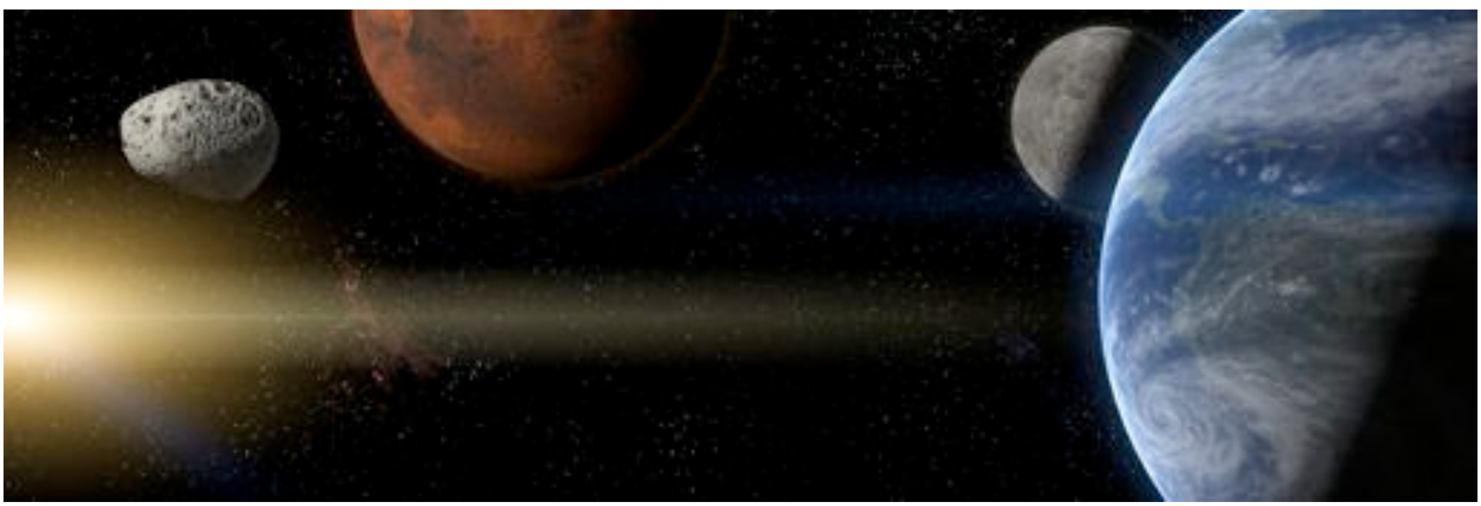
Report of the
NASA Exploration Team

Setting a Course for Space Exploration in the 21st Century

June 1999 through December 2000



October 29, 2001

Preface

The 20th century saw the dawn of the Space Age. When we took our first voyages off the planet, we looked back in wonder to see the Earth whole for the first time.

At the close of the century, we explored the surface of Mars through the eyes of an intrepid little rover called Sojourner and saw wondrous new views of the universe sent back by NASA's space telescopes. Our astronauts, working with their cosmonaut colleagues, prepared the International Space Station to receive its first crew.

The story of NASA is that of the human journey—to see the self from outside, to seek the larger reality. The need to see the whole—the Earth, the Solar System, the universe—is the hallmark of our species. And so it is that we are preparing to meet the challenges of space exploration in the century ahead.

These challenges will be great and many, and not restricted to building better spacecraft and rockets or nourishing and protecting our space explorers, but will include keeping our expeditions flexible, robust and affordable.

NASA's vision for the 21st century is to explore space *beyond* low-Earth orbit where we now operate the International Space Station. To do this will require a profound shift in the way we view space exploration. Lacking the Cold War imperative to put a man on the Moon, NASA will need to aggressively invest in technology in order to develop an ever-expanding suite of capabilities that will take our robot and human explorers ever farther into deep space in pursuit of fundamental scientific quests.

The status report of the NASA Exploration Team, "Setting a Course for Space Exploration in the 21st Century," describes a wholly new approach to space exploration and the beginnings of the work that we need to do to make it possible.

NASA's vision is bold and its strategy sound. The greatest adventure humanity has ever known will continue.

The NASA Exploration Team
October 2001

neXt
NASA Exploration Team

Table of Contents

List of Figures

I. Introduction

Except for a brief foray to the lunar surface and the launching of several planetary spacecraft, we have concentrated most of our space-exploration activities in low-Earth orbit, leaving deep space as a largely uncharted frontier. Yet this vast region offers remarkable leadership opportunities, opportunities that can catalyze science, technological innovation, and ultimately commercialization.

NASA is ready to return to deep space. This time, however, the Agency wants to do so in a bold new manner that integrates humans and robots in a partnership that accelerates the pace of discovery for the good of all humanity. The NASA Exploration Team (NEXT) has crafted a Vision that addresses this opportunity. It is an ambitious Vision in terms of costs, needed capabilities and issues associated with human adaptability to the deep space environment.

What We Gain

We should remind ourselves of what President Thomas Jefferson did for the nation as we decide whether to accept this new challenge. Two hundred years ago, Jefferson hired Lewis and Clark to explore the seemingly unbounded western frontier, and within a generation the nation was enjoying the commercial benefits brought about by a vast continental transportation network, the discovery of gold and human migration westward.

NASA's historical legacy in deep space has generated benefits that others share as well. In only 220 hours of exploring the lunar surface, Apollo astronauts gathered enough samples for scientists to rewrite the history of the Earth-Moon system. The Apollo program triggered a resurgence of interest in the fields of engineering and science, and provided the technological leadership that contributed to the end of the Cold War.

The Vision

The NEXT Vision is straightforward in its progressive approach. The aim is to develop an ever-expanding cascade of capabilities that brings humans and their robotic partners together first in a region called Earth's Neighborhood. This region extends from high-Earth orbital locales (beyond the Van Allen belts) to the Sun-Earth libration points at 1.5 million km. It also includes Earth's Moon. Missions within Earth's Neighborhood would include100-day excursions and serve as a natural stepping stone to human-robotic expeditions to Mars and accessible near-Earth objects.

All aspects of the Vision are linked to major objectives within NASA's Strategic Plan and involve activities that are enabled by an aggressive partnership between humans and robots on site. Furthermore, destinations are not predetermined; rather, they are chosen on the basis of whether they will expand our knowledge and fuel discovery as defined by our scientific imperative, which includes three simple, yet highly compelling questions: How did we get here? Where are we going? Are we alone?

Stepping Stones

While the Vision is scientifically driven, it is equally technologically enabled. Under a stepping-stone approach, NASA will build the technical capabilities needed for each step in its journey to deep space. Since each capability hinges on a previous step, NASA avoids redevelopment of critical systems and keeps program costs in check.

To carry out this approach, particularly in the areas of propulsion, power, human extravehicular activity (EVA) systems, human adaptation systems, information technology, and materials, NASA needs to execute a progressive and leveraged technology investment and development program with interacting cycles. Knowing which to invest in is made easier if NASA initially funds several promising technologies. As these technologies achieve certain milestones in their maturity, NASA would evaluate their progress and eliminate those that do not appear to hold as much promise. In addition, NASA would continually add new technologies to the development pipeline and conduct technology flight experiments and demonstrations to validate human-rated flight systems for deep space voyages.

Sustained Human Presence

The Vision would provide the first sustained human access to deep space in two generations and open the space frontier to human beings, not only for the purposes of exploration and discovery, but also for enrichment. An engaged public here on Earth can experience exploration as it happens via high-definition television and other communication technologies. If the Vision is implemented, we will begin seeing within a decade a series of technology development efforts and deep-space flight experiments that will set the stage for the first human voyages beyond low-Earth orbit in 40 years.

Jim Garvin
Chair, DPT Phase I and II Teams

NOTES

Same Mission, New Moniker

When NASA began this exercise of charting a course for the future, the Agency believed that "The Decadal Planning Team" best described the scope of the group's work and decided to name its study panel as such. As work progressed, however, it became clear that the name did not accurately reflect the group's work after all.

Although the team's Vision would require NASA to begin investing in critical technologies over the next 10 years, the benefit of that effort will be felt up to 40 years from now. For that reason, the team changed its name to NASA Exploration Team (NEXT), a moniker that does not confine it to a specific point in time. As a result, the terms Decadal Planning Team (DPT) and NASA Exploration Team (NEXT) are used throughout this document.

Electronic Copies of this Report

Electronic copies of this Status Report, including all reference documentation, is available on CD-ROM. To request copies, please contact:

Melvin Ferebee
M.J.Ferebee@larc.nasa.gov
(757)864-4421

II. Setting a New Course for Space Exploration

The NASA Exploration Team is developing a Vision and strategy for exploring space beyond low-Earth orbit. Based on a science-driven, technology-enabled approach, the strategy aggressively integrates human and robotic activities in a cost-constrained environment.

Introduction

The Office of Management and Budget (OMB) set aside a small amount of yearly funds, starting in Fiscal 2000, for NASA to "explore and refine concepts and technologies that are critical to developing a robust set of civil space initiatives at different funding levels for the next decade." This coincided with the NASA Administrator's desire to develop an overarching NASA plan, or Vision, that included scenarios and supporting technologies for space exploration in the first quarter of the new millennium. These two simultaneous events resulted in the formation of a NASA Decadal Planning Team (DPT), whose name recently was changed to the NASA Exploration Team (NEXT). This section of the report describes the team, its charter, activities from its inception in 1999 through mid-2001, its organization, and resulting Vision.

Charter

The NASA Associate Administrators for Space Science and Space Flight established the DPT in June of 1999 and chartered (ref. 1) it to analyze how NASA might undertake integrated human-robotic space exploration activities during the first 25 years of the new millennium. The DPT reported to a Steering Committee of senior NASA officials (i.e., Center Directors, Associate Administrators, and the NASA Chief Scientist, Chief Technologist, and Chief Engineer).

The team's Vision was requested to include the following characteristics:

- Top down approach
- Forward looking and *not* tied to past concepts
- Science-driven, technology-enabled program that included technology road maps, which enabled capabilities at an affordable cost
- Aggressively integrated robotic and human capabilities
- Opened the human frontier beyond low-Earth orbit by building infrastructure robotically at strategic outposts—libration points, planetary moons, planets, etc.
- Included a wide range of exploration tools (e.g., space planes, balloons, libration point-located human-constructed and -maintained observatories, etc.)
- Incremental (buy by the yard) as budget permits
- Propulsion system requirements driven by mission approaches.

The effort is an ongoing strategic planning activity to enable the inevitable and systematic migration of humans and robots into space beyond Earth orbit for the purposes of exploration, science, and commerce. The team's activities include:

- Creating and maintaining a long-term strategic Vision for science-driven human-robotic exploration
- Conducting advanced concepts analyses and developing new, innovative approaches for exploration via breakthrough technology
- Generating scientific, technical, and programmatic requirements to drive technology investments which will enable each new phase of human-robotic exploration
- Integrating NASA internal technology programs and pursuing external programs to align with the team's Vision where possible
- Identifying and promoting commercial and space development opportunities.

The Terms of Reference (ref. 2) provide assumptions, evaluation criteria, schedule, and summarize the approach for study activities.

Decadal Planning

Phase I: June 1999-October 1999

The team used the existing NASA strategic plans to synthesize a NASA-wide set of overarching science drivers called the "Exploration Grand Challenges" (ref. 3), and derived from them a set of scientific questions and pursuits. These challenges unite NASA's existing goals to provide an integrated scientific vision for NASA's future. The team used a structured process where missions, events, activities and technology development efforts are all traced to a specific scientific objective. By tracing science at its most macro level to specific measurements and experimental activities, the team can identify potential destinations at which or from which results can be attained. The team's study was, from the outset, top-down and synoptic.

The team conducted a top-down examination of space exploration in which the aggressive integration of human and robotic activities was one of the primary drivers. The team also considered opportunities for exploration in a science-driven, technology-enabled fashion where affordability was a key factor. Finally, it conducted a relatively rapid five-month initial study in which the goal of sending humans beyond low-Earth orbit (LEO) was paramount. Team members did not consider past analyses in their thinking.

The team's Phase I deliverables, as defined in the charter, were:

- A Vision for human-robotic exploration in the first quarter of the new millennium (ref. 4)
- Various scenarios with "first order" required investment and schedule to realize the Vision

- A definition of critical technologies in each of the "resource areas" defined in the Terms of Reference
- A recommendation for follow-on phases.

The team's Phase I findings, outputs, and conclusions were:

- Exploration Grand Challenges derived from existing NASA Enterprise strategic plans, and established links between the Exploration Grand Challenges and technology capabilities that are needed to implement them
- Breakthrough technology investment "portfolio" that isolates technologies that have high potential to significantly reduce exploration costs
- Technology matrix that lists current capabilities, projected ones from existing technology investment programs, and exploration breakthrough technology candidates
- Societal benefits of exploration (ref. 5)
- Analysis of NASA's technology development and missions planned for the decade 2000-2010.

Early Brainstorming. Phase I consisted largely of brainstorming, characterized by its spirited discussions and frank and open exchange of opinions. The main points the team considered and discussed were:

- Why humans? The costs, risks, and benefits associated with human space flight
- Traceability, the linking of science goals to technology needs
- The need for a sustained investment in breakthrough technologies, particularly Earth-to-orbit (ETO) and in-space transportation propulsion technologies such as nuclear thermal, nuclear electric, and catalyzed fusion.

The team considered innovative breakthrough technologies such as fuel depots in orbit and high specific impulse (Isp) propulsion approaches that could reduce one-way trips from Earth to Mars to 30 days. The team also considered evolutionary technologies. The team developed technology portfolios or road maps to illustrate today's capabilities, where the existing evolutionary strategy will take NASA by 2010, and the breakthrough technology candidates requiring aggressive investment over the next decade.

The team identified the need for an analysis process to rapidly evaluate a relatively large number of plausible technologies. The team developed a very small number of mission scenarios that assumed that one or more of the breakthrough technologies would become operational at some specific time. The example scenarios were illustrative and not definitive.

Phase I concluded with a simple recommendation: NASA must fund and/or leverage breakthrough technologies in such areas as propulsion (ETO and in-space) and materials (high strength-to-weight and "smart") to optimize the limiting variables (cost/lb. and value/lb. in space) while aggressively pursuing safety. Innovative approaches for affordable space exploration exist, and can be implemented as long as NASA invests in them over the next decade.

Phase II: January 2000-October 2000

Studies and Analyses. The Phase II effort focused on studies and analyses to design and validate an expanding set of capabilities that allow the gradual expansion of human participation in the science and discovery process. It coupled the studies with technology road maps to enable these capabilities. The team developed a portfolio of progressive enabling technologies and mission architectures in which each successive technology or architecture builds on the success of its predecessors. The team designed a process to develop these road maps that includes evaluating existing technology development plans, both within and external to NASA, so as to identify those critical exploration technologies that are not currently funded. To summarize, Phase II addressed those activities required to realize the Phase I Vision:

- Proof of Phase I concepts
- Technology credibility assessments
- Investment strategy for technology plan
- Systems engineering of multiple destination architectures
- Traceability of science and discovery-mode activities to evaluate destination sequencing
- Identification of decision points and potential criteria for use by senior management
- Expanded team, derived from Phase I participants and reaching into the expertise of every Center and Enterprise (as needed).

Sections V and VI of this report provide the details of the Phase II studies and analyses.

NEXT Phase III: January 2001-present

Continuing Analyses. The NEXT Phase III activity began in January 2001. Planned activities include an extension of work performed in Phase II:

- <u>Human-robotic partnership</u>. Continue developing metrics to quantify the relationship between astronauts and their robotic counterparts
- <u>Planetary surfaces and deep space/libration points</u>. Continue defining technology drivers and convene workshops as necessary
- <u>Systems analyses and concept studies</u>. Continue architecture studies for libration points, the Moon, asteroids, and Mars. Introduce new technologies into the architecture studies; address the value of fuel depots and satellite servicing; develop/enhance the tool set for architecture analyses
- <u>Innovative ideas</u>. Continue to explore new technologies and track technology development activities (e.g., within NASA and in the university community); identify opportunities at destinations beyond Mars.

Programmatic focuses for Phase III include developing a requirements document/data base for science, technical, and programmatic requirements; implementing programmatic leveraging within NASA (e.g., joint partnering opportunities for research and development); identifying partnership opportunities external to NASA; and completing budget-related actions such as refining the technology road maps which will update schedule and technology investment strategies.

Membership and Virtual Organization

NEXT is an interdisciplinary, cross-Enterprise, cross-Center team responsible for maintaining a multidisciplinary approach toward future exploration planning. Members include engineers, space scientists, earth scientists, astrobiologists, life scientists, astronauts, and physicians. The team's membership and organization have evolved from Phase I to Phase III.

Phase I

Phase I consisted of 20 individuals from most of the NASA Centers including members from NASA Headquarters (HQ), Johnson Space Center (JSC), Marshall Space Flight Center (MSFC), Goddard Space Flight Center (GSFC), Ames Research Center (ARC), Langley Research Center (LaRC), and the Jet Propulsion Laboratory (JPL). As the chair, Dr. James B. Garvin of NASA's GSFC led a mix of scientists, engineers, systems analysts, and managers. The Associate Administrators for the Offices of Space Flight (OSF) and Space Science (OSS) served as the primary stakeholders in the process.

The Associate Administrators for Space Flight and Space Science appointed members from across the Agency. The membership included experts in space sciences, propulsion technology, astrobiology, human biomedical sciences, general life sciences, programmatics, computer sciences, human space flight, materials sciences, microgravity and life sciences, and public outreach. The Chair had authority to modify the team as needed to ensure adequate breadth and capabilities. Team members were added to provide expertise in information technology and systems analysis.

Phase II

Phase II membership increased to approximately 70 full-time equivalents (FTEs) to support the detailed studies and analyses. Jim Garvin chaired the Phase II activity. It operated in a "virtual" manner where activities were conducted primarily through teleconference and electronic communications with periodic all-hands site meetings. The structure of the Phase II virtual organization is shown in figure 2-1.

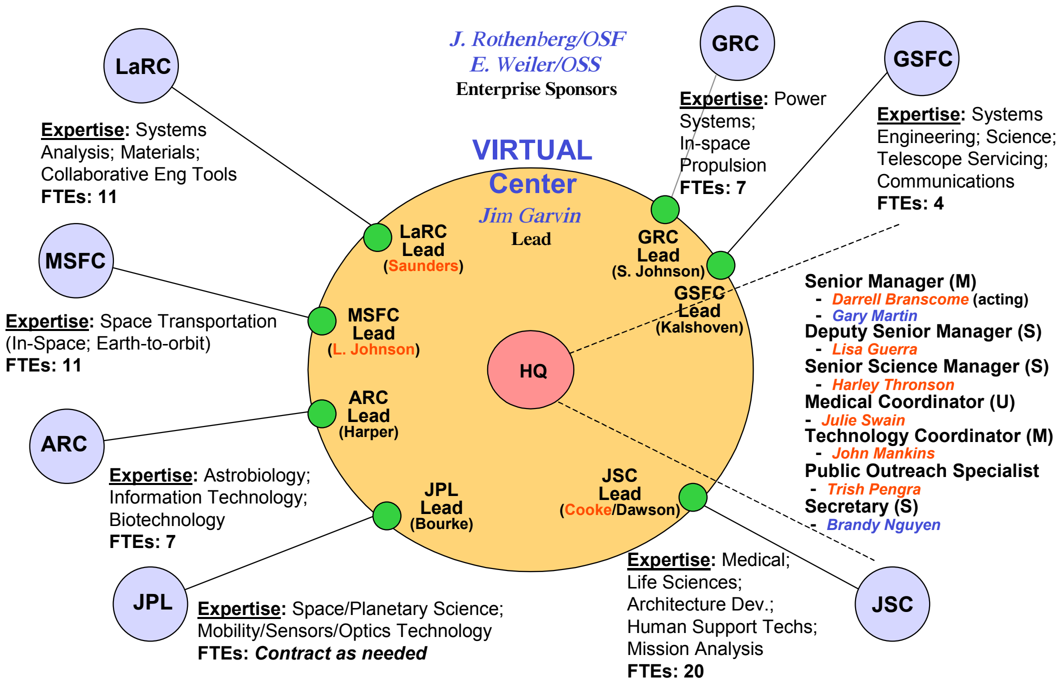


Figure 2-1: The Phase II "virtual" organization.

A membership roster for Phases I and II is provided in Appendix I.

Phase III

Phase III, now chaired by Gary Martin, is operating in a virtual manner similar to Phase II. Functionally, formal interfaces have been established with NASA senior management to provide coordination among the Enterprises, and sub-teams have been formed to focus resources on programmatic priorities (figure 2-2).

The Steering Committee (an original committee established by the DPT Charter) will maintain awareness of overall performance and will ensure coordination of the team's goals across the Agency's senior management. This committee consists of the five Enterprise Associate Administrators, the Comptroller, and key Center Directors and is co-chaired by the Associate Administrators of the Office of Space Flight and the Office of Space Science.

The Exploration Senior Management Board is a standing advisory group that will ensure coordination and integration of decadal planning among the Enterprises and across NASA Centers. The NEXT Management Team Chair leads this board which consists of senior Enterprise technology/exploration managers and Directorate-level managers from participating NASA Centers.

The Exploration Science Working Group is responsible for ensuring that the science-driven approach remains the foundation of planning and continues to generate program requirements and set priorities.

The Revolutionary Aerospace Technology Working Group is responsible for investigating innovative technologies and introducing them into the various NEXT activities.

The Human-Robotic Working Group will develop a rationale for optimizing the mix of humans and robots in space exploration, develop metrics to assess the performance of humans and robots in exploration tasks, and assess current and project future human and robotic capabilities.

The Human Subsystem Working Group will identify health and safety requirements for decadal planning activities.

The Outreach Team is responsible for public engagements and education outreach related to future space exploration.

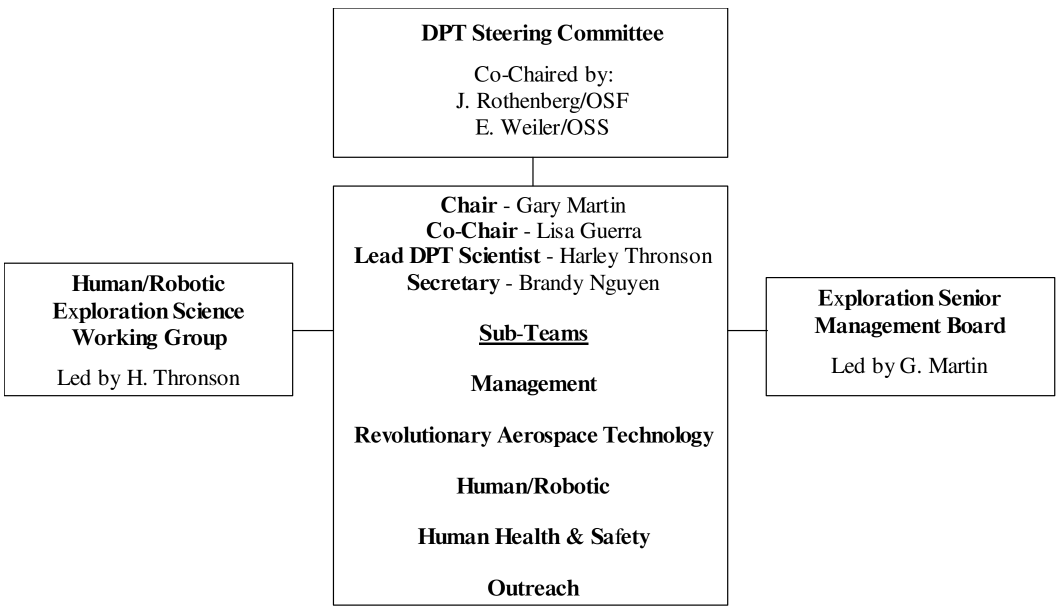


Figure 2-2: The NEXT Phase III functional structure.

The Vision: Setting a New Course for Space Exploration

The team has presented its Vision and supporting analyses in a series of briefings (refs. 6-10) to the Steering Committee, the Administrator, and recently as a conclusion to Phase II activities, to the OMB. The Vision, as of this publication date, described in detail in these briefings, is summarized as follows:

- The team's Vision would provide the first sustained human access to deep space in a generation and would open the Solar System to exploration by both humans and robots. The goal is to develop an expanding cascade of capabilities for human and robotic exploration of space in a "stepping-stone" approach (figure 2-3). The initial exploration will occur in a region referred to as the Earth's Neighborhood

Figure 2-3: The team's Vision is a cascade of stepping stones.

- The stepping-stone approach will build the technical capabilities needed for each step with multi-use technologies and capabilities. Each step will build upon the previous one to avoid re-development of critical systems

- Technology flight demonstrations are needed at each step to validate human-rated systems in which safety and reliability are critical factors

- Science discovery and exploration are inextricable. The Exploration Grand Challenges provide the sole justification for exploration. Destinations for exploration will be determined based on where the scientific activity is or will be found

- The Vision is a unified Agency vision which integrates Agency and Enterprise strategies (refs. 11-13) to address the Exploration Grand Challenges

- Exploration activities are enabled by an aggressive partnership between humans and robots

- An aggressive, Agency-wide technology investment and development program is necessary to implement the Vision. A program of multiple downselects is needed to develop critical capabilities in propulsion, power, human EVA systems, human adaptation systems, information technology (IT), and materials. In the near term, funding of technology "gaps" and leveraging a wide range of ongoing technology investments using exploration requirements are critical

- Specific mission paths do not need to be established today. If the Vision is implemented, decisions may be made within six to eight years based on sound selection criteria tied to the state of technological readiness

- NASA will leverage partnerships—international, governmental, academic and industrial—to bring together unique skills and resources

- Education is a critical component of the Vision. The NEXT education strategy will serve as a catalyst for excellence by helping to create a pipeline of scientists and engineers.

References

1. Decadal Planning Team Charter.

2. Terms of Reference for Decadal Study Team.

3. NASA's Exploration Grand Challenges.

4. Decadal Planning Team Briefing to OMB, NASA HQ, December 19, 2000.

5. Pine, Mark A., Public Engagement in Future Exploration: "Breakthrough" Concepts, NASA JPL, September 29, 1999.

6. Interim Briefing to Comptroller and Deputy Administrator, August 14, 2000.

7. Interim Briefing to the Administrator, NASA HQ, July 19, 2000.

8. Interim Brief to Steering Committee, NASA HQ, April 19, 2000.

9. Interim Briefing to the Administrator, NASA HQ, November 22, 1999.

10. Interim Brief to Steering Committee, NASA HQ, October 4, 1999.

11. NASA Strategic Plan 2000.

12. NASA Human Exploration and Development of Space Strategic Plan.

13. NASA Space Science Strategic Plan, November 2000.

III. Exploration Grand Challenges

The team's Vision incorporates all of NASA's strategic scientific priorities. All aspects of the Vision can be traced to these priorities.

Introduction

NASA's motivation for exploration is that space provides a unique perspective on our planet, other worlds, the Universe, and ourselves. The three Exploration Grand Challenges (refs. 1-4) summarize the motivation:

- How did we get here?
- Where are we going?
- Are we alone?

These exploration challenges are defined in the context of open-ended mission statements for discovery, science, and the human development of space. The goal is to articulate the motivation and core justification for space exploration in a manner that is both credible to professionals and understandable to the American public. The Exploration Grand Challenges were developed from the Agency and Enterprise strategic plans (refs. 5-7). This section of the report describes the Grand Challenges and traces these overarching scientific goals through exploration objectives, approach and priority science questions, activities, destinations, human-robotic integration, and technology investment portfolios.

Fundamental Questions

How did we get here?

This question covers the Big Bang, the origin of the Universe, and the origin of galaxies, stars, planets, and life (figure 3-1) from the origin of life on the Earth through its evolution to the human species.

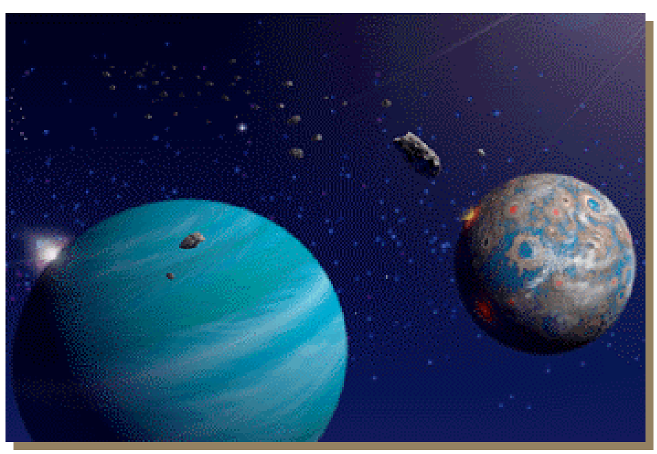


Figure 3-1: Uncovering the origin and history of the Solar System.

Figure 3-2 summarizes the scientific traceability of the fundamental question—"How did we get here?"—through its related exploration objectives and approaches and priority questions. The exploration objectives include:

- Looking backward in time toward the early Universe
- Revealing and understanding the laws of nature
- Determining the role of gravity and other fundamental processes in the origin and evolution of life
- Exploring the history of the Solar System
- Understanding the origin of solar variability and its effect on Earth
- Exploring the paths of life on the Earth.

Where are we going?

What will happen to our own planet and to the Universe itself (figure 3-3)? This question covers the concepts of fate and death in the Universe and brings to mind places in the Universe where bizarre and violent death occurs, such as exploding stars and black holes. The changing and violent nature of the Universe was demonstrated for the public in our own cosmic backyard by the collision of comet Shoemaker-Levy with Jupiter. We will approach this question by reading the destiny of the Solar System. What is its fate and what does its evolution imply for other planetary systems?

Figure 3-4 summarizes the scientific traceability of the fundamental question, "Where are we going?," through its related objectives and approaches and priority questions. The exploration objectives include:

- Understanding the future habitability and sustainability of Earth
- Expanding human presence beyond the vicinity of Earth.

The NEXT Vision includes expanding human presence beyond the vicinity of the Earth. The Vision will make safe human exploration of the Solar System possible by determining the key steps that must be taken for permanently safe and productive human habitation beyond Earth.

Are we alone?

This is the most profound question of all. Does life exist beyond Earth? Did life exist on Mars or elsewhere in our Solar System? Do civilizations exist on planets around other stars? Figure 3-5 summarizes the scientific traceability of the fundamental question, "How did we get here?," through its related exploration objectives and approaches and priority questions. The exploration objectives include:

- Revealing the cycles of life in the Universe
- Searching for life in the Solar System
- Searching for life in the Universe.

Exploration Objectives	Approach and Priority Questions
Look backward in time toward the early Universe	Explore the Universe from the formation of the first atoms, stars, and galaxies to the local neighborhood of the Milky Way. • How did the first stars and galaxies form and what were they like? • What is "dark matter" and "dark energy" and how are both related to the structure and fate of the Universe? • What produced the structure that we find in the Universe today from the largest to the smallest scales?
Reveal and understand the laws of Nature	Use the Universe as a laboratory to discover the fundamental principles of physics, chemistry, and biology in the widest range of environments found in Nature. • What are the most extreme events in the Universe? • Are there new insights into nature that might be revealed by exploring extreme environment throughout the Universe? • What are the biologically and chemically important events in the Universe? • What are the fundamental principles of biology?
Determine the role of gravity and other fundamental processes in the origin and evolution of life	Understand the importance of gravity on biological systems of all sizes and complexity. • What are the effects of gravity and other fundamental processes at the cellular level? • What are the effects of gravity and other fundamental processes on complex living organisms? • What terrestrial processes are enhanced in a low-gravity environment?
Explore the history of the Solar System	Determine how our Solar System formed and evolved. • What were the early conditions of our Solar System? • What are the evolutionary differences among the planets? • What is the evolutionary history of the "habitable zone" where liquid water exists in the Solar System? • What are the key markers in paleo-planetology that can be used to derive the history of the members of the Solar System?
Understand the origin of solar variability and its effect on Earth	The Sun's variability, on all time scales, is a complex process that significantly affects its immediate vicinity. • How and where do solar "active regions" form and how do they evolve? • What is the nature of the Sun's polar regions? • What are the global magnetic field properties of the Sun? • How do the Sun and Earth interact as a system? • What have been the effects of the Sun throughout Earth's history?
Explore the paths of life on the Earth	Determine the history of the Sun, the Solar System, and the Earth, which led to the Earth's habitability and the origin(s) of life. • What was the origin and early evolution of life on Earth? • How does the Earth's "life support system" work? • What was the effect of changing environments on life on Earth, and the effect of life on the environment? • What were the fundamental characteristics of major biological events in Earth's evolution (e.g., origins, the appearance of multi-cellularity, Cambrian explosion, intelligence, etc.)?

Figure 3-2: How did we get here?

Figure 3-3: Understanding the future habitability and sustainability of Earth.

Exploration Objectives	Approach and Priority Questions
Understand the future habitability and sustainability of Earth	Determine the major natural and human-generated processes that affect the ability of the Earth to sustain life. • What are the major natural forces that affect the global ecosystems and the climate of the Earth? • What is the effect of human activity on the environment and ecosystems of the Earth? • How does the Earth system change over time, and what are the potential impacts of these changes on human civilization? • How can we best predict ecological trends from a local to a global scale? • How does solar variability affect life and society? • How can we best insure survival of life on the Earth?
Expand the human presence beyond the vicinity of the Earth	Ensure safe human exploration of the Solar System, including the development of essential capabilities for habitation beyond the immediate vicinity of the Earth. • How can robotic explorers create a "virtual presence" throughout the Solar System as a precursor, enabler, and complement to human space travel? • What are the key steps that must be taken for permanently safe and productive human habitation beyond Earth? • What resources are available for human use in space? • How will planetary exploration affect humanity's future?

Figure 3-4: Where are we going?

Exploration Objectives	Approach and Priority Questions
Reveal the cycles of life in the Universe	Understand the universal principles and processes that are necessary for life. • How is organic material produced in the cosmos and what forms does it take? • What are the fundamental characteristics of life (e.g., origins and early evolution, frequency, use of energy and nutrients, impact on environment, etc.)? • What is the range of terrestrial, planetary, and cosmic environments that provide the necessary conditions for life, and under what conditions can life flourish? • What is the distribution of organic and biogenic material and how is it incorporated into planets?
Search for life in the Solar System	Search for life on Mars and in promising worlds in the outer Solar System. • Did life ever arise on Mars or elsewhere in the Solar System? • Do other locations in the Solar System harbor the potential for life?
Search for life in the Universe	Determine the frequency and location of life in the Universe, and the relationships between stars and planets under which life can originate. • What are the fundamental processes of planetary and stellar formation and evolution? • How common are planets like the Earth? • What are the fundamental characteristics of stars and planetary systems that affect the habitability of their environment? • Does life exist elsewhere in the Universe? • Does intelligent life exist elsewhere in the Universe?

Figure 3-5: Are we alone?

Figure 3-6 illustrates the search for life in the oceans of Ganymede. Do other locations in the Solar System harbor the potential for life?

Figure 3-6: Searching for life in the Solar System by exploring the oceans of Europa and Ganymede.

Science Traceability Process from Fundamental Questions to Pursuits, Activities, and Destinations

Understanding the traceability from the science questions and pursuits (figure 3-7) is critical to implementing the Vision. The Exploration Grand Challenges are a derived set of exploration objectives and priority science questions to be answered to achieve the objectives. The team has defined specific pursuits to be undertaken to address the science questions and to focus the science discovery process.

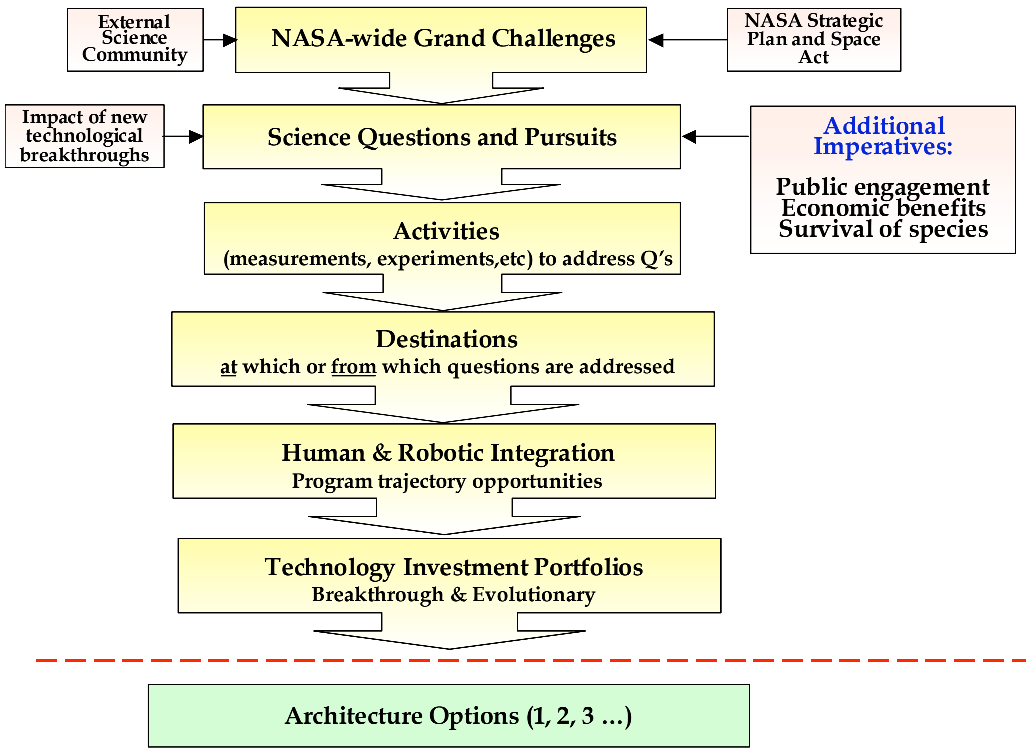


Figure 3-7: The NEXT process follows from the Grand Challenges.

Activities include experiments, protocols, and measurements needed to address the questions and pursuits. Identification of exploration destination options (figure 3-8) follows. Program and mission opportunities for humans and robots will then be defined and technology development activities and mission studies will commence.

Science Traceability Example: Terrestrial Planet Finder

One of several objectives that addresses the Grand Challenge, "Are We Alone?," is the search for life elsewhere in the Universe. A principal activity in the search for life in the Universe is the detection and imaging of planets with hospitable environments.

Detecting and imaging planets with potentially hospitable environments requires us to understand the signposts of habitability and life. These include an atmosphere (carbon dioxide); a warm, wet atmosphere (water); and an atmosphere out of chemical equilibrium (since the global presence of life can modify an atmosphere producing trace compounds).

These specific science criteria provide the framework to begin the design of systems and facilities, initiate technology investment and development activities, and begin mission and architecture studies to support our pursuit.

The NASA Origins Program is studying options for a Terrestrial Planet Finder (TPF, figure 4-3) that will perform such activities. The TPF is an optical interferometer designed to find Earth-like planets in other solar systems. The TPF will study all aspects of planets from their formation and development to their suitability as an abode for life. In addition to measuring the size, temperature, and placement of Earth-size planets in the habitable zones of distant solar systems, atmospheric chemists and biologists will use the TPF to determine whether enough carbon dioxide, water vapor, ozone and methane exist to support life.

The TPF and precursor advanced astronomical facilities may be located in the Earth's Neighborhood at the Sun-Earth L_2 libration point because this location provides an excellent vantage point for astronomy. This location provides continuous, full-sky viewing, enjoys continuous solar energy with no thermal cycling, and contains no orbital debris since the location's inherent weak instability actively removes artificially created debris. NEXT is studying concepts and technology requirements for the deployment and servicing of facilities located at the Sun-Earth L_2 libration point.

Grand Challenges	Science Questions	Pursuits	Activities	Destinations
How Did We Get Here?	• Solar System evolution 	• History of major Solar System events	• Planetary sample analysis: absolute age determination, i.e., "calibrating the clocks"	• Moon • Mars • Asteroids
Where Are We Going?	• Humans adaptability to space 	• Effects of deep space on cells	• Measurement of genomic responses to radiation	• Beyond Van-Allen belts
	• Earth's sustainability and habitability 	• Impact of human and natural events upon Earth	• Measurement of Earth's vital signs, i.e., "taking the pulse"	• Earth orbits • Libration points
Are We Alone?	• Life beyond the planet of origin 	• Origin of life in the Solar System • Origin of life in the Universe	• Detection of bio-markers and hospitable environments	• Mars • Europa • Titan • Cometary nuclei • Libration points

Figure 3-8: Exploration destinations are vantage points for scientific discovery.

Stepping Stones: Evolutionary Approach and Examples

The team's Vision is progressive, evolutionary, and requires humans and robots to work together (figure 3-9). This approach begins with outposts or observatories in the Earth's Neighborhood, defined as Earth-Moon libration points, Sun-Earth libration points, and the Moon itself, and progresses to accessible planetary surfaces, such as Mars, and outer planets as experience warrants and as technology readiness and funding permit. The approach capitalizes on progressive exploration capabilities, where the experience and infrastructure gained from each new architecture enables travel to new destinations.

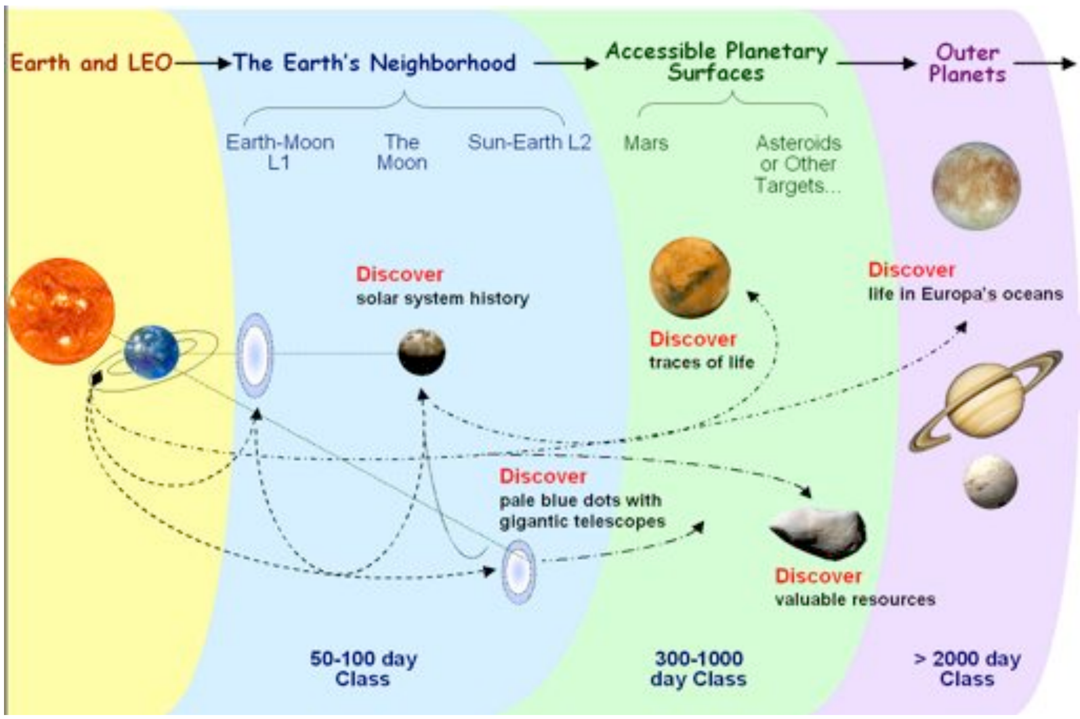


Figure 3-9: The places we must go with humans and robots working together.

Earth's Neighborhood

Going Back to the Moon. There are reasons to go back to the Moon, both for science of the Moon as well as science on the Moon. One of the most important is the history of the Earth-Moon system. Age dating of lunar stratigraphy, including the analysis of the implanted solar wind in these layers, can be used to determine the history of the Sun and predict its future evolution. Analysis of the cratering record on the Moon can establish the frequency and size distribution of asteroid impacts on the Earth. Of particular interest is the science exploration of the lunar poles. The Moon's Aitken Basin, which is located in the South Pole, is the largest impact on the Moon. Samples from this region can provide data on Earth-Moon cataclysms and, since the lower crust and upper mantle is exposed, provide samples that date to the formation of the Moon itself. While much of the preliminary work can be conducted with robotic missions under direct control from Earth, identification of the appropriate local sites, craters and selection of samples for analysis will most likely require human fieldwork on the Moon. NASA has had only a few such field investigations during the Apollo program and many more are needed to reveal the history of the Earth-Moon system.

Sun-Earth Libration Point. Sometime in the first half of this century, humankind will be treated to the first image of an Earth-like planet around another star. This image will likely come from a Terrestrial Planet Finder-type facility that uses space interferometry and is located at the Sun-Earth L_2 libration point. Several 20- to 100-meter class telescopes optically coupled as an interferometer over a baseline of 10,000 km could accomplish this extrasolar planet imaging. At these distances, about 1.5 million km from Earth, human construction, servicing, and evolutionary development of a telescope network is a feasible concept (figure 5-2).

Asteroids and Comets

A fleet of micro-robotic spacecraft initially may be sent to study near-Earth objects such as asteroids and comets. The goal would be to survey their bulk properties and to understand their diversity. This type of information could be helpful to scientists attempting to develop mitigation plans should any one of them present a danger to Earth in the future. Other products from this survey would include an understanding of their origin, their role in the formation of planets, their potential for supplying resources either for future space exploration or for export to Earth, and their value as a potential destination for human exploration.

Mars

After traveling to more distant libration points and living on the Moon, the next likely target is Mars. By this time robotic precursor missions to Mars will have fully characterized the surface environment and identified the primary science targets.

There are three main reasons for the scientific exploration of Mars. The first and most significant is to search for evidence of past or current life. Should robotic missions find any leading evidence of early or extant life, whether surface or subsurface, there is no doubt that human fieldwork on Mars will be required.

Other reasons to explore Mars are to understand Mars as a planet—including how it has evolved and the availability of resources that might be useful for human exploration—and to understand the Martian weather and climate history.

Outer Planets

The outer planets will almost certainly be the exclusive realm of robotic exploration for the near-term. This is the realm not just of the giant planets themselves, but of a large number of diverse satellites and free small bodies. Among the most interesting are Europa, with its potential for a subsurface ocean; Titan, which may have hydrocarbon fluids and organic snows on its surface; and cometary objects, which may contain the most primitive Solar System material including prebiotic organic compounds.

References

1. NASA's Exploration Grand Challenges.

2. York, Harold W., Artur Chmielewski, Mark Dragovan, Potential of Discovery at L_2, NASA JPL, May 15, 2000.

3. Weiler, Dr. Edward J., Associate Administrator, Office of Space Science, NASA Space Science Grand Challenges, NASA HQ.

4. Huntress, Dr. Wesley T., Geophysical Laboratory, Carnegie Institution of Washington, Grand Challenges for Space Exploration, Second Annual Carl Sagan Memorial Lecture, American Astronautical Society Annual Meeting, Houston, TX, November 17-19, 1998.

5. NASA Strategic Plan 2000.

6. NASA Human Exploration and Development of Space Strategic Plan.

7. NASA Space Science Strategic Plan, November 2000.

IV. In-Space Operations—Humans Make a Difference

The Vision of scientific discovery is enabled by an aggressive partnership between humans and robots.

Introduction

Humans have made significant contributions to exploration with the Apollo program, the Hubble Space Telescope (HST), and other space programs. Humans provide unique cognitive capabilities required for science, and have the ability to cope with the unexpected or unknown and improvise when required. Robots are indispensable for exploration, particularly in environments that are too dangerous for humans. A carefully crafted partnership between humans and robots will provide the maximum return on investment. This section discusses specific instances where humans made significant contributions to exploration science and identifies future opportunities for similar contributions.

Astronauts Enable Discoveries: Historical Perspective

Humans, in an optimized working relationship with their robotic partners, significantly enhance or accelerate the scientific return from high-priority NASA programs and assets (ref. 1). Historically, this has been proven in the following areas:

- Deployment, construction, instrument replacement, and repair of scientific facilities
- Coordination, operation, control, and maintenance of complex robotic/observatory networks
- Field expeditions.

In the future humans will *enable* major scientific programs that would be extremely difficult or impossible to undertake otherwise. Examples of human-enabling capabilities include:

- Construction of extremely large optical systems at the Sun-Earth L_2 libration point or elsewhere
- Geological and biological exploration, particularly of Mars.

Support within the scientific community for future human-enabled/enhanced programs will likely depend upon the caliber of the resulting science and whether it is of high quality. Another discriminator is whether the human-related activity is part of a broader scientific program.

The Apollo program and HST are high profile examples of the science benefits of the human-robotics partnership.

Apollo and its science legacy. Apollo provides an historical example of human-enabled science—840 lbs. of lunar rocks gathered within 10 days. Apollo 15 returned the Genesis Rock, a sample of the Moon's primordial, 4.5-billion-year-old crust. This dust-covered white crystalline rock and other exotic samples returned by Apollo crews would not have been discovered without field geology-trained human explorers on site (ref. 2).

These lunar samples and other scientific data from the Apollo program gave scientists a completely revised understanding of the Moon and its history. This information allowed scientists to ask new questions to advance their understanding. These questions, in turn, have been addressed by robotic spacecraft, including Clementine and Lunar Prospector, and have provided new data such as the potential existence of ice at the lunar South Pole which may someday benefit human explorers.

A series of robotic forerunners, the Lunar Orbiter and Surveyor probes, provided the initial understanding of the lunar surface. In the exploration of the Moon, humans and robots have acted in tandem and operated in cycles to advance our scientific knowledge. Robots acted as forerunners providing initial scientific information, humans were inserted tactically and performed a series of advancing, scientifically more challenging missions, and robotic probes were subsequently deployed to pursue answers to new questions raised by on-site exploration (figure 4-1).

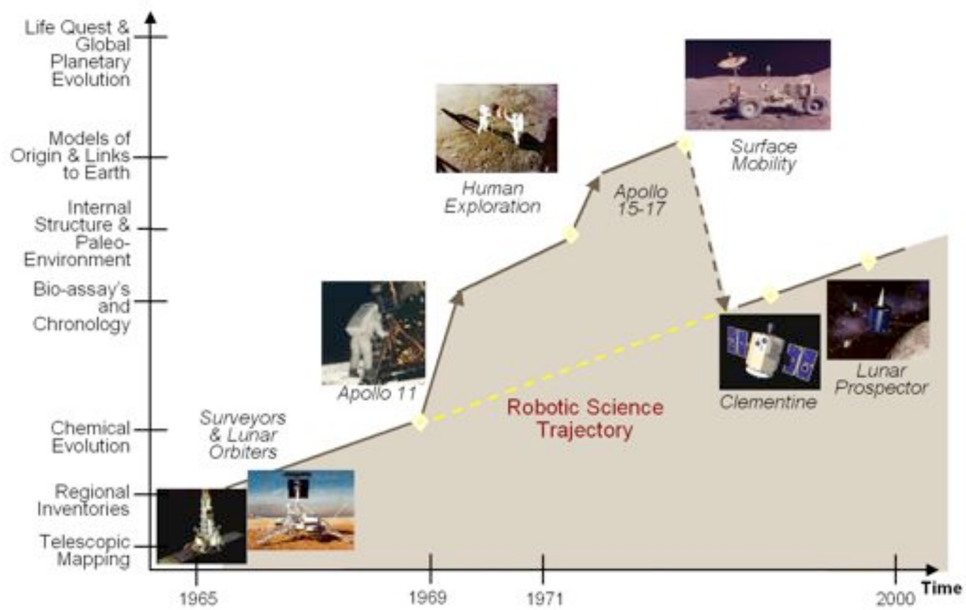


Figure 4-1: Apollo astronauts accelerated the pace of discovery on the Moon.

The Hubble Space Telescope and scientific discovery. The Hubble Space Telescope (HST) is an example of a large robotic asset deployed and serviced by humans. HST was launched in 1990 and opened a new era in optical astronomy. Even with its spherical aberration, the optical distortion caused by an incorrectly shaped mirror, HST provided significant new information and discoveries about the Universe.

Although the initial 1993 servicing mission to correct the spherical aberration was extremely challenging from a technical and operational perspective, it was *feasible* because HST was designed for routine servicing by humans. This servicing mission, which included a record five EVAs, was a complete success. The two subsequent servicing missions, in February 1997 and December 1999, have provided HST with enhanced instruments and upgraded systems allowing it to expand its imaging capabilities to the infrared portion of the electromagnetic spectrum.

Figure 4-2 is a timeline of HST milestones, including servicing missions and the resulting impact to scientific discovery as measured by the annual "most important science stories" (as identified by *Science News*). This information also shows the expanding pace of scientific discovery as a result of HST.

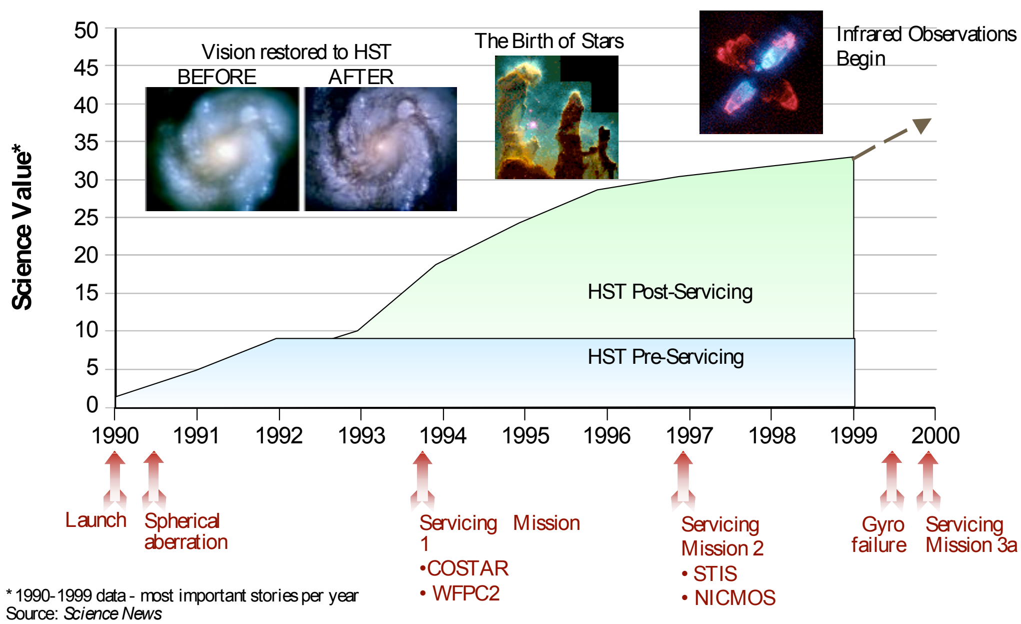


Figure 4-2: Astronaut servicing enhanced HST's discovery capabilities.

Astronauts Enable Discoveries: Future Opportunities

Earth's Neighborhood

The HST experience demonstrates that *humans* can enhance or enable *robotics* to do science.

For HST follow-on missions, which will likely include systems similar to the proposed Terrestrial Planet Finder (TPF, figure 4-3) located at the Sun-Earth L_2 libration point, quantum leaps in technology and operational capability will be required to achieve our science goals.

Humans will enable the assembly, deployment and positioning of these much larger, more sophisticated optical systems. Humans also will minimize program risks by ensuring the safety of space assets through maintenance, repair, and the periodic upgrading of systems and instruments.

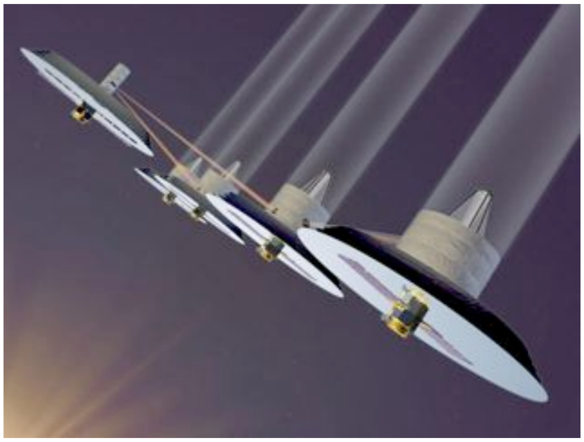


Figure 4-3: The Terrestrial Planet Finder is a modest aperture, 4-5 element spatial interferometer.

During the critical post-assembly system checkout and testing activities, humans working onsite will control the initial operational checkout and testing and be on hand to diagnose and repair problems. With the capability for revisits by astronauts, more innovative optical designs become possible, including the reconfiguration of aperture arrays, addition of elements, realignment of beam directions, and adjustment of tether systems.

Humans will facilitate the in-space aperture construction, acceptance testing and maintenance of the new-generation "Gossamer" observatories (ref. 3, figure 4-4) that cannot be tested or constructed in Earth's gravity or wind currents.

Humans also will enhance the science discovery of our next phase of lunar exploration. Potential roles for humans include:

- Selection of core and surface samples to provide geological context and/or history
- Preparation/training for both human and robotic exploration of Mars
- Control/maintenance of robotic and communications networks
- Placement/construction/operation/maintenance of astronomical observatories.

The lunar South Polar region, which humans and robots have not visited, represents an excellent initial foothold for human-extended exploration (figure 4-5) for several reasons: high science potential; relatively benign and invariable environmental conditions; and surface conditions conducive to testing of Mars exploration system analogs.

Mars

For Mars exploration, *robots* will enable *humans* to do science. Humans will share in the adventure—as the ultimate geologic field explorers (figure 4-6) and as great erectors of systems to be left behind and operated from Earth.

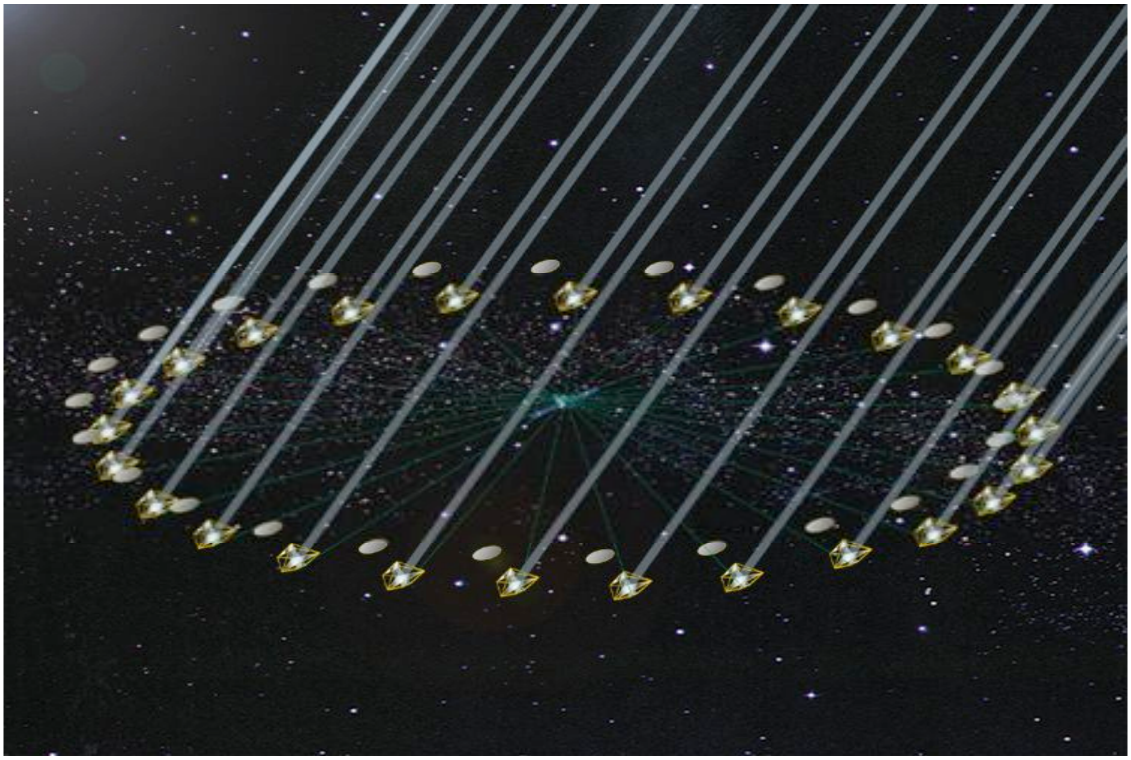


Figure 4-4: The Planet Imager—humans enable Gossamer observatories with individual 40-meter telescopes.

Potential roles for humans to enhance the science of Mars exploration include:

- The search for life (extant or extinct). An active human presence will facilitate the exploration of more and more varied terrain. The search will include the versatile and direct investigation of promising sites
- Complex on-site sample preparation including iterative/repetitive sample collection and analysis (on the order of hundreds of kilograms vs. 1 kg for Mars Sample Return)
- The construction and maintenance of large, complex instruments and facilities
- Geologic field work. An active human presence will facilitate the versatile and direct investigation of challenging sites.

Science capabilities enabled by humans as a function of location include:

- Polar sites—drilling to access and sample ground ice
- Gully sites—searching for modern water by drilling and conducting instrument soundings with in-situ analysis
- Equatorial sites—sampling aqueous minerals in the subsurface
- Channel sites—establishing a drilling rig set up after performing a geophysical sounding

Hellas Basin sites—accessing the deep crust via electromagnetic sounding to study the evolution of Mars.

Human-supported science investigations on the way to and from Mars may include the collection and analysis of solar wind, variable gravity biological studies, and the detailed study of Martian moons or other targets of opportunity.

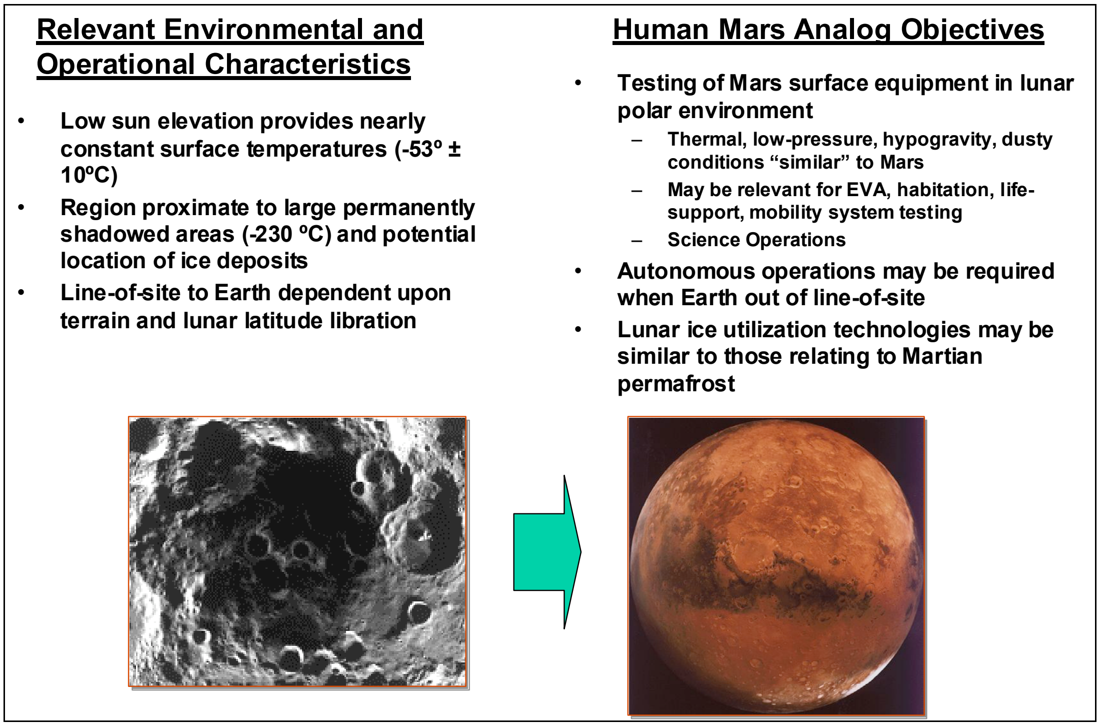


Figure 4-5: Lunar Pole-Mars analogs.

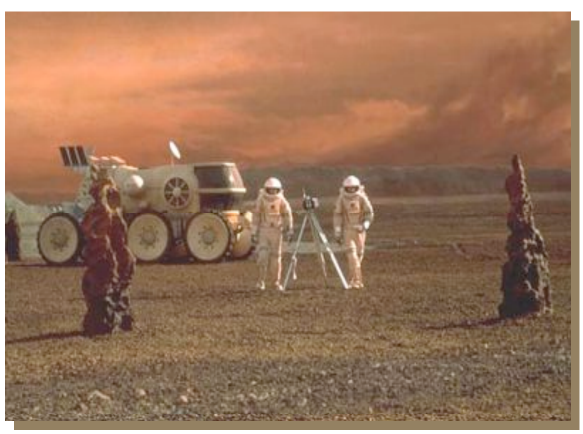


Figure 4-6: Searching for biomarkers throughout the Martian surface and subsurface.

An example of a progressive, human-robot integrated Mars exploration strategy is illustrated in figure 4-7.

Era / Categories	I	Today II	Decision III	IV	V
Capability	• Robotics Alone; • Orbiters and landers	• Robotics Alone; • Many surface sites, networks, rovers, orbital SAR, etc.	• First Human Visits; Robots with multi- site access (robot outpost(s))	• Human outposts with Robotic Global Access	• Permanent Human Outpost(s) with global human robotic access
Activities	• Survey • Inventory • Characterize	• Model • Optimize landing sites • Sample management	• Access subsurface; • Achieve multi-scale mobility; • Conduct intensive fieldwork; • Assess resources and hazards; • Identify long-term sites	• Deploy/utilize in-situ labs; • Search for bio-markers; • Emplace outpost infrastructure; • Utilize in-situ resources	• Explore long-term human adaptation; • Search for Extant life signs
Outcomes	• First Global Maps	• First Analysis (biohazards, etc.)	• First human exposure to Martian environment; • First subsurface samples	• First in-situ analyses; Initial global access	• Initial human evolutionary studies

Figure 4-7: A progressive, human-robot integrated Mars exploration strategy.

References

1. Thronson, Harley, Human Space Flight and Enhancement of the NASA Science Program, NASA HQ.

2. Cooke, Douglas R., An Overview of Recent Coordinated Human Exploration Studies, NASA JSC, January 2000.

3. Chmielewski, Art B., Enabling Aspects of Astronauts for Gossamer Observatories, JPL, August 28, 2000.

V. Stepping Stones—System and Architecture Concepts

The NEXT Vision would provide the first sustained human access to deep space in two generations and open the Solar System to human exploration.

Introduction

The team's architecture analysis included inputs from all of the participating NASA Centers. The Johnson Space Center (JSC) hosted and led the analysis. The purpose of the analysis was to identify needs and requirements for technologies that could provide significant improvements in cost, safety or performance, and to identify high payoff technologies. With this analysis and future studies, the team hopes to develop common architectural elements that may be used as stepping stones or building blocks for multiple destinations. None of the destinations or architectures studied in Phase II met the cost or safety criteria. This section discusses analysis scope, goals, evaluation criteria, and process; provides a brief summary of the study results; and provides recommendations for future studies.

Scope of Architecture Analysis

The NEXT architecture study team has focused primarily on mission analyses for human and robot exploration of the Earth's Neighborhood and Mars. Initial work has been performed for human and robot exploration of near-Earth asteroids. The system and architecture concepts span the technology envelope. Current and alternative concepts using today's technology as well as current and new concepts using new and breakthrough technologies are under study. Development of architectures for these missions serves as an "existence proof" of the various technology options and mission approaches under consideration**.**

The architecture studies include detailed end-to-end analyses of:

- Mission goals and objectives
- Mission sequence
- Approaches to minimize risks and maximize crew safety
- Vehicles and systems
- Technology applicability and benefits
- System drivers
- Operations concepts
- Schedules.

Goals

The goals were to determine which architectures and technologies provide the highest payoffs in terms of safety and cost, and to develop progressive exploration capabilities that take us from Earth's Neighborhood to planetary surfaces where we ultimately can achieve a sustained presence. The early architectures provide points of departure, capabilities, or infrastructure for later architectures.

Evaluation Criteria

The evaluation criteria (ref. 1) used to compare the options are defined at a top level by addressing key questions:

- Which architecture provides the most flexibility for meeting future human exploration and development of space needs (performance criteria)?
- Which architecture best ensures crew safety and productivity for all mission phases (safety criteria)?
- Does one architecture have a significantly higher technological risk (technical criteria)?
- Does one architecture need to start design and development activities significantly earlier (schedule criteria)?
- Which architecture is expected to provide lower initial and/or total life cycle costs (cost criteria)?

Process

JSC led the architecture study effort and provided the engineers to conduct the studies. The Langley Research Center (LaRC) provided systems engineering support and documented ground rules and assumptions for each architecture. Other Centers provided technology inputs and assessments according to their respective areas of expertise. Team scientists defined science goals and objectives for each architecture.

Architecture Study Summary

NEXT analyzed eight major architecture cases. Three of the major cases included several sub-cases. These cases are:

- Sun-Earth L_2 "evolutionary" with Evolved Expendable Launch Vehicle-Heavy (EELV-H) and low-Earth orbit departure
- Sun-Earth L_2 "stepping stone" with EELV-H and low-Earth orbit departure
- Moon with EELV-H and low-Earth orbit departure
- Earth-Moon L_1 Gateway
- Mars short stay
  - Low-Earth orbit departure with EELV-H or with "big dumb boosters"
  - High-Earth orbit departure with EELV-H or with "big dumb boosters"
- Mars long stay
  - Low-Earth orbit departure with EELV-H or with "big dumb boosters"
  - High-Earth orbit departure with EELV-H or with "big dumb boosters"

- Mars short stay—1-year round trip option
- Asteroid
  - Low-Earth orbit departure with "big dumb boosters"
  - High-Earth orbit departure with "big dumb boosters."

Figure 5-1 summarizes the architectures, science objectives, enabling technologies, and unique stepping-stone technologies.

Architecture	Science Objectives	Enabling Technologies	Unique Stepping-Stone Technologies
L_2 Evolutionary	Advanced Astronomy; Solar Monitoring	Advanced, Deep-Space EVA	—
L_2 Stepping Stone	Advanced Astronomy; Solar Monitoring	—	Advanced Propulsion
Moon	History of Solar System; History of Solar Activity	Lightweight Power; Avionics; Life Support Systems	Advanced Surface EVA; Advanced Propulsion
Earth-Moon L_1 Gateway	Operational Support of L_1, L_2; Lunar Science; Opportunistic Deep-Space Biology	Advanced Life Support	Advanced Structures; Radiation Protection
Mars Short Stay 1, Mars Short Stay 2	Local Exploration; Search for Current or Past Life; History of Mars	Advanced Life Support; Advanced Propulsion; Radiation Protection	—
Mars Long Stay 1, Mars Long Stay 2	Regional Exploration; Search for Current or Past Life; History of Mars	Advanced Life Support; Advanced Propulsion; Advanced Surface EVA; Radiation Protection	—
Mars Short Stay—1 Year Round Trip Option	Local Exploration; Search for Current or Past Life; History of Mars	Advanced Life Support; Advanced Propulsion; Radiation Protection	—
Asteroid 1, Asteroid 2	History of the Solar System	Advanced Life Support; Advanced Propulsion; Radiation Protection	Advanced Propulsion

Figure 5-1: NEXT studied multiple architectures spanning a range of destinations and science objectives to validate technology needs and requirements.

Destination Descriptions: Earth's Neighborhood

The initial exploration region for humans and their robotic partners is a location referred to as the Earth's Neighborhood. It includes the region of space encompassing the Sun-Earth L_1 and Sun-Earth L_2 libration points extending approximately 1.5 million km from Earth as shown in figure 5-2. For reference purposes, the Earth-Moon L_1 libration point is approximately 327,000 km from the Earth's center (58,000 km from the Moon's center) and is a four-day trip from the Earth (or a two-day trip from the Moon) using high-thrust propulsion.

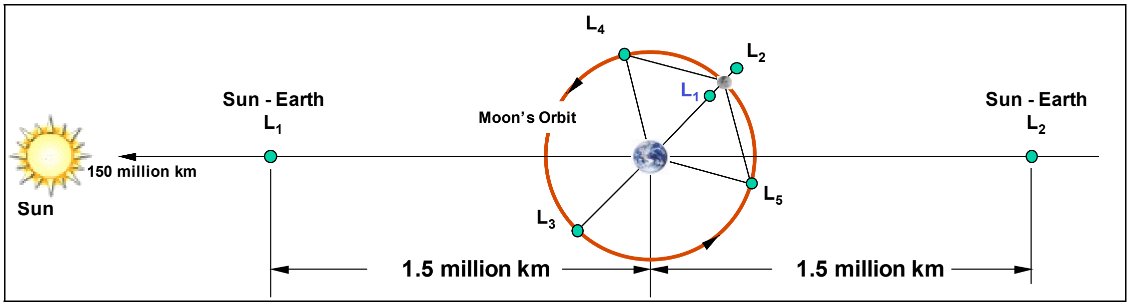


Figure 5-2: Earth's Neighborhood libration point geometry.

The primary end-point destinations within the Earth's Neighborhood are the lunar surface, which may be accessed via an Earth-Moon L_1 Gateway (i.e., a deep-space habitation and operations facility) and a Sun-Earth L_2 Gateway, which may be used as a servicing facility for advanced astronomical facilities (figure 5-3). Low-Earth orbit and medium-Earth orbit destinations within the context of the NEXT analyses are primarily staging areas for exploration missions beyond these locations.

Primary architectural systems and elements for Earth's Neighborhood include:

- L_1 Gateway—a deep-space habitation and operations facility used as a transportation node for routine sorties to the lunar surface including polar regions. Initial concepts for this habitation and operations facility are based on a "half-length" inflatable habitat and a solar electric propulsion system which provides initial transport from low-Earth orbit to Earth-Moon L_1 and remains attached to provide system power and attitude control during operations (figure 5-4). The L_1 Gateway provides docking and vehicle support (i.e., power and attitude control) for the Lunar Transfer Vehicle and Lunar Lander; pressurized crew transfer and crew habitation for ≥12 days per lunar mission (needed for return-to-Earth opportunities which is a function of orbital phasing). The L_1 Gateway will initially be launched to low-Earth orbit on a Delta IV heavy-class vehicle or the Space Shuttle

- L_2 Gateway—an ideal facility and location for testing Mars Transfer Vehicle (MTV) systems in interplanetary space. The Sun-Earth L_2 Gateway is conceptually and functionally similar to the Earth-Moon L_1 Gateway. This facility provides crew habitation for ≥20 days per mission necessary for return-to-Earth opportunities. The L_2 Gateway provides a true stepping-stone capability

- Crew Transfer Vehicle (CTV)—provides transport of crew from the ISS to destinations in Earth's Neighborhood and back. The CTV utilizes a high-energy injection stage for propulsion to the L_1 or L_2 locations and returns using its integral LOX/CH4 propulsion system. The CTV will be launched and recovered by the Space Shuttle and based at ISS for timing flexibility. The CTV provides an 18-65 day independent mission capability for a crew of four and includes a water jacket "storm shelter" for protection from space radiation (solar proton events)

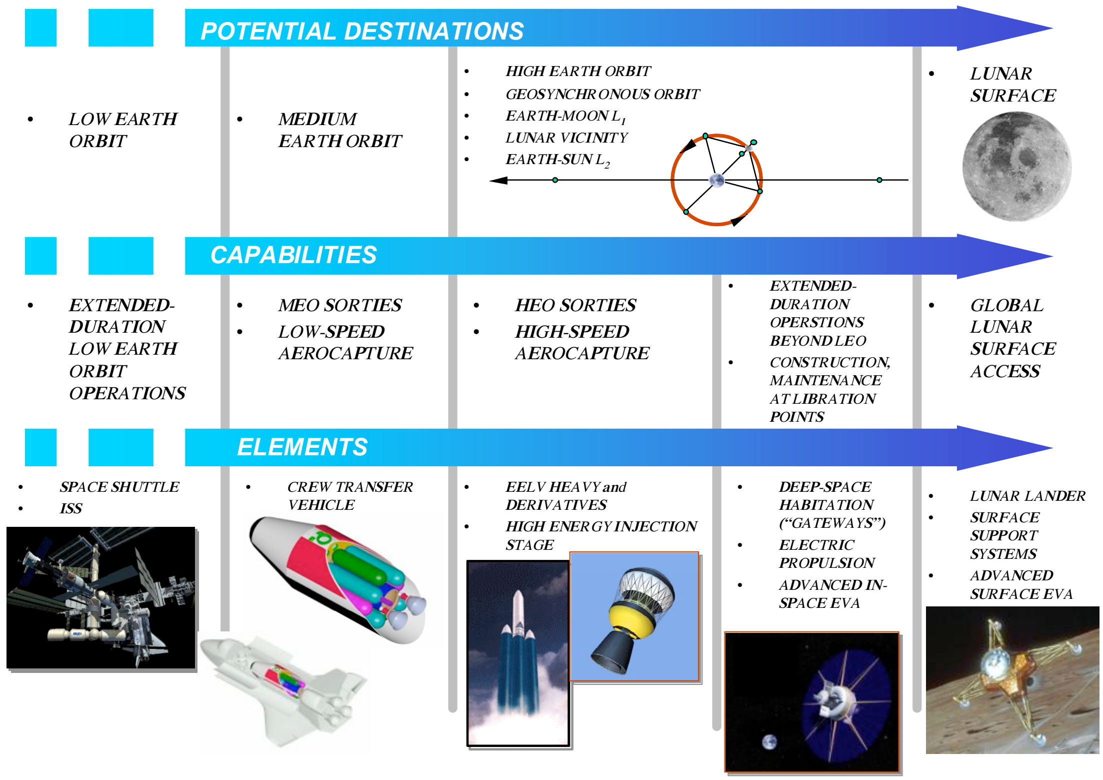


Figure 5-3: The Earth's Neighborhood—destinations, capabilities and elements.

- High-energy injection stage—initially launched on a Delta IV Heavy-class vehicle or the Space Shuttle, this stage provides boost for the CTV from the ISS to L_1 or L_2. This element has the capability to achieve and maintain an orbit in the vicinity of ISS for >30 days after launch to LEO

- Lunar Lander—provides a seven-day independent mission capability and will be designed to transport up to four crewmembers from the L_1 Gateway to the lunar surface and back to the L_1 Gateway (ref. 2). The Lunar Lander transportation system will enable access to any point on the lunar surface and will be able to remain on lunar surface for an "extended" duration if a lunar surface infrastructure exists.

Assuming the L_1 Gateway has been pre-positioned and is operational, the sequence for the lunar surface sortie is as follows (figure 5-5):

- The CTV and crew are launched to the ISS by the Space Shuttle

- The high-energy injection stage is launched to the vicinity of ISS on a Delta IV Heavy-class launch vehicle

- The CTV and injection stage are mated and the crew is transferred from the ISS staging location to the L_1 Gateway

Figure 5-4: The L_1 Gateway is a transportation node providing access to all regions of the lunar surface.

- At the L_1 Gateway, the crew transfers to the Lunar Lander and transfers to the lunar surface

- After completion of the lunar surface sequence of the mission, the crew and Lunar Lander return to the L_1 Gateway

- On the return trip from the L_1 Gateway, the crew and CTV aerobrake and transition to the ISS. The crew and CTV are then returned to Earth via the Space Shuttle.

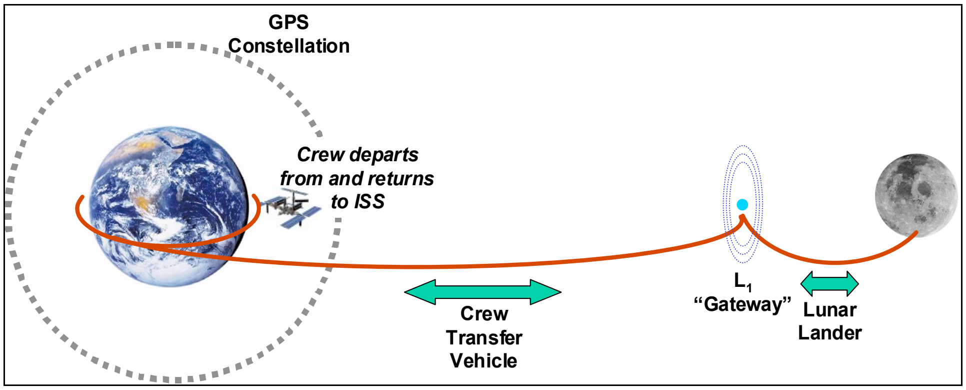


Figure 5-5: L_1 Gateway—lunar architecture mission overview.

Lunar surface sortie via an L_1 Gateway

Use of an L_1 Gateway as a transportation node for human exploration of the Moon is attractive for a number of operational reasons. L_1 provides excellent access to the entire lunar surface since this libration point is naturally synchronized with the lunar orbit. This allows unconstrained opportunities for sorties to and from the lunar polar regions which have excellent potential for science discovery and local resource utilization. Also, unique science opportunities may exist at L_1 where formation-flying scientific spacecraft may be mutually accessible with minimal energy expenditure. Similar to the Sun-Earth L_2 libration point, the Earth-Moon L_1 libration point provides a potential staging point for deep-space exploration missions and may serve as an excellent location for testing deep-space systems for missions to Mars.

Sun-Earth L_2 extended operations

Two architectures using the Sun-Earth L_2 libration point as a destination have been studied: an L_2 "evolution" architecture driven by science operations requirements, and an L_2 "stepping stone" architecture based on human Mars mission requirements (ref. 3).

The L_2 stepping stone architecture operational approaches, technologies, and schedule are being defined to reflect assumptions for an emerging Mars exploration architecture. The L_2 Gateway and scale of L_2 capabilities (e.g., crew and mission duration) are likely to be much more robust in the stepping-stone approach than in the L_2 evolution approach. That is because the Gateway may become the Mars Transfer Vehicle (MTV) habitation element, and extensive testing of MTV systems may be performed in the L_2 deep-space environment.

An overview of the L_2 missions is shown in figure 5-6. A summary of the L_2 evolution mission is provided below.

The Sun-Earth L_2 evolution scenario is a 100-day class mission using an approach similar the lunar sortie mission:

- The CTV and crew are launched to the ISS by the Space Shuttle

- A high-energy injection stage is launched to the vicinity of ISS on a Delta IV Heavy-class launch vehicle

- The CTV and injection stage are mated and the crew is transferred from the ISS staging location to the L_2 Gateway

- After completion of the L_2 science mission, the crew and CTV transfer from the L_2 Gateway, aerobrake into the ISS orbit and transition to the ISS

- The crew and CTV are then returned to Earth via the Space Shuttle.

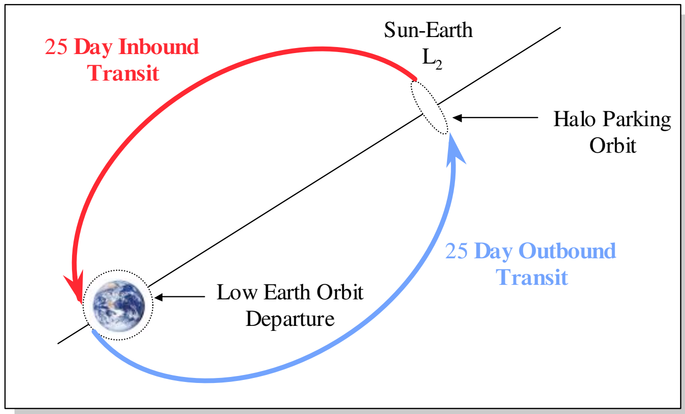


Figure 5-6: Earth-Sun L_2 mission overview.

Earth's Neighborhood architecture attributes

The architectures supporting the lunar surface sortie and L_2 Gateway missions benefit from the use of common systems and elements. For example, the Crew Transfer Vehicle (CTV) used to transfer crew from the ISS to the L_1 Gateway also may have the capacity to support crew transfer for missions to the L_2 Gateway, and the high-energy injection stage may be sized to support transportation to L_2. Similarly, the L_1 and L_2 Gateways may use common technologies such as inflatable structures and solar electric propulsion systems.

The crew radiation environment risk identification and mitigation approaches require additional work, primarily in the areas of environment definition, biological effects, materials selection, and vehicle/habitat configuration options.

Destination Descriptions: Human Mars Exploration

Evolution of common capabilities

The exploration architectures for Mars benefit from the capabilities developed for Earth's Neighborhood. (figure 5-7). Examples under study include:

- Use of L_1 and/or L_2 Gateways as Mars transit habitats (with the capability to provide long-duration support of mission crew in the interplanetary environment with limited resupply capabilities)

- Use or evolution of L_1 and/or L_2 electric propulsion capability for Mars system propulsion (to transport mission payloads from low-Earth orbit to the mission destination)

- Use or evolution of the Earth's Neighborhood Crew Transfer Vehicle for the Mars "taxi" (to transport the Mars Transit Habitat, Surface Habitat, and Ascent/Descent Vehicle from low-Earth orbit to high-energy Earth orbit for mission departure)

- Use or evolution of lunar and deep-space extra-vehicular systems for Mars (to enable routine human access to planetary surface and space environments).

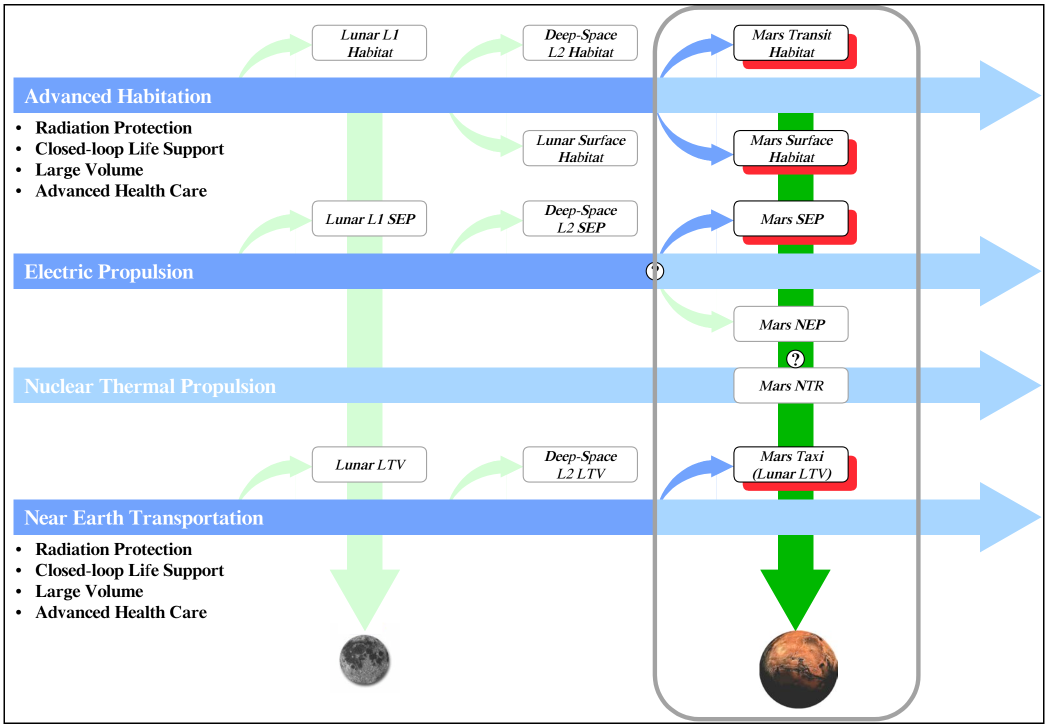


Figure 5-7: Technology-driven capability evolution.

The Hybrid Propellant Module (HPM, ref. 4) is an example of a common architecture element which may potentially be used for missions to the L_1 and L_2 libration points, the Moon, Mars, and near-Earth asteroids as the basic propellant unit for the mission transfer vehicles. A common HPM (figure 5-8) used for multiple missions would allow the on-orbit storage of liquid oxygen, liquid hydrogen, and electric propulsion propellant (at this point assumed to be xenon). Units could be aggregated or positioned optimally in various orbits to provide mission support. The HPM would be completely self-sufficient using zero boil-off cryogenic fluid management technology with a common fluid transfer interface. To maximize the cost benefits of this element, the HPM would be designed to be highly reusable. HPMs with spent hydrogen and oxygen would be ferried back to LEO via an electric propulsion transfer vehicle for refueling.

Mars architecture alternatives

Human Mars mission concepts under study are categorized as either short-stay tactical missions with a mission duration of 12-22 months (a one-year round trip mission is a special case) or long-stay outposts with a total mission time of approximately three years (figure 5-9). The mission objectives of each mission concept vary based on capability and resource availability.

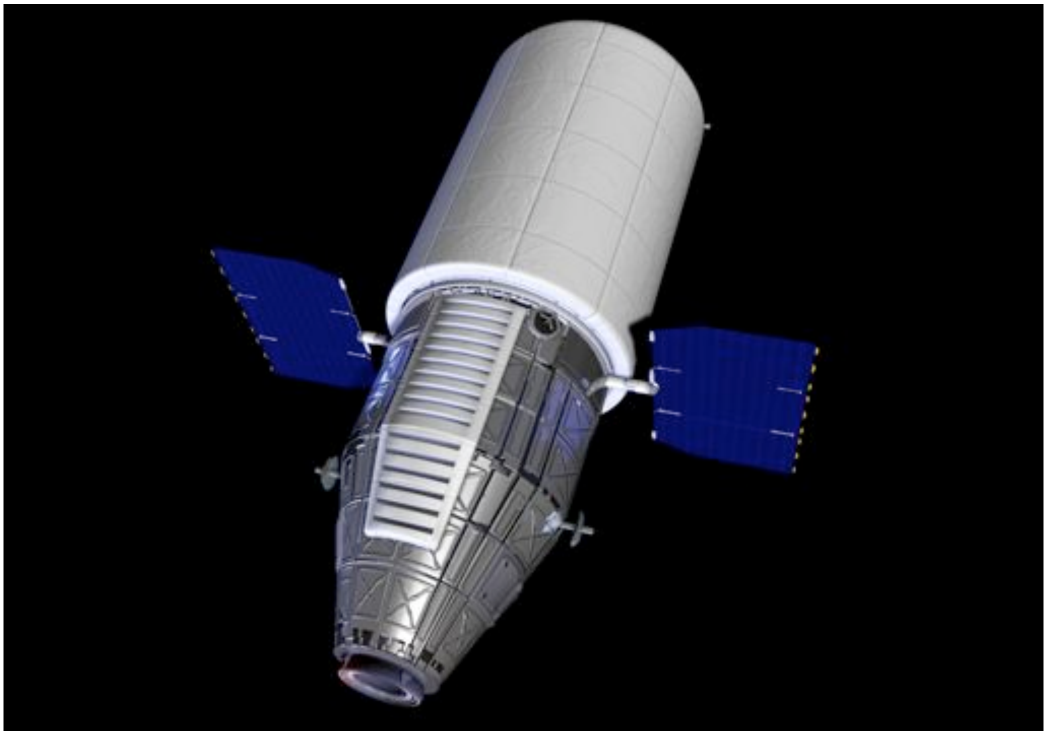


Figure 5-8: Concept for a reusable, self-sufficient Hybrid Propellant Module fuel aggregation depot.

The short-stay missions focus on local exploration of pre-determined sites. Diversity of exploration coverage with the short-stay mission concepts is achieved by visiting separate locations within three or four flight opportunities.

The long-stay outpost missions focus on regional scientific exploration of a 100 km x 100 km area. Crew members will explore a scientifically compelling region with adequate time to conduct activities and adapt to observations. Once the mission is completed, the outpost will be left behind for subsequent revisits.

Primary systems and elements for human Mars exploration architectures include:

- Transit Habitat. The Mars Long-Stay Transit Habitat shown in figure 5-10 supports a mission crew of six for up to 200-day transits to and from Mars. It also provides zero-g countermeasures and deep-space radiation protection, includes a return propulsion stage integrated with the transit system, and provides return-to-Earth abort capability for up to 30 hours post trans-Mars injection. The Mars Short-Stay Transit Habitat supports a mission crew of four for up to 365-650 day round-trip missions to Mars. The nuclear thermal rocket (NTR) transit vehicle provides power generation

- Surface Habitat. Used for the long-stay mission, this vehicle supports a mission crew of six for up to 18 months on the surface of Mars and provides robust exploration and science capabilities

- Descent/Ascent Vehicle. The descent vehicle is capable of landing 36,000 kg. The long-stay vehicle transports a crew of six from Mars orbit to the surface and back to Mars orbit and supports the crew for up to 30 days. It provides contingency abort-to-orbit capability and can utilize locally produced propellants. The short-stay vehicle supports a crew of four for 30 days

- Interplanetary Transportation. For the long-stay missions, chemical and NTR propulsion options are under study for interplanetary transit of the Surface Habitat and Transit Habitat. A Solar Electric Transfer Vehicle (SETV) is used to transfer the Surface Habitat and Transit Habitat from low-Earth orbit to high-Earth orbit prior to trans-Mars injection with the chemical propulsion option. The short-stay mission uses an NTR vehicle for cargo and piloted flights

- Launch Vehicle. A "Shuttle-compatible" launch vehicle capable of delivering 80 metric tons to a 220 nautical mile, 28.5° inclination circular orbit is assumed available for the cost-effective delivery of large payloads. This vehicle maximizes the cost-effective use of common Shuttle boosters and launch facilities.

Mars short mission

This is a mid-term (Calendar Year 2018) option (refs. 5, 6) using a nuclear-thermal propulsion system for interplanetary transits. Objectives for this study are to establish a "go anytime" capability for a human Mars mission, limit the total mission duration to approximately one Earth year, and to push advanced technologies including advanced in-space propulsion and materials.

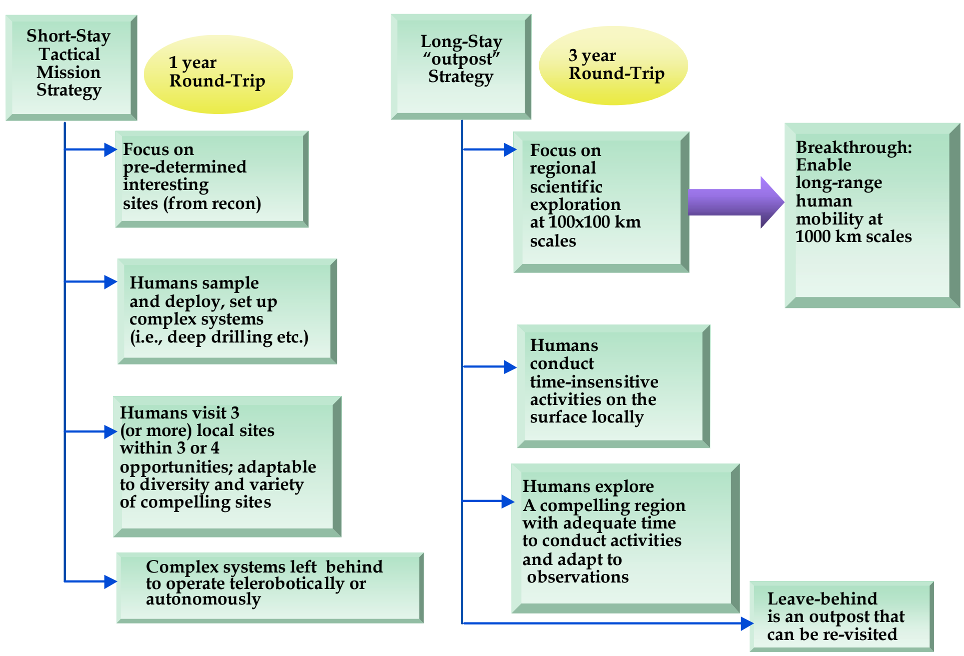


Figure 5-9: Human Mars exploration alternatives.

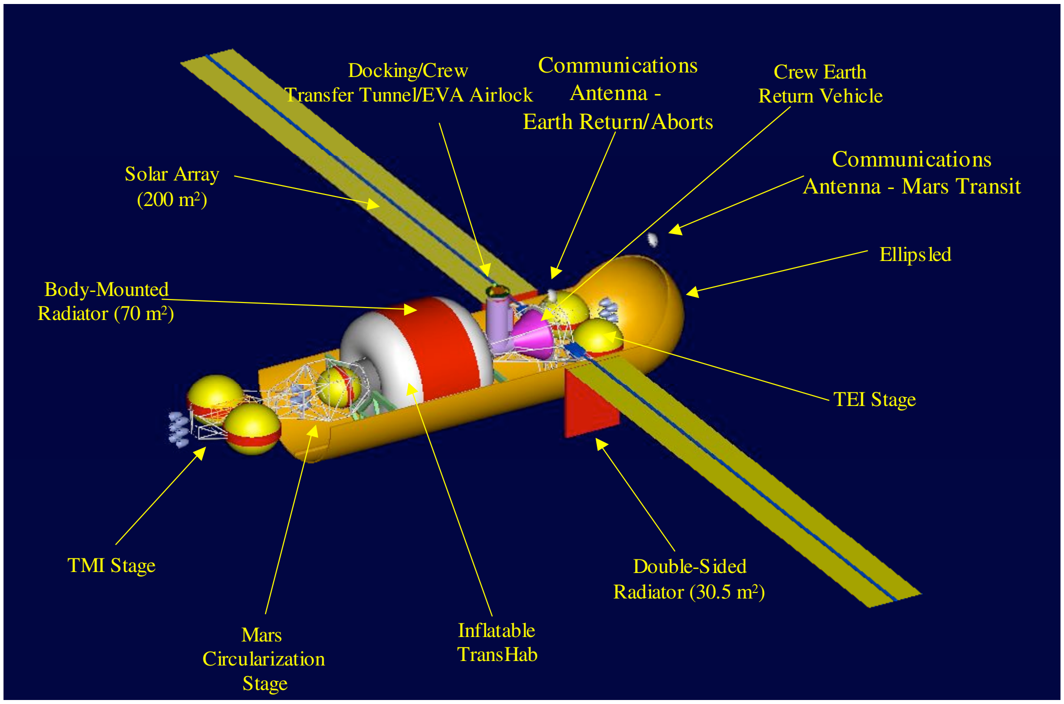


Figure 5-10: Example Mars Transit Habitat configuration.

An overview of this mission concept is shown in figure 5-11.

Mars long mission

Objectives of this study (refs. 7-9) are to: balance technical, programmatic, mission, and safety risks; provide an operationally simple mission approach emphasizing the judicious use of common systems; provide a flexible implementation strategy; limit the length of time that the crew is continuously exposed to the interplanetary space environment; define a robust planetary surface exploration capacity capable of safely and productively supporting crews on the surface of Mars for 500-600 days per mission; enable the capability to "live off of the land;" design systems capable of performing within the schedule and constraints of each launch opportunity; and to examine at least three human missions to Mars.

An overview of this mission scenario is shown in figure 5-12.

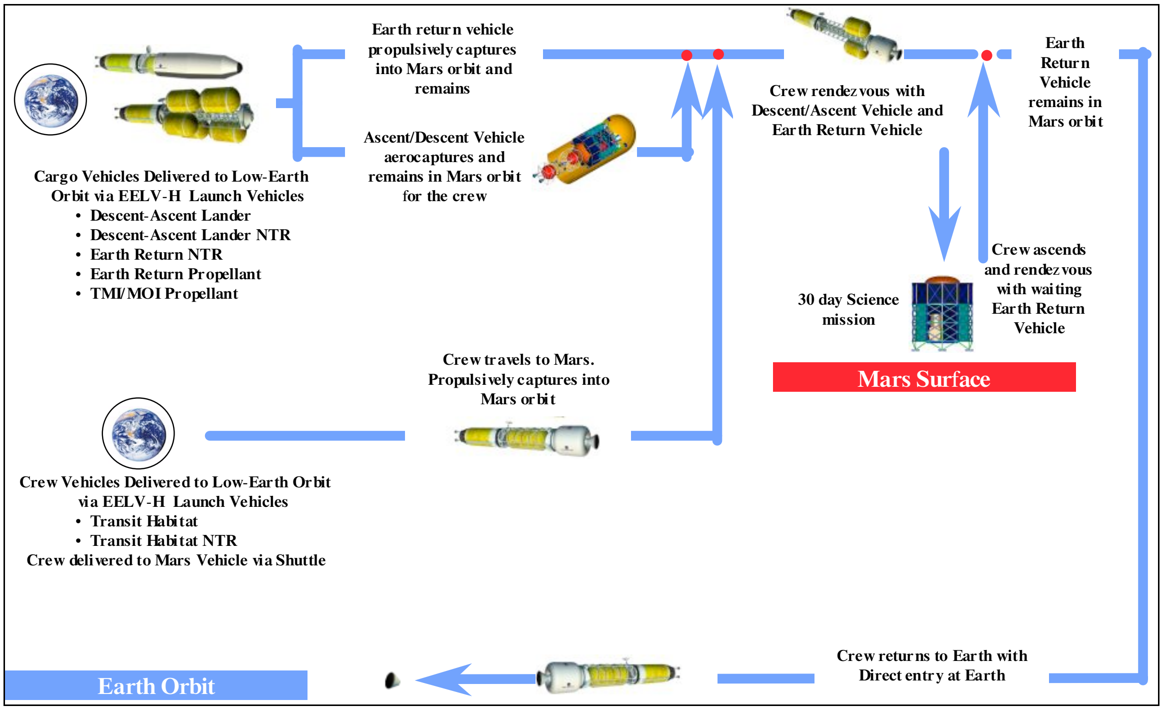


Figure 5-11: Mars short mission overview—nuclear thermal propulsion option.

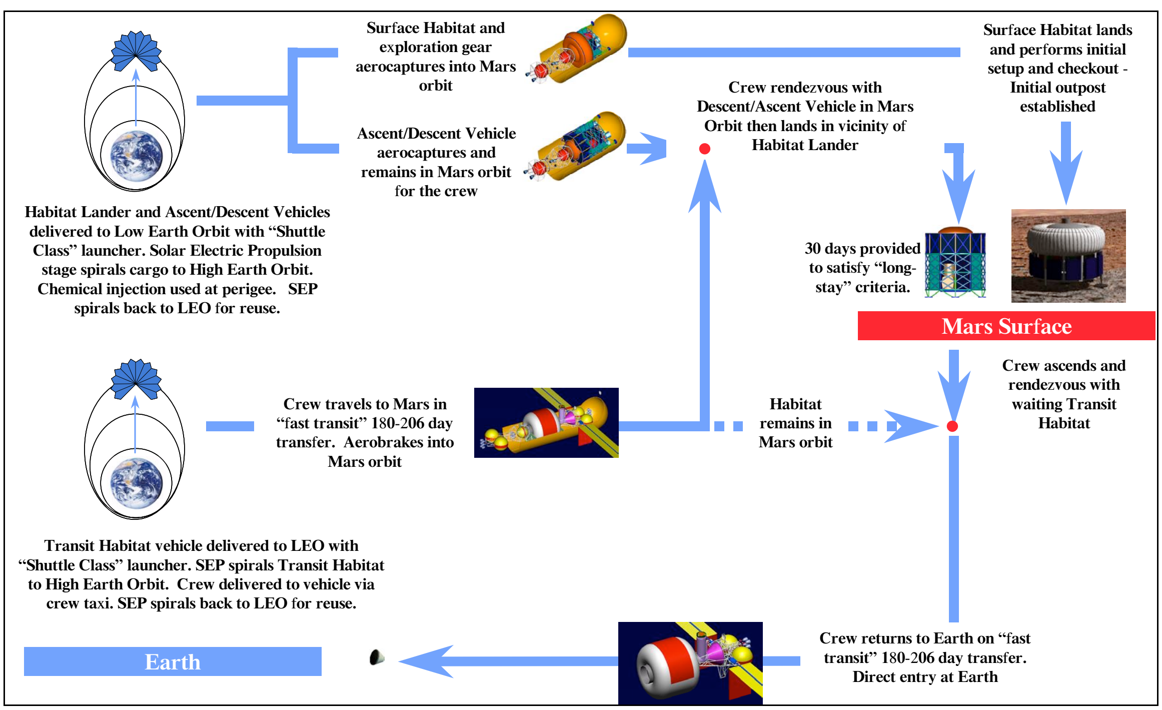


Figure 5-12: Mars long mission overview—solar electric propulsion option.

Exploration Architecture Future Studies

The Fiscal 2001 plan for system and architecture analyses includes a focus on Earth's Neighborhood concepts:

- Earth-Moon L_1 Gateway concept verification
- Lunar Lander definition and operational scenario development
- Demonstrations including characterization and verification of invariant manifold trajectories (i.e., trajectories between libration points that require very low delta-V) and prediction and mitigation of deep-space radiation
- Human-robotic development activities including deployment of structures and contamination control
- Trade studies including Gateway utilization (logistics and resupply strategy); L_1 medical care options such as on-site care vs. injured crew evacuation; sequence of lunar capability (as well as the assessment of earlier lunar missions without a Gateway); alternate transportation architectures; and utilization of ISS vs. end of ISS lifetime.

References

Architecture Comparison and Evaluation

1. Drake, Bret G., Human Exploration Architecture Comparison Approach, NASA JSC, January 2000.

Lunar Architecture Analyses

2. Joosten, B. Kent, Lunar Architecture—Lunar Lander Design Status, NASA JSC.

3. Joosten, B. Kent, "Exploration in the Earth's Neighborhood" Architecture Analysis, NASA JSC, July 11, 2000.

4. Hybrid Propellant Module and Fuel Aggregation Depot Concept, Fuel Aggregation Study Team, NASA LaRC, September 29, 2000.

Mars Architecture Analyses

5. Drake, Bret G., DPT Mars Short-Stay Mission Architecture Status—Mid-Term (2018) Nuclear Thermal Propulsion System Option, NASA JSC, July 11, 2000.

6. Mars 'Short-Mission' Scenario/Architecture Ground Rules and Assumptions, April 20, 2000.

7. Drake, Bret G., DPT Mars Long-Stay Mission Architecture Status—Mid-Term (2018) Nuclear Thermal Propulsion System Option, NASA JSC, July 11, 2000.

8. Mars Long-Mission Ground Rules and Assumptions, April 20, 2000.

9. Drake, Bret G., DPT Architecture Status—Mars Missions, Near-Earth Asteroid Missions, Common Capabilities, NASA JSC, September 12, 2000.

VI. Technology Needs and Benefits

> ***The NEXT consensus is that an integrated, sustained technology breakthrough investment program, which is linked to specific capability goals that are themselves traceable to major, NASA-wide scientific objectives, is pivotal.***

An aggressive, integrated, Agency-wide technology investment and development program is critical to enabling humans to participate in onsite scientific exploration. We must develop specific technologies to enable affordable, integrated human and robotic exploration. While the Vision is science-driven, it is technologically enabled on the basis of derived requirements associated with specific "stepping-stone" capabilities (figures 6-1 and 6-2).

	Near-By Solar System (50-100 day Class)	Accessible Planetary Surfaces (300-1000 day Class)	Sustainable Planetary Surface
Solar System Resources Development			In-Situ Resource Extraction; Resource Processing; Product Storage & Distribution
Space Utilities and Power	Space Solar Power Generation	Cryogenic Propellant Depots	Space Nuclear Power Generation; Wireless Power Transmission
Habitation and BioAstronautics	Biological Risk (Radiation); Adaptation & Counter-measures (Gravitation); Extra-vehicular Activity Systems	Regenerative Life Support Systems; Space Medicine And Health Care	
Space Assembly, Maintenance and Servicing	In-Space System Deployment; Servicing, Maintenance And Repair	AR&C/ Self-Assembling Systems; In-Space Assembly and Construction	
Exploration and Expeditions		Subsurface Access and Knowledge	Surface Systems; Flying Systems
Space Transportation	In-Space "Electromagnetic" Propulsion; In-Space "Chemical" Propulsion	In-Space "Nuclear" Propulsion	Launch Assist / Direct Launch; Propellant-less In-Space Propulsion; ETO Propulsion
Cross-Enterprise Technology	Structures and Materials	Intelligent Systems	Nano-technology

Figure 6-1: Breakthrough technologies for "stepping-stone" capabilities.

The Technology Hurdles

Investments in an exploration technology portfolio should be balanced between "breakthrough" and "evolutionary" technologies. Breakthrough technologies are speculative technologies with potentially profound pay-offs. These will revolutionize how we explore and are beneficial regardless of destination. Conversely, evolutionary technologies are part of the Agency's current investment pool and are focused on a specific exploration theme. Multiple development paths are commonly utilized for evolutionary technologies to assure development results.

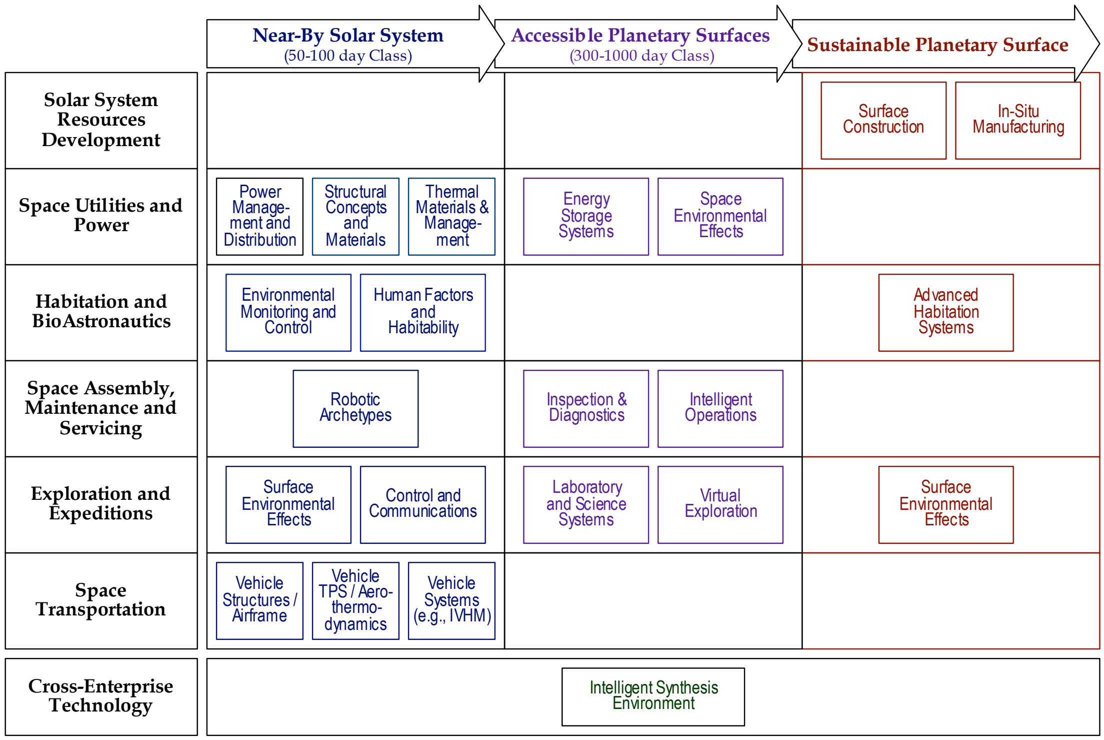


Figure 6-2: Additional enabling technology advances.

The largest inhibitor to safe, affordable human-robotic exploration beyond LEO is the fragmented investment in evolutionary and breakthrough technologies. Example breakthrough technology areas include in-space transportation, crew health and safety, human-robotic tools, and space systems performance (figure 6-3). Without progress in several of these technology areas over the next 5-10 years, the ability to implement a robust, affordable, omni-destination exploration program will not be possible.

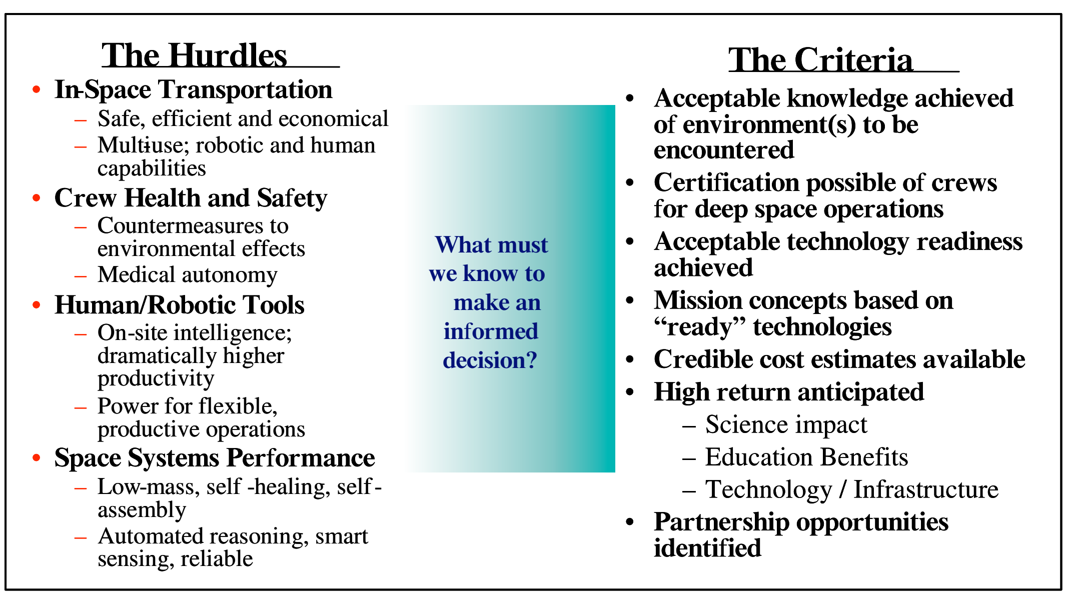


Figure 6-3: Hurdles to overcome and criteria to be met.

Space Transportation Technologies

Our space transportation technology goals are to significantly increase crew safety and reliability of future human exploration campaigns beyond Earth orbit; dramatically reduce the cost of human exploration missions and campaigns; and establish a foundation of advanced transportation infrastructures needed to enable future commercial development of space in the mid- to far-term.

Our objectives in pursuit of these goals include:

- To develop and demonstrate the technologies needed to assure that future human exploration transportation systems are safe and robust
- To identify and mature new, highly promising options for very low-cost Earth-to-orbit (ETO) transportation
- To develop and validate technologies for the affordable transportation to and from targets in space beyond low-Earth orbit
- To enable reliable and affordable transportation to all points of interest globally on the Moon or Mars
- To research, identify and possibly nurture speculative ETO and in-space transportation technologies and concepts.

In-space transportation

We are assessing specific in-space transportation technologies (figure 6-4) with the goal of establishing priorities for future funding. Additionally, we are performing in-space transportation systems studies to support our exploration architecture definition and analysis (refs. 1-10).

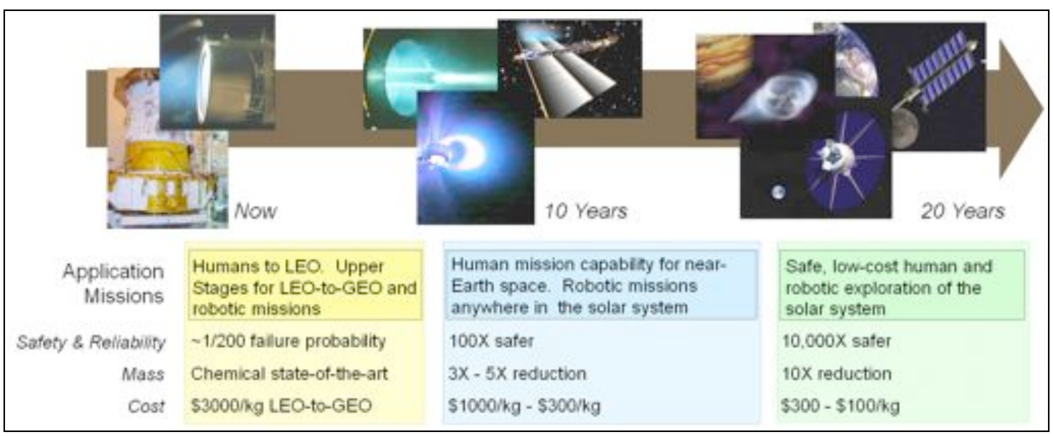


Figure 6-4: Breakthrough in-space transportation needs.

Representative examples of our in-space transportation technology assessment activities are presented in figure 6-5. Information from these assessments is being used to prioritize these technologies using a collaborative analytic hierarchy process. This prioritization is based on the following criteria: safety, reduce initial mass to low-Earth orbit (IMLEO), reduce trip time, reduce costs, potential multi-mission use, development risk, commercialization potential, and "other factors."

Technology	Objectives/Status

High Power Electric	Current Activities:
	• Pulsed Inductive Thruster
	  ○ Design, build, and test a repetitive-pulsed power and delivery system
	• Self Compressed Plasma Thruster
	  ○ Experimentally validate the scaling laws governing the dynamics and physics of the self-compression of a cluster of plasma jets
	• Magnetoplasmadynamic (MPD) Thruster
	  ○ Demonstrate efficient high power MPD thruster operation at the MW-class power levels
	• 500 kWe Lithium-fed Thruster
	  ○ Design, build, and assemble a 500 kWe Lithium-fed Lorentz force accelerator
	• VASIMR
	  ○ Laboratory testing of prototype thruster with hydrogen and deuterium propellants

Nuclear Propulsion Experiments	Current Activities:
	• Nuclear Electric Propulsion (NEP) end to end demonstrator
	  ○ Demonstrate operation of a complete nuclear electric propulsion system, including a resistively-heated (unfueled) reactor core, power conversion system, power processing unit using the DS-1 spare ion thruster
	• LANTR "Hot Fire" Demonstration
	  ○ Perform Unambiguous Hot Fire Demonstration of Lox Augmentation (30+% Thrust Gain)
	• Nuclear-based Magnetohydrodynamic Propulsion Energy Conversion
	  ○ Electrical conductivity will be measured in helium-3 at density ranging from 10^{-4} - 1 standard atmospheric density for comparison to computational models

Pulsed Inductive Thruster (PIT)	Objectives: • Design, build, and test a repetitive-pulsed power and delivery system for the PIT • Elevate PIT status as a viable candidate for multi-megawatt propulsion option to meet future demand on extreme high power missions in space
High Power Magnetoplasmadynamic Thruster	Objective • Demonstrate efficient high power MPD thruster operation at the MW-class power levels
Variable Specific Impulse Magnetoplasma Rocket (VASIMR)	Objective • Develop VASIMR technology with initial goal of 10-kilowatt thruster for space demonstration Status • Testing prototype thruster in chamber with hydrogen and deuterium propellants
Nuclear Electric Propulsion (NEP) End-to-End (non-nuclear) Demonstration	Objective • Demonstrate operation of a complete nuclear electric propulsion system, including a resistively-heated (unfueled) reactor core, power conversion system, power processing unit using the DS-1 spare ion thruster

Figure 6-5: Example in-space transportation technology activities.

Initial results of our prioritization are as follows:

Top three technologies:
- Electric Propulsion: Ion Thrusters
- Nuclear Thermal Propulsion
- Electric Propulsion: Hall Thrusters.

Top three technologies (safety emphasis):
- Electric Propulsion: MPD Thruster
- Electric Propulsion: Pulsed Inductive Thruster
- Electric Propulsion: VASIMR.

Top three technologies (cost emphasis):
- Electric Propulsion: Ion Thruster
- Electric Propulsion: MPD Thruster
- Electric Propulsion: Pulsed Inductive Thruster.

For our in-space transportation system studies, we are assessing multiple transportation systems per mission scenario in addition to the transportation system concepts provided to our exploration architecture team. As an example, figure 6-6 summarizes results from our Mars One-Year Study.

Earth-to-orbit transportation

NASA is currently studying technologies for a Second-Generation Reusable Launch Vehicle (RLV) through the Space Launch Initiative (SLI). The specific goals of the SLI are to improve the safety of a second-generation system by two orders of magnitude—equivalent to a crew risk of 1 in 10,000 missions—and to decrease the cost ten-fold to approximately $1,000 per pound of payload.

While these goals meet our requirements for safe human transportation to orbit, the SLI goals are not aggressive enough to meet our Vision requirements for cargo delivered to low-Earth orbit (ref. 11). Our objectives for Earth-to-orbit cargo delivery capability include a 100x reduction in the cost of mass-to-orbit with a high launch rate and sustainable systems (figure 6-7).

To overcome this technology gap, we must augment funding for both traditional and non-traditional propulsion technology options to allow a realistic assessment of the potential to meet our cargo-to-orbit requirements. We are currently studying "gun launch" options for "insensitive cargo" delivery to low-Earth orbit (ref. 12). Mission requirements for gun launch options are:

- Payload mass up to 500 kg resulting in a 1,000 kg to 2,000 kg launch mass
- Launch velocity of 7 to 9 km/sec
- 1,000,000 lbs. of payload per year to orbit.

Transportation System Scenario	Assessment Summary
Abundant Chemical via "Gun Launch"	• 3,550 MT total IMLEO • No. of Launches: 47 (42 cargo/5 crew; Delta IV-H launch system)—excludes propellant launches via gun • MAJOR ISSUE: Cost-effective gun launch system and supporting on-orbit aggregation and processing infrastructure (three separate elements) must be developed and in place. No capability of this type currently exists • SYSTEM LEVEL TRL: 2
Momentum Tether / Chemical	• 1,306 MT IMLEO (excludes tether facility, which supports other mission applications) • No. of Launches: 44 (40 cargo/4 crew; Delta IV-H launch system) • MAJOR ISSUE: Requires an on-orbit infrastructure • SYSTEM LEVEL TRL: 3
Minimagnetospheric Plasma Propulsion (M2P2)	• Very promising for missions > 1 year • MAJOR ISSUE: Cannot meet the 1-year total trip time requirement • SYSTEM LEVEL TRL: 1
Nuclear Thermal Propulsion	• 493 MT total IMLEO • No. of Launches: 21 (17 cargo/4 crew; Delta IV-H launch system) • MAJOR ISSUE: Requires significant propellant to meet the trip time requirement • SYSTEM LEVEL TRL: 4
Nuclear Electric Propulsion	• 987 MT total IMLEO • No. of Launches: 32 (23 cargo/9 crew; Delta IV-H launch system) • SYSTEM LEVEL TRL: 3
VASIMR (with Nuclear Power)	• 404 MT total IMLEO • No. of Launches: 14 (10 cargo/4 crew; Delta IV-H launch system) • MAJOR ISSUE: Validation of the propulsion concept • SYSTEM LEVEL TRL: 2-3
Solar Electric Propulsion	• IMLEO: 3,941.7 MT (assumes availability of ultra-light power system technology) • Crew Mission Duration: 365 days • Total Mission Operation Time: ~10.2 years • No. of Launches: 121 (110 cargo/11 crew; Delta IV-H launch system)
SEP/Chemical	• IMLEO: 434 MT • Crew Mission Duration: 365 days (a=23) • Total Mission Operation Time: ~6.4 years • No. of Launches: 16 (11 cargo/5 crew; Delta IV-H launch system)

Figure 6-6: Mars 1-year transportation study results summary.

Examples of gun launch systems under study include:

Blast wave accelerator. This concept utilizes well-timed chemical detonation (blast) waves to accelerate the projectile (figure 6-8). Limited testing has been performed to date. Achievable velocities are >10 km/sec. Past analytical and computational efforts have been limited to ideal calculations.

Slingatron. The Slingatron accelerates a projectile by Coriolis force. This Coriolis force is generated by driving a small-amplitude "hula-hoop" motion of the entire accelerator tube using rotary drive machinery distributed around the circular path (figure 6-9).

Electromagnetic launch concepts. Examples include the Coil Gun which accelerates a particle with a traveling magnetic pressure wave, and the Rail Gun which accelerates a particle using Lorentz force.

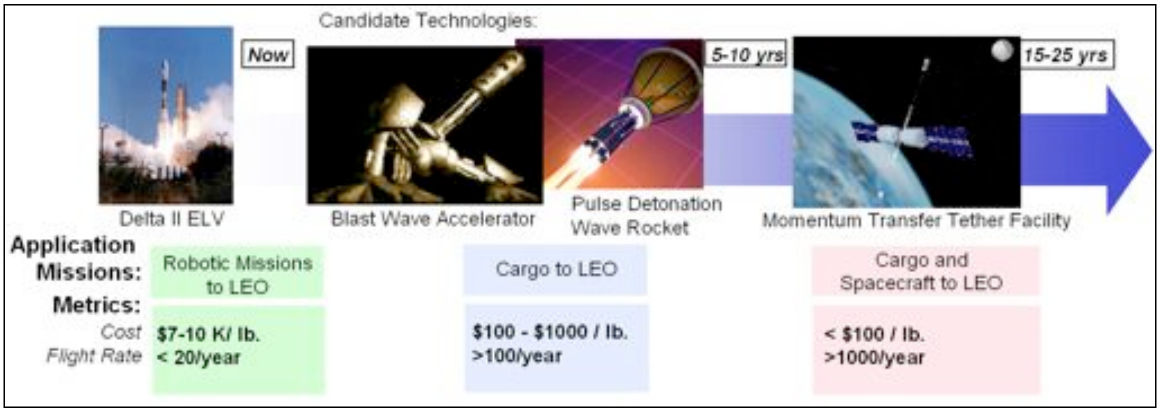


Figure 6-7: Breakthrough Earth-to-orbit technology needs.

Figure 6-8: The Blast Wave Accelerator.

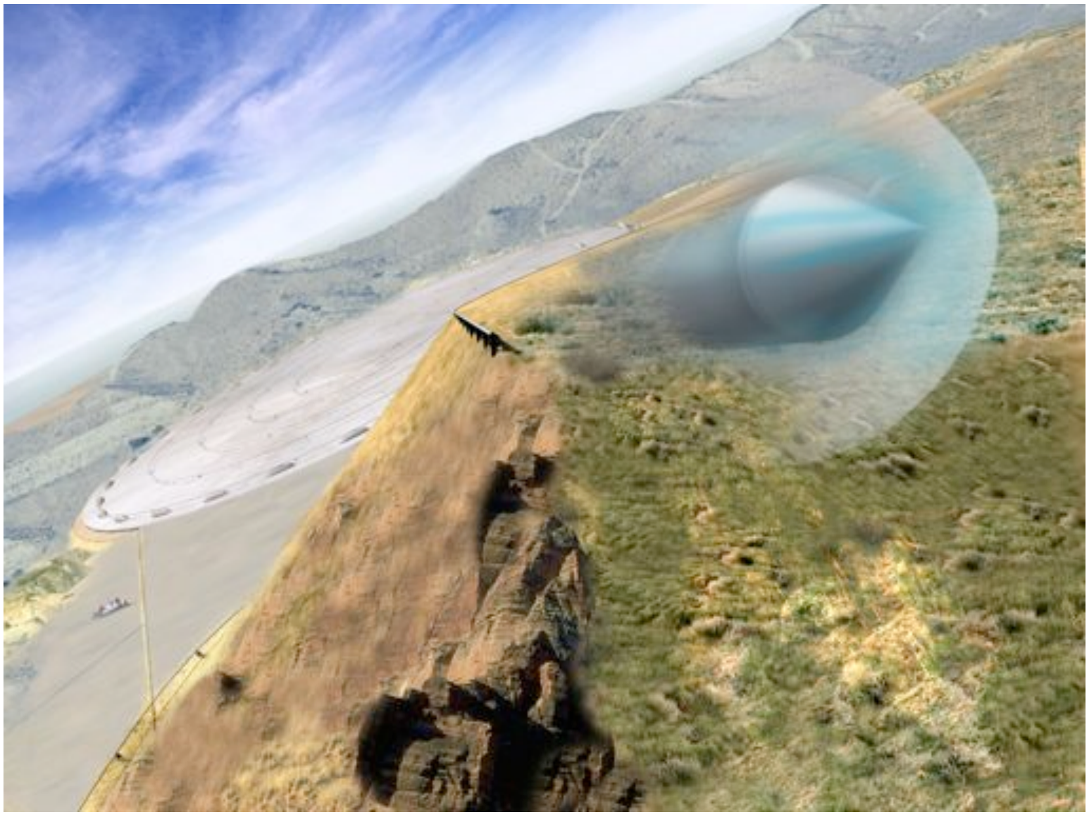


Figure 6-9: The Slingatron.

Power System Technologies

Our purpose for pursuing breakthrough power systems technologies (figure 6-10) is to establish the capability to provide abundant, affordable energy wherever needed for exploration (refs. 13, 14). Goals for our development activities include: establishing robust sources of power for in-space, surface and transportation systems; reducing the cost of human-robotic exploration missions; and establishing a foundation for commercial space power systems and/or applications in the future.

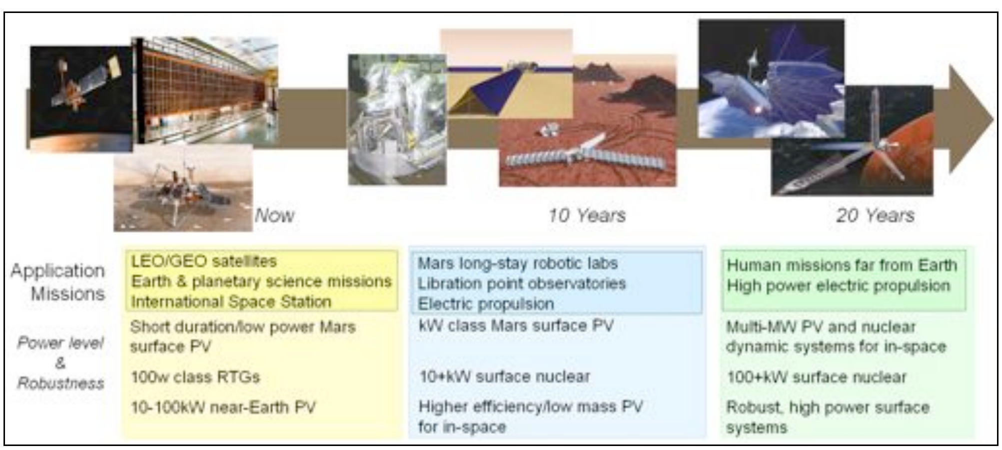


Figure 6-10: Breakthrough power systems technology needs.

We are accomplishing these goals by:

- Identifying performance-enabling technologies. High-payoff technology candidates include: thin film and high-efficiency photovoltaic cells/arrays; advanced dynamic and static conversion; high-temp/high-strength materials; high-density energy storage; high-efficiency power management/distribution; and lightweight, deployable structures
- Generating technology development plans/road maps/budget
- Conducting conceptual design and analysis of in-space and planetary surface power systems.

NASA Glen Research Center (GRC) activities for FY2000 in pursuit of these goals include:

- Developing designs for Mars surface power options. Options have been developed for 30-day short stay and 500-day long surface stay mission scenarios. Power system concepts utilizing flexible tent arrays have been developed for a mission near the Mars equator
- Establishing a power systems trade space (figure 6-11)
- Defining nuclear and solar power systems pros and cons (figure 6-12)
- Establishing power system specific mass
- Identifying and assessing in-situ Mars power concepts
- Supporting related nuclear and electric propulsion/transportation activities.

Applications	Nuclear	Isotope	PV only	PV/RFC	PV/Batt	FC/RFC	Batt.	Beam	Power Level
LEO Fuel Depot	X		**X**					X	~3 MW
BNTR	**X**					X			30-50 kW
NEP	**X**								30-50 kW/100 kW-MMW
SEP/Chem				**X**	X				20-30 kW/1-2MW
Ascent/Descent/Re		X				**X**	X		3-5 kW
30 day Mars	**X**	X		X	X	X			10-20 kW
500 day Mars	**X**								60-100 kW
10 hour rover		X				**X**	X		crewed, 1-3 kW
Multi-day rover	X	**X**		X		X			crewed, 5-10 kW
Mars mobile drill	X	**X**		X		X		X	1-5 kW
14 day lunar	X	X	**X**						2-100 kW
45 day Lunar	**X**	X						X	10-100 kW
Lunar S. pole	**X**	X	**X**			X	X	X	2-100 kW
L2	X		**X**	X				X	2-10 kW

(shaded box; shaded cells shown in bold) = Preferred concept

Figure 6-11: Power systems trade space.

Mars in-situ power concepts

Utilization of Mars in-situ resources such as wind, areothermal, geothermal and solar energy for support of a crewed mission have been assessed by the space power community at large and by NASA GRC. In general, these energy sources are low density and require large infrastructures to harvest the required energy and convert it to electricity. The most promising of these sources is solar energy since it draws upon the technology base of NASA, commercial, and military in-space applications. Solar energy varies hourly and yearly, but is predictable—except for magnitude and duration of atmospheric dust obscuration of the Sun and power output loss rate of settled dust on the array. Recent studies show that solar power appears applicable for small (up to 10 kW), short-duration power needs. Analysis, testing, and flight experiments have been proposed to develop the ability to mitigate dust accumulation necessary for long-duration use of solar arrays.

Solar Power	
Pros	**Cons**
• Avoids political and programmatic issues associated a nuclear development program • Simplifies the safety review & launch approval process • Leverages current technology development (terrestrial & space) • Synergistic technology with SEP & large scale Space Solar Power	• Scalability in packaging and deployment of large arrays • Relatively low insulation at Mars surface due to distance from Sun and atmospheric dust • Accumulation of dust on array surface • Sensitivity to diurnal, seasonal and latitude variations • Requires energy storage for night operation • Cost and reliability
Nuclear Power	
Pros	**Cons**
• Constant day/night power at any latitude • Power production nearly insensitive to planetary environment (e.g. dust, temp) • Mass and volume scale favorably with power output • Brayton power conversion heritage - 10kWe/38,000 hours (1970's) • Negligible Curies at launch	• Public perception/political resistance • Rigorous safety review process • Deployment of reactor cart and radiators • Development of kV power transmission • Integrated nuclear system testing • Cost and reliability

Figure 6-12: Solar and nuclear power pros and cons.

Robotic/EVA Technologies

The goals for NASA robotic/EVA technologies research are to: enable a much more robust set of options for affordable implementation of modular space systems and missions; drive down the cost of human exploration missions and campaigns beyond Earth orbit; and establish a foundation for commercial space assembly, inspection and maintenance systems and services in the mid- to far-term (ref. 15, figure 6-13).

We are pursuing these goals with the following objectives:

- Develop and validate technologies for the space assembly of large systems
- Enable the autonomous and/or tele-presence inspection of space systems
- Advance remote or shared control of these capabilities in near-Earth and interplanetary space

- Develop and validate the capability to extend the life and reduce the costs of a new generation of space systems through repair, refueling, upgrades and re-use of components from one system to another
- Minimize the impact of space system failures by enabling easy access for repair—thus reducing system-level functional redundancy (and associated costs)
- Enable a reduction in the total mass launched to orbit for given mission architectures.

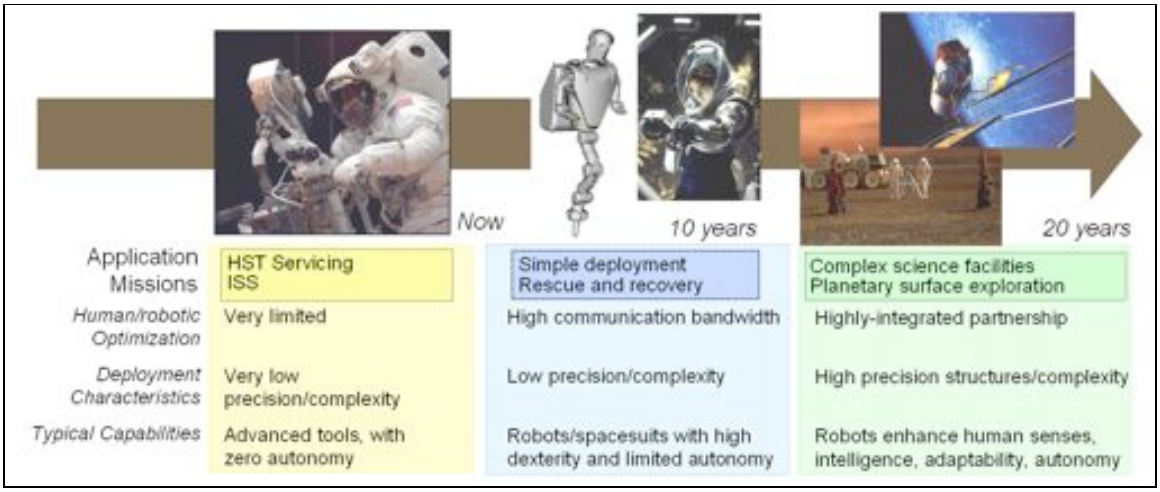


Figure 6-13: Breakthrough robotics/EVA technology needs.

Our "leading candidate" technologies include:

- Advanced fabrics for spacesuits: high strength-to-flexibility ratio
- "Smart fabrics" for spacesuits with embedded sensors and control systems
- Advanced materials for robots: high strength-to-weight ratio
- Information technology: increased autonomy of robotic systems including optimized integration with humans
- High communication bandwidth among robots and humans
- Advanced sensors: multi-band vision, increased dexterity and delicacy, multi-level feedback systems.

Robotics

Robots will play an ever-increasing role as we search for life beyond the Earth, erect space structures to support research and commercial activities in space, and undertake research missions that would be extremely costly and dangerous if performed by people. The robots that we envision will have to operate autonomously. They will have to monitor their environment, dynamically adapt to unexpected events, and operate reliably throughout a mission.

Robotics technology will be employed in all domains of future space activity, and robotics research must focus on issues that are critical to the growth of each domain (figure 6-14).

Requirement/ Utilization	Functionality and Research Needs
Reliability	• Robot mechanical and computational reconfiguration and redundancy must achieve the reliability necessary for lifetimes of years, millions of cycles of operations and potentially thousands of kilometers of travel • Computer hardware and software architectures must be robust to radiation-induced upsets and must adapt to changes in system behavior resulting from electrical or mechanical damage or environmental shifts
Autonomy	• Research must imbue robots with independent reasoning which will eliminate the need for persistent oversight by humans • Future robot operators should be able to direct complex tasks with a specification of the goal and constraints • Should a robot require assistance when presented with a particularly difficult task or in an emergency, the robot operator must be able to supercede the automatic functionality, controlling the robot at the level of manipulation or locomotion
Robot Team Coordination	• Building construction and regional planetary survey are campaigns beyond the capability of any one robot. Bold agendas such as these will require teams of autonomous agents working in concert • Robot teams must be able to organize themselves to perform successfully and efficiently despite team member heterogeneity, equipment malfunction and constantly evolving goals
Robots for Labor	• Robots will be required to construct large-scale orbiting facilities which may be kilometers in extent and composed of millions of elements; space solar power facilities are envisioned in geosynchronous orbit whose harsh radiation environment may eliminate the possibility of employing human construction crews • Software architectures and communications networks must support the coordination of robots, which will walk and work together to build and maintain, where success is ensured despite occasional robot failure • Surface robots must be light enough for transportation to a planetary surface but massive enough for earth moving operations

Robots for Exploration and Discovery	• Robots will take a greater role in planetary surface exploration, both independently and alongside astronauts
	  o Future robots will handle the repetitive or time-consuming tasks of data collection, leaving humans to handle the high-level interpretation of information
	  o Research must drive autonomous science and discovery capabilities far beyond the current level, enabling efficient geologic and biologic surveys of vast regions
	• On a planning level, robots must be able to determine the path across a planetary landscape which will lead to the greatest scientific information gain, and optimize its collection and use of solar power and other resources
	• Interaction between humans and robots will require new interfaces, with speech and gesture recognition, which are natural for the humans and effective for scientific field use

Figure 6-14: Robotics research issues.

Crew Health and Safety

Exploration crew health and safety issues are the responsibility of the NASA Bioastronautics Research Division at NASA JSC. Goals of this research division are to identify and understand crew health and safety risks, reduce uncertainties associated with predicting them, and manage risks by preventing them or reducing their effects to acceptable levels (refs. 16-21).

Our general philosophy for NEXT-related Bioastronautics activities (figure 6-15) is to pursue tasks that are more speculative or have breakthrough potential in previously defined areas of research, and to invest in critical key risk mitigation areas to enable success within the scope of the NEXT thrust on an accelerated schedule. Three areas for accelerated Bioastronautics research related to NEXT have been identified:

- Radiation protection beyond low-Earth orbit (research and technology)
- Development of advanced technologies for autonomous human operations
- Definition and validation of an artificial gravity concept.

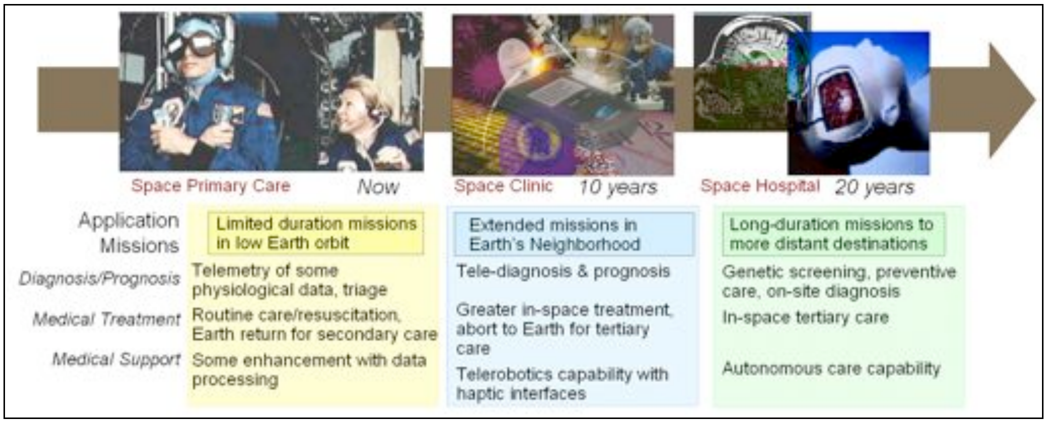


Figure 6-15: Crew medical care technology needs.

Medical care

Clinical problems and resulting medical care challenges for human space explorers are anticipated to include:

- Expected illnesses and problems (orthopedic and musculoskeletal problems; infectious, hematologic, and immune-related diseases; and dermatologic, ophthalmic, and ear/nose/throat problems)

- Acute medical emergencies (wounds, lacerations, and burns; toxic exposure and acute anaphylaxis; acute radiation illness; dental, ophthalmic, and psychiatric)

- Chronic diseases (radiation-induced problems; responses to dust exposure; and presentation or acute manifestation of nascent illness).

Providing clinical care in space to address these health issues (figure 6-16) will be complicated by factors such as limited resources (mass, volume, power, bandwidth); medical training and expertise of the crew; distance from specialized facilities and the impracticality of evacuation; and the non-ideal space environment (radiation, vacuum, isolation and confinement, microgravity or partial gravity, recycled air and water).

Technology Areas	Issues and Description of Technology Need
Adaptation and Countermeasures	• Countermeasures are necessary to maintain health and performance during flight and upon return to Earth • Adaptations to space flight including fluid shift which initiates cardiovascular changes, continual bone demineralization, muscular atrophy, initial neurosensory and neuromotor dysfunction during transition between different gravity environments (e.g., space motion sickness), etc. • Further technology development is needed for countermeasures involving exercise regimens, pharmacologic supplements and/or enhanced nutrition, neurosensory and neuromotor monitoring and stimulation, and exploration of artificial gravity as a multi-system countermeasure
Health Care Systems and Clinical Care	• Broader range of health care capabilities are needed as medical evacuation to Earth becomes more impractical • Modeling and simulation technologies • In-flight systems to perform in-vivo, non-invasive analysis and to process/downlink data (biosensors to monitor blood chemistry, pulmonary gases, and metabolites; telemedicine systems for orbital operations, etc.)
Advanced Human Support	• Life support and environmental monitoring o Highly reliable, self-sufficient life support systems that minimize mass, power, volume and crew time requirements o Real time, autonomous monitoring of air, water and food for microbial and chemical contamination • Crew accommodations o Exploration missions require self-sufficient and highly reliable systems and resources o Technology needs include: repair and maintenance systems without Earth support, extension of shelf life for diet needs, decision-support systems for critical event response
Crew Performance	• Human factors o Non-intrusive methods for monitoring individual/group performance over time o Autonomous means for information capture and collection o Improved user interfaces and displays • Training o Advanced computer and simulation systems o Onboard training systems for new or infrequent tasks • Psychosocial health o Continuous, integrated assessment of mental status o Means for personal communications and recreation through interactive systems o Adaptive diagnostic system
Radiation Risk and Mitigation	• Technology development is required to reduce radiation effects o Monitoring the radiation environment and dose equivalent received o Predicting changes in the radiation environment o Development of radiation shielding and pharmacology • Specific technologies include: o Active, solid state, personal radiation dosimeter o Neutron dosimeter o Solar particle event early warning system o Improved models for the radiation environment, shielding, and radiation transport o Chemical and biological modifiers and radioprotectants o Improved composite materials for radiation and hypervelocity impact shielding

Figure 6-16: Bioastronautics/medical care technology areas.

To address space adaptation and countermeasure issues the Bioastronautics Research Division sponsored an artificial gravity workshop in January 2000. The purpose of this workshop was to debate the merits of artificial gravity as a countermeasure (ref. 22) and to develop a research and development plan. Workshop conclusions included:

- Artificial gravity may be most effective if combined with existing countermeasures
- Artificial gravity research should not preclude other countermeasure research and development activities
- Modeling cannot substitute for systematic studies of the human response to artificial gravity.

Radiation protection

The natural space radiation environment is comprised of interplanetary galactic cosmic rays, high-energy solar protons, and protons and electrons trapped in planetary magnetic fields. Interactions of these radiations with condensed matter can produce secondary fields of high-energy neutrons and photons. Astronauts face potential, unquantified health risks from this radiation during and after mission completion including radiation sickness, cancer induction, central nervous system damage, cataracts and hereditary risks.

Additional resources and facilities are needed to qualitatively understand the radiation biology associated with human interplanetary flights and to establish dose limits. Recommendations by the National Academy of Science, National Council on Radiation Protection and Measurements, and the radiation protection community have remained constant since 1970:

- Develop a sustained heavy ion accelerator capability to simulate space radiation
- Determine relative biological effectiveness factors for protons and heavy ions using animal cancer models
- Perform critical research to optimize use of data to predict cancer risks in humans
- Perform research to understand effects of heavy ions and protons on the central nervous system (CNS)
- Use new radiobiology knowledge and data to develop optimal shielding approaches
- Develop technologies to provide better advanced warning of solar particle events
- Perform research on development of biological countermeasures
- Understand the role of individual variations in radiation sensitivity.

The Bioastronautics Research Division is developing the Integrated Space Radiation Protection Plan to achieve radiation safety goals (refs. 23-25). In response to the above recommendations, the Bioastronautics Research Division is supporting the construction of the Booster Application Facility at Brookhaven National Laboratory with planned completion in 2003. This facility will allow NASA to collect critical data and perform research to reduce the uncertainties in risk projection and develop effective mitigation approaches.

NEXT is also currently sponsoring a radiation protection study titled *Summary Health Risk Evaluation for Alternative Exploration Scenarios* to evaluate risk for cancer incidence and mortality for L_2, Lunar, and Mars missions. In this study we are:

- Considering shielding/material approaches
- Exploring approaches to quantify CNS and cancer risks
- Estimating the potential role of countermeasures (operational, biological, pharmacological)
- Evaluating technology readiness of solar particle event protection
- Evaluating the necessity for new shielding and physical and biological dosimetry technologies
- Establishing the baseline correlation between shielding weights and risk reduction.

Materials Technologies

Our focus in evolutionary and breakthrough materials technologies (figure 6-17) emphasizes the analyses of requirements for specific mission applications and the assessment of materials identified as candidates for these applications.

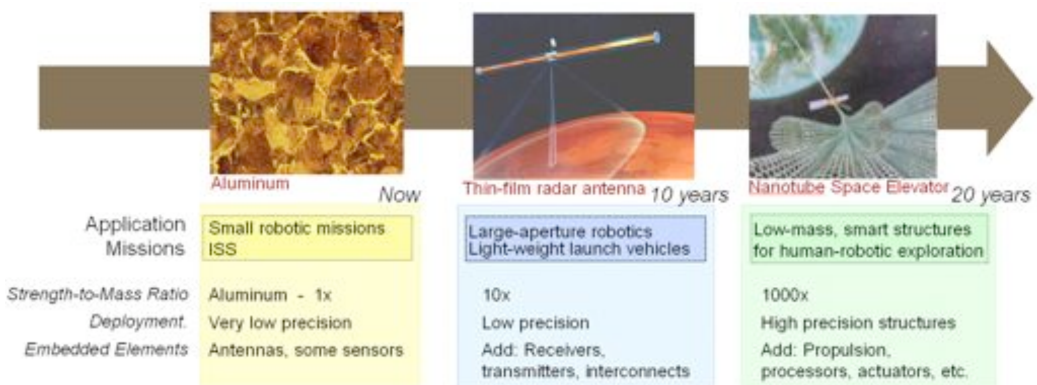


Figure 6-17: Breakthrough materials technology needs.

Mission applications under consideration include space access vehicles; planetary entry vehicles; in-space vehicles and propulsion systems; and avionics and electronics (figure 6-18).

Our materials assessments include the following activities:

- Perform complete scans for materials and properties data
- Assess the state-of-the-art and identify the most attractive materials options
- Conduct systems analyses to evaluate the trade-off in material systems properties
- Develop first-order technology maturation strategies
- Develop list of recommendations including investment strategy.

Application	Advanced Materials Requirements
Space Access Vehicles	• Nanostructured, functionalized materials for ultra-lightweight, highly efficient structure • Integrated thermal structure/TPS/cryo-insulation • High temperature, durable materials for propulsion components • Integrated vehicle health monitoring/management system for high reliability • Validated, physics-based computational tools for reliability-based design methodology
Planetary Entry Vehicles	• TPS materials and concepts to enable vehicle to change directions • All-weather, self-diagnostic, and self-healing TPS materials • TPS materials/concepts constructed from in-situ resource utilization
In-Space Vehicles and Propulsion Systems	• Cryogenic propellant tanks and novel vehicle configurations • Radiation shielding materials and integrated vehicle/habitat configurations • Self-assembled, self-diagnostic, and self-healing materials and in-space fabrication methods • On-site habitat construction using regolith mining and fabrication methods
Avionics and Electronics	• Wide bandgap semiconductors for high-temp, high-power, and high-strength microelectromechanical systems (MEMS) devices • Multifunctional materials • Nanostructured, functionalized materials for nano-electromechanical systems (NEMS) devices • Biomimetic materials for electronic devices and molecular computing

Figure 6-18: Exploration applications and advanced materials requirements.

In the near-term, numerous advanced materials exist that have attractive properties and can mature to a technology readiness level (TRL) of +6 within five to ten years or less, but only with a compelling technology pull and the associated resource investment. In the far-term, biomimetic, nanostructured materials, especially carbon nanotubes, are attractive for every materials application but dramatic breakthroughs will be required to realize the potential of the materials systems within the next 10-20 years.

Applications of new materials must be evaluated in a systems context. For example, advanced structural design methods and highly efficient structural concepts will be required to fully exploit the potential benefits of biomimetic, nanostructured, multi-functional materials in revolutionary aerospace vehicles. Also, the building-block approach to manufacturing scale-up will be essential to validate the advanced materials and concepts.

A nanotube application—sensors for space missions

Carbon nanotube (CNT) is a remarkable material with an unprecedented combination of mechanical, thermal and electronic properties. Though naturally inert, it can be chemically functionalized. With such a breadth of characteristics, CNT lends itself, perhaps better than any material to date, for multifunctional applications. Examples of potential NASA applications for CNTs include sensors for astrobiology, and imaging and characterization tools for atomic force microscopy using nanotube tips.

However, the history of this material development is very short and numerous challenges related to synthesis, design, and characterization need to be addressed to exploit CNT for space applications:

- Growth control. Regardless of the growth approach, control of diameter and nature of the CNT (semiconductor vs. metallic) is not possible at this time. Growth mechanisms are unknown and currently unpredictable. It is critical to know what controls the diameter and chirality and develop the capability to select the type of nanotubes based on application needs. Growth at low temperatures is also desirable

- Limited yield. Yield must be improved so that post-processing operations such as purification/separation can be minimized or eliminated

- Functionalization. Identification of molecular groups, through modeling and simulation, which can be "glued" to the nanotubes is a necessary capability to control and optimize CNT functionality.

A project currently underway at the NASA Ames Research Center (ARC) focuses on carbon nanotube-based sensor development for space missions (ref. 26). Ultrasmall and highly sensitive sensors for the detection of analytes and other molecular elements are of great interest for space missions, medicine, biotechnology and environmental monitoring. The tasks in this project include synthesis through plasma-enhanced chemical vapor deposition, chemical functionalization, and extensive characterization to demonstrate appropriate characteristics for sensor design.

It is the intention of this effort to address the above challenges using a combination of experiment and theory, i.e., synthesis, process diagnostics, material characterization and testing, sensor design, modeling and simulation.

Survey of advanced materials

The following information on exploration applications for advanced materials is from a survey of five NASA Field Centers conducted by NASA LaRC in July 2000 (ref. 27):

Structural materials for vehicles and habitats. Carbon-fiber-reinforced polymers, metal-matrix composites, and intermetallics may offer a factor of two gain in weight savings; carbon-nanotube-reinforced polymers (and metals) may offer a factor of ten gain in weight savings.

Structural materials for propulsion components. Ceramics may offer a factor of two gain in temperature range, but may never become attractive for structural design. Advanced metallic alloys and intermetallics may offer a factor of two gain in weight savings, but only modest temperature improvements; polymer matrix composites, including carbon nanotubes, may offer significant weight savings but at a reduction in the usable temperature range.

Materials for radiation shielding. Near-term gains by selecting structural materials may offer only modest improvement in shielding potential; additional improvements in radiation protection may be achieved with vehicle and habitat configurations.

Thermal protection systems. Breakthroughs will not come from improved material properties, but from revolutionary concepts and capabilities such as sharp leading edges, rapid heat transfer, all-weather durability, self-diagnostics, and self-repair.

Electronic and photonic materials. Dramatic breakthroughs will occur from functionalized nanostructured materials enabling the fabrication of nano-electromechanical systems.

Information Technology

Information Technology (IT) has a unique role in human exploration of space because it is an infrastructure technology which enables other technologies and capabilities (ref. 28). As such, the application of IT must be considered from a system viewpoint rather than in isolation. As an infrastructure technology, IT is crosscutting and affects many areas such as life cycle design, ground operations, transportation, and surface operations. In addition to impacting many application areas, IT also facilitates increased safety.

In assessing the potential impact of IT on human space exploration, there are two prime areas of consideration: increasing safety and reducing cost. In these areas, IT applications have been identified that potentially have the greatest impact. For increasing safety, the IT application with the greatest impact is Vehicle Health Management (figure 6-19). For reducing cost, the IT applications with the greatest impact are Automated Assembly and Automated Operations.

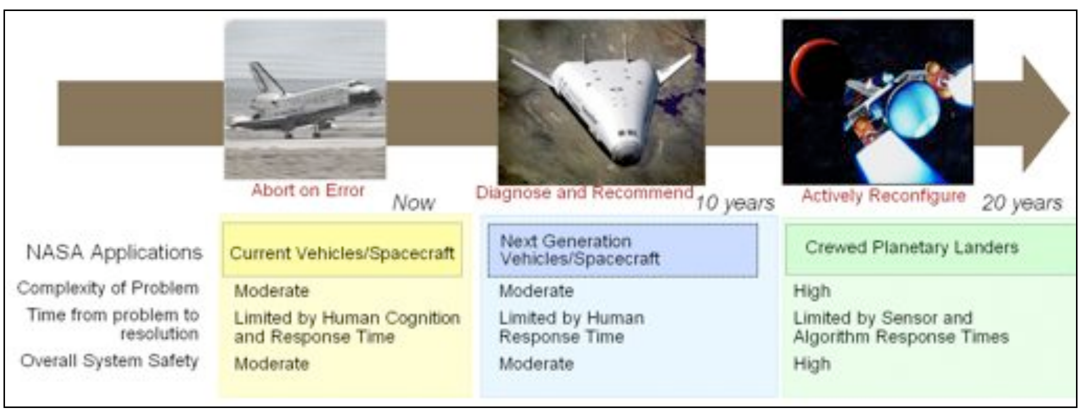


Figure 6-19: Breakthrough vehicle health management technology needs.

Although the range of IT applications supporting human space exploration is large, we can group them into five major areas and sub-areas:

- Vehicle Health Management
  - Launch vehicles
  - Transit vehicles
  - Safe landing/hazard avoidance
- Automated Assembly
  - On-orbit assembly of transit vehicles
  - On-orbit assembly of observatories
  - Human surface habitat assembly
- Automated Operations
  - Automated life-support
  - Unattended in-situ resource production
- Autonomous Science
  - Rover-based science mapping
  - Human exploration extensions
- Human Amplification
  - Spacecraft design automation
  - Flight control automation
  - Astronaut "cyber-suits."

Vehicle health management

Vehicle Health Management (VHM) encompasses all areas involving the health and safety of a vehicle including flight control, thermal management, system monitoring and diagnostics, fault isolation and recovery, and hazard identification and avoidance. Some VHM applications involve passive techniques, such as thermal tiles, while others involve active techniques requiring high levels of system intelligence. The latter are targets of Information Technology.

Automated assembly

Automated or robotic assembly involves the construction of large structures, either in zero gravity or on planetary surfaces, without direct human manipulation capabilities. This may be accomplished either with human-in-the-loop teleoperation of robotic manipulators or with autonomous robotic systems commanded at a relatively high level. The objective of robotic assembly is to enable the construction of vehicles, instruments, or habitats in environments either too hazardous or costly for humans to function.

Automated operations

Automated operations involve control systems capable of operating complex systems without direct human control. This is very similar to advanced industrial automation in which a physical plant or process is supervised but not directly controlled at a low-level by the human operator. In the NASA application, the automated system must be able to operate for longer periods of time under harsh conditions and make complicated decisions with very limited human support due to time delays in communications.

Autonomous science

Autonomous science is the ability to conduct scientific investigations with systems in "collaboration" with humans rather than "remotely operated" by humans. The distinction is in the level of interaction required by the human scientist. A remote instrument must typically be told step-by-step what to do and has relatively little decision-making capability. An autonomous science platform will be able to accept a high-level science goal such as "characterize the geology of this site" and then generate and execute a plan to accomplish this goal. In the extreme case the platform will be able to generate and test simple scientific hypotheses.

Human amplification

Human amplification is an umbrella label encompassing the use of information or physical systems to augment a single human or a team of humans enabling them to accomplish a task better than they could alone. At one end of the spectrum are collaborative design tools that amplify a human designer's ability to quickly construct, model, and test spacecraft designs. At the other end of the spectrum are physical amplification systems that enable a weakened or disabled astronaut to perform tasks otherwise impossible.

References

Space Transportation Technologies

1. Johnson, Les, <u>In-Space Propulsion Options</u>, NASA MSFC.

2. Johnson, Les, <u>Transportation Technology Tasks Status</u>, NASA MSFC, May 2000.

3. Johnson, Les, <u>Transportation Technology Tasks Status</u>, NASA MSFC, September 2000.

4. Johnson, Les, <u>In-Space Technology Status</u>, NASA MSFC, NASA MSFC, April 2000.

5. Johnson, Les, <u>Exploration Transportation Systems Study</u>, NASA MSFC, May 2000.

6. Johnson, Les, <u>Transportation System Study Options for Mars Exploration Missions (Sweet Spot Analysis)</u>, NASA MSFC, September 29, 2000.

7. Johnson, Les, <u>Transportation System Options for 1-Year Round Trip Mars Exploration Missions in the Mid-Term</u>, NASA MSFC, September 29, 2000.

8. Johnson, Les, <u>Human Exploration Transportation Technologies Prioritization</u>, NASA MSFC, September 2000.

9. Hybrid Propellant Module and Fuel Aggregation Depot Concept, Fuel Aggregation Study Team, NASA LaRC, September 29, 2000.

10. Johnson, Les, Breakthrough In-Space Transportation Technologies, NASA MSFC.

11. Johnson, Les, Earth-to-Orbit Technology Status, NASA MSFC, April 2000.

12. Jones, Jonathan et al., Gun Launch Status Report, NASA MSFC, May 24, 2000.

Power System Technologies

13. Johnson, Steve, Power System Activities and Technology Status, NASA GRC, April 13, 2000.

14. Johnson, Steve, GRC Status Report for DPT Meeting, NASA GRC, September 11-13, 2000.

Robotic/EVA Technologies

15. Robotic Research at NASA and Carnegie Mellon University.

Crew Health and Safety

16. Bioastronautics—Wye River Retreat, Advanced Technology Integration Group, NASA JSC, October 12-13, 2000.

17. Bioastronautics—An Integrated Approach to Ensure Healthy and Safe Human Space Travel, Presentation to the OMB, September 21, 1999.

18. Bioastronautics—An Integrated Approach to Ensure Healthy and Safe Human Space Travel, Follow-up Discussion with the OMB, September 28, 1999.

19. Bioastronautics - An Integrated Approach to Ensure Healthy, Safe and Productive Human Space Travel, POP 2000 Budget Considerations.

20. John W. Hines and Marina A. Saltman, Medical and Biological Technologies for Human Space Exploration (2001-2020)—Fiscal Year 2000 Report to the NASA Decadal Planning Team, NASA ARC, September 1, 2000.

21. Dawson, David L. and John B. Charles, Bioastronautics Critical Path to Crewmember Certification for Exploration-Class Missions, NASA JSC, July 10-12, 2000.

22. Artificial Gravity Science.

23. Cucinotta, Francis A., A Coherent Radiation Protection Strategy For Deep Space Exploration, NASA JSC, July 10, 2000.

24. Integrated Space Radiation Protection Plan, Briefing to NASA Administrator, Space and Life Sciences Directorate, NASA JSC.

25. Space Radiation Health Project Road Map 2000.

Materials Technologies

26. Meyyappan, M. et al., Carbon Nanotube based Sensors for Space Missions, NASA ARC, December 2000.

27. Harris, Charles E., Survey of Breakthrough Materials, NASA LaRC, July 2000.

Information Technology

28. Hine, Butler et al., The Role of Information Technology in Human Space Exploration, NASA ARC.

VII. Exploration Paths and Technology Leveraging

A near-term leveraged technology investment and development program with annual evaluation is required to execute the stepping-stone approach and enable the decision space and pathways to achieving human permanence in deep space.

Introduction

The NEXT Vision requires careful attention to technology gaps, which warrant funding, as well as leveraging a wide range of ongoing technology investments using NEXT-based requirements. The goal is to pursue multiple promising technologies that will provide a decision space five or six years in the future with options based on varying funding levels (figure 7-1). This section describes the technology leveraging process and the resulting recommended technology development program.

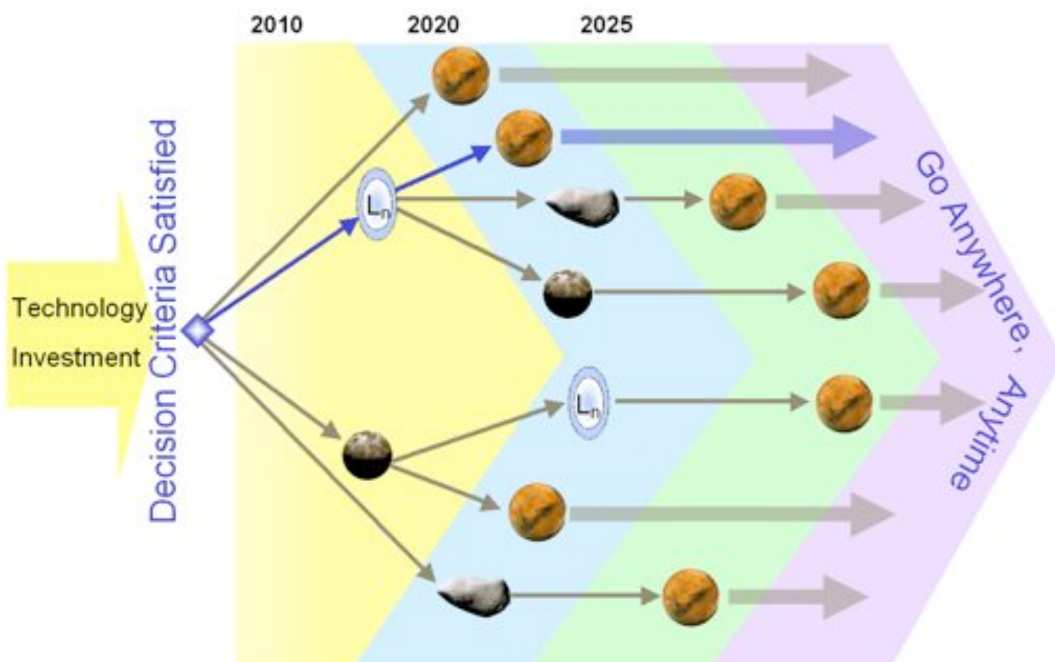


Figure 7-1: Optional paths with varying capability.

Technology Leveraging Process

The NEXT process to develop a technology portfolio and road maps is an annual Agency-wide and interagency approach. The team has evaluated existing technologies and technology development plans within NASA, at other government agencies, universities, and industry, to make the maximum use of any new funds. The team identified technology needs, as discussed in Section 6, then conducted a "gap analysis" to identify the gap between those needed technologies that are currently funded, whether internal or external to NASA, and those needed technologies that are not funded. The gap analysis included an exhaustive review of all existing NASA technology development programs to avoid overlap. The planning team also includes both formal and informal liaisons to the Department of Defense (DOD) which provide insight into which technologies the DOD is funding. The team revisits the gap analysis annually to take advantage of the newest developments. Figure 7-2 illustrates the breadth of the technologies evaluated.

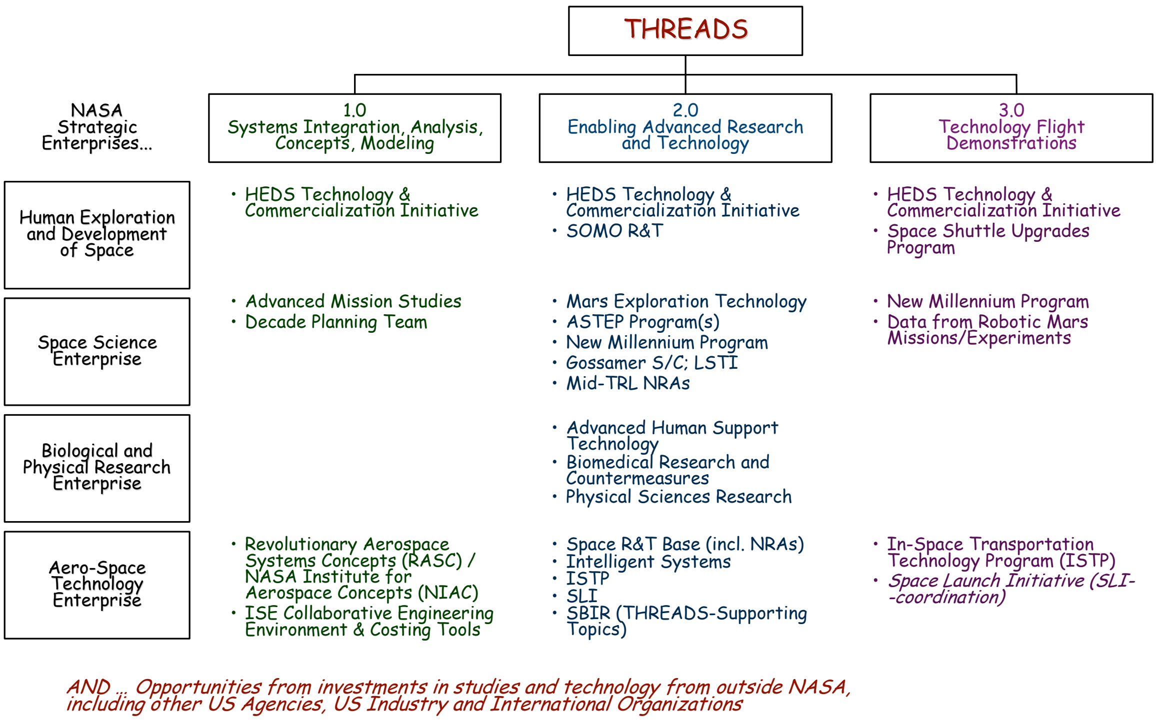


Figure 7-2: THREADS—an Agency-wide approach.

Technology for Human/Robotic Exploration and Development of Space (THREADS)

THREADS is the sum of all the technologies required to implement the NEXT Vision (figure 7-3, ref. 1). It is recommended, high-payoff, breakthrough technology. The gap analysis resulted in a "top 10" list of high-priority technologies without a current funding source (figure 7-4). NEXT developed funding requirements for those technologies and presented the proposed program to the OMB for a Fiscal 2002 new start. Unfortunately, International Space Station funding difficulties have deferred a new start for the entire proposed THREADS effort. However, as a result of this work, an extremely important portion of the desired space transportation technology development (ref. 2) did receive a 2002 start as the Integrated In-Space Transportation Program.

THREADS, if funded within the next year, will develop specific products by the 2007 timeframe to provide necessary information to make path decisions. Projected products include: an established knowledge base for microgravity and radiation effects and countermeasures for humans beyond LEO; a technology flight demonstration of 100 kW-class spacecraft; a flight validation of technology for a hybrid cryogenic propellant depot; a ground test bed validation of next-generation EVA systems; a flight validation of in-space assembly of >50-meter class hybrid structural systems, and a ground test bed validation of modular planetary systems concepts.

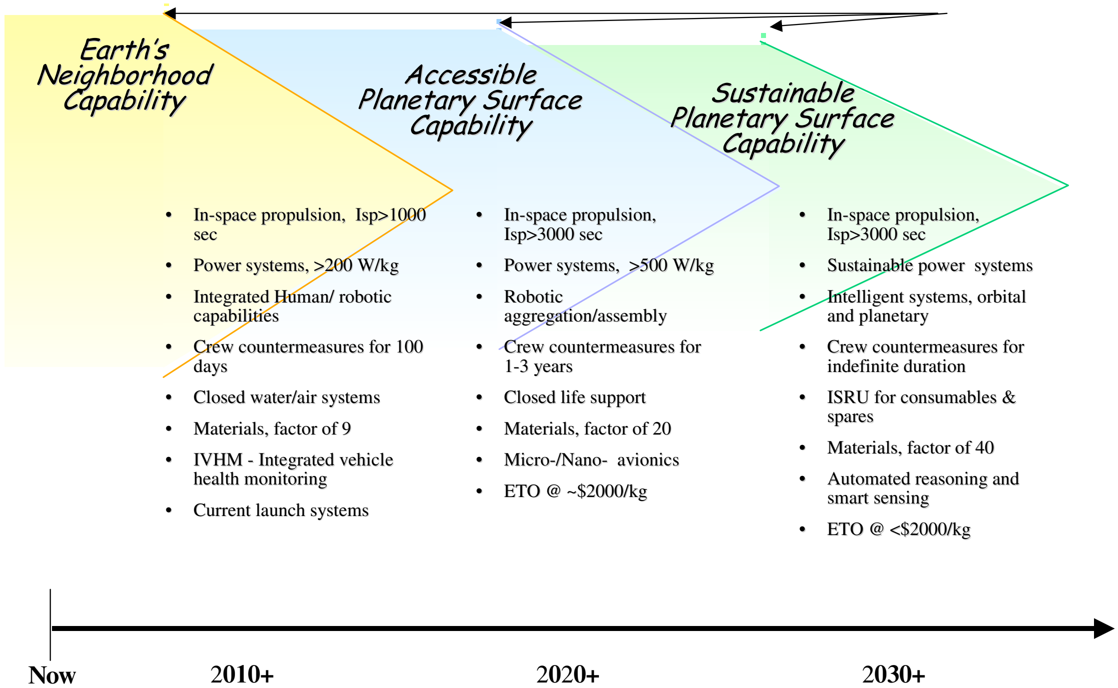


Figure 7-3: Progressive exploration capabilities—the NEXT/THREADS research and technology approach.

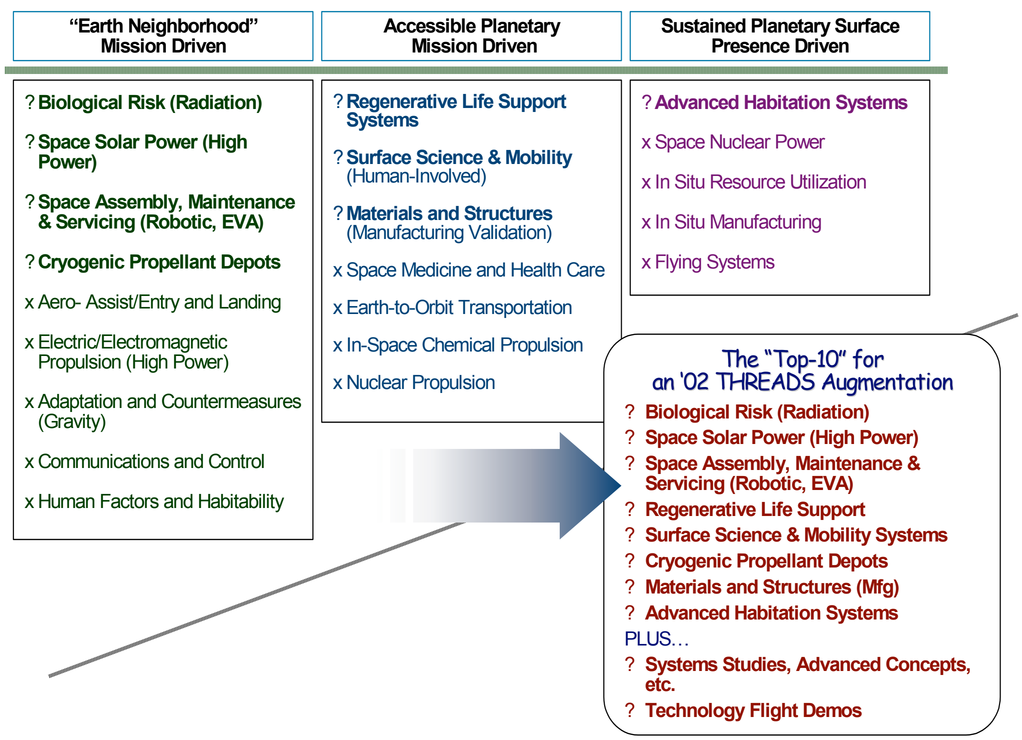


Figure 7-4: "Top 10" high-priority, unfunded technologies.

THREADS will generate a technology portfolio that provides a selection space for the Stakeholders (NASA's Senior Management) to consider. THREADS will populate several "what-if" scenarios under the assumption that one or more breakthrough technology investments will deliver flight-worthy capabilities during the next decade.

Technology Leveraging Example: MARS

The NEXT/THREADS leveraging strategy emphasizes investments that enable leveraging of existing NASA (or other Agency) programs and investments that support dual-purpose applications such as nearer-term NASA space science, commercial space, or other applications, followed by a down-select to higher-priority research and development investments.

In the example below (figure 7-5), THREADS needs (as defined by its work breakdown structure) are shown to be leveraged with Mars technology program investments in surface power; sample-return technologies; and entry, descent, and landing (EDL) technologies.

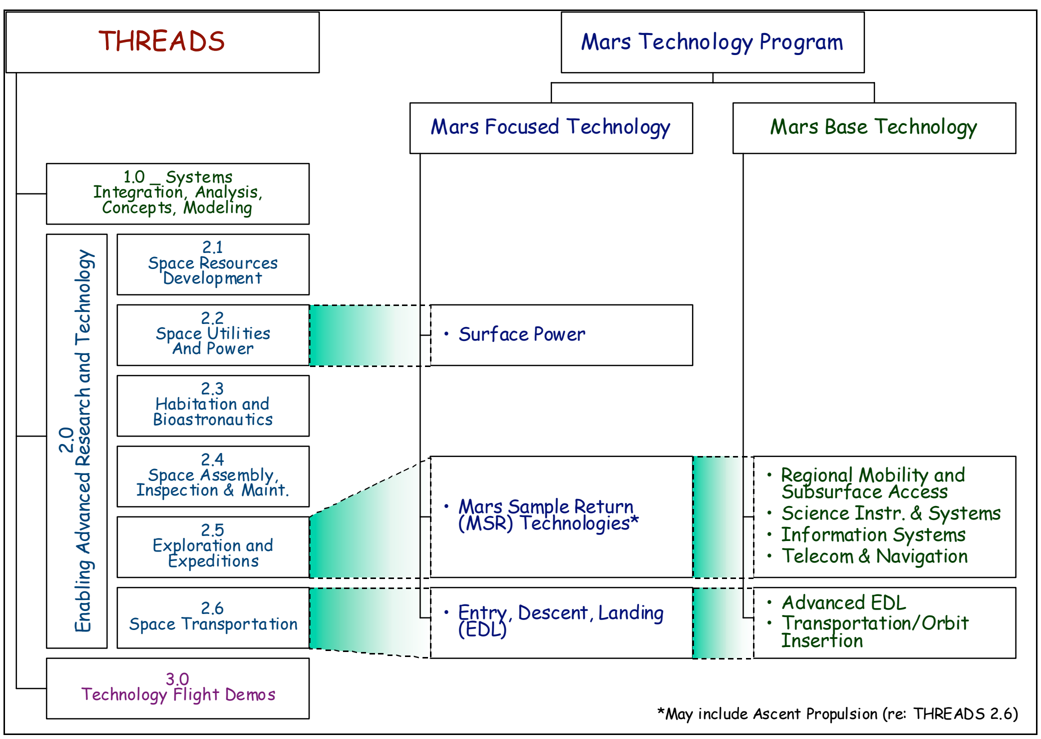


Figure 7-5: A leveraging example—the Mars technology program.

Technology Integration Focus for Fiscal 2001

THREADS priorities for Fiscal 2001 include: organizing available information on new concepts/technologies into a taxonomy to support further discussion/analysis; identifying "silver bullet" innovations from the initial set based on proposed criteria and within the proposed hierarchy/taxonomy; updating strategic research and technology road maps and developing an integrated package to support "bully pulpit" communications; supporting the NEXT in identifying and studying selected concepts; orchestrating all NEXT technology activities to assure strong connections to key technology programs; and further developing the strategy and tactics for technology leveraging.

References

1. Mankins, John C., Technology for the Human/Robotic Exploration and Development of Space [THREADS], NASA HQ, December 2000.

2. Johnson, Les, Human/Robotic Exploration and Development of Space Strategic Research & Technology Road Maps—Exploration Transportation Technology, NASA MSFC, June 9, 2000.

VIII. Partnership Opportunities

The strategy to implement the NEXT Vision includes partnership opportunities which will leverage NASA resources by benefiting from the interests, skills and resources of others.

NASA plans to establish and effectively use partnerships with other U.S. government agencies, international space agencies, universities, and industry where there is mutual benefit. NASA has existing interagency and international agreements and programs that can be catalysts for future partnerships. The NEXT has started to explore and leverage the existing relationships. Figure 8-1 summarizes partnering opportunities.

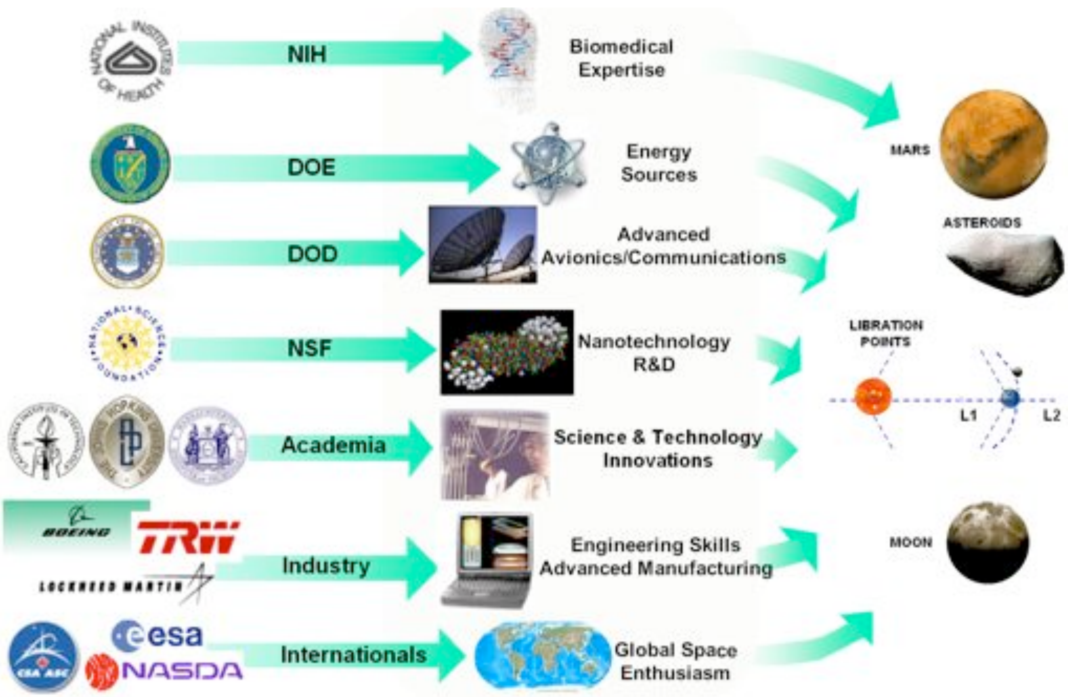


Figure 8-1: The NEXT Vision will benefit from effective partnerships bringing together unique skills and resources.

Interagency Cooperation

NASA already participates extensively in cooperative activities with other U.S. government agencies. They include partnerships with:

- The Department of Defense (ref. 1) to develop system technology and sensors for space applications
- The National Institutes of Health to develop smaller, more sensitive, and more specific medical sensors to monitor and treat astronauts on long-duration space missions
- The Department of Energy to characterize and study the effects of space radiation.

NEXT is tracking these existing partnerships and establishing working relationships with key personnel at these agencies to continue the dialogue for future opportunities.

International Cooperation

The Space Act established international cooperation as one of the objectives of the civilian space program. International partnerships help NASA achieve its goals by providing access to unique capabilities and expertise, increasing mission flight opportunities, providing access to locations outside the United States, and distributing the costs of discovery (refs. 2, 3).

NASA has well-established cooperative partnerships with other space agencies and will seek new opportunities for mutually beneficial cooperation in human-robotic space exploration activities with current partners, emerging space programs, and other appropriate international government agencies.

References

1. DiMarcantonio, Albert, An Analysis of the Report of the Commission to Assess United States National Security Space Management and Organization—Toward a Strategy and Opportunities for Interagency Technology Import/Export with an Objective of "Leveraging a Way out of LEO. Managing a Stay beyond Apollo," NASA DAA Interagency Enterprise, March, 2001.

2. Cline, Lynn F.H. and Jeffrey D. Rosendhal, An Assessment of Prospects for International Cooperation on the Space Exploration Initiative, NASA HQ, *Acta Astronautica* Vol. 28, pp. 391-399, 1992.

3. Cline, Lynn F.H., Primer on International Agreements, NASA HQ.

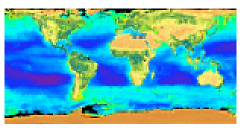
IX. Commercialization Opportunities

NEXT is building commercial opportunities at the onset. Through the Human Exploration and Development of Space Technology/Commercialization Initiative (HTCI), NASA is developing new capabilities for human space exploration and commercial development through partnerships with the private sector.

NASA Space Commercialization Goals

NEXT continues NASA's work establishing commercial opportunities for the human-robotic exploration of space. This activity is consistent with NASA space commercialization goals as documented in the NASA Strategic Plan (ref. 1) and the Human Exploration and Development of Space (HEDS) Enterprise Strategic Plan (ref. 2). Figure 9-1 illustrates examples of NASA's commercialization approaches.

- Merge government and commercial ventures/R&D to enable space activities



- Integrate commercially-provided capabilities into flight and ground systems
- Promote commercial use of space through non-traditional partnerships

- Encourage spin-off applications of space-based technologies

NATIONAL AERONAUTICS and SPACE ACT OF 1958
42 U.S.C. § 2451 et.seq

- Use the authority granted NASA in the Space Act to further commercialization

Figure 9-1: NASA is creating new approaches for the human-robotic exploration and commercial development of space.

The HEDS Technology/Commercialization Initiative (HTCI)

The NASA HEDS Enterprise implemented the HEDS Technology/Commercialization Initiative (HTCI) in fiscal year 2001. This cooperative program will explore options for—and the viability of—highly innovative new concepts and technologies that might dramatically lower the cost and increase performance of critical exploration technologies and/or system concepts (ref. 3).

NASA will use HTCI cooperative agreements to examine architectures that take advantage of potentially robust future commercial infrastructures that could dramatically lower the cost of future space activities.

HTCI research and development projects will focus on pre-competitive technologies and novel applications supporting high-risk and high-payoff opportunities that demonstrate strong potential for commercial space benefits.

The initial emphasis will be on technology development and demonstrations that allow safer, more affordable and more effective infrastructures and operations in Earth orbit and in near-Earth space. It is anticipated that these developments will provide a foundation for a broad range of future exploration missions.

The HTCI activities will result in the identification, refinement, analysis and validation of innovative architectures, infrastructures and systems concepts that can advance the emergence of key capabilities needed for future human exploration and commercial development of space activities, with particular emphasis on infrastructures that might meet the needs of both.

The HTCI also will validate the key results of studies through the identification, development and experimental testing of critical, sometimes-competitive technologies needed by those systems and capabilities. Where possible, these efforts will be implemented in partnership with industry to accelerate or enable the successful commercial application of these technologies.

In addition to advancing the HEDS strategic goal of enabling the commercial development of space, the HTCI also will advance several important HEDS strategic goals and objectives. They include establishing by the 2010 timeframe those capabilities needed to enable safe, effective and affordable 50-100 day human missions beyond low-Earth orbit. The HTCI also will advance the objective of establishing by the 2015-2020 timeframe those capabilities needed to enable comparable 300-1,000 day missions beyond low-Earth orbit.

HTCI Program Status

In September 2001, NASA announced that, due to fiscal year 2001 budget issues, it would not go forward with the previously planned funding of proposals submitted in response to the NASA Cooperative Agreement Notice for the HTCI Program.

This final disposition of funds for HTCI is documented in correspondence to proposal submitters (ref. 4).

References

1. NASA Strategic Plan 2000.

2. NASA Human Exploration and Development of Space Strategic Plan.

3. Mankins, John C., Technology for the Human/Robotic Exploration and Development of Space [THREADS], NASA HQ, December 2000.

4. HTCI Program Notice of Cancellation (letter to offerors), NASA HQ, September 13, 2001.

X. Education Strategy

Educating and inspiring future generations is a vital component of the strategy to implement the NEXT Vision.

A strong U.S. capability in science and engineering is crucial for both NASA and the nation as a whole. The number of new science and engineering graduates estimated for the first decade of the new millennium will not meet the workforce demand. The NEXT education strategy is aimed at strengthening the science and engineering interests and capabilities of American students and ensuring an expert workforce able to achieve cutting-edge goals (ref. 1).

Kindergarten through 12th Grade: Catalyst for Excellence

The NEXT education strategy will serve as a catalyst for excellence by creating a pipeline for scientists and engineers (ref. 2). The approach includes providing instructional materials that meet state and local curriculum standards, establishing professional development programs for educators, involving educators in research and development activities, and conducting in-school projects and activities that inspire and motivate (figure 10-1).

Figure 10-1: The NEXT education strategy will inspire students and enlighten inquisitive minds.

Universities: An Enabling Capability

NASA partnerships with universities will continue to benefit the goals and objectives of both. This includes providing undergraduate scholarships; providing university grants for basic research, applied research, and component-level hardware development; supporting graduate students and post-doctoral researchers in high-priority areas; supporting rotators

(NASA/University exchange program); and establishing university-based centers of excellence.

References

1. NASA Implementation Plan for Education 1999-2003.

2. Owens, Frank C. and Malcom V. Phelps, Rationale for the Education Component of the Decadal Plan, NASA HQ, September 2000.

XI. Looking Ahead

NEXT has delivered its Vision for human-robotic space exploration beyond low-Earth orbit for the next quarter century. Implementation of this Vision within a decade—including a series of technology developments, deep-space flight experiments, and multi-use "plug-ins" across other NASA programs—would set the stage for the first human voyages beyond low-Earth orbit in 40 years.

With the completion of Phase I and Phase II, the team has produced a focused Vision of exploration. Science priorities are the foundation and technology is the enabler.

Implementing the Vision will provide opportunities. Within the decade, revolutionary technologies will enable new government and commercial applications, and technology paths will be established to allow a Presidential decision on the direction of human-robotic exploration beyond the International Space Station. The current goal is not to select, or foresee, a given path of human exploration, but to enable it for humans and machines.

Therefore, implementing the Vision will require leveraging existing and new funding within a progressive technology investment and development program. Nearer-term technology requirements must be open to innovative ideas with a program of multiple downselects to achieve the critical capabilities in propulsion, power, human EVA systems, human adaptation systems, information technology, and materials.

The Phase III activity is refining the work completed in Phase I and Phase II. Phase III is revisiting architectures for exploring Earth's Neighborhood using a new orbital transfer technique that shows great promise for reducing costs. This technique, utilizing invariant manifold trajectories, allows the transfer from low-Earth orbit to one of the weak stability boundary points, also called unstable libration points, for a tiny fraction of the energy required in a conventional trajectory. Transfer from one of the weak stability boundary points to the stable libration points is also possible for a very small specific impulse. NEXT anticipates that these new trajectories will provide new paradigms for architecture development.

NEXT continues to refine and update a technology investment strategy that will ultimately enable us to reveal the past, protect the future of the planet, seek out life, and ultimately send our progeny to the stars. The team reevaluates the strategy annually, incorporating the results of the previous year's work. The recommended technologies also should address the challenges of life on Earth, such as energy, fresh water, food, land, population growth, wealth generation, pollution, global warming, disease vectors, and general improvement of the human condition.

The NEXT planning process is an ongoing strategic planning activity to direct Agency technology investment that proposes new NASA initiatives, such as THREADS, but exists independent of those initiatives. The NEXT provides a unified, interdisciplinary approach to focus NASA's technology investment strategy.

NEXT will evaluate a series of candidate missions using different technologies and different approaches for architecture to determine which new technologies provide maximum benefits. NEXT also will develop a set of analytical capabilities to aid in assessing potential mission architectures and new technologies. These capabilities include, but are not limited to:

- Sensitivity analyses and the tools to perform these analyses
- Orbit trajectory analyses and the tools to perform these analyses
- Databases for requirements, requirements flow down and technology tracking
- Tools for assessing and comparing human and robotic capabilities
- Workshops for knowledge capture
- Cost estimation methodology and tools.

NEXT will continue to track, develop, identify, and evaluate new technologies or technology capabilities that have the potential to significantly reduce cost, risk, and travel times. This is an ongoing, iterative process.

NEXT will begin to consider cost or safety-driven architectures to see what capabilities are required to meet certain cost or safety goals for a given architecture (e.g., which technologies or new architecture concepts are needed to achieve a manned Mars mission for less than $5 billion?).

NEXT will continue to identify new architectures with the potential to significantly reduce cost, risk, travel time, and improve safety. NEXT will perform detailed studies when time and funding permit. Finally, the NEXT will start to look beyond Mars and the asteroids and consider destinations such as Europa, Pluto, and interstellar space.

References

II. Setting a New Course for Space Exploration

1. Decadal Planning Team Charter.

2. Terms of Reference for Decadal Study Team.

3. NASA's Exploration Grand Challenges.

4. Decadal Planning Team Briefing to OMB, NASA HQ, December 19, 2000.

5. Pine, Mark A., Public Engagement in Future Exploration: "Breakthrough" Concepts, NASA JPL, September 29, 1999.

6. Interim Briefing to Comptroller and Deputy Administrator, August 14, 2000.

7. Interim Briefing to the Administrator, NASA HQ, July 19, 2000.

8. Interim Brief to Steering Committee, NASA HQ, April 19, 2000.

9. Interim Briefing to the Administrator, NASA HQ, November 22, 1999.

10. Interim Brief to Steering Committee, NASA HQ, October 4, 1999.

11. NASA Strategic Plan 2000.

12. NASA Human Exploration and Development of Space Strategic Plan.

13. NASA Space Science Strategic Plan, November 2000.

III. Exploration Grand Challenges

1. NASA's Exploration Grand Challenges.

2. York, Harold W., Artur Chmielewski, Mark Dragovan, Potential of Discovery at L_2, NASA JPL, May 15, 2000.

3. Weiler, Dr. Edward J., Associate Administrator, Office of Space Science, NASA Space Science Grand Challenges, NASA HQ.

4. Huntress, Dr. Wesley T., Geophysical Laboratory, Carnegie Institution of Washington, Grand Challenges for Space Exploration, Second Annual Carl Sagan Memorial Lecture, American Astronautical Society Annual Meeting, Houston, TX, November 17-19, 1998.

5. NASA Strategic Plan 2000.

6. NASA Human Exploration and Development of Space Strategic Plan.

7. NASA Space Science Strategic Plan, November 2000.

IV. In-Space Operations—Humans Make a Difference

1. Thronson, Harley, Human Space Flight and Enhancement of the NASA Science Program, NASA HQ.

2. Cooke, Douglas R., An Overview of Recent Coordinated Human Exploration Studies, NASA JSC, January 2000.

3. Chmielewski, Art B., Enabling Aspects of Astronauts for Gossamer Observatories, JPL, August 28, 2000.

V. Stepping Stones—System and Architecture Concepts

Architecture Comparison and Evaluation

1. Drake, Bret G., Human Exploration Architecture Comparison Approach, NASA JSC, January 2000.

Lunar Architecture Analyses

2. Joosten, B. Kent, Lunar Architecture—Lunar Lander Design Status, NASA JSC.

3. Joosten, B. Kent, "Exploration in the Earth's Neighborhood" Architecture Analysis, NASA JSC, July 11, 2000.

4. Hybrid Propellant Module and Fuel Aggregation Depot Concept, Fuel Aggregation Study Team, NASA LaRC, September 29, 2000.

Mars Architecture Analyses

5. Drake, Bret G., DPT Mars Short-Stay Mission Architecture Status—Mid-Term (2018) Nuclear Thermal Propulsion System Option, NASA JSC, July 11, 2000.

6. Mars 'Short-Mission' Scenario/Architecture Ground Rules and Assumptions, April 20, 2000.

7. Drake, Bret G., DPT Mars Long-Stay Mission Architecture Status—Mid-Term (2018) Nuclear Thermal Propulsion System Option, NASA JSC, July 11, 2000.

8. Mars Long-Mission Ground Rules and Assumptions, April 20, 2000.

9. Drake, Bret G., DPT Architecture Status—Mars Missions, Near-Earth Asteroid Missions, Common Capabilities, NASA JSC, September 12, 2000.

VI. Technology Needs and Benefits

Space Transportation Technologies

1. Johnson, Les, In-Space Propulsion Options, NASA MSFC.

2. Johnson, Les, Transportation Technology Tasks Status, NASA MSFC, May 2000.

3. Johnson, Les, Transportation Technology Tasks Status, NASA MSFC, September 2000.

4. Johnson, Les, In-Space Technology Status, NASA MSFC, NASA MSFC, April 2000.

5. Johnson, Les, Exploration Transportation Systems Study, NASA MSFC, May 2000.

6. Johnson, Les, Transportation System Study Options for Mars Exploration Missions (Sweet Spot Analysis), NASA MSFC, September 29, 2000.

7. Johnson, Les, Transportation System Options for 1-Year Round Trip Mars Exploration Missions in the Mid-Term, NASA MSFC, September 29, 2000.

8. Johnson, Les, Human Exploration Transportation Technologies Prioritization, NASA MSFC, September 2000.

9. Hybrid Propellant Module and Fuel Aggregation Depot Concept, Fuel Aggregation Study Team, NASA LaRC, September 29, 2000.

10. Johnson, Les, Breakthrough In-Space Transportation Technologies, NASA MSFC.

11. Johnson, Les, Earth-to-Orbit Technology Status, NASA MSFC, April 2000.

12. Jones, Jonathan et al., Gun Launch Status Report, NASA MSFC, May 24, 2000.

Power System Technologies

13. Johnson, Steve, Power System Activities and Technology Status, NASA GRC, April 13, 2000.

14. Johnson, Steve, GRC Status Report for DPT Meeting, NASA GRC, September 11-13, 2000.

Robotic/EVA Technologies

15. Robotic Research at NASA and Carnegie Mellon University.

Crew Health and Safety

16. Bioastronautics—Wye River Retreat, Advanced Technology Integration Group, NASA JSC, October 12-13, 2000.

17. Bioastronautics—An Integrated Approach to Ensure Healthy and Safe Human Space Travel, Presentation to the OMB, September 21, 1999.

18. Bioastronautics—An Integrated Approach to Ensure Healthy and Safe Human Space Travel, Follow-up Discussion with the OMB, September 28, 1999.

19. Bioastronautics - An Integrated Approach to Ensure Healthy, Safe and Productive Human Space Travel, POP 2000 Budget Considerations.

20. John W. Hines and Marina A. Saltman, Medical and Biological Technologies for Human Space Exploration (2001-2020)—Fiscal Year 2000 Report to the NASA Decadal Planning Team, NASA ARC, September 1, 2000.

21. Dawson, David L. and John B. Charles, Bioastronautics Critical Path to Crewmember Certification for Exploration-Class Missions, NASA JSC, July 10-12, 2000.

22. Artificial Gravity Science.

23. Cucinotta, Francis A., A Coherent Radiation Protection Strategy For Deep Space Exploration, NASA JSC, July 10, 2000.

24. Integrated Space Radiation Protection Plan, Briefing to NASA Administrator, Space and Life Sciences Directorate, NASA JSC.

25. Space Radiation Health Project Road Map 2000.

Materials Technologies

26. Meyyappan, M. et al., Carbon Nanotube based Sensors for Space Missions, NASA ARC, December 2000.

27. Harris, Charles E., Survey of Breakthrough Materials, NASA LaRC, July 2000.

Information Technology

28. Hine, Butler et al., The Role of Information Technology in Human Space Exploration, NASA ARC.

VII. Exploration Paths and Technology Leveraging

1. Mankins, John C., Technology for the Human/Robotic Exploration and Development of Space [THREADS], NASA HQ, December 2000.

2. Johnson, Les, Human/Robotic Exploration and Development of Space Strategic Research & Technology Road Maps—Exploration Transportation Technology, NASA MSFC, June 9, 2000.

VIII. Partnership Opportunities

1. DiMarcantonio, Albert, An Analysis of the Report of the Commission to Assess United States National Security Space Management and Organization—Toward a Strategy and Opportunities for Interagency Technology Import/Export with an Objective of "Leveraging a Way out of LEO. Managing a Stay beyond Apollo," NASA DAA Interagency Enterprise, March, 2001.

2. Cline, Lynn F.H. and Jeffrey D. Rosendhal, An Assessment of Prospects for International Cooperation on the Space Exploration Initiative, NASA HQ, *Acta Astronautica* Vol. 28, pp. 391-399, 1992.

3. Cline, Lynn F.H., Primer on International Agreements, NASA HQ.

IX. Commercialization Opportunities

1. NASA Strategic Plan 2000.

2. NASA Human Exploration and Development of Space Strategic Plan.

3. Mankins, John C., Technology for the Human/Robotic Exploration and Development of Space [THREADS], NASA HQ, December 2000.

4. HTCI Program Notice of Cancellation (letter to offerors), NASA HQ, September 13, 2001.

X. Education Strategy

1. NASA Implementation Plan for Education 1999-2003.

2. Owens, Frank C. and Malcom V. Phelps, Rationale for the Education Component of the Decadal Plan, NASA HQ, September 2000.

Acronyms

AR&C	Autonomous Rendezvous & Capture
ARC	Ames Research Center
BNTR	Bimodal Nuclear Thermal Rocket
CNS	Central Nervous System
CNT	Carbon Nanotubes
CTV	Crew Transfer Vehicle
DOD	Department of Defense
DOE	Department of Energy
DPT	Decadal Planning Team
EDL	Entry, Descent and Landing
EELV-H	Evolved Expendable Launch Vehicle-Heavy
ETO	Earth-To-Orbit
EVA	Extravehicular Activity
FTE	Full-Time Equivalent
GEO	Geostationary Earth Orbit
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center
HEDS	Human Exploration and Development of Space
HEO	High-Earth Orbit
HPM	Hybrid Propellant Module
HQ	Headquarters
HST	Hubble Space Telescope
HTCI	HEDS Technology/Commercialization Initiative
IMLEO	Initial Mass to Low-Earth Orbit
Isp	Specific Impulse
ISRU	In-Situ Resource Utilization
ISS	International Space Station
IT	Information Technology
IVHM	Integrated Vehicle Health Management
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
L_1	Libration (or Lagrange) Point 1
L_2	Libration (or Lagrange) Point 2

LANTR	LOX-Augmented Nuclear Thermal Rocket
LaRC	Langley Research Center
LEO	Low-Earth Orbit
M2P2	Minimagnetospheric Plasma Propulsion
MEMS	Microelectromechanical Systems
MEO	Medium-Earth Orbit
MPD	Magnetoplasmadynamic
MSFC	Marshall Space Flight Center
MTV	Mars Transfer Vehicle
NASA	National Aeronautics and Space Administration
NEMS	Nano-electromechanical Systems
NEP	Nuclear Electric Propulsion
NEXT	NASA Exploration Team
NIAC	NASA Institute for Advanced Concepts
NICMOS	Near-Infrared Camera and Multi-Object Spectrometer
NIH	National Institutes of Health
NRA	NASA Research Announcement
NSF	National Science Foundation
NTR	Nuclear Thermal Rocket
OMB	Office of Management and Budget
OSF	Office of Space Flight
OSS	Office of Space Science
PIT	Pulsed Inductive Thruster
PV	Photovoltaic
R&D	Research and Development
R&T	Research and Technology
RASC	Revolutionary Aerospace Systems Concepts
RLV	Reusable Launch Vehicle
RTG	Radioisotope Thermal Generator
SEP	Solar Electric Propulsion
SETV	Solar Electric Transfer Vehicle
SLI	Space Launch Initiative
TEI	Trans-Earth Injection
THREADS	Technology for Human/Robotic Exploration and Development of Space
TMI	Trans-Mars Injection

TPF	Terrestrial Planet Finder
TPS	Thermal Protection System
TRL	Technology Readiness Level
VASIMR	Variable Specific Impulse Magnetoplasma Rocket
VHM	Vehicle Health Monitoring

Glossary

"Breakthrough" Technologies — Breakthrough technologies are speculative technologies with potentially profound pay-offs. These will revolutionize how we explore and are beneficial regardless of destination.

"Evolutionary" Technologies — Evolutionary technologies are part of NASA's current investment pool and are focused on a specific exploration theme. Multiple development paths are commonly utilized for evolutionary technologies to assure development results.

Blast Wave Accelerator — The Blast Wave Accelerator is a Russian concept for ETO transportation which has been verified analytically in the U.S. (figure 6-8). This concept utilizes an 80 foot evacuated barrel with internal bands of sequentially detonated explosives and will accelerate ~1,000 lbs. to orbit for ~$50/lb. The Blast Wave Accelerator may be especially useful for lofting fuel.

Carbon Nanotube (CNT) — CNT is a remarkable material with an unprecedented combination of mechanical, thermal and electronic properties. Roughly speaking, CNT is almost a hundred times stronger than steel but one-sixth its weight. The history of this material development is very short and numerous challenges related to synthesis, design, and characteristics need to be addressed in order to exploit CNT for space applications.

Earth's Neighborhood — Earth's Neighborhood is the region of space encompassing the Sun-Earth L_1 and Sun-Earth L_2 libration points extending approximately 1.5 million km from Earth (figure 5-2).

Exploration Grand Challenges — NASA's motivation for space exploration is summarized by the three Exploration Grand Challenges:

- How did we get here?
- Where are we going?
- Are we along?

These Exploration Grand Challenges were developed from the Agency and Enterprise strategic plans and incorporate NASA's strategic scientific priorities.

Gateway — Gateways are deep-space habitation and operations facilities consisting of an inflatable habitat element, a docking facility, and a solar electric propulsion system. These are architectural elements for Earth's Neighborhood, Mars, and near-Earth asteroid missions (figure 5-4).

Gossamer Spacecraft Technology

Gossamer spacecraft technology activities focus on developing revolutionary spacecraft architectures for very large, ultra-lightweight apertures and structures. The overarching goal of Gossamer spacecraft technology development is to achieve breakthroughs in mission capability and cost, primarily through revolutionary advances in structures, materials, optics, and adaptive and multifunctional systems. Gossamer spacecraft technology will enable very large ultra-lightweight systems for new missions of discovery for Space Science such as: very large aperture telescopes for imaging extra-solar planets (figure 4-4); large deployable and inflatable antennas for space-based radio astronomy; solar sails for low-cost propulsion; and large solar power collection and transmission systems for future exploration missions and for the commercial development of space.

Hybrid Propellant Module (HPM)

The HPM (figure 5-8) is an example of the use of commonality in design of space systems concepts. The HPM may potentially be used for Earth's Neighborhood, Mars, and near-Earth asteroid missions as the basic propellant unit for mission transfer vehicles. A common HPM would allow the on-orbit storage of liquid oxygen, liquid hydrogen, and electric propulsion propellant (assumed to be xenon). To maximize the cost benefits of this element, the HPM would be designed to be highly reusable.

Interferometer

An interferometer consists of two or more separate telescopes that combine their signals almost as if they were coming from separate portions of a telescope as big as the two (or more) telescopes are apart (figure 4-3). The resolution of an interferometer approaches that of a telescope of diameter equal to the largest separation between its individual elements (telescopes). However, not as many photons are collected by the interferometer as would be by a giant single telescope of that size.

Invariant Manifold Trajectories

Orbital transfer techniques utilizing invariant manifold trajectories are being studied for Earth's Neighborhood missions. These trajectories allow the very low energy transfer between weak stability boundary points (i.e., unstable libration points) and show great promise for reducing mission costs.

L_2 "Stepping Stone" Architecture

The L_2 stepping stone architecture is based on human Mars mission requirements. As an example, extensive testing of Mars Transfer Vehicle technologies is likely to be performed at the Earth-Sun L_2 libration point with this architecture concept.

L_2 "Evolution" Architecture

The L_2 evolution architecture is based on science operations requirements at the Earth-Sun L_2 libration point. Such requirements may include the deployment and servicing of a TPF- or Planet Imager-class observatory.

Libration (or Lagrange) Points

Named after the 18th century mathematician and astronomer, Joseph Lagrange, the Lagrange points for two celestial bodies in mutual revolution, such as the Earth and Moon or Earth and Sun, are the five points such that an object placed at one of them will remain there indefinitely (e.g., the object will always appear stationary relative to the two celestial bodies).

Planet Imager

Planet Imager (figure 4-4) is an Origins Program concept consisting of an array of TPF-class interferometers flying in formation. Each interferometer carries four 8 m telescopes to collect starlight and one 8 m telescope to relay collected light to the beam combiner spacecraft. The total array baseline is 6,000 km. The science objective of the Planet Imager is to locate and provide detailed images of Earth-like planets.

Slingatron

The Slingatron (figure 6-9) is a circular mass-accelerator concept in which projectile of large mass could be accelerated to high velocity using a relatively low-power input. The radius of the accelerator ring could range from meters to kilometers. Potential applications include hypervelocity impact research, ETO launch of rocket projectiles, and propulsion.

Technology Readiness Levels

Technology Readiness Levels (TRLs) are a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology. The TRL approach has been used on-and-off in NASA space technology planning for many years and is incorporated in the NASA Management Instruction (NMI 7100) addressing integrated technology planning at NASA. The NASA TRL scale ranges from TRL 1 - basic principles observed and reported, through TRL 10 - actual system "flight proven" through successful mission operations.

Terrestrial Planet Finder (TPF)

TPF (figure 4-3) is an Origins Program concept consisting of four 3.5 m telescopes configured as an interferometer with a baseline of 75 to 1,000 m. The TPF will study all aspects of planets, from their formation and development in disks of dust and gas around newly forming stars to the presence and features of those planets orbiting the nearest stars.

Appendix I—Membership Roster

Area of Expertise	Team Member	Address/Phone	Phase I	Phase II
Information Systems	Jerome Bennet	NASA Goddard Space Flight Center M/S: 930.0 Greenbelt, MD 20771-0001 Phone: (301) 286-8543	√	
Science Management	Darrell Branscome	NASA Langley Research Center M/S: 117 Hampton, VA 23681 Phone: (757) 864-2836		√
Technology	Dennis Bushnell	NASA Langley Research Center M/S: 110 Hampton, VA 23681 Phone: (757) 864-8987	√	√
Bioscience	John Charles	NASA Johnson Space Center Code SF 2 2101 NASA Rd. 1 Houston, TX 77058 Phone: (281) 483-7224		√
Spacecraft Systems	Art Chmielewski	Jet Propulsion Laboratory M/S: 180-603 4800 Oak Grove Dr. Pasadena, CA 91109 Phone: (818) 354-0255		√
Mission Concepts	Douglas Cooke	NASA Johnson Space Center Code EX 2101 NASA Rd. 1 Houston, TX 77058 Phone: (281) 483-8422		√
Science	Roger Crouch	NASA HQ Code M Washington, DC 20546 Phone: (202) 358-0689	√	
In-situ Resource Usage	Peter Curreri	NASA Marshall Space Flight Center Bldg 4481, Rm: 102A Huntsville, AL 35812 Phone: (256) 544-7763	√	
Medicine	David Dawson	NASA Johnson Space Center Code SD 2101 NASA Rd. 1 Houston, TX 77058 Phone: (281) 483-7329	√	√
Mission Architectures	Bret Drake	NASA Johnson Space Center Code EX 2101 NASA Rd. 1 Houston, TX 77058 Phone: (281) 483-1806		√
Planetary Mission Concepts	Bob Easter	Jet Propulsion Laboratory M/S: 301-230 4800 Oak Grove Dr. Pasadena, CA 91109 Phone: (818) 354-3552		√
Systems Engineering	Melvin Ferebee	NASA Langley Research Center M/S 328 Hampton, VA 23681 Phone: (757) 864-4421		√
Life Sciences	Guy Fogleman	NASA HQ Code UL Washington, DC 20546 Phone: (202) 358-2217		√

Area of Expertise	Team Member	Address/Phone	Phase I	Phase II
Mars Science; Chair, Phase I and II	James Garvin	NASA HQ Code SR Washington DC 20546 Phone: (202) 358-0113	√	√
Mars Science	Matt Golombek	Jet Propulsion Laboratory M/S: 183-501 4800 Oak Grove Dr. Pasadena, CA 91109 Phone: (818) 393-7948	√	
Management	Lisa Guerra	NASA HQ Code S Washington, DC 20546 Phone: (202) 358-0741	√	√
Genomic Science	Lynn Harper	NASA Ames Research Center M/S: 244.10 Moffett Field, CA 94035 Phone: (650) 604-4930	√	√
Management	Scott Hubbard	NASA HQ Code S Washington, DC 20546 Phone: (202) 358-0876	√	
Propulsion	Les Johnson	NASA Marshall Space Flight Center M/S: TD-15 Huntsville, AL 35812 Phone: (256) 544-0614	√	√
Power and Propulsion	Steven Johnson	NASA Glenn Research Center M/S: 500-203 21000 Brookpark Rd. Cleveland, OH 44135 Phone: (216) 433-5370		√
Mission Architectures	Kent Joosten	NASA Johnson Space Center Code EX 2101 NASA Rd. 1 Houston, TX 77058 Phone: (281) 483-4645		√
Technology	James Kalshoven	NASA Goddard Space Flight Center M/S: 712.0 Greenbelt, MD 20771-0001 Phone: (301) 286-8506		√
Mission Engineering	Julie Kramer	NASA Johnson Space Center Code ES2 2101 NASA Rd. 1 Houston, TX 77058 Phone: (281) 483-8866	√	
Technology	John Mankins	NASA HQ Code MP Washington, DC 20546 Phone: (202) 358-4659		√
Management	Gary Martin	NASA HQ Code M Washington, DC 20546 Phone: (202) 358-4470		√
Spacecraft Systems and Robotics	Rud Moe	NASA Goddard Space Flight Center M/S 442.0 Greenbelt, MD 20771-0001 Phone: (301) 286-2180		√
Administration	Brandy Nguyen	NASA HQ Code S Washington, DC 20546 Phone: (202) 358-0113		√
Information Technology	Peter Norvig	NASA Ames Research Center M/S: 269-10 Moffett Field, CA 94035 Phone: (650) 604-6207	√	√

Area of Expertise	Team Member	Address/Phone	Phase I	Phase II
Outreach	Patricia Pengra	NASA HQ Code S Washington, DC 20546 Phone: (202) 358-2261		√
Astronaut	Donald Pettit	NASA Johnson Space Center Code CB 2101 NASA Rd. 1 Houston, TX 77058 Phone: (281) 244-8917	√	
Outreach	Mark Pine	Jet Propulsion Laboratory 4800 Oak Grove Dr. Pasadena, CA 91109	√	
Precursor Mission Planning	Marianne Rudisill	NASA Langley Research Center M/S: 328 Hampton, VA 23681 Phone: (757) 864-2317		√
Systems Engineering	Mark Saunders	NASA Langley Research Center M/S: 117 Hampton, VA 23681 Phone: (757) 864-9862	√	√
Medicine	Julie Swain	NASA HQ Code U Washington, DC 20546 Phone: (202) 358-1996		√
Science	Harley Thronson	NASA HQ Code S Washington, DC 20546 Phone: (202) 358-0362	√	√
Technology	Paul Westmeyer	NASA Goddard Space Flight Center M/S 730.0 Greenbelt, MD 20771-0001 Phone: (301) 286-4842	√	
Management	Alan Wilhite	NASA Langley Research Center M/S 215 Hampton, VA 23681 Phone: (757) 864-4800	√	
Technology	Barbara Wilson	Jet Propulsion Laboratory M/S: 180-600 4800 Oak Grove Dr. Pasadena, CA 91109 Phone: (818) 354-2969	√	