL) and dress rehearsal
- Develop other major capabilities
- Expand Mars telecom infrastructure
- Human habitation and ops validation on Moon
- Select and validate human Mars architecture
- Select site for robotic outpost
- Commit to timetable for human Mars exploration

<u>2025-2035:</u>
- Understand and predict Mars weather and atmospheric variability
- Robotic outpost/landing site detailed surface characterization and resource surveys
- Discovery-driven opportunistic science
- Develop tools for human scientists and explorers and build flight elements
- Emplace infrastructure at Mars and verify performance of key elements, including ISRU capabilities
- Demonstrate sustained human exploration on the Moon
- Prepare to launch the first human crew to Mars

<u>2035-beyond:</u>
- Unified human-robotic exploration and science
- Human surface expeditions and outpost development
- Deep drilling for resources and samples
- Human teleoperation of robotic explorers in harsh Martian locales
- Return to Earth of first Mars crew
- Continuation of sustained robotic-human Mars exploration

Growing the Community of Mars Explorers

Overview: Analysis of Needs and Priorities

A 30-year roadmap for robotic and human exploration would not be complete without considering the next generation of explorers, who will carry forth the Vision and roadmap outlined today. Out there in classrooms across America are the talented and curious students who will play vital roles in leading future scientific discoveries or in creating technologies that will eventually land humans safely on Mars, sustain them on the surface, and enable them to conduct ambitious first-hand scientific studies on another world. Among these young students are those who will set foot themselves on the surface of Mars, representing humankind as a whole in a quest for knowledge about the habitability of worlds beyond our own. Reaching and inspiring these students is a paramount goal.

The NASA workforce is aging, and many critical skills are at risk of being lost. National Science Foundation and other studies show undergraduate and graduate enrollment in science and engineering has steadily decreased over the past decade, while job opportunities in these fields have grown. Because diversity in science and engineering fields remains low, much more must be done first to attract diverse talent, and then to retain it. As cited in NASA's Education Enterprise Strategy, national education statistics also show that roughly one-third or more of K-12 students score below average in science and mathematics. It is from this currently weakened pool that NASA and the overall US economy are fed.

Of concern is a decline in the NASA budget for higher education programs as detailed in NASA's FY06 Budget Estimate (from \$77.4M in FY04 to \$39.4M in FY06 and roughly stable thereafter). While many effective efforts are made at the K-16 level, a break in the pipeline seems to occur at the pre-professional (graduate) and early career level, exactly where traditional NASA education and outreach (E/PO) programs end. That gap should be corrected.

Next-generation Explorer: Graduate student working with mentor on mission data.

For a robust program, strong links must also be maintained between NASA education programs and the science and engineering communities. The mission teams hold the content, are the current practitioners in relevant career fields, actively serve as role models for future generations, make strong contributions to NASA educational programs and materials, and are mentors for career paths in space science and engineering. E/PO programs should be rigorously evaluated for educational effectiveness, but not decoupled from the heart of research and exploration taking place in the mission directorates, at universities, and with industry partners.

Cultivating a future NASA workforce with strong science, technology, engineering, and math (STEM) skills is critical, but not sufficient, to achieving the Vision over three or more decades. Sustained public support is essential to a robust, long-term program. As recent internet records for public interest suggest, Mars exploration has the chance to become a true “people’s program” if investments are made to increase opportunities for direct experiences. A strong commitment to public participation would recognize that NASA ventures into space on behalf of citizens who support its scientific discovery and technological innovation through hard-earned tax dollars. Along with enhancing public awareness of the goals, challenges, and potential rewards of Mars exploration, opportunities for direct public involvement should be prioritized as part of an effort to build a greater return on the public’s investment than ever before.

Strategy for Growing the Community of Next-Generation Mars Explorers

Attracting and retaining a diverse workforce to support the Mars Robotic and Human Exploration Roadmap depends on a strong strategy to strengthen and expand needed talent across the nation at universities, research centers, and industry. Such a strategy would actively support NASA’s goal of inspiring and motivating students to pursue careers in science, technology, engineering, and mathematics and help meet NASA’s Office of Education “pipeline” goals.

Increasing Diversity: Attracting women and other underrepresented graduate students is a key strategy for Growing the Mars Community.

In designing a strategy, the first step is to understand what success would look like in terms of workforce size and disciplinary mix. That understanding is important so that NASA can assess which specific areas may need targeted efforts to ensure an adequate workforce and which will likely have a ready supply based on trends in graduates and career choices. From the student and recent-graduate perspective, it is also important not to oversell the availability of possible NASA jobs—transparency in prospective job availability in various disciplines, at given timeframes, is important.

On the science side, an initial assessment of impediments for graduate students in choosing to enter Mars (or planetary science) careers was conducted by the Mars Exploration Program Analysis Group (MEPAG), which has a membership of 100+ Mars scientific researchers. Student input was found to be essential in assessing barriers and solutions, as many of the impediments cited by the students were not anticipated by those already established in the field.

Factors limiting a future Mars Science Community addressed in this report include: financial uncertainties in Mars research; inaccessibility of data and slow publication of research results; few student opportunities for involvement in flight missions; lack of awareness of planetary science as a career option; and, too few inter- and cross-disciplinary researchers.

Recommendations: Grow the Community
1. Define and characterize the current Mars science and engineering communities (size, disciplines, age distribution, diversity etc.)
2. Characterize and quantify future needs in the Mars science and engineering communities, both in terms of numbers and disciplines, to support both robotic and human exploration. Specifically, determine how many will be needed, and in what careers, in 2010, 2015, 2020, and 2025 (i.e., in 5-year increments or by program milestone) to support Mars (and lunar) exploration.
3. Determine gaps, barriers and solutions on the basis of findings. Incorporate results from prior studies, such as MEPAG's *Grow the Community* report, and commission similar studies for engineering fields.
4. Adequately fund solutions, ensuring that mission (and not R&A) funding for attracting and retaining early-career professionals from diverse backgrounds is a high priority

Potential solutions offered include: enhanced research and data- analysis funding; improvements related to data accessibility and online student publishing; competitive intern programs in all Mars missions; changes in proposal selection criteria to encourage graduate-student participation; the creation of a Young Postdoc/Mentor program; Mars visiting lecturers for student and faculty training at and beyond universities producing most of the current planetary science candidates; training for graduate students and faculty to access Mars data; websites laying out “stepping stones” to Mars science careers; and, interdisciplinary technical workshops and NRAs.

Among these recommendations, adequate funding for early career professionals is of highest priority. Most research grants are not large enough to cover a competitive salary, so mission funding is recommended. Increasing funding to “livable” levels is important so that the best and brightest are not forced to go elsewhere career-wise. Early-career funding is also important to attracting and retaining diverse talent in the NASA workforce, as more attractive possibilities for new graduates are currently found elsewhere. For example, there were 68 participating scientists in the past four Mars missions. Only 15% were within 5 years of their Ph.D., and only 7% were women.

Beyond graduate-student and early-career science professionals, funding is also inadequate for retaining many outstanding researchers interested in studying Mars. Nor does funding exist to address many of the most compelling questions in Mars research. Therefore, it is also necessary to increase average grant size and duration of Mars investigations, and provide new opportunities for trans-disciplinary teams to attack large problems in Mars research.

Mars science will flourish only with increasingly interdisciplinary teams of researchers, and there is insufficient connection between the Mars community and other relevant areas of science. Increasing inter- and cross-disciplinary opportunities for collaboration is key. For example, the health of the community would benefit from convening technical workshops that bring Mars researchers together with Earth researchers and encouraging collaborations by adding interdisciplinary research to the funded post-doc portfolio.

In terms of instruments, there are two significant areas that need attention. First, the community of instrument scientists at universities is insufficient to sustain Mars exploration, as evidenced by the complete lack of university PIs in the recent Mars Science Laboratory investigations. For that reason, it is imperative to ensure that instrument development programs like MDIP are well-funded and focused on university PIs. Second, capability for in-situ instrument development is very low, and has dropped considerably since Viking. To meet the Mars roadmap goals, support is recommended for enabling scientists to continue to push the state-of-the-art in laboratory studies of meteorites, samples returned from flight missions, and Earth rocks. Funding scientists to adapt and apply cutting-edge techniques to flight instruments on the basis of laboratory studies will also be important.

Recommendations: Handling Large Data Sets
9. Allocate funding to ensure an accessible data system by establishing uniform standards, reconciling dataset discrepancies, and developing user-friendly software tools for data access, analysis, and visualization.
10. Fund MO&DA at a healthy level. [ADD]
11. Form a cross-institutional education and training program to teach graduate students and faculty how to process and analyze data.

On the engineering side, reports from the Capability Roadmap teams provide initial information for characterizing future jobs that are essential to the robotic and human exploration of Mars. A formal MEPAG-style study addressing barriers to engineering students and recommended actions should be formally conducted as well, with solutions adequately funded.

Handling Large Data Sets

The Mars science community is grappling with the need to handle exponential increases in the return of scientific data. Mars Reconnaissance Orbiter alone, for example, plans to return 34 terabits of data, 3 times as much as five other missions put together (DS1, Odyssey, MGS, Cassini, and Magellan).

Having a large enough scientific community to analyze the results of successful missions is a goal that will enable NASA and the nation to fully capitalize on their investment in Mars exploration. Currently, the community struggles with access to Mars data and research results. Access to data is crucial to the health of the existing community and to attracting talented researchers from other related disciplines.

Developing uniform standards and reconciling data discrepancies is a baseline need. The software currently in place is cumbersome and discouraging to users who are unfamiliar with the tools. Creating user-friendly software tools for data access, analysis and visualization is key. Robust and sustained funding for Mission Operations and Data Analysis (MO&DA) is also critical.

Instituting an education and training program at universities, perhaps employing postdocs and early-career professionals as mentors and trainers, would assure that more of the data returned would be accessed. The purpose would be to teach graduate students and faculty how to process and analyze data, thus making career and research opportunities more accessible and attainable to the next generation of researchers.

Mars Public Engagement

The 2015 – 2030 workforce is in school now, so continued and expanded reach to the K-16 level is necessary. Currently, the Mars Exploration Program's efforts in Mars Public Engagement have begun to build a strong infrastructure for reaching students and teachers in key areas of interest to growing a future generation of Mars explorers.

Next-generation Explorers: Considering the best place for humans to land on Mars.

The current Mars Public Engagement Program is a model for comprehensive and coordinated efforts to reach teachers, students, and the general public. Organized programmatically rather than mission-by-mission, the effort has several advantages. When the plan was first adopted, it was considered a model for the Agency, and with adaptations for roadmap priorities, it can be again.

The longevity of the program (tied to current and next-decade missions) enables the development of lasting relationships with partner networks that increase in depth, sophistication and reach over time. Missions do not "reinvent the E/PO wheel" every 26 months, resulting in considerable cost-savings, leverage, and continuity. Missions are highlighted within the overall thematic context, allowing key messages to be conveyed about Mars Exploration, while bringing in current science to enliven content and to enable an experience of discovery as it happens.

Recommendations: Mars Public Engagement
12. For K-16 and informal learning, build on the current 20-year Mars Public Engagement Plan and related infrastructures for a 30-year timeframe, seeking expanded opportunities in areas that promote Grow the Community goals: student imaging and analysis (science, data analysis), robotics education (engineering), and other areas promoting Mars-related career skills and general STEM literacy. 13. Create greater opportunities for direct public participation in Mars exploration, including a citizen's advisory group, public engagement payloads, and other interactive ways for citizens to participate in discovery. Assess areas where NASA is willing to take input and ensure opportunities are authentic.

Mars Public Engagement has consistently received excellent reviews from NASA HQ, and has established a number of baseline programs that can be expanded and built upon. The current 20-year plan can be easily modified to incorporate Mars roadmap goals over a 30-year period and to accommodate cross-Program, cross-Roadmap (especially moon-Mars) priorities.

Among current Mars Public Engagement activities, several relate directly to the goals of growing the community by developing Mars-related career skills and science, technology, engineering, and mathematics (STEM) literacy.

Student imaging and analysis is a key focus in the Mars Public Engagement Plan. Several pilots are in place, with the goal of increasing the number and quality of students working with real Mars data. For example, students in the Mars Student Imaging Project target a camera on the Odyssey orbiter and analyze the resulting data. This program is being expanded to include Mars Reconnaissance Orbiter, Phoenix, and other future mission data sets. To date, 700 high-school students in the Mars Exploration Student Data Teams created data products during the Mars Exploration Rover mission, and 26 student interns worked for more than a year with mentoring science team members before participating in science operations during MER's primary mission.

In these programs, students have proven they can produce data products that aren't critical to mission success, but still of high interest to the science teams (e.g., rock abundances, weather animations etc.)

The Mars Public Engagement Program's focus on robotics education is designed to reach the next generation of engineers. As with student imaging, opportunities beyond the existing baseline can be built, and is an appropriate area for cross-Program coordination.

Next-generation Engineers: Tribal college students learning robotics principles.

Another existing sample program that aligns with the roadmap, and relates directly to human exploration, is Imagine Mars. This program asks students to design an ideal community on Mars. The program has resonance with elementary schools and with teachers who do not have strong science backgrounds themselves. In essence, it is It is a "gateway" activity for introducing Mars topics given its multidisciplinary approach (a blend of science, technology, civics, and the arts). An interagency partnership with the National Endowment for the Arts and HUD, it is beginning to attain national reach, particularly with after-school groups.

Because it is one of the few NASA education and outreach programs that is thematically and programmatically organized, Mars Public Engagement is already in a good position to carry forward Roadmap priorities, building on current partnerships and a strong baseline of student, teacher, and public participation.

The Mars Public Engagement Program's focus on public participation is highly encouraged. Mars exploration is undertaken on behalf of the American public and reaches the world.

A new initiative to be considered is a citizens' advisory group. Notionally, two individuals from each state could be randomly drawn from entries collected at museums and other venues. Participants would serve a two-year-term, learn about NASA programs, and have the opportunity to offer input on given topics. A caution is that opportunities for input should be authentic – NASA should be careful in selecting in what areas it is willing to take input.

The plan's concept of public engagement payloads has begun to be incorporated at the margin by missions. For instance, the upcoming "People's Camera" on Mars Reconnaissance Orbiter and video capabilities on Mars Science Lander recognize the importance of public participation and direct, immersive experiences of Mars and exploration on the red planet. Commitment to public engagement payloads, however, could be formally built into mission planning.

The Mars Robotic and Human Exploration Roadmap is ambitious and visionary, with many technical challenges and risks associated with its fulfillment. Following the Mars Exploration Program's Risk Communication Plan, continuing to be transparent and open about the challenges of Mars exploration with the general public and specific stakeholders is vital, and a cross-Roadmap issue. Engaging stakeholders such as environmental groups, the launch-area community, sample-handling-facility communities, and Native American groups among others is recommended, with a focus on fulfilling NASA's public-information responsibilities.

Other innovative ways of engaging the public should also be considered, especially those that provide virtual experiences of Mars exploration. Some ideas include a video game analogous to that funded recently by the Army in which the game is augmented every few months to keep interest high. NASA could also celebrate exploration each year with an event with prizes for the best exploration of the year. It would keep the public aware of the value of exploration, and would resonate with the concept of a nation of explorers.