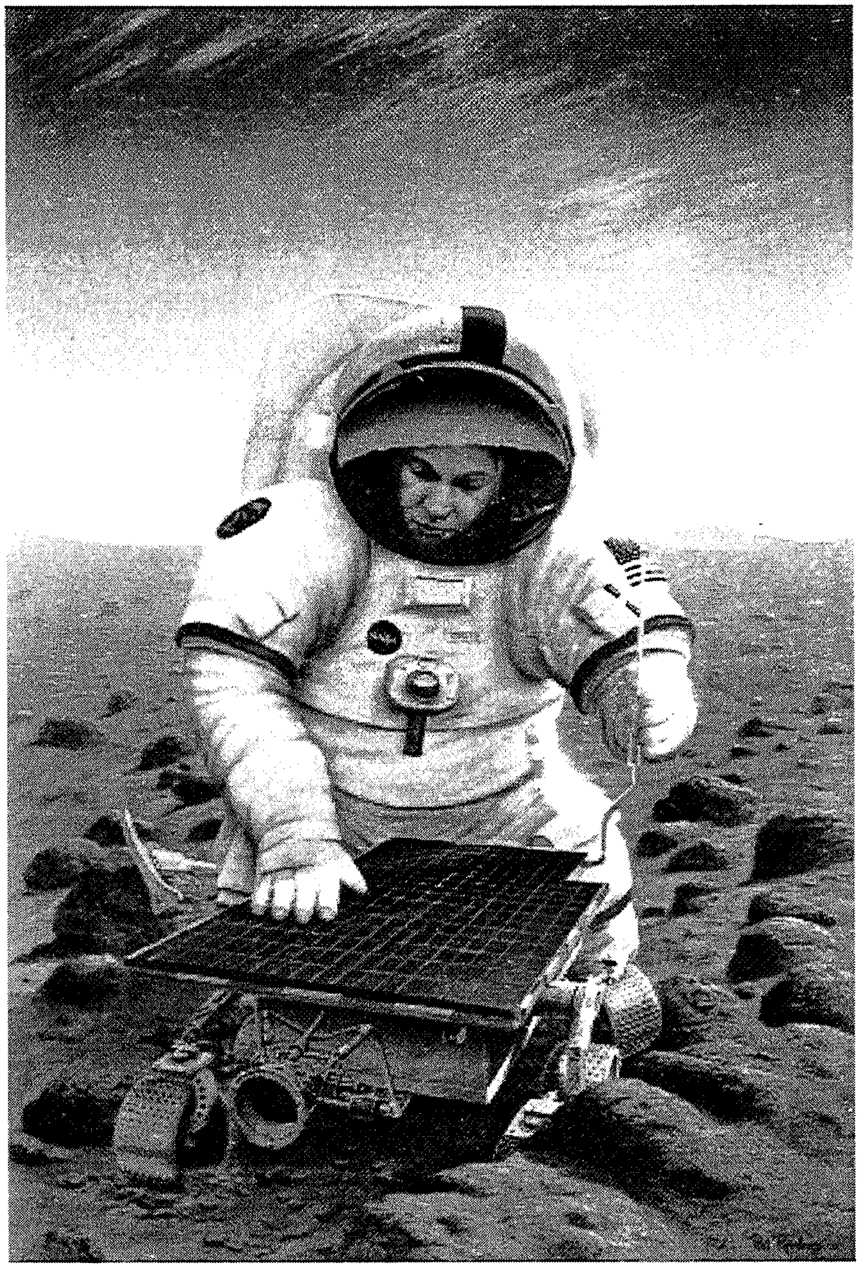
HEDS–UP
MARS EXPLORATION FORUM



May 4–5, 1998
Lunar and Planetary Institute, Houston, Texas

HEDS–UP MARS EXPLORATION FORUM

Edited by

Nancy Ann Budden and Michael B. Duke

Held at
Lunar and Planetary Institute
Houston, Texas

May 4–5, 1998

Sponsored by
Lunar and Planetary Institute

Lunar and Planetary Institute 3600 Bay Area Boulevard Houston TX 77058-1113

LPI Contribution Number 955

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Preface

In the early 1990s, Duke and Budden convened a series of workshops addressing mission rationale, exploration objectives, and key constraints and issues facing human crews on Mars (*Duke and Budden,* 1992, 1993). The focal point was "why" the U.S. should fly humans to Mars. In the mid-1990s, strategies for a Mars mission matured and evolved, driven formally by NASA Johnson Space Center's Office of Exploration. In 1997, NASA published a report capturing the current thinking: the NASA Mars Reference Mission (*Hoffman,* 1997). In the 1997–1998 school year, HEDS-UP sponsored six universities to conduct design studies on Mars exploration, using the Reference Mission as a basis for their work. The 1998 Mars Exploration Forum presents the results of these university studies, suggesting "how" we might explore Mars, in terms of specific technical components that would enable human missions to Mars.

A primary objective of the HEDS-UP Mars Exploration Forum was to provide a forum for active interaction among NASA, industry, and the university community on the subject of human missions to Mars. NASA scientists and engineers were asked to present the state of exploration for Mars mission options currently under study. This status "snapshot" of current Mars strategies set the stage for the six HEDS-UP universities to present their final design study results. Finally, a panel of industry experts discussed readiness for human missions to Mars as it pertains to the aerospace industries and technologies. A robust poster session provided the backdrop for government–industry–university discussions and allowed for feedback to NASA on the Mars Reference Mission. The common thread woven through the two days was discussion of technologies, proven and emerging, that will be required to launch, land, and sustain human crews on the Red Planet.

As this decade (and indeed this millenium) draws to a close, Mars will continue to loom in our sights as the next target for human space exploration. It is our hope that the efforts of the Mars Exploration Forum will serve as one small contribution toward the ultimate goal of humans exploring Mars.

The conveners would like to thank all the meeting participants, without whom this effort would not have been possible. The Mars Exploration Forum was supported by the NASA Headquarters Office of Manned Space Flight. Logistical, administrative, and publications support was provided by the Publications and Program Services Department of the Lunar and Planetary Institute (LPI). Photographic support was provided by Debra Rueb of the LPI's Center for Information and Research Services.

Nancy Ann Budden
Michael B. Duke
Houston, Texas

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Letter of Invitation

LUNAR AND PLANETARY INSTITUTE
3600 BAY AREA BOULEVARD HOUSTON, TEXAS 77058-1113
TEL (281) 486-2139 FAX (281) 486-2162

March 1998

Dear Mars Exploration Forum Participant,

The Lunar and Planetary Institute's Human Exploration and Development of Space/University Partners (HEDS UP) organization is sponsoring a "Mars Exploration Forum", to be held at the LPI in Houston, Texas, on May 4-5, 1998. Attendees will include the NASA Integrated Team Members, and representatives from aerospace industry, universities, and the government laboratories. You are invited to participate.

Enclosed is a copy of our recently-released "Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team" which provides a basis for studies NASA is pursuing of the possible human exploration of Mars. At the request of, and with the support of NASA Administrator, Dan Goldin, NASA is moving forward with technologies and planning for future human missions to Mars.

The objective of the Mars Exploration Forum is to facilitate active interaction among government, academia, and industry on the subject of human missions to Mars. During the forum, NASA scientists and engineers will present the "State of Exploration" for Mars mission options currently under study. In addition, the HEDS UP universities will be presenting the final results of their respective Mars Exploration design studies they have produced during the school year. Finally, a panel of industry participants will discuss Mars exploration as it affects and applies to the aerospace industries and technologies. There will be opportunities for representatives from NASA, aerospace industry and government laboratories, and universities to share in panel discussions and to provide feedback regarding the Mars Reference missions.

If you plan to participate, please return the enclosed registration form prior to April 7, 1998. In late April, a second mailing that will include an agenda, map, and details of the meeting will be sent out to organizations or individuals indicating interest.

Sincerely,

Michael B. Duke
Lunar Planetary Institute

Nancy Ann Budden
Lunar Planetary Institute

Enclosure

NASA's HEDS Enterprise

The Human Exploration and Development of Space (HEDS) is NASA's Strategic Enterprise that encompasses NASA's programs of human space flight. The goals of the HEDS are to:

- Increase human knowledge of nature's processes using the space environment
- Explore and settle the solar system
- Achieve routine space travel
- Enrich life on Earth through people living and working in space

This endeavor currently is represented in NASA by several programs:

- The Office of Space Flight, which is responsible for developing and operating the space shuttle and the International Space Station
- The Office of Life and Microgravity Sciences, which conducts research on the effects of the space environment on humans and on utilizing human space flight opportunities to conduct scientific and technological experiments in the life sciences and materials sciences
- The Office of Space Sciences, which conducts robotic flight missions that prepare the way to the Moon, Mars, and elsewhere for human explorers who will follow

All three offices are working to develop an integrated approach to the human exploration and development of space. The Enterprise is a long-term affair that will encompass groundbased research, space flight experimentation, and exploration missions beyond low Earth orbit.

The Exploration Office at the NASA Johnson Space Center, in Houston, Texas, is the lead office for the post-space-shuttle/space-station elements of the HEDS program. Emphasis at this time is on the robotic and human exploration of the Moon and Mars. Offices at most NASA Centers are also involved:

- Lewis Research Center (Cleveland, Ohio)
- Marshall Space Flight Center (Huntsville, Alabama)
- Langley Research Center (Hampton, Virginia)
- Goddard Space Flight Center (Greenbelt, Maryland)
- Jet Propulsion Laboratory (Pasadena, California)
- Ames Research Center (Moffet Field, California)

HEDS–UP Activity

1998 Activity

Human Exploration and Development of Space–University Program (HEDS–UP) is a mechanism for involving people (faculty and students) in one of civilization's grandest undertakings, the human exploration and development of the space frontier. By building strong linkages between the U.S. space program, administered by the National Aeronautics and Space Administration, and universities, the voices of imagination, innovation, and vision that reside in the university community can be combined with the engineering and technical skills of NASA to advance space exploration and development as well as the educational and research objectives of the universities. From NASA's point of view, the universities can be prime contributors of new ideas and effective partners in developing and implementing scientific, engineering, and technological innovations associated with human exploration and development of space. From the universities' perspective, mechanisms are needed that allow visibility into NASA programs and directions and access to communications channels that allow universities to identify and propose areas in which they can contribute to the enterprise.

Human Exploration and Development of Space is a movement rather than a program. It is multifaceted, involving technical, legal, business, humanitarian, philosophical, and practical issues in almost every area associated with everyday life on Earth. In its beginnings, most of the work has been and will be technical — figuring out the possible and optimal means of sending payloads and humans into space and conducting beneficial work in space, on the Moon, and on Mars. With developments now planned or anticipated, the cost of working in space will diminish and the breadth of activities in space will increase. Discussions of human exploration of Mars, space industrialization, and space tourism conducted now anticipate reduced cost, improved capability, and a much wider sphere of activity in space. If carried out to logical conclusions, these same thoughts move in the direction of self-sufficient human settlements outside Earth, which could be as complex as terrestrial society is now. Although settlement is not the objective of NASA's HEDS program, it is surely within the scope of consideration for the HEDS–UP program. Indeed, the timescale for HEDS activities is very long, and the universities, as institutions, should be prepared to participate with long-term objectives in mind.

In the short term, HEDS–UP will be represented by (1) an infrastructure that recognizes the importance of communications, and (2) projects that provide avenues for exchange of ideas and problem solutions. The infrastructure will provide services to the universities and to NASA through the mechanisms of communications channels and databases, utilization of which will promote understanding of HEDS objectives, problems, and needs to the university community on one hand and the resources, capabilities, and skills of the universities to the NASA side. Projects will be organized elements in which the universities can contribute to NASA thinking through the conduct of design studies, collaborative research, conferences, and other means. The projects developed under HEDS–UP have the objective of improving the interaction between NASA and the universities, not funding R&D. If opportunities for funded research are identified by university and NASA personnel and the communication linkages can be forged between the interested universities and NASA as a result of the HEDS–UP program, HEDS–UP will have done its job. HEDS–UP anticipates that opportunities to perform specific research and development to meet NASA needs will result from HEDS–UP projects; however, HEDS–UP is not a funding mechanism for university research and development.

Future of HEDS–UP

The HEDS–UP program will continue in the coming year, focusing on university work that can begin in the fall semester. The main topical focus in 1998–1999 will be the surface exploration of Mars and specific surface mission components. Universities that are interested in participating should keep track of announcements made on the HEDS–UP home page (**http://cass.jsc.nasa.gov/lpi/HEDS-UP/**).

HEDS–UP will continue to stress surface design as a focus, but will also be adding a Mars Field Site Simulation Project in 1998–1999 that may be of interest to geoscience departments. HEDS–UP is also open to other topics and approaches to integrating university students and faculty with the human exploration efforts at NASA.

References

Drake B. G., ed. (1998) *Reference Mission 3.0: Addendum to the Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team.* JSC Publ. No. EX13-98-036.

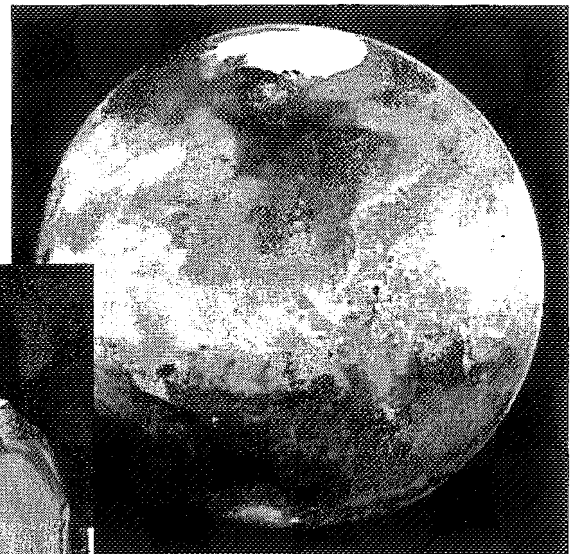
Duke M. B. and Budden N. A. (1993) *Mars Exploration Workshop II.* NASA CP-3243.

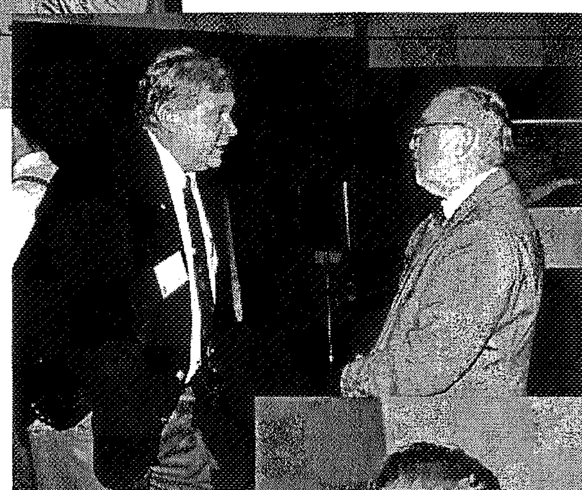
Duke M. B. and Budden N. A. (1992) *Results, Proceedings, and Analysis of the Mars Exploration Workshop.* JSC Publ. No. 26001.

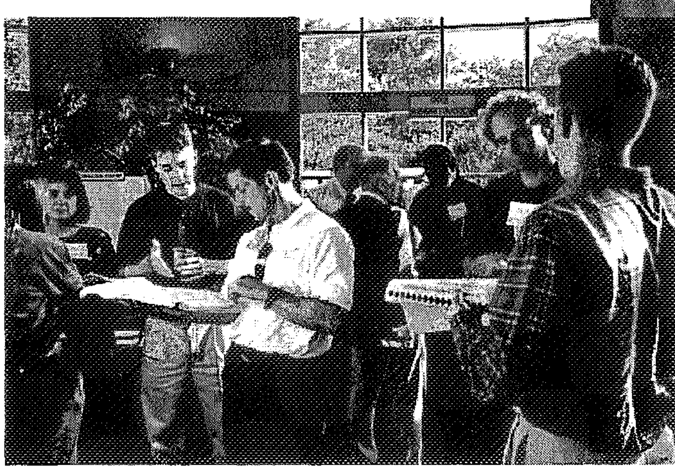
Hoffman S. J. and Kaplan D. I., eds. (1997) *Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team.* NASA SP-6107.

McKay D. S. et al. (1996) Search for past life on Mars: Possible biogenic activity in martian meteorite ALH84001. *Science, 273,* 924–930.

Scenes from the Mars Forum







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Agenda

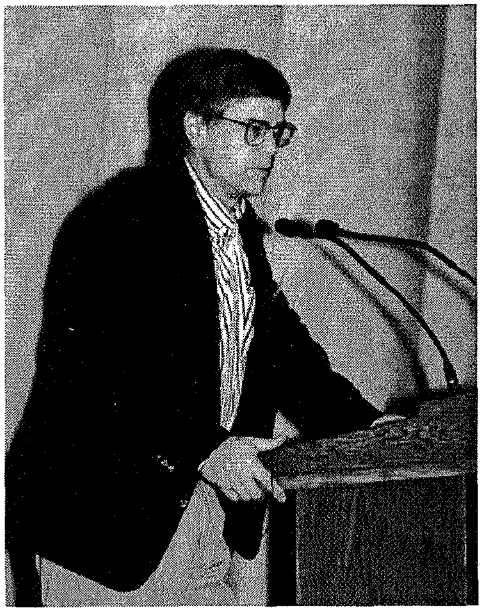
<u>*Monday, May 4, 1998*</u>

7:30 a.m.	***Registration/Continental Breakfast***	*LPI Great Room*
8:30 a.m.	Welcome	David Black/Lunar and Planetary Institute (LPI)
8:40 a.m.	HEDS Mission Planning	George Abbey/NASA Johnson Space Center (JSC)
8:50 a.m.	HEDS UP on Mars	Mike Duke/Nancy Ann Budden/LPI
9:10 a.m.	Human Exploration: The Vision	Douglas Cooke/JSC Office of Exploration
9:40 a.m.	Mars Missions: Now and Beyond	Bill O'Neil/Jet Propulsion Laboratory (JPL)
10:10 a.m.	*Coffee Break*	*LPI Great Room*
10:45 a.m.	Mars Human Exploration Objectives	Geoffrey Briggs/NASA Ames Research Center (ARC)
11:15 a.m.	Mars Human Exploration Reference Mission	Bret Drake/NASA JSC Exploration Office
11:50 a.m.	HEDS: Strategic View	Joe Rothenberg/NASA Headquarters
12:00 noon	*Lunch*	
1:30 p.m.	A Nominal Mission to Mars	The University of Texas at Austin
2:00 p.m.	EVA Roadmap: New Space Suit for 21st Century	Robert Yowell/JSC EVA Project Office
2:30 p.m.	Crew Health and Performance on Mars	Charlie Stegemoeller/NASA JSC Life Sciences
3:00 p.m.	Better, Cheaper, Faster Way	University of California, Berkeley
3:30 p.m.	Technology Readiness for Mars	Kent Joosten/NASA JSC Exploration Office
4:00 p.m.	Mars Power Systems	Bob Cataldo/NASA Lewis Research Center (LeRC)
4:30 p.m.	Surface Infrastructure	Texas A&M University
5:00 p.m.	*University Poster Session*	*LPI Great Room*
6:00–7:00 p.m.	*Reception*	*LPI Great Room*

Tuesday, May 5, 1998

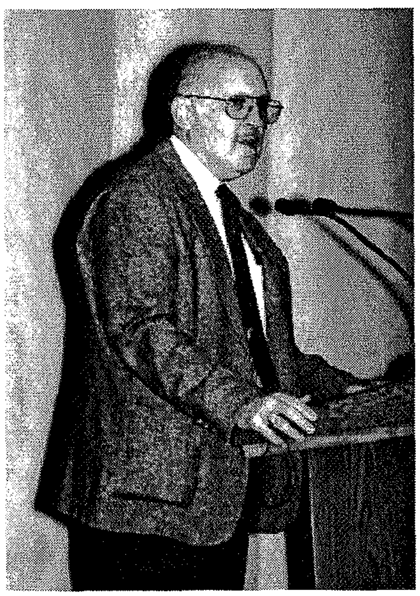
8:00 a.m.	***Registration and Continental Breakfast***	*LPI Great Room*
8:30 a.m.	In-Situ Resource Utilization on Mars	Jerry Sanders / NASA JSC
8:50 a.m.	Extraction of Atmospheric Water	University of Washington
9:20 a.m.	Analytical Capabilities & Finding Life on Mars	Carl Allen / Lockheed Martin
9:40 a.m.	Mars Analytical Laboratory	Wichita State University
10:10 a.m.	*Coffee Break*	*LPI Great Room*
10:30 a.m.	Transportation: Destination Mars	Bill Eoff / NASA Marshall Space Flight Center (MSFC)
11:00 a.m.	Robotic Technologies	Timothy Krabach / JPL
11:30 a.m.	Pressurized Rover	University of Maryland
12:00 noon	*Lunch*	
1:30 p.m.	Keynote Address: Human Exploration Beyond LEO	John Young / NASA JSC
2:00 p.m.	*"Readiness for Mars Exploration" (or* "What do we Really Need for a Mars Mission?") Doug Cooke / NASA JSC, Moderator Joe Kerwin / Wyle Laboratories Life Sciences Harvey Willenberg / Boeing Mike Henry / Lockheed Martin Eric Rice / Orbitec	*Panel Discussion*
3:30 p.m.	Discussion	
4:00 p.m.	Wrap-Up and Comments for the Future	Mike Duke / LPI
4:30 p.m.	*Adjourn*	

Plenary Session



Lunar and Planetary Institute Director David Black opens the Mars Forum and introduces George Abbey.

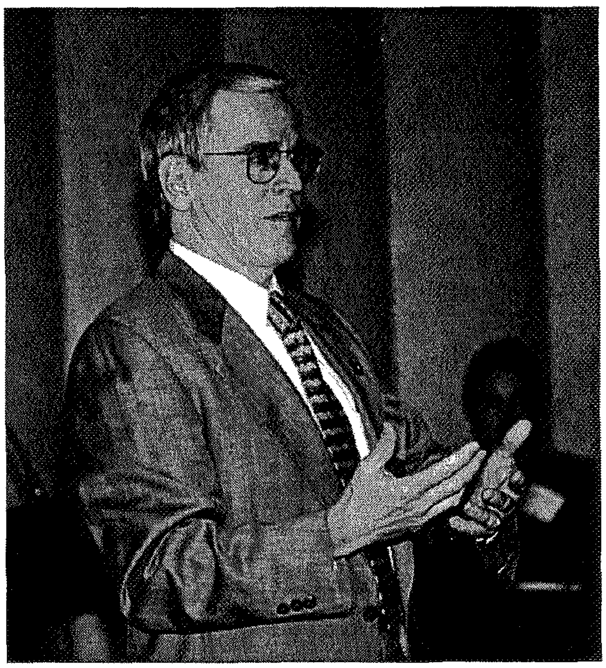
NASA Johnson Space Center Director George Abbey welcomes the Mars Forum participants with a brief review of Johnson Space Center activities supporting future missions beyond low-Earth orbit, such as human performance on space station, BIO-Plex, Advanced Life Support long-duration stays in the human test chamber, and KC-135 reduced gravity training flights.



Convener Mike Duke sets the stage for the two-day Mars Forum by describing the university contributions and participation in the HEDS-UP effort.

Convener Nancy Ann Budden puts the Mars Forum in a historical context and reviews anticipated goals for the meeting.

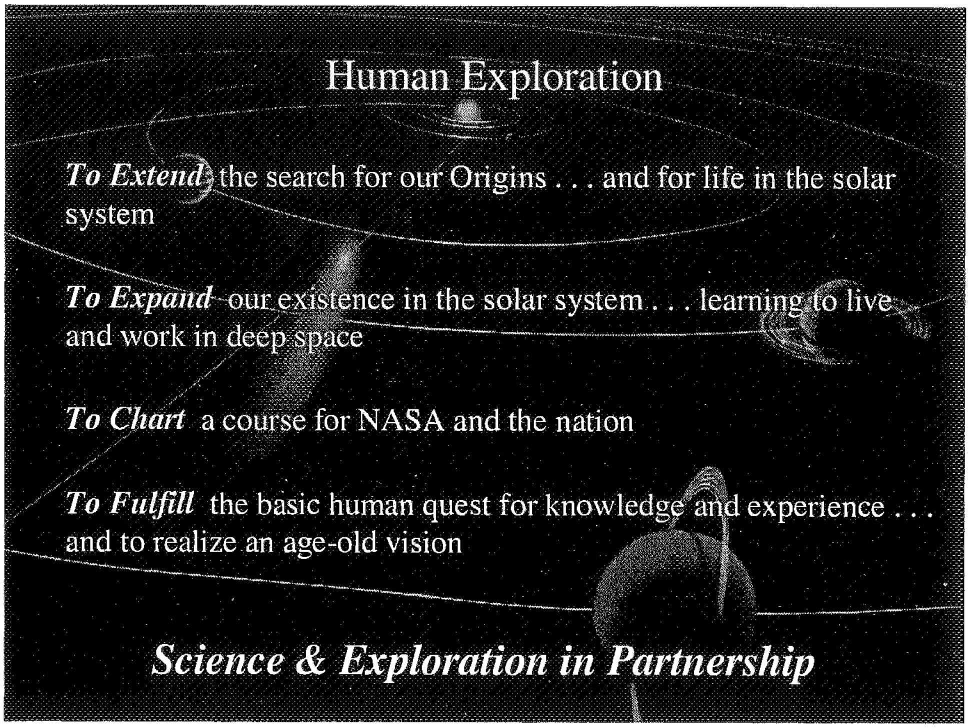
Doug Cooke of the NASA/JSC Office of Exploration presents the vision for human exploration and discusses some of the goals as well as challenges for human exploration.

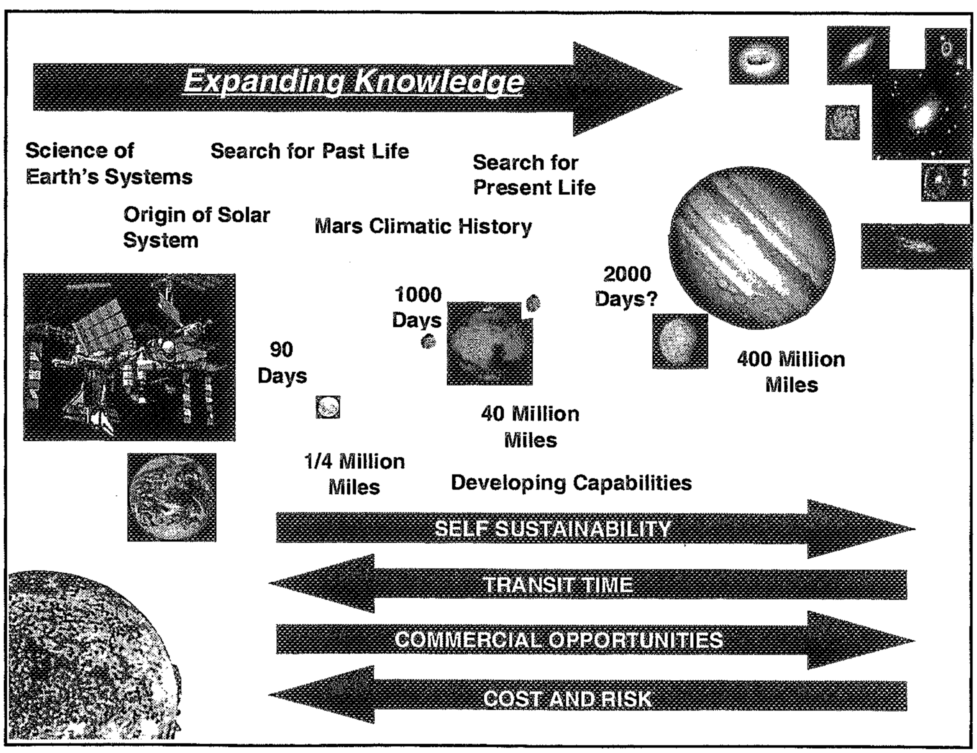


Bill O'Neil of JPL's Mars Missions Group discusses the successes of past Mars robotic missions and looks at future missions to the martian surface.

EXPLORATION: THE VISION

Dóuglas Cooke
NASA Johnson Space Center
Exploration Office





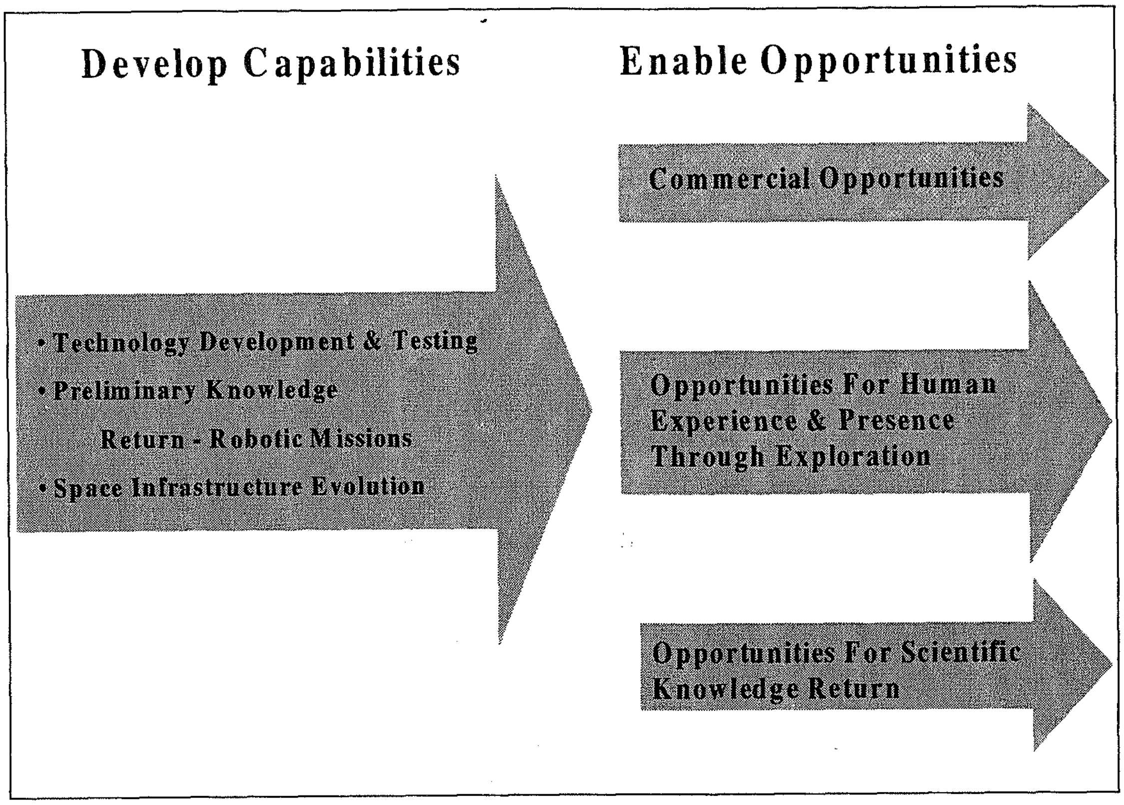
Expand Knowledge

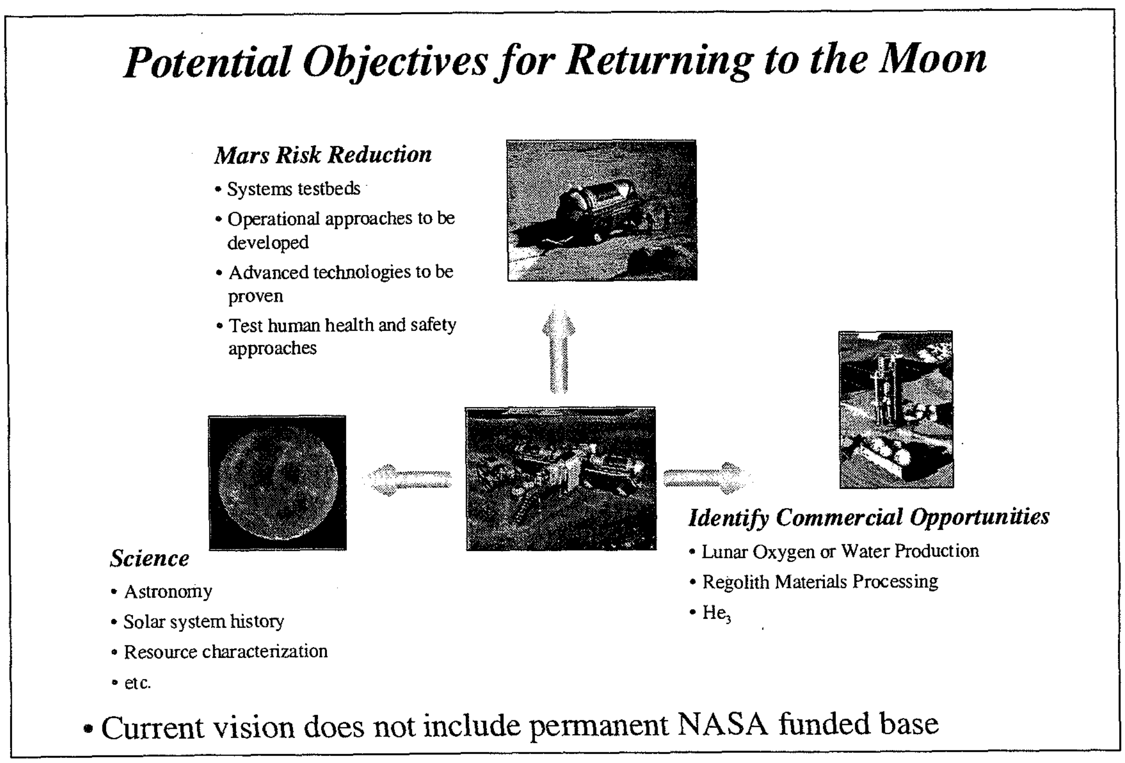
- **Science**
  - Origin of Life
    - Search for life beyond Earth
    - Environmental conditions promoting life
  - Solar System Formation and Evolution
    - What is the history recorded at the Moon?
    - What caused climatic changes on Mars?
    - What can asteroids tell us about the formation and evolution of the solar system?
    - What is in store for Earth?

- **Life Science**
  - Understand how to live and work effectively in space
  - Understand key physical, chemical, and biological processes
- **Exploration - A basic human quest for knowledge and first hand experience**
  - To dream of great discoveries
  - To venture beyond normal everyday life
  - To find great treasures
  - To see the wonders of the planets, the solar system, the universe
  - To overcome great odds

Developing Capabilities

- **Developing Self-sustainability**
  - **The ability to reduce or break the chain of supply into Earth; to live off resources discovered at other destinations as we explore out in to the Solar System**
  - **Decrease Transit Times**
  - **Develop efficient propulsion and related space transportation capabilities that reduce human exposure to the space environment for long trips**
  - **To effectively shrink the size of our solar system, making planets more accessible**
- **Provide Commercial Opportunities**
  - **Develop capabilities that commercial enterprises can take advantage of**
  - **Buy services where possible rather than develop independent capabilities**
  - **Privatize space assets**
  - **Develop technologies with commercial potential**
- **Reduce Cost**
  - **Develop revolutionary technologies and innovative mission approaches that make exploration affordable**


Develop Capabilities
Enable Opportunities
Commercial Opportunities
• Technology Development & Testing
• Preliminary Knowledge
Return - Robotic Missions
• Space Infrastructure Evolution
Opportunities For Human
Experience & Presence
Through Exploration
Opportunities For Scientific
Knowledge Return


Potential Objectives for Returning to the Moon
Mars Risk Reduction
• Systems testbeds
• Operational approaches to be developed
• Advanced technologies to be proven
• Test human health and safety approaches
Science
• Astronomy
• Solar system history
• Resource characterization
• etc.
Identify Commercial Opportunities
• Lunar Oxygen or Water Production
• Regolith Materials Processing
• He_3
• Current vision does not include permanent NASA funded base

"Conditions for Human Exploration"

- **Compelling Scientific or Exploration Rationale**
- **Strong Commercial Potential for High Return...**
- **Public support**
- **Credible cost estimate**

Exploration & Commercialization

'NASA must undertake the difficult tasks that companies simply can't do...' Dan Goldin

As the space horizon is advanced, behind it are opened opportunities for commercial activity at acceptable levels of risk

As this occurs, NASA's research funds can then be redeployed toward ever-advancing that horizon.

NASA's role: Exploration of the solar system, outer space and the universe beyond

1. **Answer fundamental questions about the solar system**
   --history of the solar system and planets
   --origin of life
   --relevance to life on earth
2. **Develop low cost access to space and planetary surfaces. Transition to commercial ventures as early as possible**
3. **Make choices that enable future commercialization - including elimination of barriers to commercialization**

Industry's role (Aerospace & Non-Aerospace)

1. **Identify commercial goals and promising opportunities**
2. **Help guide and partner with NASA to define technology investments that:**
   --support commercial needs
   --open up commercial opportunities
3. **Seek and acquire investment capital to exploit these opportunities**

Potential Commercial Roles vs NASA Roles: Near Term

Low Earth Orbit:
NASA's Role
Shuttle operations
ISS development
Begin privatization of shuttle, International Space Station
Develop/enable low cost access to space

Industry's Role
Expendable & reusable launch vehicles
Communications satellites
Privatization of shuttle, plan for privatization of ISS

Joint venture: X-33 Research

Moon, Mars, Asteroids:
NASA's Role
Basic Research: Fly Robotic Missions to:

- answer fundamental questions about composition, environment for humans and machines
- test environment dependent technologies (ISRU, etc)

Initiate development systems to enable low cost human and robotic access to to orbit and for surface operations

Industry's Role
Explore potential concepts for development of resources, tourism, space transportation, services and others for the moon and asteroids, etc.

Develop candidate technologies through IRAD, SBIR's

Help NASA strategize for developing future commercial technologies and opportunities at Mars

Evaluate science data returned for potential return on investments, early concept development

Outer Planets & Moons
NASA's Role
Basic research on planetary composition
Identify compelling destinations for future exploration

Industry's Role
Help NASA plan for technologies and capabilties that allow for future expansion

PUBLIC SUPPORT

WHAT WE KNOW TODAY:

- Extremely Positive Public Support of Pathfinder
- Outstanding Press Coverage of MGS, Prospector, Pathfinder
- Yankelovich Polls Show Broad But Inconsistent Public Support for Space Programs
- TV Network (Non-Scientific) Polls Show Strong Support for Human Space Exploration
- Many Anecdotal Stories of Public Support for Mars Exploration

CHALLENGES:

- Provide More of the Benefits of Space Exploration Directly to People on Earth
- Develop Techniques of Bringing the Excitement of Discovery and Exploration and the Experience of Living in Space to People on Earth
- Implement a Systematic Approach to Measure Public Support

PUBLIC SUPPORT

SPECIFICS OF WHAT WE PROPOSE TO DO:

- Implement a Systematic Approach to Assessing and Developing Public Support
- Undertake Projects Immediately to Increase Public Awareness and Understanding
    - Develop a Business Plan, Including Plans for:
        - Stakeholder Engagement
        - Customer Engagement
        - Communications
        - Outreach
    - Deliberative Poll to Develop Metrics, Targets
    - HEDS-UP Academic Partnerships
    - Partnerships with Specialists in Customer Engagement (Anteon, GSD&M,..)
    - Involvement of NASA Technology Transfer Centers in Commercialization Studies
    - Partnerships with State, Regional Interests
    - International Conferences
    - Policy Analysts' Forum

AFFORDABLE, CREDIBLE COSTS

Today's Facts and Assumptions:

- Costs Must be Bounded by NASA's Current Funding Levels
- Mr. Goldin's Challenge of $20B
- Yearly Funding Levels on the Order of Space Station Funding: $2-3B/Year
- Costs are Heavily Influenced by Management and Programmatic Approaches

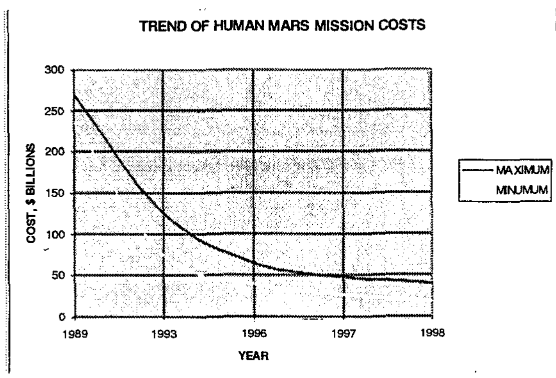
Status:

- Current Estimates Approximate the Affordability Criteria
- Credibility of Cost Models are Being Evaluated and Questioned
- NASA Management of Programs is Continuously Scrutinized for Improvement

Challenges:

- Improvements in NASA and Other Government Processes to Efficiently Manage Large Programs
- The Details of Spacecraft and Mission Designs are Needed to Develop High-Fidelity, High-Probability Cost Estimates
- Fidelity in Development of Costs Must be Improved
- Technologies, Mission and Design Approaches, and Management Approaches Must be Constantly Scrutinized to Maximize Efficiency
- Credibility in Costs Must be Earned Through Peer Review, Independent Evaluation
- Communication of the Fidelity of Costs

EXPLORATION OFFICE



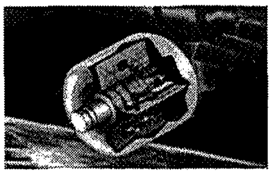
NOTE: 90 DAY STUDY COSTS IN 1989 ASSUME MOON/MARS COSTS EQUAL

Innovation Enables Human Exploration

A lynchpin to the planning of viable and affordable human exploration missions is innovative ideas

Working with new partners

- Pan-enterprise partnership between HEDS and Space Science for Mars robotic missions
- Internationals
- Industries
- Universities



Evolving capabilities through applying new technologies such as:

- Inflatable structures
- Micro and Nano technologies
- In-situ Resource Utilization

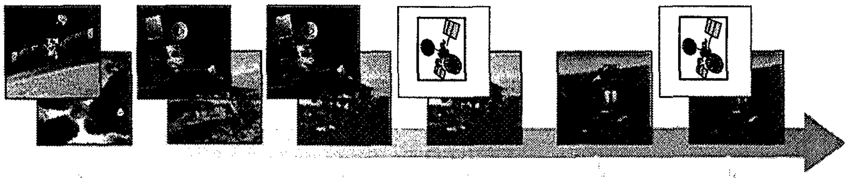
Testing in new places

- The International Space Station
- Technology demonstrations on asteroids, the Moon, and Mars

Exploration Activities

- **Human Exploration and Robotics Team**
  - **–Integrated human and robotic mission planning**
  - **–Technology planning**
  - **–Science strategy development**
  - **–Human Health and Performance planning and development**
  - **–Management and Customer Engagement**
- **HEDS technology planning**
  - **–Test and Demonstration identification and implementation**
- **Mission design and design concept development**
- **Participation in HEDS strategic planning**

Robotic Mission Strategy



Science	✦Mars Global Surveyor ✦Mars Pathfinder	✦'98 Polar Orbiter ✦'98 Polar Lander	✦Surface Mineralogical Orbiter ✦'01 Sample Caching Rover	✦High-Bandwidth Com. Orbiter ✦'03 Sample Caching Rover	✦'05 Mars Sample Return	✦High-Bandwidth Com. Orbiter ✦'07 Mars Sample Return
Exploration			✦Oxygen production ✦Radiation ✦Soil & Dust ✦Aerocapture ✦Precision Landing	✦End-to-End ISRU demo. ✦Surface engineering characteristic ✦Biconic entry and landing ✦Life science data	✦Sample return using in-situ type propellants ✦Mars orbit rendezvous ✦Surface cryogenic storage ✦Life science data	✦Sample return using in-situ propellants ✦Kw-class power system demonstration

Note: Refinement of mission objectives is currently underway

Exploration Critical Factors

Maintain Low Levels of Risk in Human Space Travel

Basic Performance

☆ ***Affordable & Safe Planetary Exploration***

Human Health & Safety

☆ ***Safe and Reliable Exploration Strategy***

***Reduced Cost** (Mass)*

☆ ***Reduced Launch Costs***

☆ ***Jucicious Reduction of Mass:***

Every pound to Mars and back = 40 pounds launched to Low-Earth-Orbit

Exploration Critical Factors

Basic Performance
☆ ***Affordable & Safe Planetary Exploration***

Human Support

- Advanced, light-weight, space suit and surface mobility for routine, robust exploration
- Advanced life support

Space Transportation

- Lift Capability ~ 80 metric tons for large payload volumes
- Efficient transportation to and from planetary surfaces

Advanced Space Power

- High continuous power (110 kWe) for robust exploration (In-Situ resource utilization, food closure)

Information & Automation

- Advanced operations in remote environments
- Science and mission data storage / computation / transfer

Sensors & Instruments

- Science data
- Medical & hardware health monitoring
- Advanced scientific field laboratories and capabilities

Exploration Critical Factors

Reduced Cost (Mass)
☆ ***Every pound to Mars and back = 40 pounds launched to Low-Earth-Orbit***

Human Support

- Closed-loop life support reduces mass (25%)
- Advanced EVA Suit minimizes expendables and maintenance
- Advanced inflatable structures = reduced mass (25%)

Advanced Space Power

- Reduced mass/kw = reduced cost

Sensors & Instruments

- Micro/Nano Technology = reduced mass

Space Transportation

- Space Transportation Efficiencies (IMLEO Reduction) Compared to Chemical Propulsion Scenario:
  - Aerobraking: 40-45% reduction
  - In-Situ Resource Utilization: 21-25% reduction
  - High Efficiency In-Space Propulsion: 55% reduction
  - Combined: 68% reduction

Human Health & Safety
☆ ***Safe and Reliable Exploration Strategy***

Human Health & Safety (Human Support)

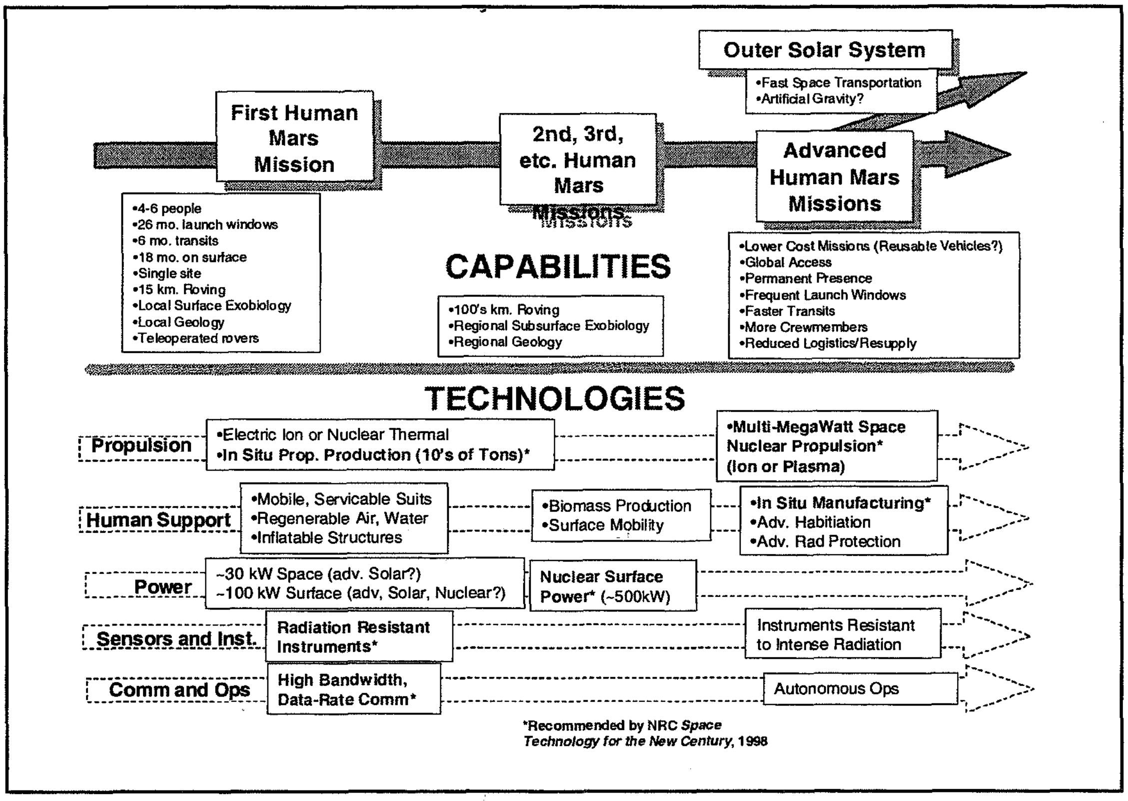
- Radiation research
- Zero and partial gravity research
- Medical care

Space Transportation

- Quick trips to and from planetary destinations

Sensors & Instruments

- Environmental & medical monitoring



Human Support

Health & Human Performance

☆Radiation protection research

• *Countermeasure development*

• *Medical care & environmental health*

• *Human factors*

Advanced Life Support

• *Air and water loop closure*

• *Solid waste processing*

• *Thermal control*

• *Food production*

Advanced Habitation Systems

• Habitat concepts and emplacement methods

• Advanced light-weight structures (inflatable vs "hard")

• Integrated radiation protection

EVA & Surface Mobility

• Enable routine surface exploration

• *Highly reusable, light-weight, high-mobility suit and portable life support system*

• Short and long-range surface mobility for advanced surface exploration capabilities

• *Minimize resupply, repair, and maintenance*

Human Support

	Self Sustain-ability	Reduce Transit Time	Commer-cial Oppor-tunities	Reduce Cost	Increase Know-ledge	Reduce Risk	Near Term Candidate Projects
Health & Human Performance	☒	☐	☑	☐	☒	☒	Mars 2001 Tissue Equivalent Proportional Counter, Radiation Test & Demonstration Mission; ISS Micro-g Countermeasures
Advanced Life Support	☒	☐	☑	☒	☐	☐	ISS Node III ALS Implementation
Advanced Habitation Systems	☒	☐	☑	☑	☐	☑	ISS TransHab Implementation
EVA & Surface Mobility	☒	☐	☑	☑	☑	☑	Mark III Technology Demonstrator Field Test; ISS Advanced Gloves

☒ Highly Applicable
☑ Somewhat Applicable
☐ Limited Applicability

Space Transportation

Affordable Earth-to-Orbit Transportation

- ☆ Low Cost Technologies Scaled to Large Launcher
  - *Tanks & Structures*
  - *Propulsion Systems*
  - Shrouds
  - Upper Stages
- Accommodate large-volume payload requirements
- *Minimum on-orbit assembly costs*
- Minimum impact to launch facilities

Advanced Interplanetary Propulsion

- All Chemical Propulsion Option
- ☆ *Solar-Electric Propulsion Option*
- Nuclear-Electric Propulsion Option
- ☆ Nuclear-Thermal Option
- Ascent & Descent Propulsion

Cryogenic Fluids Management

- ☆ Long-Term (1700 days) Cryogenic Fluid Storage
- ☆ Cryogenic Liquefaction of In-Situ Propellants
- Cryogenic Refrigeration
- *Zero-G Fluid Management*

Aeroassist

- Earth/Mars Orbital Insertion & Direct Entry
- ☆ Advanced Thermal Protection Systems
- Mars Atmospheric Modeling
- ☆ Guidance & Navigation for Precision Landing & Aerocapture

In-Situ Resource Utilization

- ☆ *Propellant Production from Mars Atmosphere*
- Human Mars Ascent Propellant
- ☆ Mars Sample Return Using In-Situ Resources
- *Lunar Demonstration from Soil*

Space Transportation

	Self Sustain-ability	Reduce Transit Time	Commer-cial Oppor-tunities	Reduce Cost	Increase Know-ledge	Reduce Risk	Near Term Candidate Projects
Affordable Earth-to-Orbit Transportation	☐	☐	☒	☒	☐	☐	NASA/TRW Ultra Low-Cost Engine Demo
Advanced Interplanetary Propulsion	☐	☒	☒	☒	☐	☒	50kW Hall Thruster Static Test; Bimodal Fuels Evaluation; Radiation Test & Demonstration Mission
Cryogenic Fluid Management	☒	☒	☑	☒	☐	☐	Cryogenic Liquid Acquisition, Storage & Supply Exp.
Aeroassist	☐	☒	☐	☒	☐	☐	Mars 2001 Aerocapture; Advanced Ablative Materials Testing
In Situ Resource Utilization	☒	☐	☒	☒	☐	☑	Mars 2001 In Situ Propellant Production

☒ Highly Applicable
☑ Somewhat Applicable
☐ Limited Applicability

Advanced Space Power

☆Advanced Power Generation

- Lightweight, high reliability, high efficiency systems for multi-year missions
  - Megawatt-class systems for efficient spacecraft propulsion
  - 100 KW-class fixed surface power systems
  - 10 KW-class mobile systems
  - 1 KW-class human-portable systems
- *Advanced PV systems for 1-100 KW*
- Solar Dynamic options for 10-1000's KW
- Potential Nuclear options for 100 - Multi-MW

Energy Storage

- High capacity regenerative fuel cell and lightweight battery options for long-term storage and fixed surface operations
- *Compact, mobile systems (batteries, fuelcells or flywheel systems)*

Power Management

- *Very lightweight, high efficiency systems (10-100X better than state-of-the-art)*
- Broad power range: KW to MW
- Reconfigurable, fault tolerant power networks

Advanced Space Power

	Self Sustain-ability	Reduce Transit Time	Commer-cial Oppor-tunities	Reduce Cost	Increase Know-ledge	Reduce Risk	Near Term Candidate Projects
Advanced Power Generation	☒	☐	☑	☑	☐	☒	Thin Film PV Array Manufacturing & Performance Testing
Power Management	☒	☐	☑	☑	☐	☒	
Power Storage	☒	☐	☑	☑	☐	☒	Proton Exchange Membrane Fuel Cell Flight Exp.; ISS Flywheels

☒ Highly Applicable
☑ Somewhat Applicable
☐ Limited Applicability

Information & Automation

Communications & Networks

- High Bandwidth communications
- Robust communications capability at exploration destinations
- Fast and reliable data acquisition, transmission, and delivery to remote operations sites

☆Intelligent Synthesis Environment

- State-of-the-art simulation based system engineering & analysis environment for all phases of development and execution
- Integrates remote teams in virtual environments: scientists, technology developers, project engineers
- Provides for rapid and efficient systems analysis and integration

Intelligent Systems & Advanced Operations

- *Autonomous system operation for remote operations independent of direct earth-based control*
- Systems health management
- Performance Support Systems for both astronauts and ground operations personnel
- Integration of robotic and human interfaces

Information and Automation

	Self Sustainability	Reduce Transit Time	Commercial Opportunities	Reduce Cost	Increase Knowledge	Reduce Risk	Near Term Candidate Projects
Communications & Network	☑	☐	☒	☐	☑	☒	Miniaturized Optical Com System
Advanced Operations	☒	☐	☒	☒	☐	☒	Mars Mission Simulation Project, SSE/HEDS Collaboration
Intelligent Systems	☒	☐	☒	☒	☑	☒	On-Board Automation Architecture Tests
Intelligent Synthesis Environment	☑	☐	☒	☒	☐	☒	Integrated Design Environment Development

☒ Highly Applicable
☑ Somewhat Applicable
☐ Limited Applicability

Science & Engineering Field Labs

- In-situ sample analysis
  - Organic chemistry and age dating
  - Electron microscopy
  - Sample preparation
- Remote geologist
  - Sample context visualization
  - Chemical and mineral analysis
  - Interior and weather
- Virtual presence
  - Imaging and remote sensing

Planetary Prospecting

- Sample acquisition
  - on-site analysis
  - sample screening and selection
  - cross-sample contamination control
- Site safety and selection
- Resource identification and mapping

☆ *Environmental & Medical Monitoring*

- Alarm monitors (fire, toxics, radiation, etc.)
- Environmental monitors (food, water, air)
- Human health monitors (suit/EVA, IVA, routine check-ups)
- Emergency medical systems/telemedicine
  - Care provider virtual presence
- Global monitoring and hazard avoidance (e.g. dust storms)

Sample Curation

- Long-term packaging/preservation and "witness-plate" monitoring
- Hazards/contamination analysis
- On-site caching and archival

Crosscutting Technologies

☆ *Micro/Nano Technologies*

Sensors & Instruments

	Self Sustain-ability	Reduce Transit Time	Commer-cial Oppor-tunities	Reduce Cost	Increase Know-ledge	Reduce Risk	Near term Candidate Projects
Science and Engineering Field Labs	☒	☐	☒	☐	☒	☑	University Surface Science Studies
Planetary Prospecting	☒	☐	☒	☐	☒	☑	Devon Island Field Site Invstigation
Sample Curation	☒	☐	☒	☐	☒	☑	MSR 2001 Soil & Dust Characterization Instrument
Environmental and Medical Monitoring	☒	☐	☒	☐	☒	☒	Enhanced Catalyst Trace Contaminant Control System Test

☒ Highly Applicable
☑ Somewhat Applicable
☐ Limited Applicability

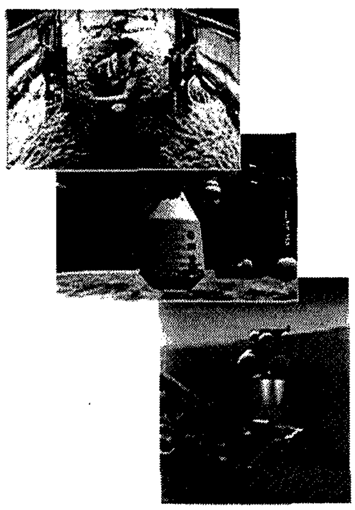
Test Beds and Flight Demonstrations

Leveraging and Evolving Current Capabilities

Developing Relevant Capabilities Early

Test Beds

- Ground Test Facilities
  - BIOPLEX
  - MIST
  - Others
- KC135
- Space Shuttle as a test bed
- Space Station as a test bed
- Robotic Missions
  - Partnering on Mars robotic missions
  - Partnering on other robotic missions
    - Earth orbit
    - Lunar
    - Beyond

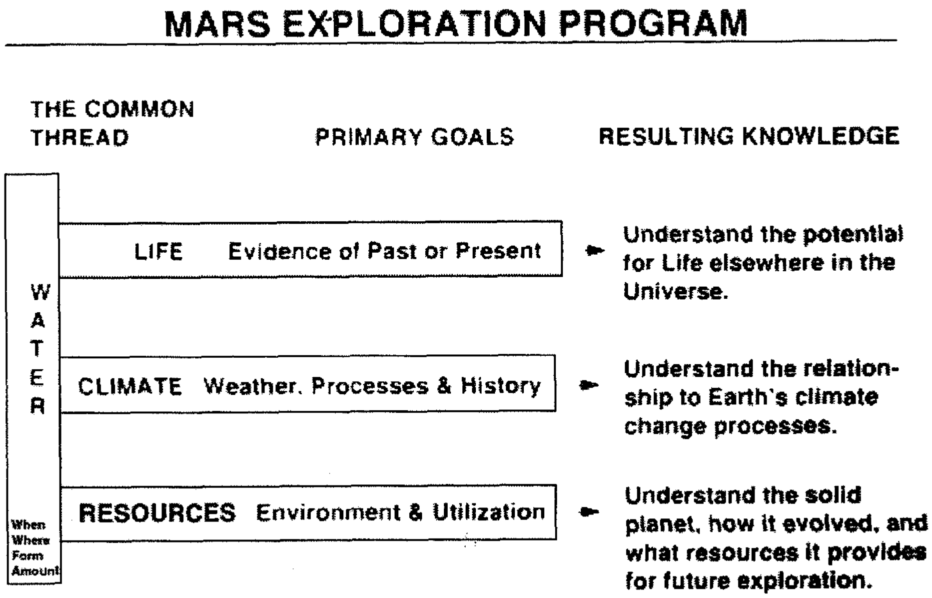


MARS MISSIONS: NOW AND BEYOND

William O'Neil
Jet Propulsion Laboratory

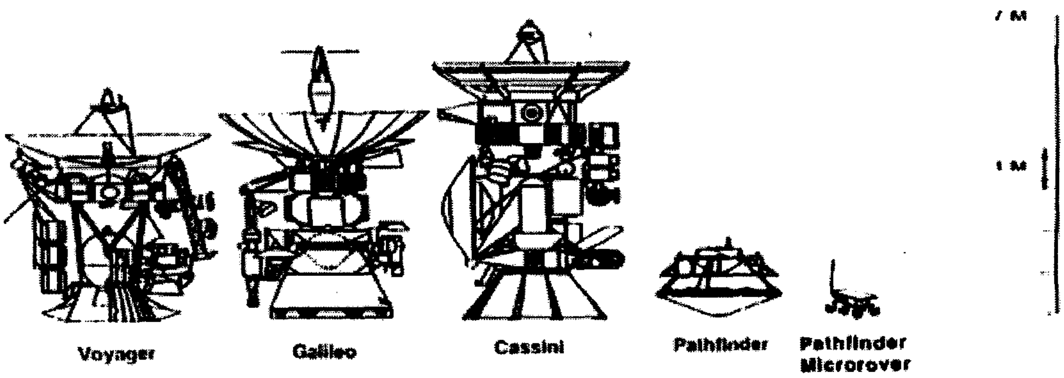
MARS EXPLORATION PROGRAM

We have entered a new, exciting era of Mars exploration with the fabulous landing of Pathfinder on Mars last July 4th, and the subsequent captivating operations of the Sojourner Rover it deployed. The Mars Global Surveyor (MGS) entered Mars orbit in September and has been executing a series of aerobraking phases to achieve its 300-km circular mapping orbit next spring when it begins a very detailed mapping of the entire Mars surface over a full martian year. This December and in January 1999, we launch the Mars '98 Orbiter and Lander, respectively. The Lander is to land in the polar region at 70°S latitude. Basically, every Mars opportunity we will launch a pair of missions. In 2001 and in 2003, we plan to launch Orbiters and Landers with Rovers to acquire and cache carefully selected Mars samples. Then in 2005 the first Mars Sample Return Mission (MSR) is to be launched to return one of the caches to Earth in 2008. Ultimately, scientists in laboratories world-wide will analyze the samples and bounty of other data being returned from Mars on a continual basis.

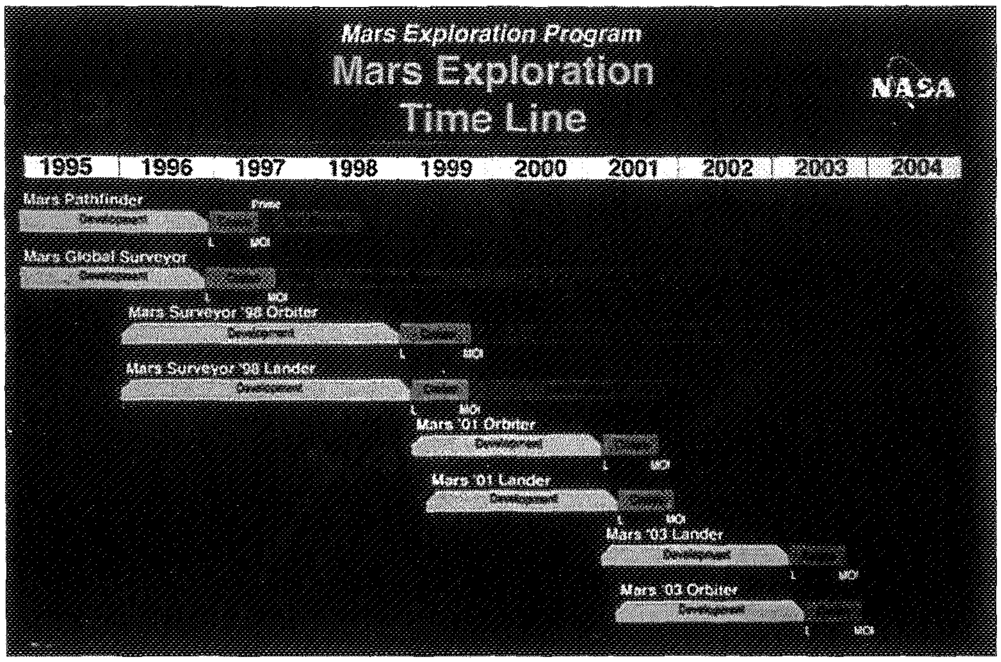


The common thread for Mars exploration is water. It is the key to our understanding of the possibility of extraterrestrial life, Mars climate, and resources.

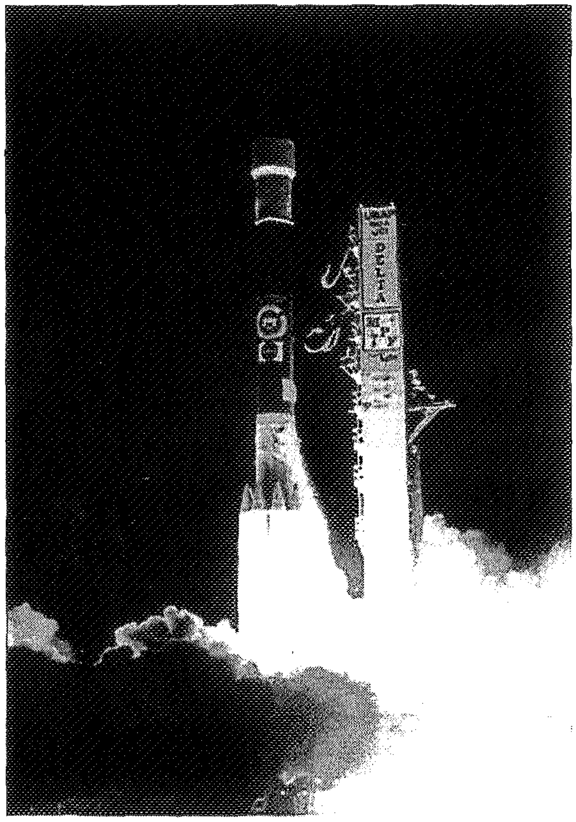
NASA Space Science Spacecraft



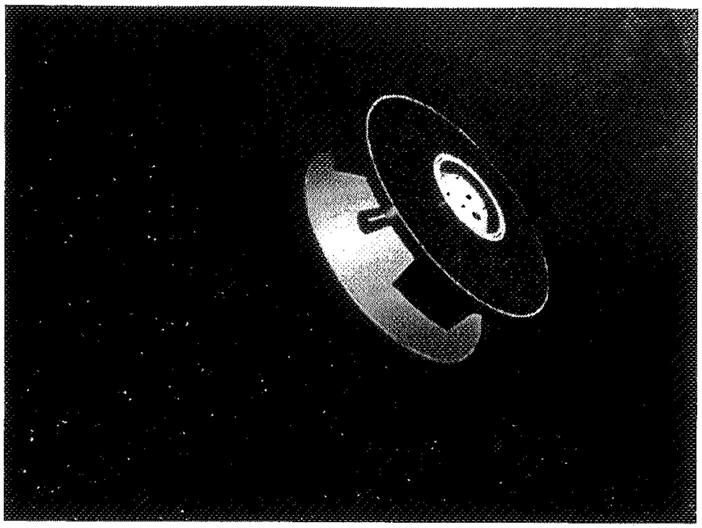
The reduction in the size of NASA/JPL planetary spacecrafts is dramatically illustrated.



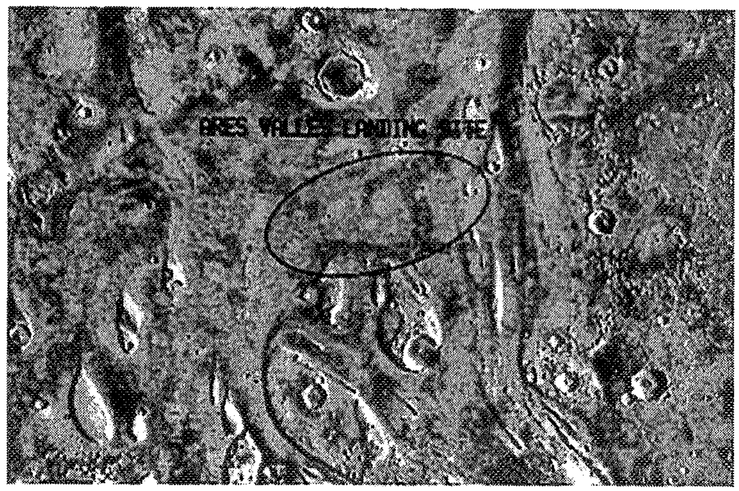
The very ambitious robotic Mars Exploration Program is illustrated showing the two launches — one orbiter and one lander — every opportunity. The development period, interplanetary cruise and mars operations periods are shown for each mission. And this chart shows the Program BEFORE the "Mars rock" resulted in the addition of the near term Mars sample return missions.



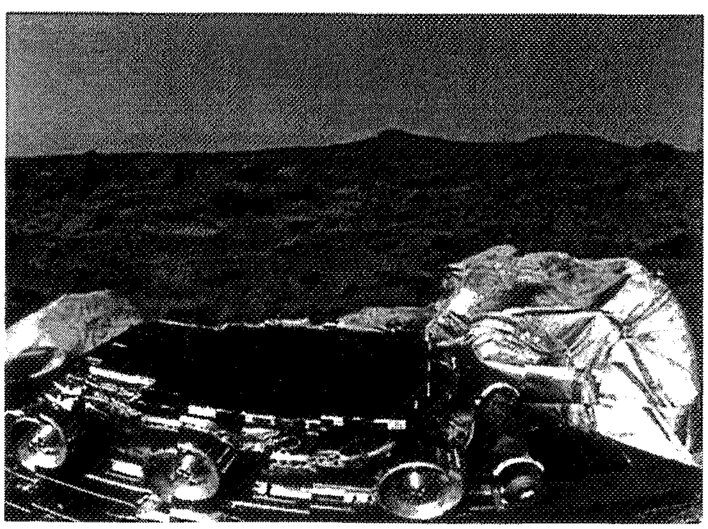
The launch of Mars Pathfinder on the Delta rocket.



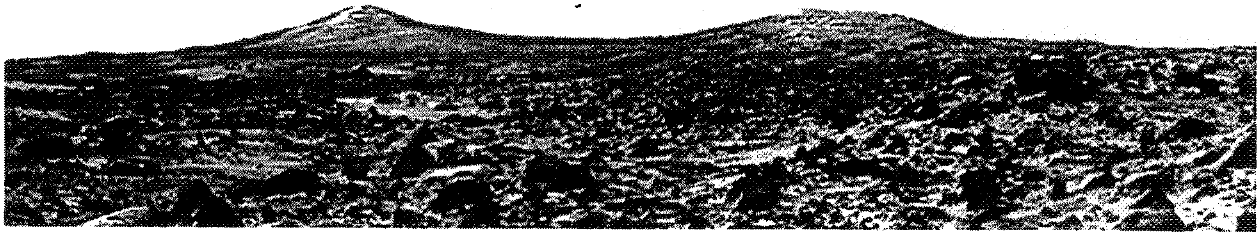
An artist's rendering of the Mars Pathfinder in interplanetary cruise to Mars. The cruise stage with its annular solar panel array is shown carrying the aeroshell with its precious cargo.



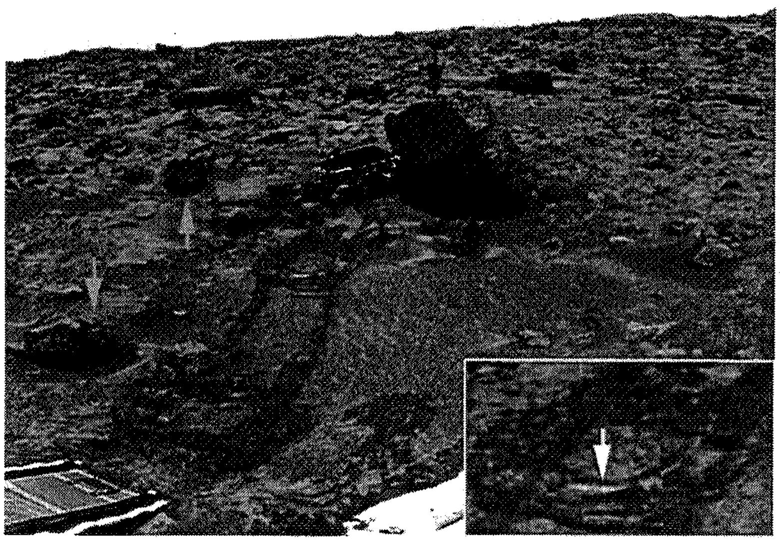
The pathfinder three-σ landing accuracy ellipse is shown on the Ares Valles Landing Site. Pathfinder landed one-σ (~25 km) to the left of the center of the ellipse.



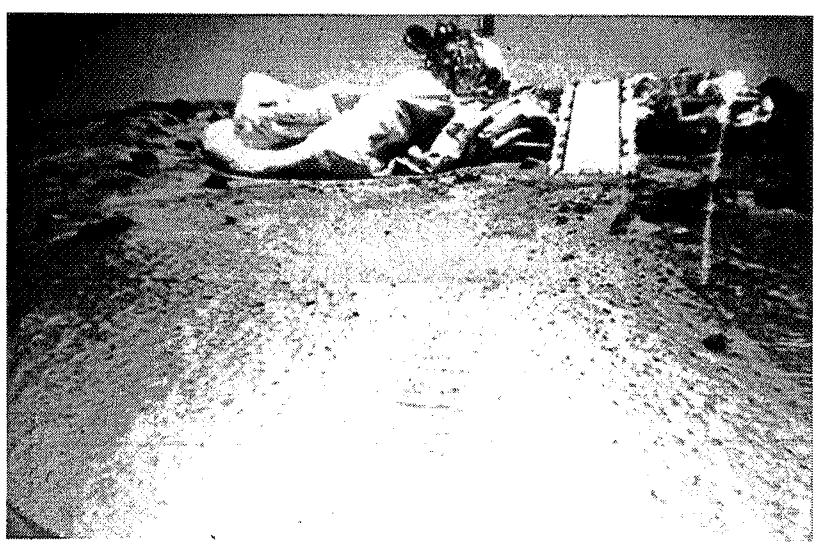
The now famous first color image of the Sojourner Rover on its Pathfinder deployment petal. The obstructing airbag on the back ramp is clearly seen. The petal was subsequently raised and the airbag further retracted out of the way by ground command to allow Sojourner to drive down that ramp, which it did perfectly.



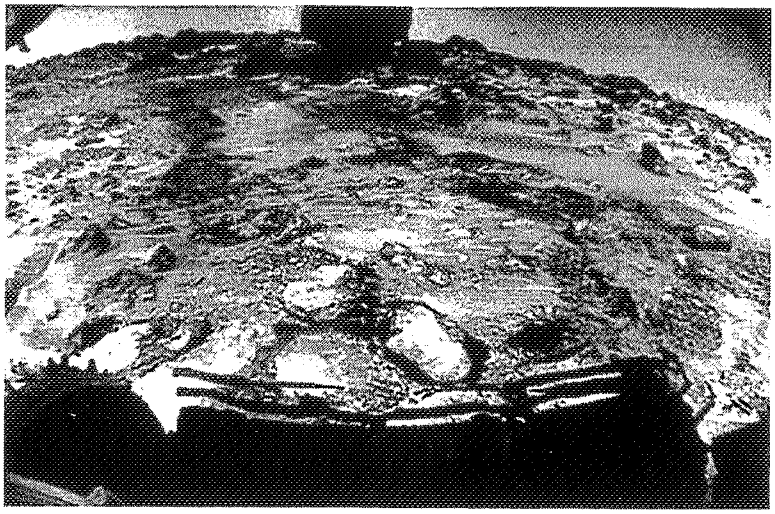
A view from the Lander's camera. A great flood of water washed over this region long ago, passing from left to right across this portion of the landscape. The Twin Peaks on the horizon are just about one kilometer away.



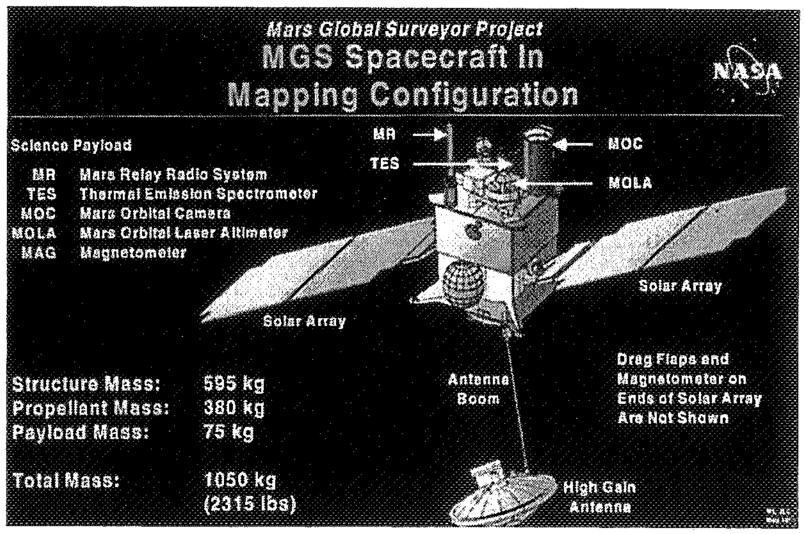
This view from the Lander camera shows the tracks of Sojourner over to the large rock called Yogi, about one meter tall. Sojourner has placed its Alpha Proton X-ray Spectrometer instrument against the rock to determine its elemental composition.



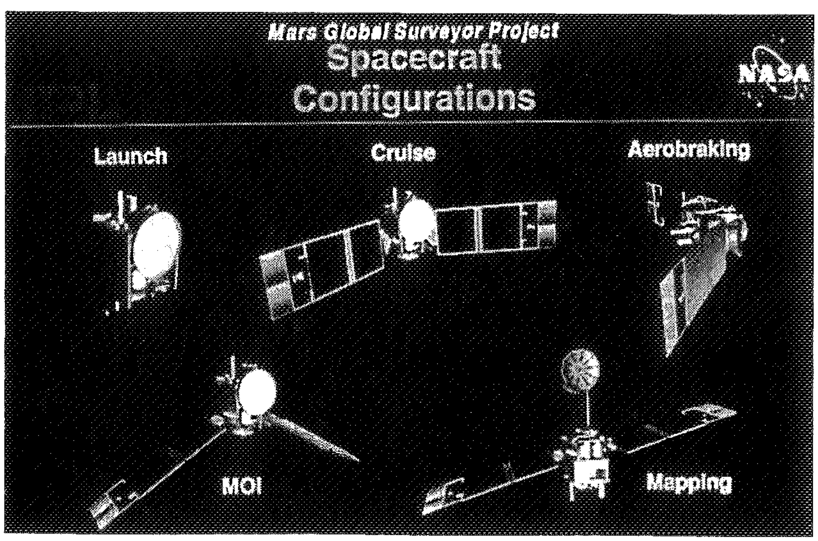
A view from Sojourner's camera looking back at the Pathfinder Lander.



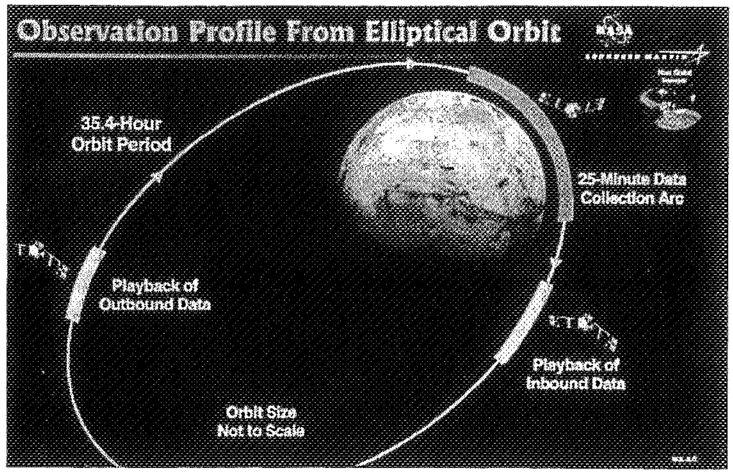
A view from Sojourner showing the shadows of its hazard avoidance detectors.



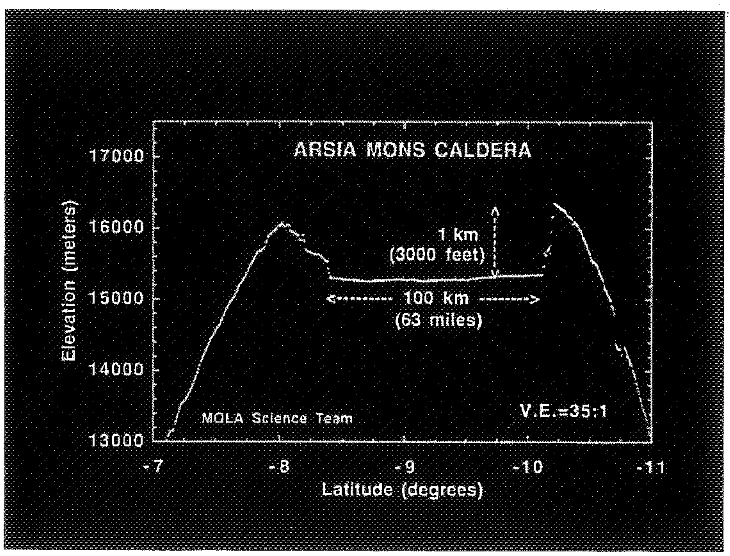
This cartoon illustrates the Mars Global Surveyor Spacecraft in Mapping Configuration. The body-fixed instruments are nadir pointed while the solar arrays and high gain antenna are articulated to track the Sun and the Earth, respectively.



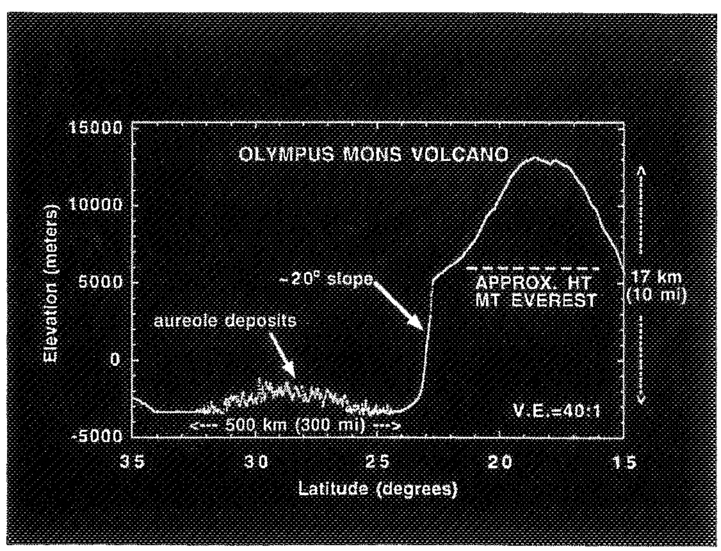
Here MGS is shown in all its different mission configurations.



As MGS proceeds through its aerobraking phases it will be in a highly elliptical orbit for many months allowing the record and playback strategy illustrated here.

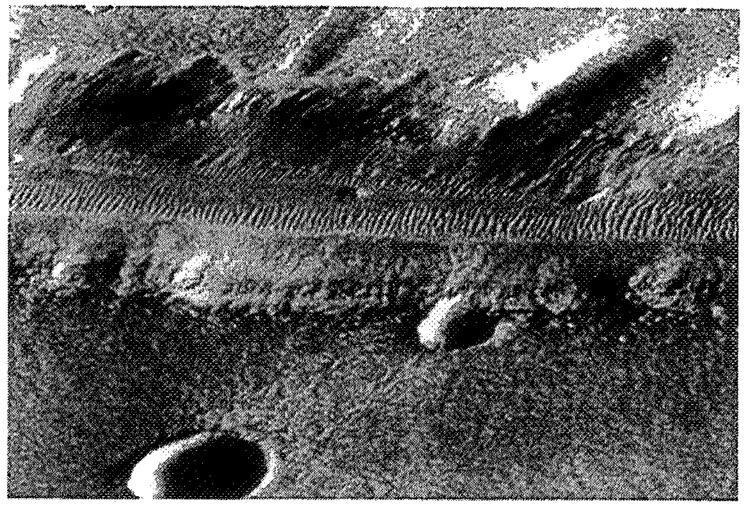


The MGS Mars Orbital Laser Altimeter (MOLA) measured this dramatic elevation profile of the Arsia Mons Caldera.

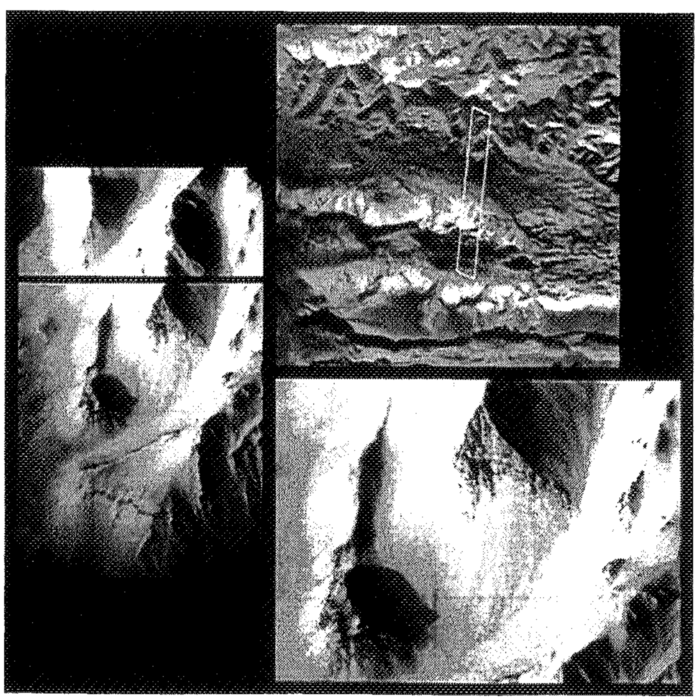


The MOLA measured the profile of Olympus Mons Volcano, which is more than twice the height of Earth's Mt. Everest.

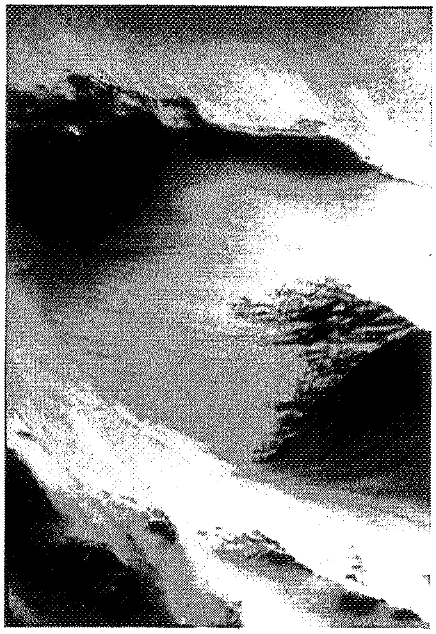
An MGS color image looking down on Olympus Mons.



This view from MGS shows a Mars landscape looking like beach sand with craters.



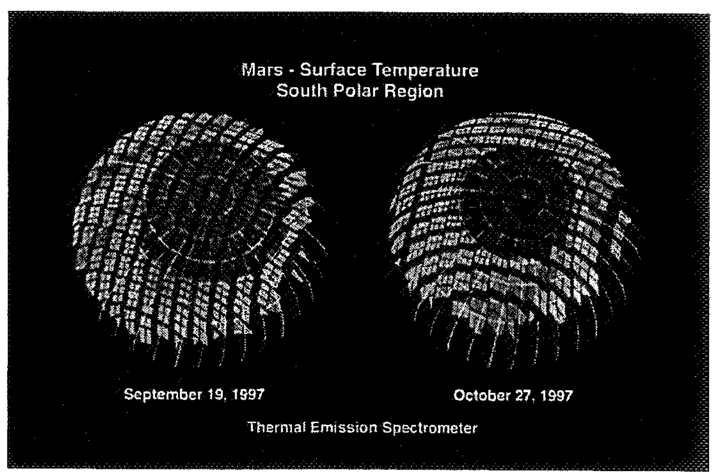
These images from MGS show several views of a cliff face with quite remarkable features.



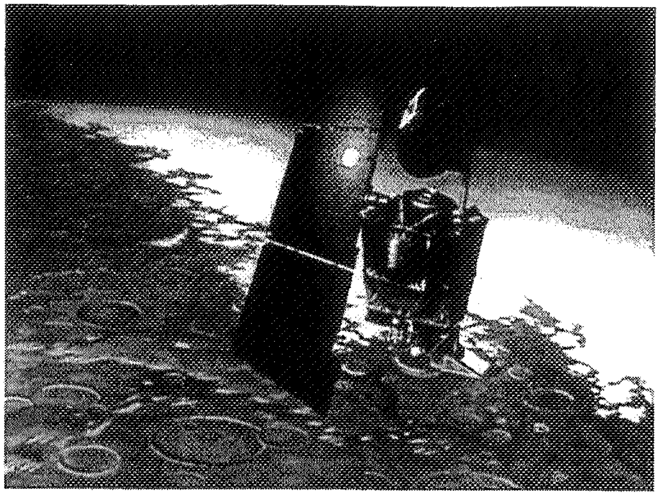
This is the highest resolution view of the cliff.

One of the most important images from MGS to date showing a river canyon with great stratification in the banks and clear evidence the river changed its path over time in the top part of the image.

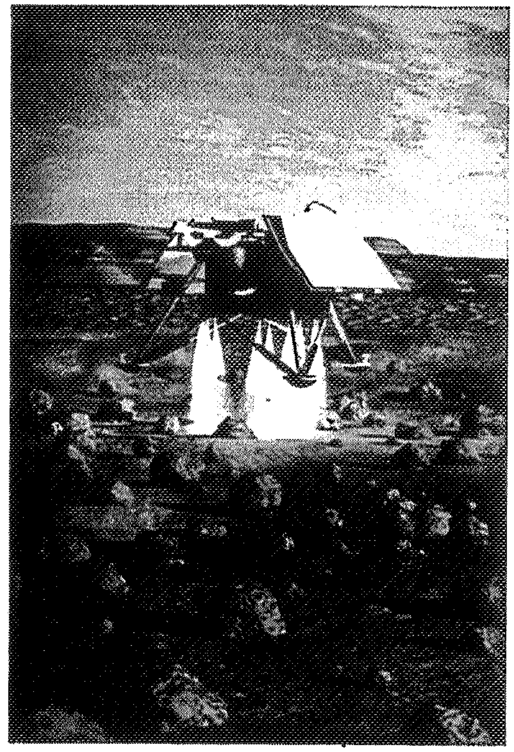
A riverbed seen by MGS.



Thermal imagery from the MGS Thermal Emission Spectrometer (TES) showing the receeding of the Mars South Polar Cap last fall.

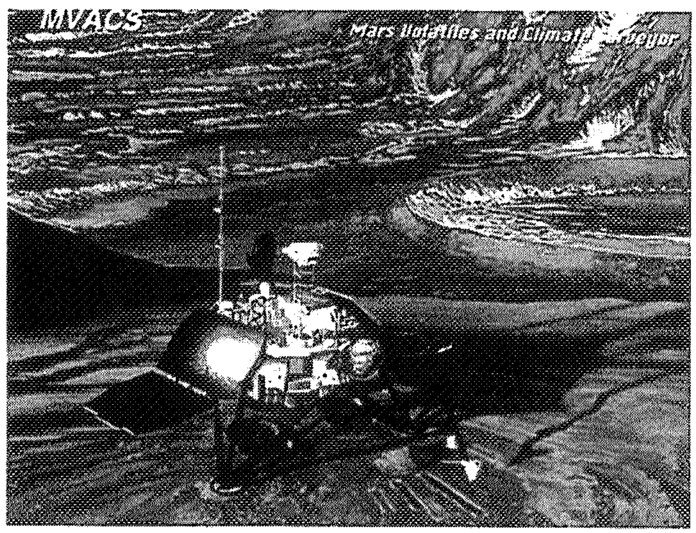


An artist's rendering of the Mars '98 Orbiter at Mars. The Orbiter is about the size of a household refrigerator.



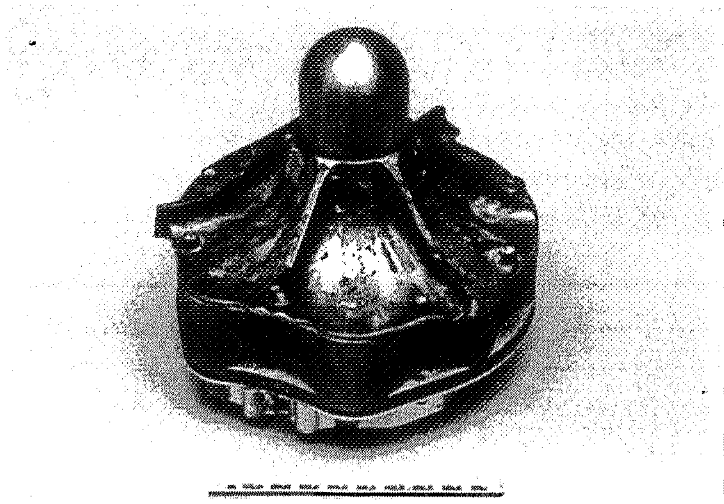
A rendering of the Mars '98 Polar Lander just before touchdown on Mars. The Lander is about the size of a household clothes dryer.

Mars Global Surveyor image of the planned Mars '98 Polar Lander landing area near 70°S latitude. The image on the left is raw and on the right is the image after processing to bring out details and contrast. The scientists and engineers may be rethinking about landing in this area based on the terrain seen here.



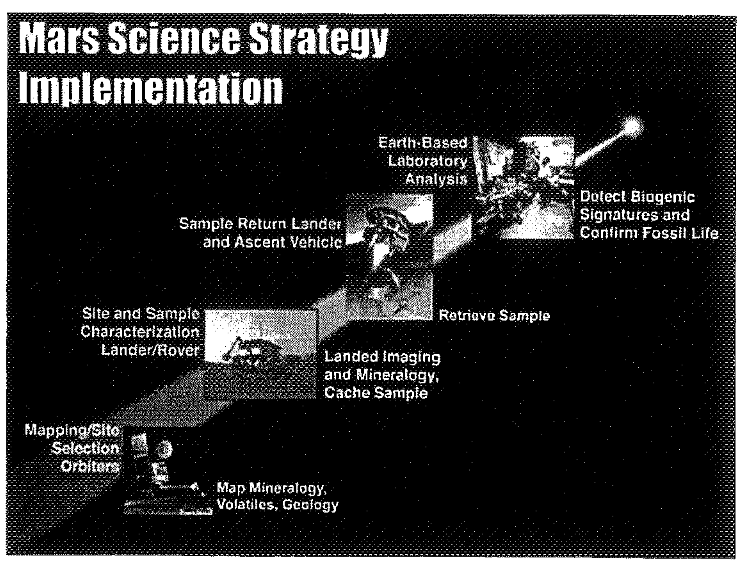
A rendering of the Mars '98 Polar Lander operating on the surface of Mars with its sampling arm, camera, antenna, weather mast, and solar panels deployed.

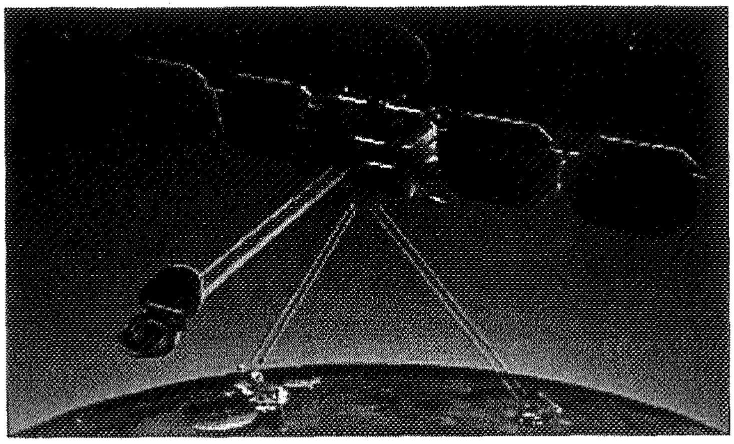
A photograph of a Deep-Space-2 Penetrator test article. Two of these penetrators are planned to fly aboard the Mars '98 Lander Cruise stage and be released shortly before entry to follow unbraked ballistic trajectories to impact the surface with high speed for substantial penetration below the surface.



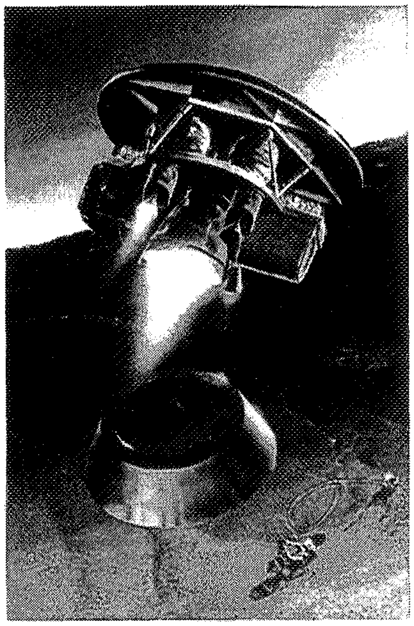
The famous Allan Hills meteorite from Antarctica that scientists declared in August 1996 suggests evidence of ancient martian life. This declaration caused tremendous excitement and resulted in the NASA decision to advance the schedule for the first robotic sample return from Mars. We are now planning to launch the mission in 2005 and have the first sample back to Earth in 2008.

Here is our new Roadmap showing the science mission activities leading to landing site selection, sample selection, the first Mars Ascent Vehicle leaving the surface with the samples that the Rover acquired, and ultimately, the extensive Earth laboratory-based analysis of the returned samples.

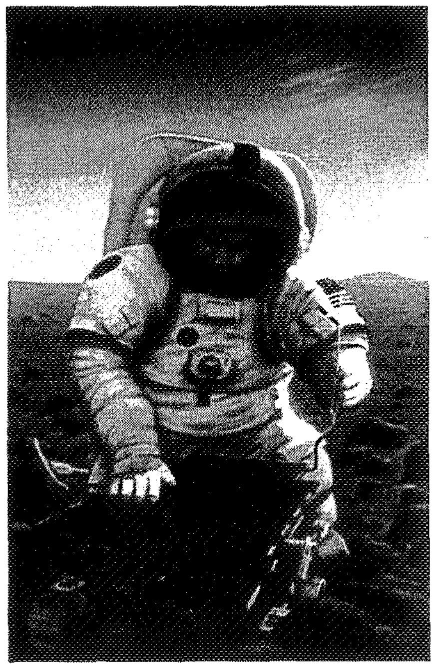




An artist's rendering of the Mars '01 mission at Mars showing the '01 Oribiter relay links communicating to both sample acquisition Rover and the Lander that delivered the Rover and is operating an extensive HEDS payload to help characterize the martian environment for Human exploration and testing *in situ* production of Oxidizer propellant that the Human missions will use to launch from the surface of Mars for the trip back to Earth. Note the large solar panels on the Lander to support the HEDS experiments.



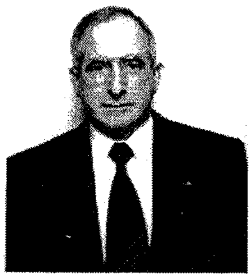
A rendering of the '05 Mars Sample Return Ascent Vehicle just after the first stage has been jettisioned and its second stage has ignited to complete the powered flight to the Mars parking orbit. The Earth return Orbiter will rendezvous and dock with the Ascent Vehicle and the sample cache will be transfered to the return vehicle, which will subsequently use its rocket engine to inject into the interplanetary Earth return trajectory. The Lander that delivered the Ascent Vehicle and served as its launch pad and the Rover that fetched the sample cache are seen on the surface below.



And here we have Ms. Sojourner Truth, the great, great granddaughter of the namesake of the NASA/JPL Rover that landed on Mars, July, 4, 1997, inspecting that very Rover on the surface of Mars, hopefully in the second decade of the next century.

HEDS: STRATEGIC VIEW

Joe Rothenberg
NASA Headquarters



Joe Rothenberg, NASA Headquarter's Associate Administrator for the Office of Space Flight, participated in the HEDS-UP Mars Exploration Forum by teleconference from Capitol Hill in Washington, DC. As director of "Code M," Rothenberg is responsible for establishing the policies and direction of NASA's human space flight programs, putting him in charge of NASA's Human Exploration and Development of Space Enterprise (HEDS). Rothenberg reviewed the long-term goals for human space flight, placing it in the context of NASA's long-term strategic plan and the fiscal realities of the U.S. investment in space.

National Aeronautics and
Space Administration
Headquarters
Washington, DC 20546-0001

Reply to attn of: M

TO: Officials-in-Charge of Headquarters Offices
Directors, NASA Field Installations
Director, Jet Propulsion Laboratory

FROM: M/Associate Administrator for Space Flight

SUBJECT: Future Human Exploration Initiative

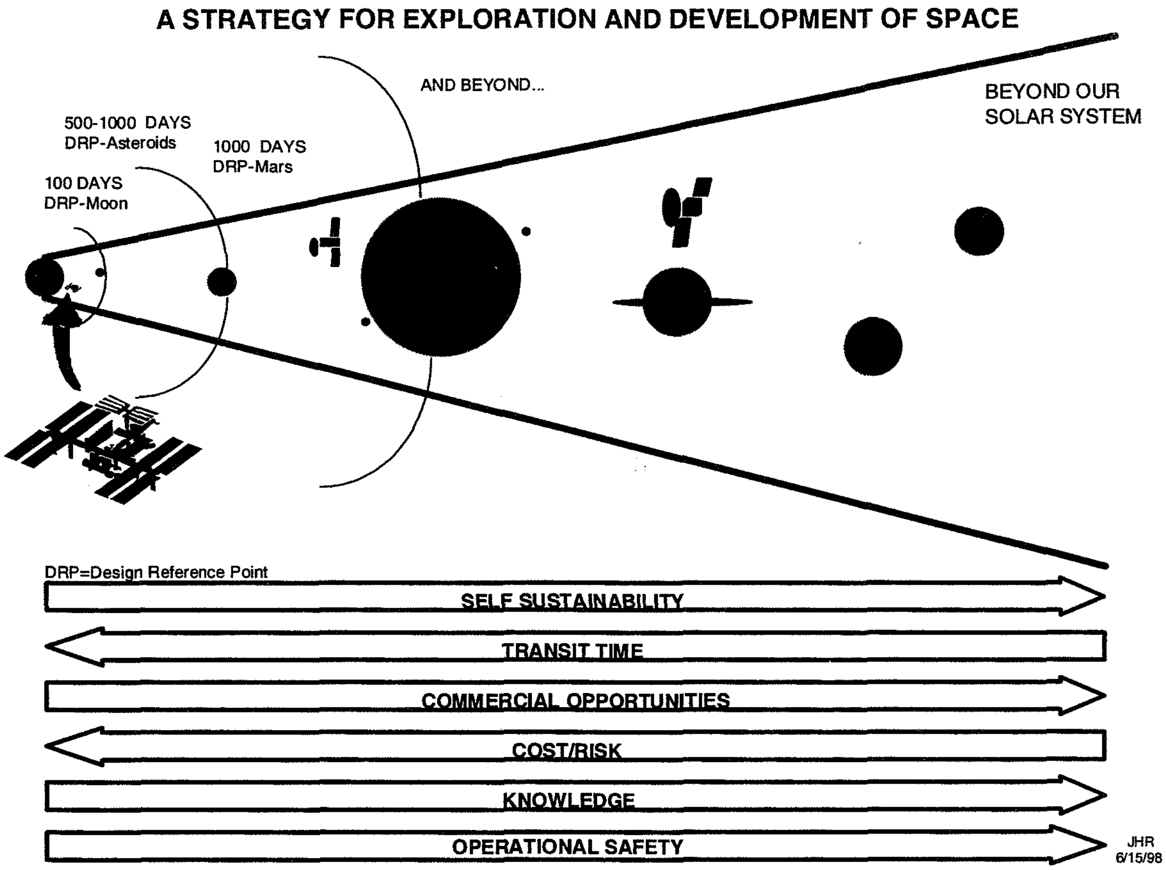
One of the goals of the National Space Policy is to "Enhance knowledge of the Earth, the solar system, and the universe through human and robotic exploration." NASA must continue studies, using its civil service workforce, to identify and evaluate key technologies to enable exploration beyond Earth orbit.

The Human Exploration and Development of Space Enterprise will continue studying options for human exploration in support of the national policy. We will accomplish this through a small cadre of civil service employees across all Centers, along with our international and industry partners. We will look at a variety of mission scenarios to identify and evaluate the feasibility of supporting technologies that provide the significant improvements in areas such as cost reduction, supportability, and operations. These technology areas will include propulsion, power, life support, communication, navigation, and involve exploration of the Moon, Mars, and asteroids. A key element of these efforts will be scientific partnerships and international cooperation.

We will continue to pursue the advanced technology initiative for human exploration with the Administration as the International Space Station (ISS) schedule milestones are achieved.

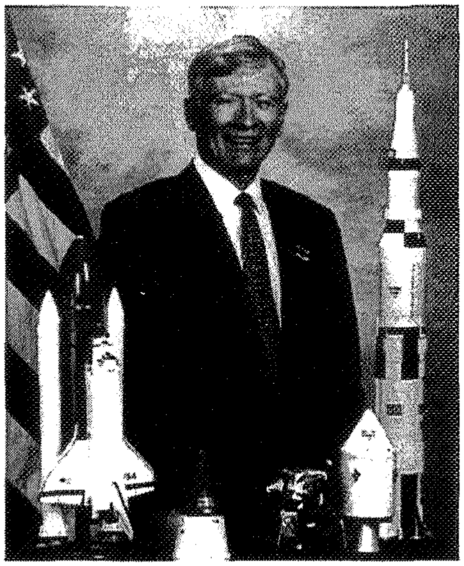
As always, the highest priorities for human space flight are to fly the Shuttle safely and to complete the ISS.

Joseph H. Rothenberg

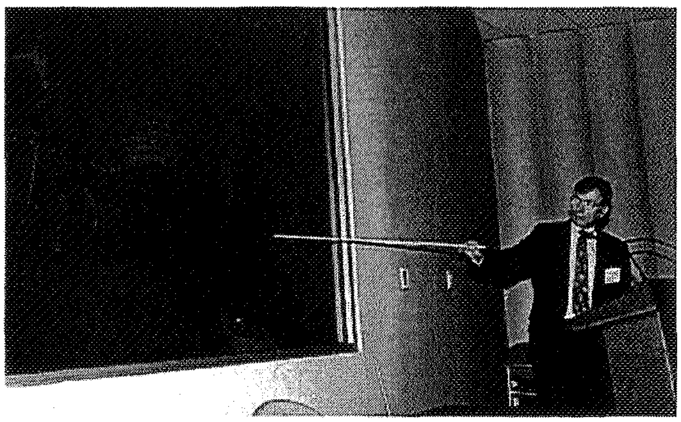


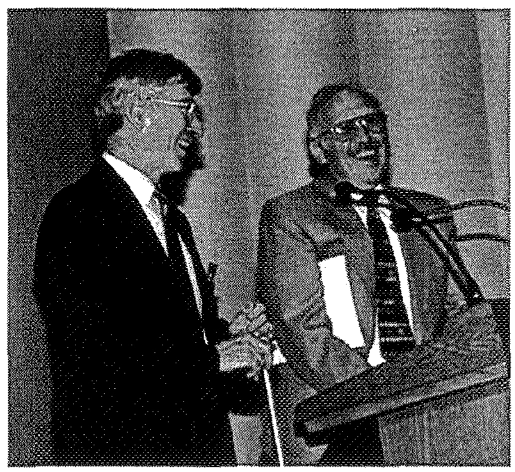
Joe Rothenberg, 1998
Associate Administrator for Space Flight,
NASA Headquarters

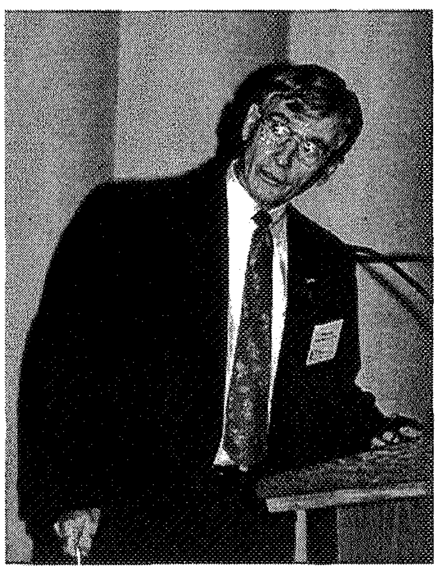
Keynote Address



John Young was selected as an astronaut in September 1962. He is the first person to fly in space six times from Earth. Young's first flight was in Gemini 3, the first manned Gemini mission, on March 23, 1965. Young next flew on Gemini 10. On Apollo 10, Young served as Command Module pilot. During Apollo 16, Young walked on the Moon, exploring the lunar highlands and setting up scientific equipment. His fifth flight was as Spacecraft Commander of STS-1, the first flight of the space shuttle, and he also served as commander of STS-9. Young currently is Associate Director (Technical) of the NASA Johnson Space Center, and is responsible for technical, operational, and safety oversight of all agency programs and activities assigned to JSC. As an active astronaut, Young remains eligible to command future shuttle astronaut crews.







John Young spoke to the Mars Exploration Forum about exploring other planetary surfaces and the challenges of reduced gravity environments. He applied his experiences while exploring the Moon during Apollo 16 to the future surface missions on Mars.

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Invited Technical Presentations

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MARS HUMAN EXPLORATION OBJECTIVES

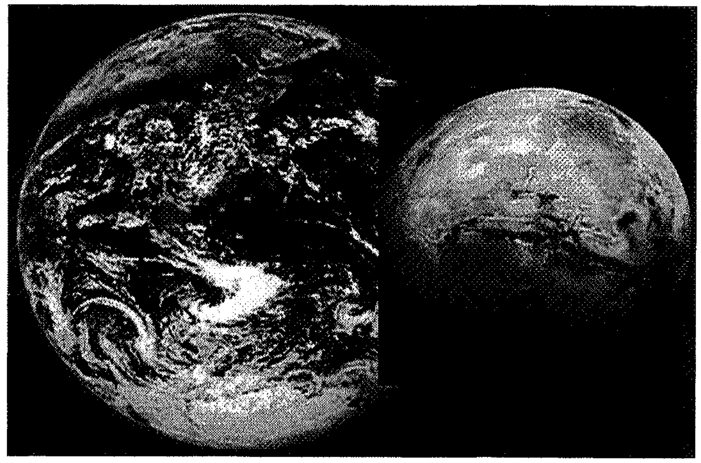
Geoff Briggs
NASA Ames Research Center

Human Exploration Objectives

To explore Mars and learn how Mars is similar to, and different from, Earth

- whether life evolved on Mars and, if so, whether and how such life may have become extinct
- whether Mars is still a geologically live planet
- how early Mars may illuminate the history of Earth

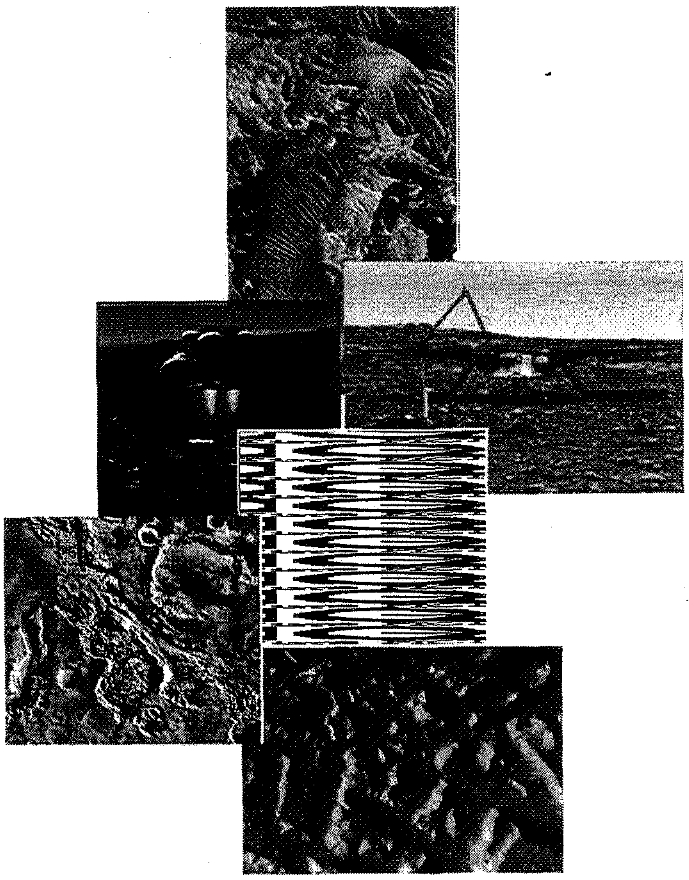
- To determine whether Mars has the potential to be a second home for life — toward the eventual establishment of a self-sufficient human presence on Mars
  - Achieve substantial life support self-sufficiency on a local scale in terms of breathable air, water, and food
  - Determine potential for self-sufficient expansion of base capabilities using indigenous natural or processed resources
  - Determine, through exploration/prospecting, the availability of surface and subsurface resources essential for the future growth of human presence



Human Exploration: Science Objectives

Life Past and Present

- Chemical and fossil evidence of life will be sought by sample return missions
  - Will not allow such life to be characterized at the molecular level
- Positive evidence from sample return will motivate a thorough evaluation of how long such life was sustained and if, in fact, life could be extant
- Human exploration will be enabling to such in-depth explorations
- Extant life could exist in hydrothermal vents or in the kilometers-deep subsurface hydrosphere
  - Samples would allow comparison to terrestrial tree of life
  - Would raise challenging problems of sample contamination and of PQ
- Evidence of ancient liquid water on Mars emphasises the choice of particular sites e.g. paleolakes, regions of past hydrothermal activity, runoff channels

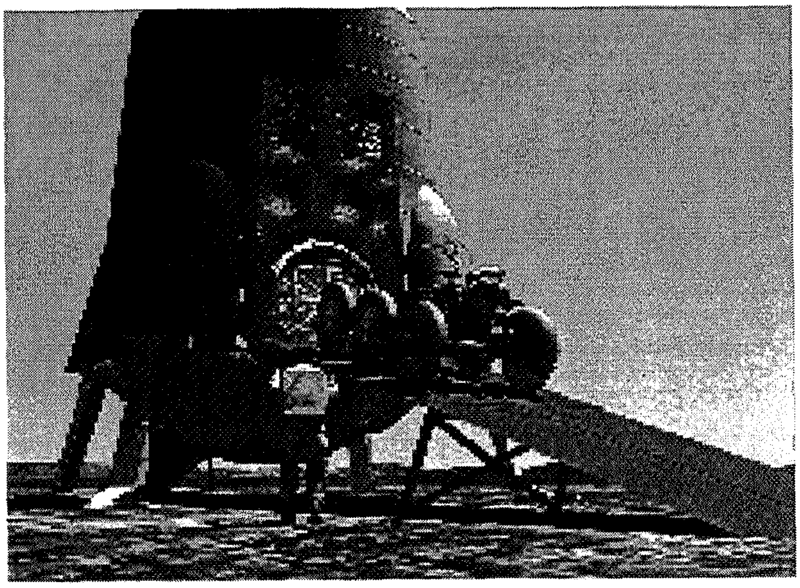


Geoscience and Geologic History

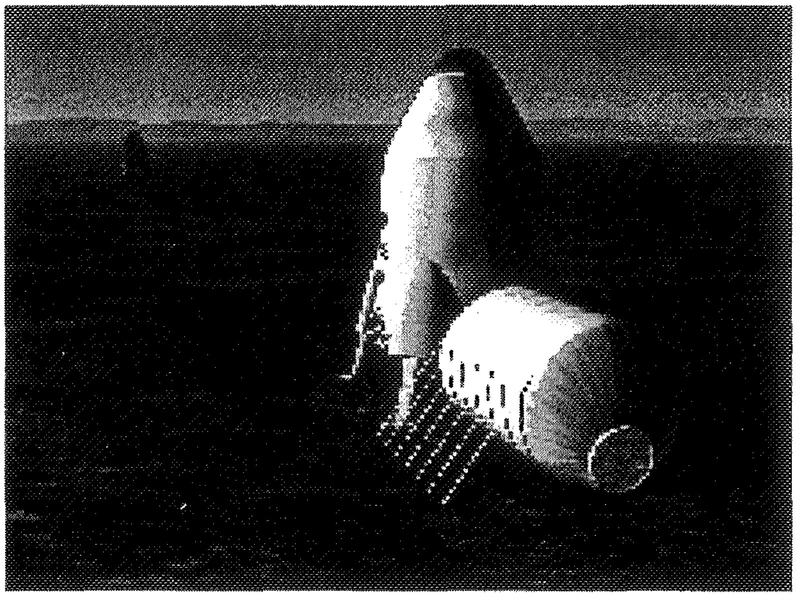
- What is Mars like now?
  - Crust, mantle and core
  - Distribution, type and age of rocks exposed at the surface
  - Is Mars still volcanically active?
  - Is water present in quantity — permafrost and aquifers?
- How did Mars form and how did this compare to Earth?
  - Materials from which Mars formed
  - Accretionary history
  - Timing and nature of differentiation
- How did Mars evolve to its present state?
  - Impact history
  - Volcanic history
    - Is Mars still active?
  - Deformation history and contrast with plate tectonics
  - Erosion and sedimentation history
    - Action of water and ice, atmospheric composition and variation

Geoscience and Gelogic History

- Precursor missions will allow us to pick sites for human exploration that are both safe and of critical scientific interest
- Crew will carry out Iterative, adaptive field work to collect/ document samples for analysis at the base laboratory and, later, on Earth
  - Systematic survey near base
  - Use of telepresence robots — rovers and airplanes — globally, capable of: returning samples to base; remote sensing; geophysical surveys
  - Pressurized vehicles to increase the radius of action of the crew to hundreds of kilometers
  - Highly capable base laboratory
- Active seismic and em surveys
- Drilling
- Heat flow experiments
- Deploy geophysical stations



Science Objectives -- Considerations



- Science objectives will be achieved primarily through field geologic exploration of sites
  - Capable base laboratory is key to allow rapid interaction
  - Long range transportation is desirable as early as possible
  - Operational autonomy of crew is needed to permit adaptivity
  - Crew will require a range of new cognitive prostheses along with easy communications with terrestrial colleagues
- Complexity/diversity of Mars argues for many bases
- Other considerations argue for one base
  - Maximum/increasing redundancy
  - Maximum/increasing science capability
    - Vehicles, laboratory, drills
  - Quasi-human global access can be provided by telepresence robots

Science Objectives -- Landing Sites

Complexity/diversity of Mars leads to an over-abundance of key sites

A human base that may be the center of operations for many years must be one of compelling and continuing interest

Access to the hypothesized hydrosphere implies that the landing site should be at as low an elevation as possible

Avoidance of seasonal extremes implies a site within the martian tropics

The site of the base will also have to meet other requirements for landing safety and trafficability

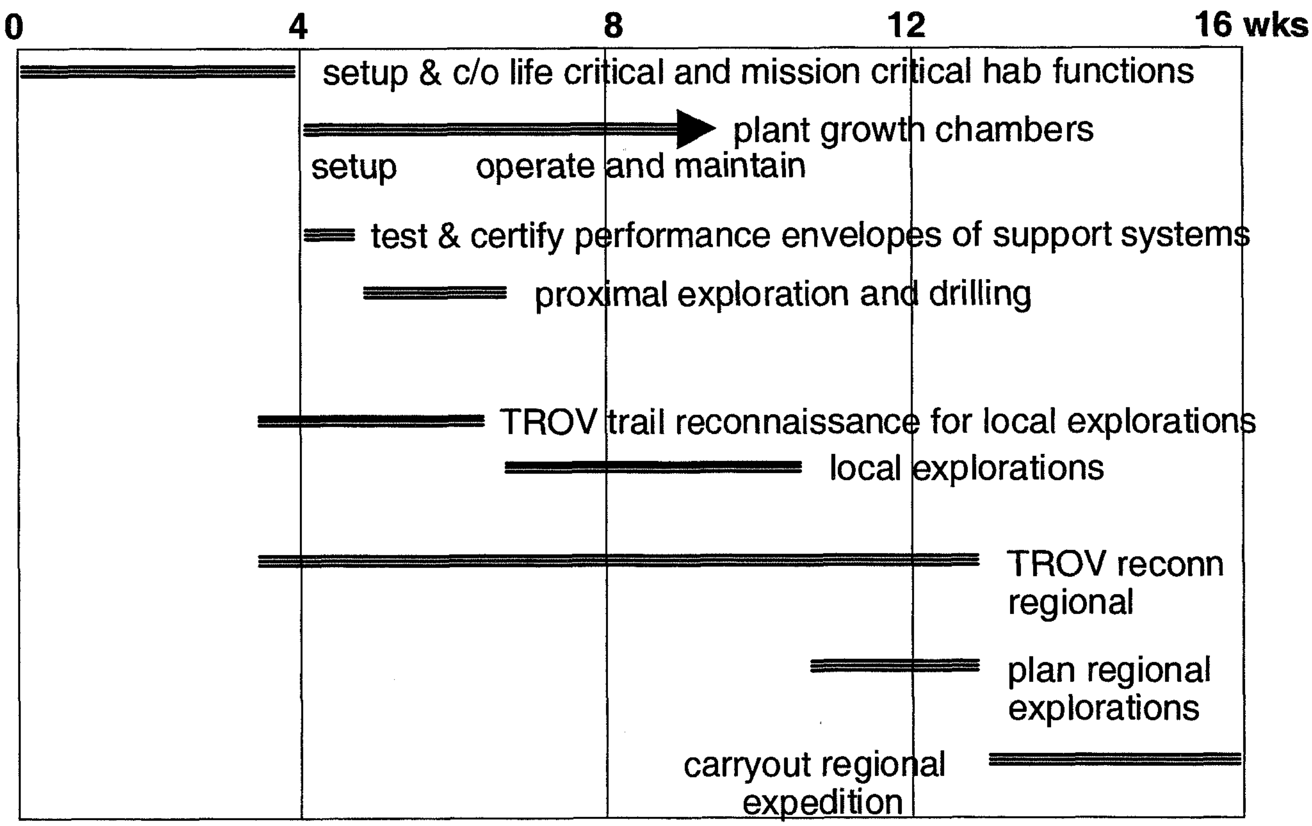
An example of an attractive landing site that appears to meet these needs as we understand them today is:

Candor Chasma in the Valles Marineris

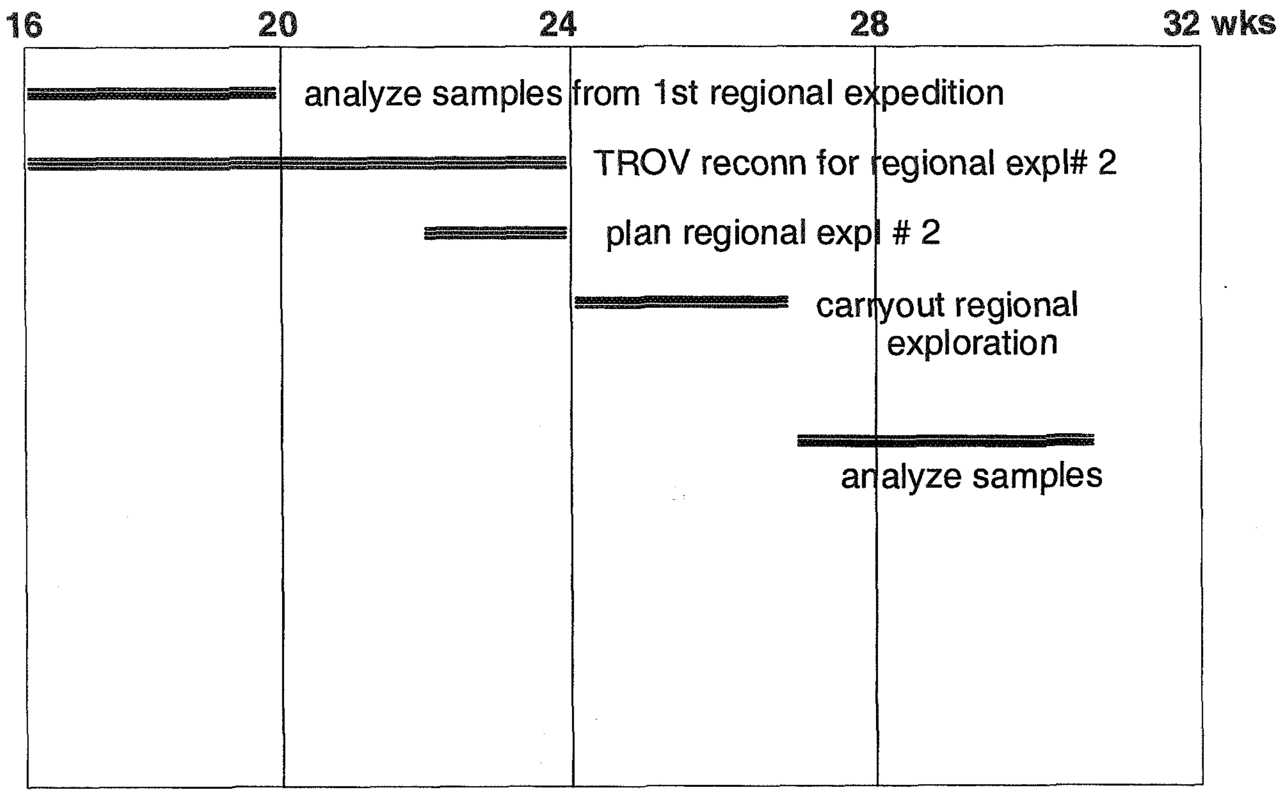
Science Objectives — Allocation of Time

- **Geo-bioscientist *net* time needs to be balanced**
  - **Activity in the field**
  - **Laboratory analysis at base**
  - **Analysis and Interaction with terrestrial colleagues**
  - **Telepresence field work**
  - **Planning field trips**
- **Must have cognitive prostheses and have *support* team of terrestrial colleagues**
- **On a 600 day surface mission, only 60 - 100 days may be spent on EVA in the field**
- **Thorough exploration of the base site, even within 500 km of the base, may take many missions using vehicles of increasing range**

Operation Phases

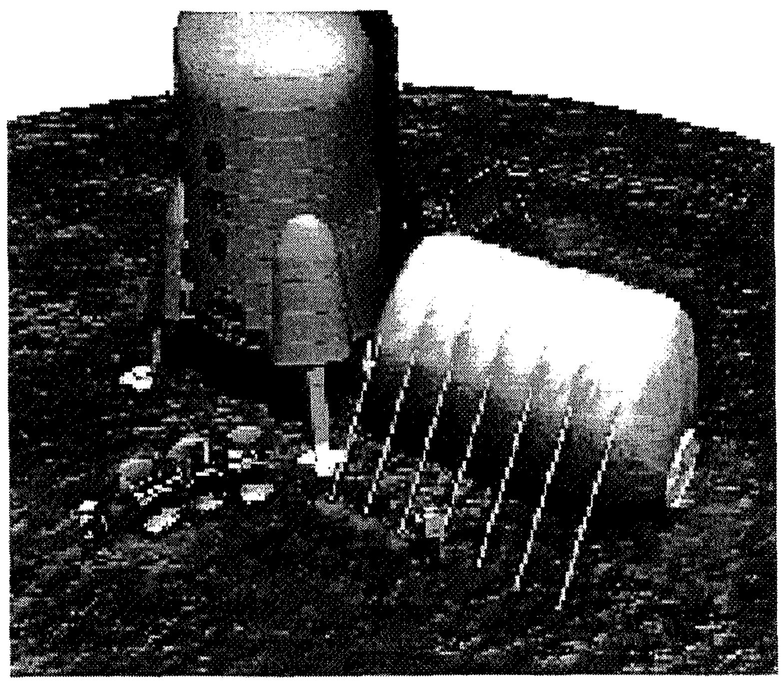


Operation Phases



Habitability Objectives -- General

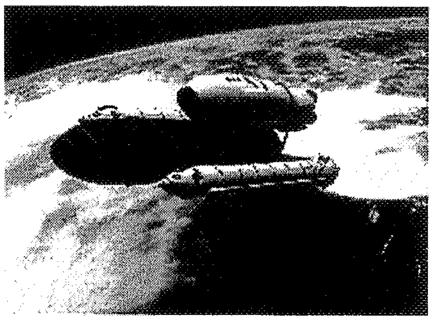
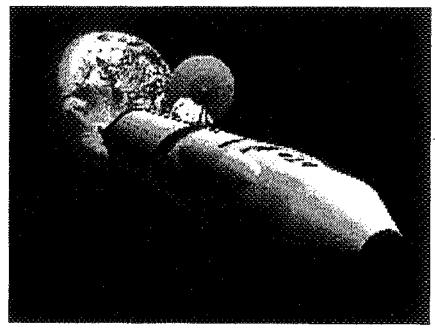
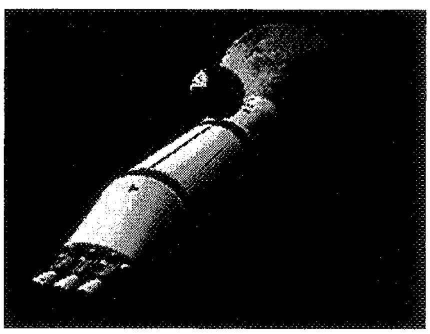
- Demonstrate that self-sufficiency can be achieved on the local scale of a Mars base
- Determine potential for self-sufficient expansion of base capabilities (habitable volume, increased crew sizes, longer duration occupancy, longer range EVA ...) using indigenous natural or processed Mars resources
- Investigate the biological adaptation to Mars over multiple generations of representative plant, animal, and microbial species
- Assay the volatile inventory of Mars available in surface rocks and in the regolith and crust

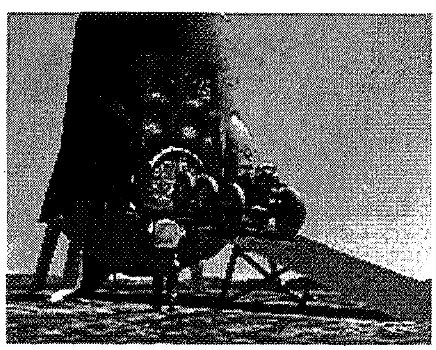
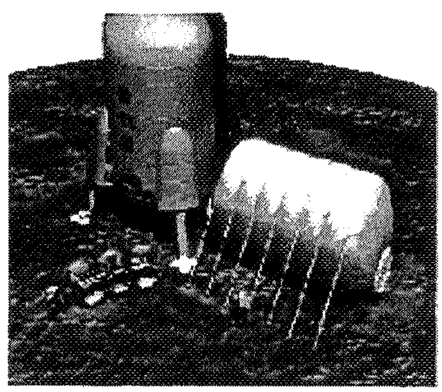


Habitability Objectives
Human Factors Considerations

For long duration missions, with inevitably high stress levels, the trade-off between cost and crew comfort must be weighed with especial care —

quality of shelter, water, food, health monitoring, psychological support, communications, rest/ relaxation/sleep, crew factors, crew autonomy, privacy, exercise, human-machine-automation interaction, human-robotic partnership, recreation and entertainment

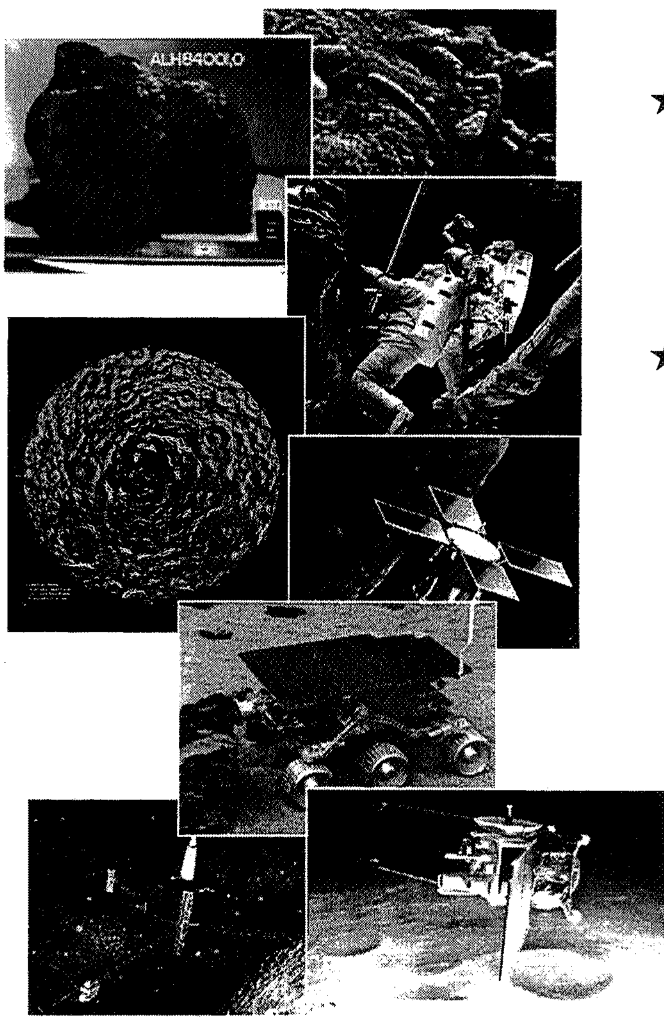



High quality habitats and environmental design features are critical to relieve stress/increase comfort — increase the likelihood of mission success. Providing little more than the capability to survive invites mission failure.

MARS HUMAN EXPLORATION REFERENCE MISSION

Bret Drake
NASA Johnson Space Center
Exploration Office

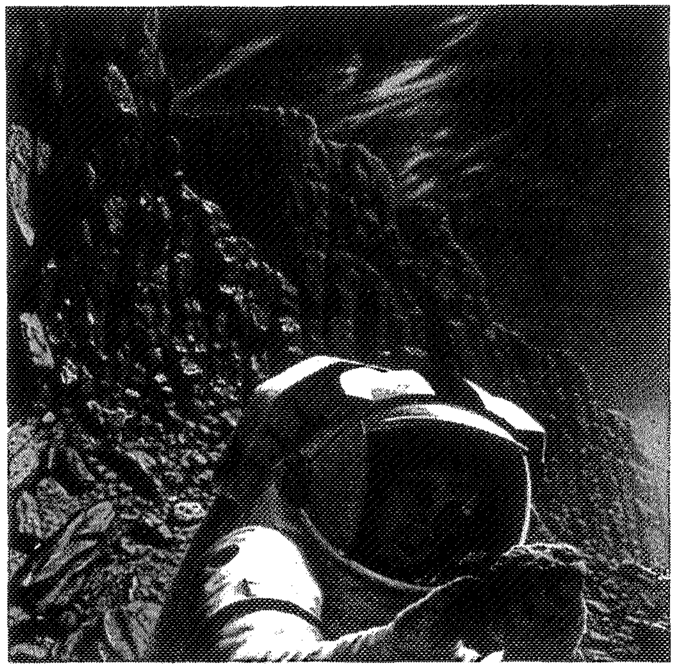
Human Space Exploration -- Next Steps



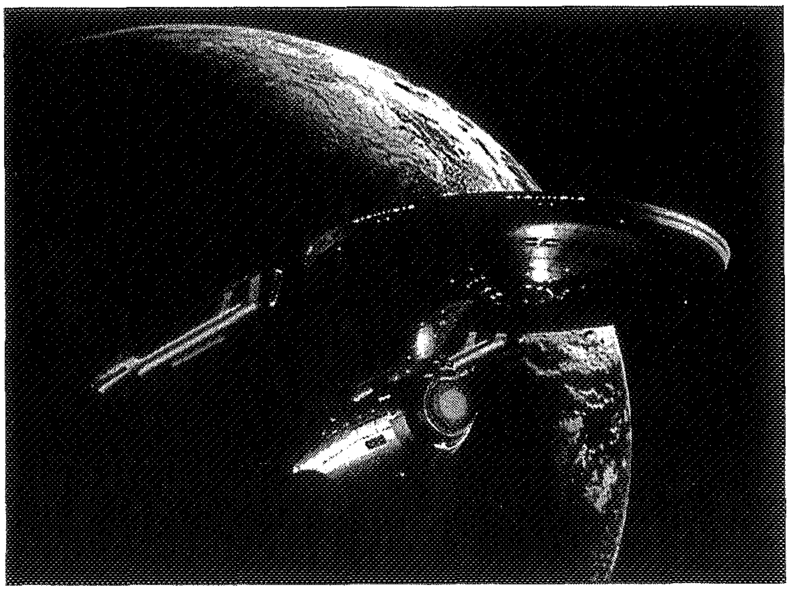
- ★ The Opportunity - An explosion of recent discoveries
  - Allan Hills Meteorite
  - Pathfinder
  - Clementine
- ★ The Challenge - Affordable human exploration
  - Significant reductions in cost
  - Efficient mission approaches
  - Development of leveraging technologies
  - Mars knowledge return
  - Enable a mission in early 2010's

Increase Knowledge

- Today's Exploration program focuses on understanding planetary and asteroid environments for what they can teach us about life on Earth
- Human capabilities will tremendously extend the scientific breadth and depth of the Exploration program
  - Sample selection, rapid analysis, and reselection
  - Operate sophisticated *in-situ* laboratories and observe, react to data, modify strategies, retest, verify and *think*
  - Repair, adjust, and control robotic science activities with no time delay
  - Access sites that are too challenging for robotic missions
  - *In-situ* sample screening, analysis, preservation and selection for return to Earth
  - Assessment of resources and technologies through experience



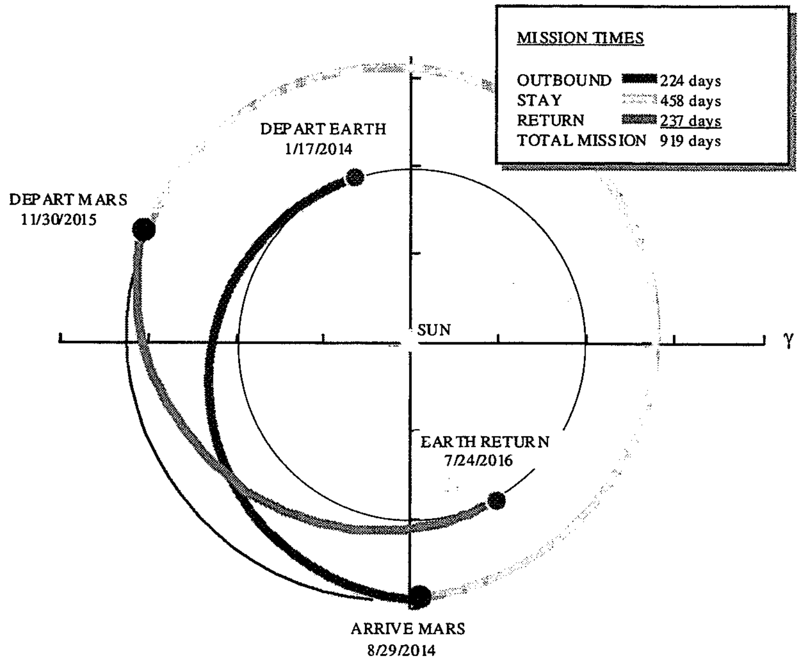
The best sensor is the human eye....
.....the best computer is the human mind



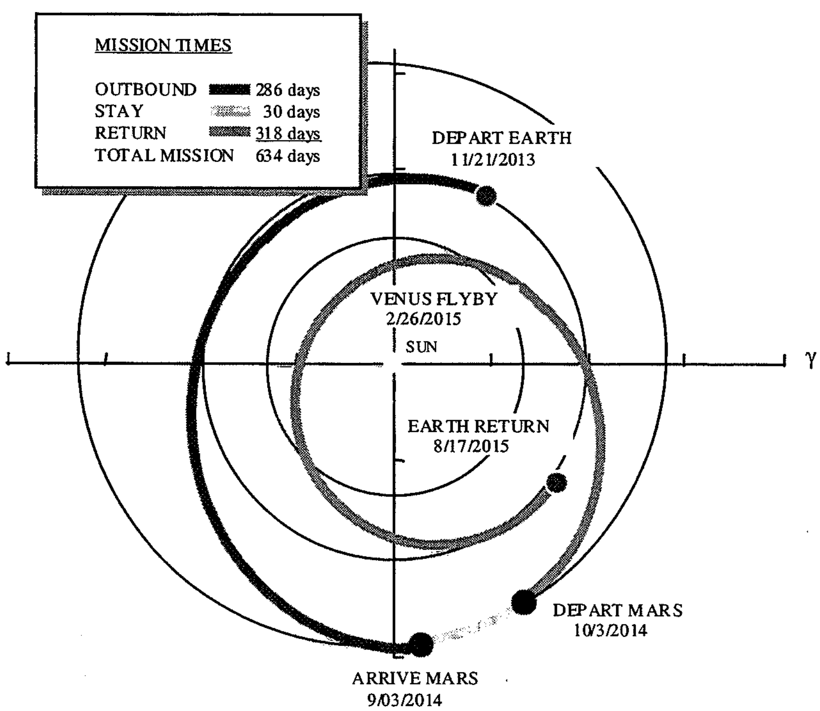
Mars Mission Strategies -- Old Paradigm

- ★ Most past Mars studies employ "Starship Enterprise" approach
  - Large "mothership" constructed in Earth orbit, travels to and from Mars orbit
  - Crew takes "shuttlecraft" to surface and explores for a short time
  - If problems occur, abort to Earth
- ★ Basically incompatible with economical spaceflight and Mars mission objectives
  - "Mothership" requires huge propellant quantities or exotic propulsion technology
  - Complex and risky construction and integration in Earth orbit
  - Short surface stay limits mission objectives
  - "Abort to Earth" implies long duration interplanetary flight times

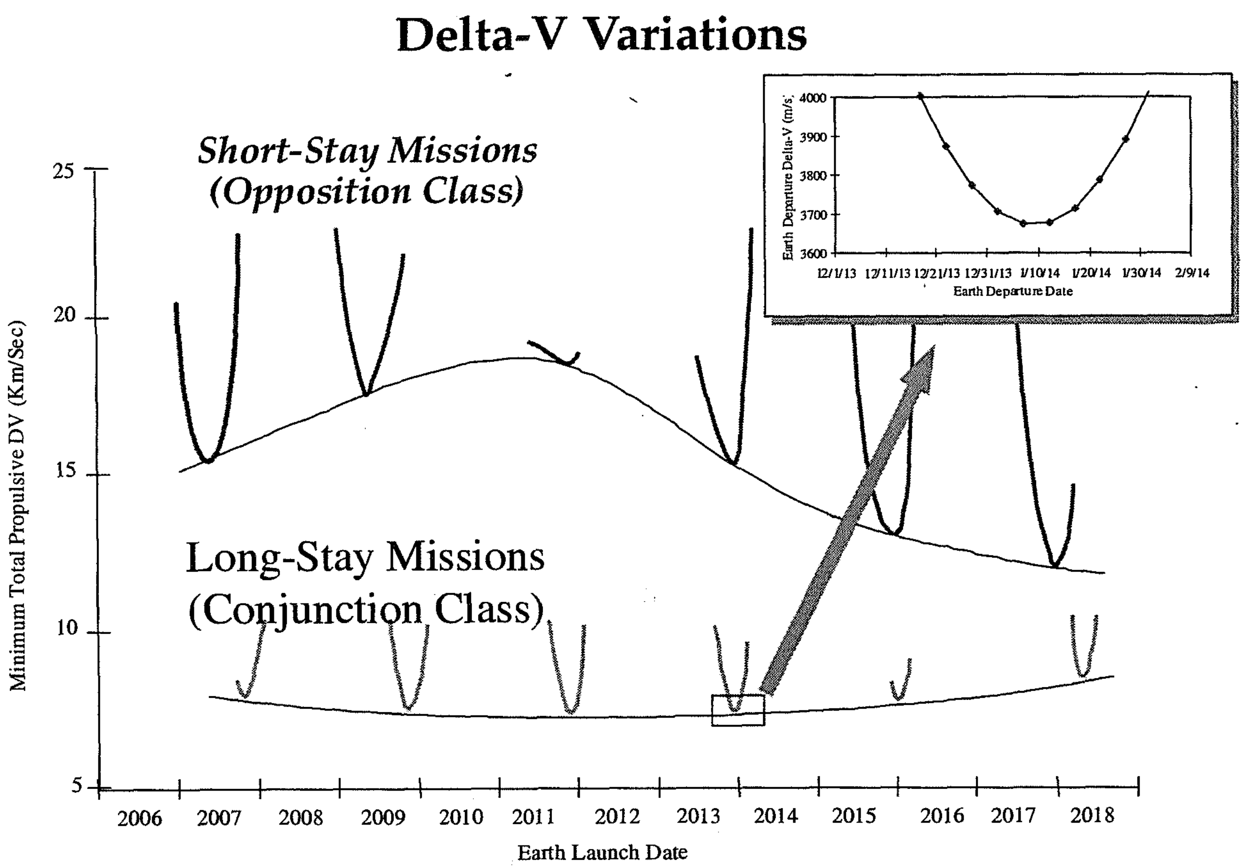
Mars Trajectory Classes

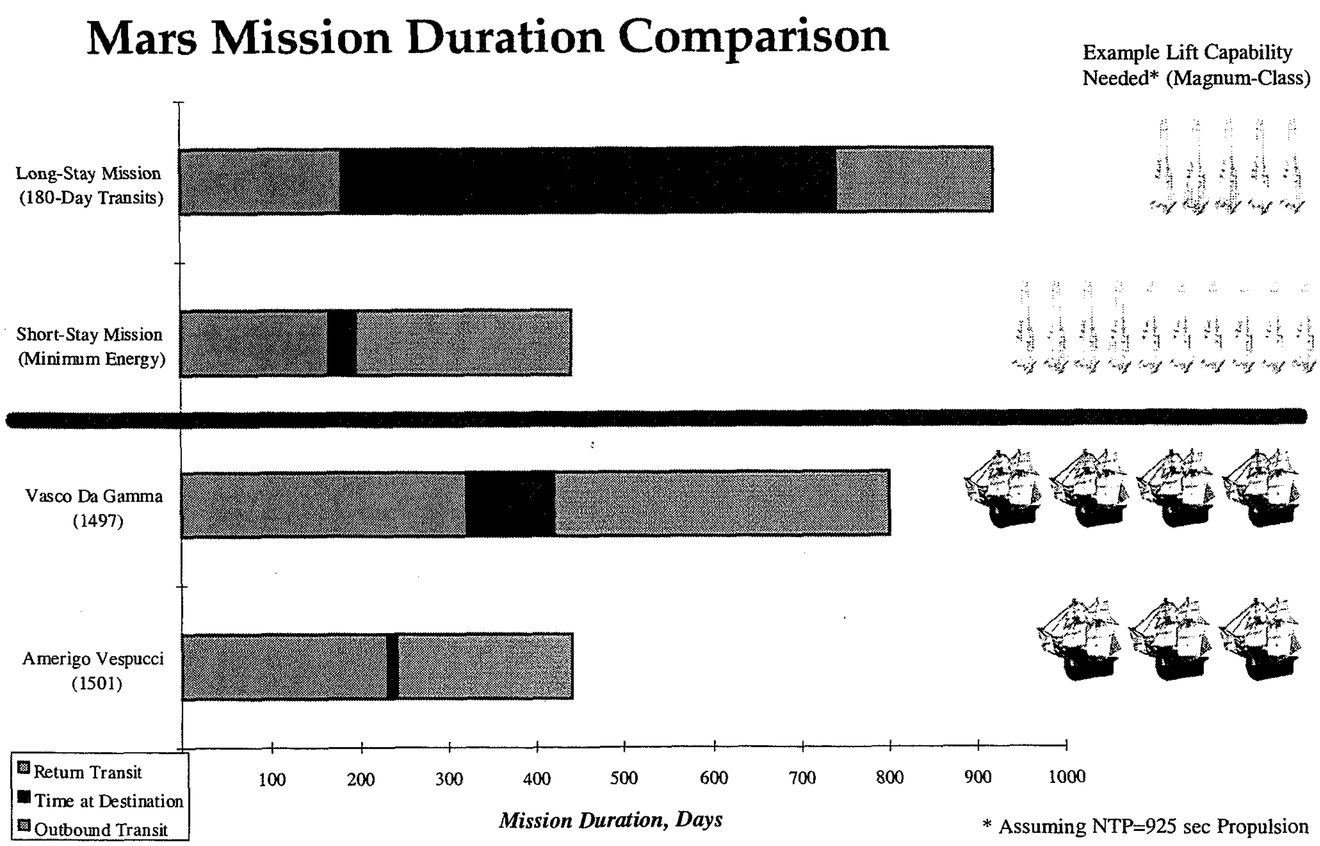


- **Long-Stay Missions**
  - **Variations about the minimum energy mission**
  - **Often referred to as Conjunction Class missions**



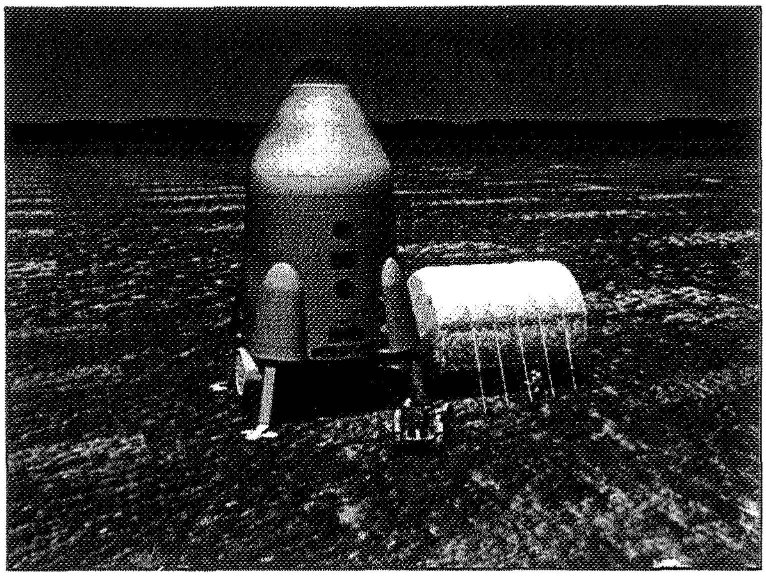
- **Short-Stay Missions**
  - **Variations of missions with short Mars surface stays and may include Venus swing-by**
  - **Often referred to as Opposition Class missions**


Delta-V Variations
Short-Stay Missions
(Opposition Class)
Long-Stay Missions
(Conjunction Class)
Minimum Total Propulsive DV (Km/Sec)
25
20
15
10
5
2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Earth Launch Date
Earth Departure Delta-V (m/s)
4000
3900
3800
3700
3600
12/1/13 12/11/13 12/21/13 12/31/13 1/10/14 1/20/14 1/30/14 2/9/14
Earth Departure Date


Mars Mission Duration Comparison
Example Lift Capability
Needed* (Magnum-Class)
Long-Stay Mission
(180-Day Transits)
Short-Stay Mission
(Minimum Energy)
Vasco Da Gamma
(1497)
Amerigo Vespucci
(1501)
Return Transit
Time at Destination
Outbound Transit
100 200 300 400 500 600 700 800 900 1000
Mission Duration, Days
* Assuming NTP=925 sec Propulsion

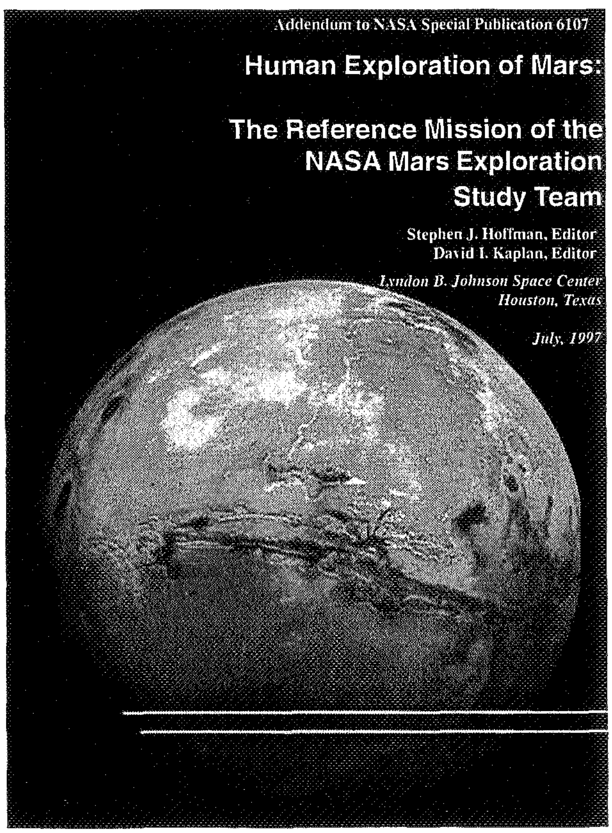
New Approach

- Key in new paradigm is shifting focus from interplanetary spaceflight to planetary surface
  - Make Mars the safest place in the solar system
  - Pre-deploy assets to Mars, ensure operational before crew departs
- Planetary departure / return windows can allow critical operational advantages
  - Pre-deployed assets for "next" crew available as redundant elements for "current" crew
- Redundancy through "forward deployment" rather than "abort to Earth"



Mass Reduction Strategies

- Major component of economical human esploration of Mars is through the reduction of mass. Current mass reductions achieved by:
  1. Utilizing energy-efficient trajectories to pre-deploy mission assets
  2. Proper application of advanced technologies
  3. Achieving proper tradeoffs of mass and power
     - Advanced Space Propulsion
     - Utilizing locally produced propellants (In-Situ Resource Utilization)
     - Employing advanced (bioregenerative) life support systems to close air, water, and potentially food loops

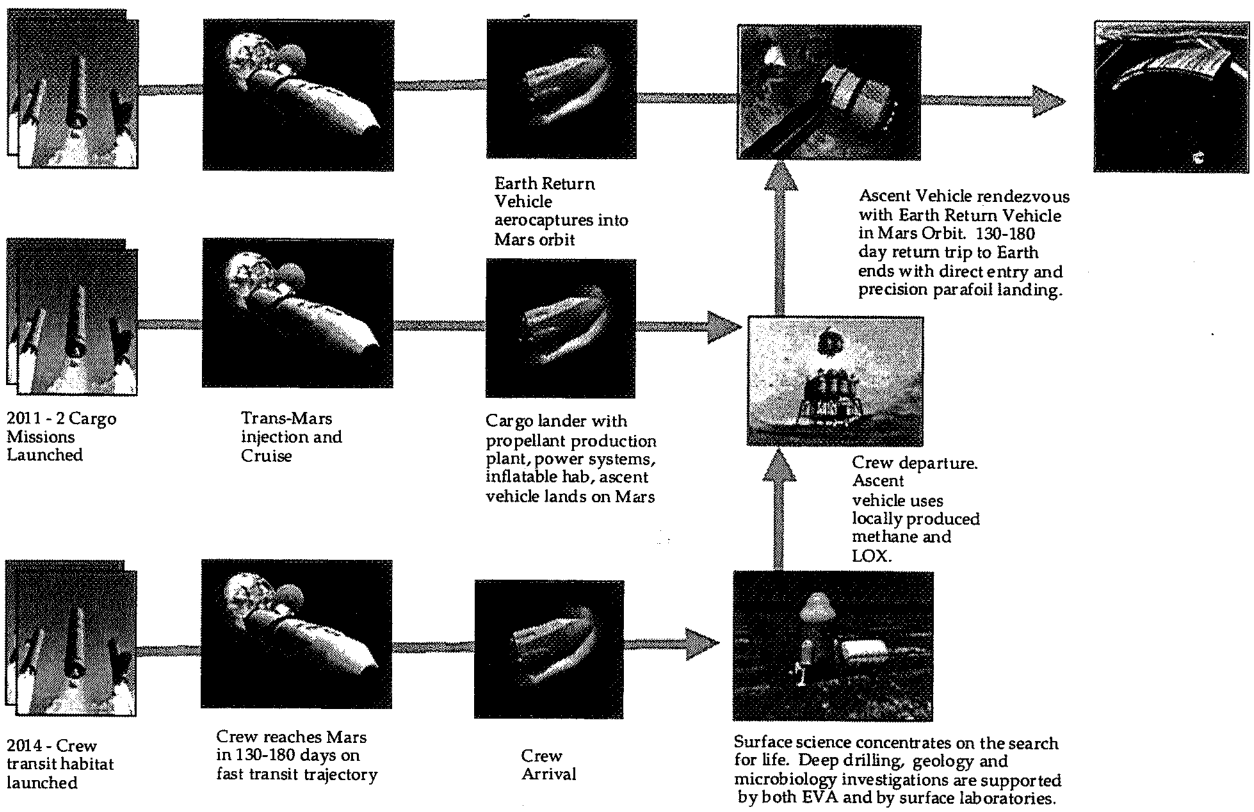


www-sn.jsc.nasa.gov/marsref/

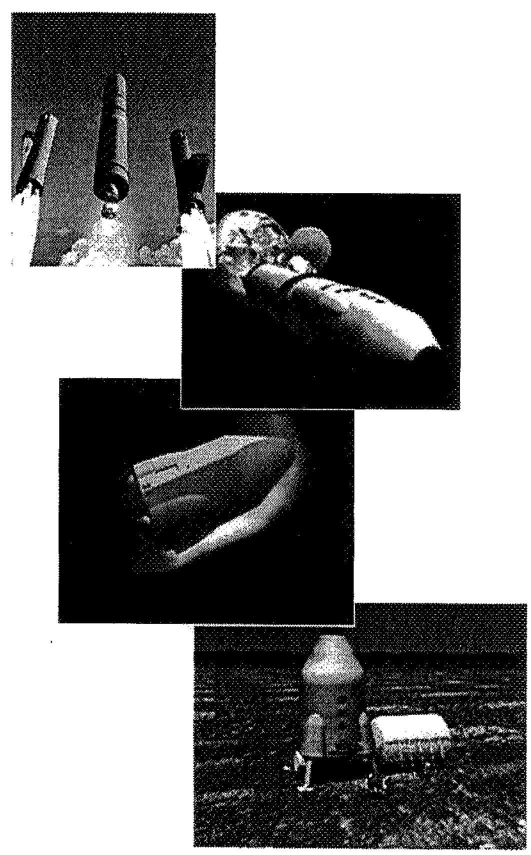
Mars Reference Mission

- Exploration mission planners maintain "Reference Mission"
- Represents current "best" strategy for human Mars missions
- Purpose is to serve as benchmark against which competing architectures can be measured
- Constantly updated as we learn
- Probably does not represent the way we will end up going to Mars

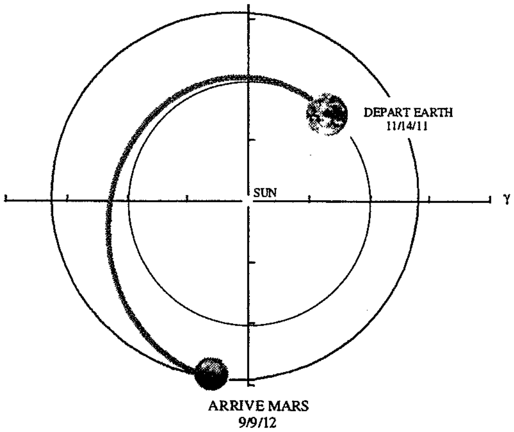
Reference Mission Scenario Overview



Forward Deployment Strategy



- Twenty-six months prior to crew departure for Mars, predeploy:
  - Mars-Earth transit vehicle to Mars orbit
  - Mars ascent vehicle and exploration gear to Martian surface
  - Mars science lab to Martian surface
- Crew travels to Mars on "fast" (six month) trajectory
  - Reduces risks associated with zero-g, radiation
  - Land in transit habitat which becomes part of Mars infra-structure
  - Sufficient habitation and exploration resources for 18 month stay



Cargo Missions

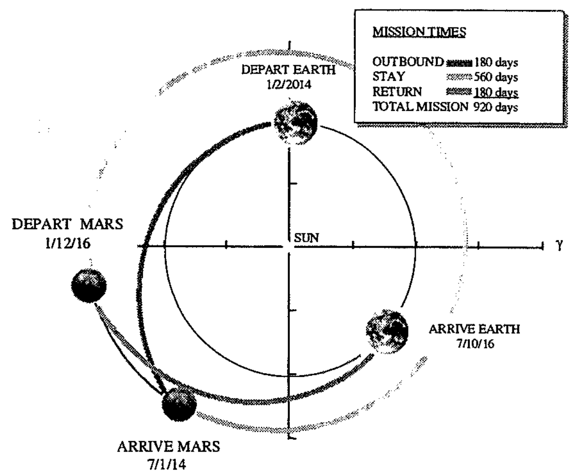
Two Cargo Missions (2011)

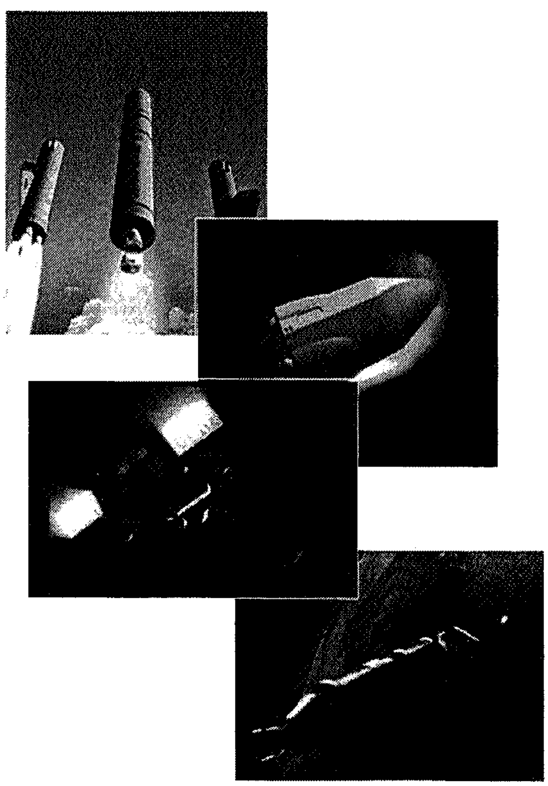
- Leave Earth November 4, 2011
  TMI DV = 3590 m/s
- 310-day outbound trip
- Arrive at Mars September 9, 2012
- Aerocapture into 1-Sol orbit
- Descent vehicle descends to surface
- Return vehicle remains in orbit

Piloted Mission

Piloted Mission (2014)

- Leave Earth January 2, 2014
  TMI DV = 3680 m/s
- 180-day outbound trip
- Arrive at Mars July 1, 2014
- Aerocapture into 1-Sol orbit
- 560-day stay on the Martian surface
- Leave Mars January 12, 2016
- TEI DV = 1080 m/s
- 180-day inbound trip
- Arrive at Earth July 10, 2016
- Direct entry to Earth's surface

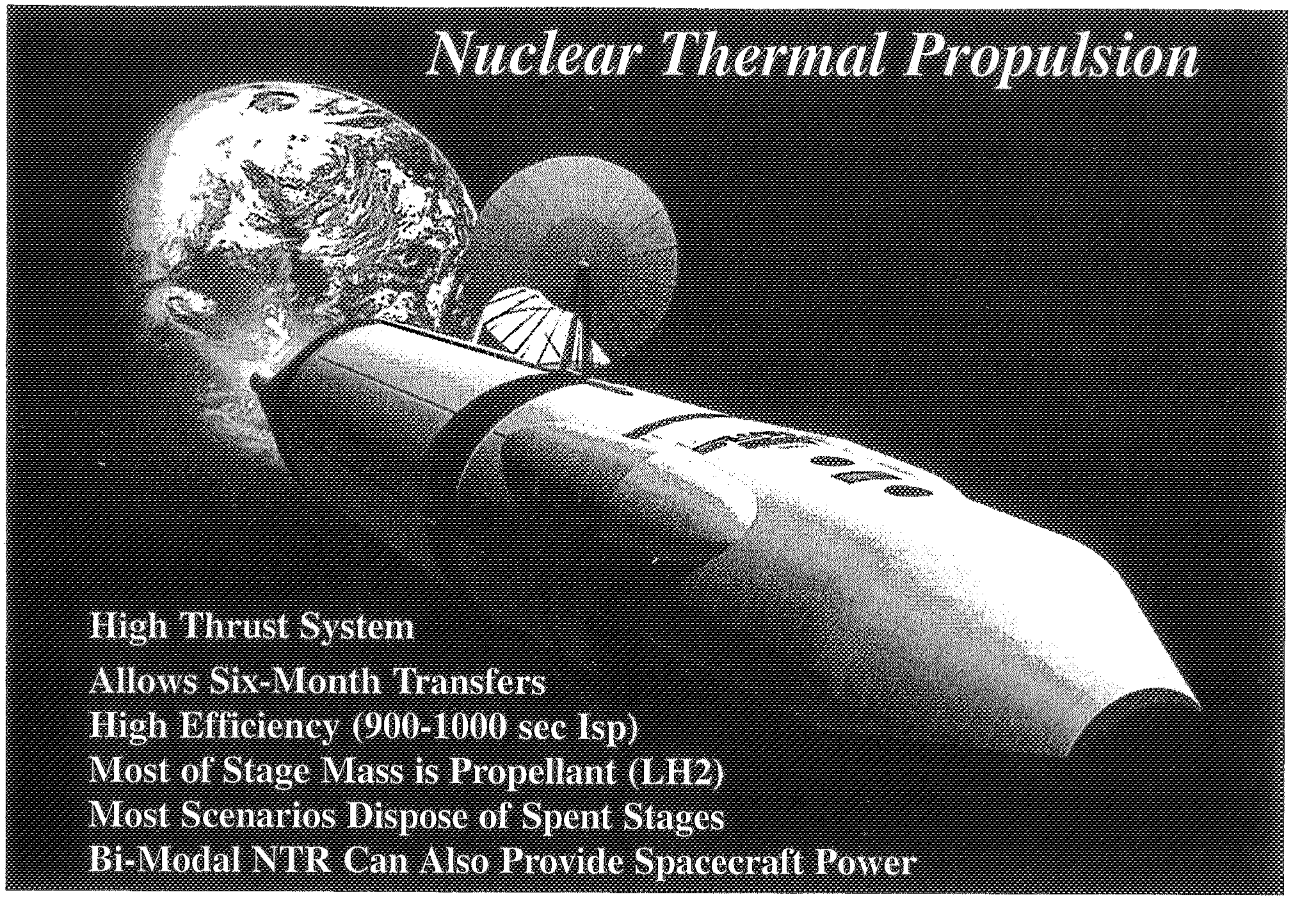


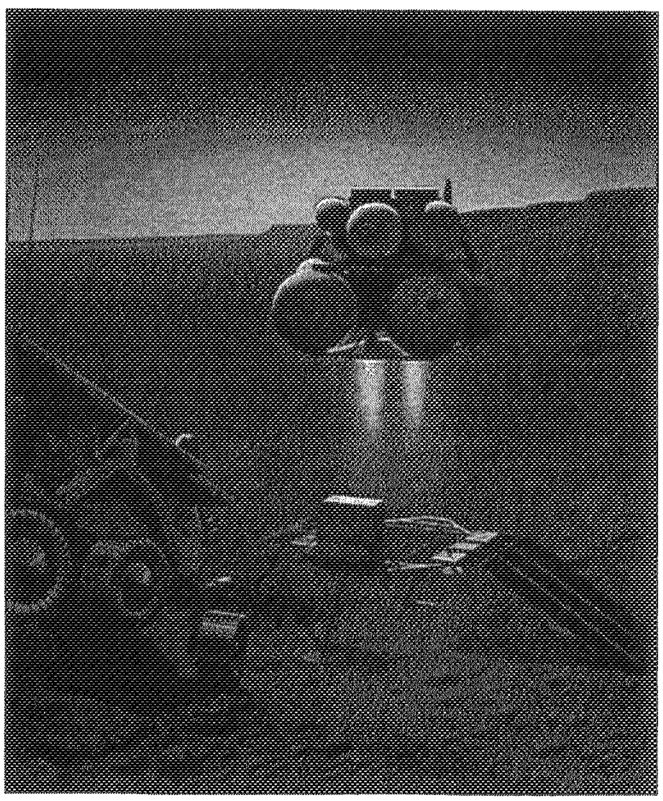


Space Transportation

Examining all mission phases for cost-effective transportation options and additional customers

- Earth-to-Orbit
  - Second generation Shuttle-derived launcher
  - Other potential customers - DoD Payloads, Next Generation Space Telescope
- Earth Orbit to Mars Orbit
  - Electric Propulsion
  - Nuclear Thermal Propulsion
  - Other potential customers - GEO payloads, Solar Power Satellites ?
- Mars Orbit Injection
  - Aerocapture
- Ascent from Martian Surface
  - In situ propellant production

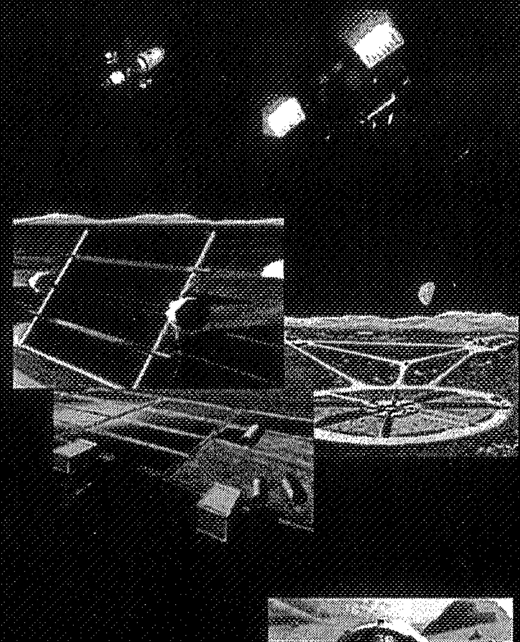




Mars In Situ Resources

- Traditional exploration architectures advocate investigation of Martian resources during "early" human missions
  - Idea is to reduce cost of subsequent missions
- Relying upon in situ resources from the outset presents some advantages
  - Producing ascent propellant greatly reduces required Earth launch mass
  - Producing caches of water and oxygen provides backup to life support systems
  - Can reduce level of closure (and expense) of systems
- Technical risk can be mitigated by robotic tests of Martian resource extraction
  - Could also make sense as a sample return strategy

Power Needs for Exploration



Electric Propulsion

- High Power (500 kWe - 4 MWe)
- Specific Mass (7-10 kg/kWe)
- Solar and Nuclear Power Generation Options
- Radiation Degradation < 35%
- Some Scenarios Include Vehicle Reusability

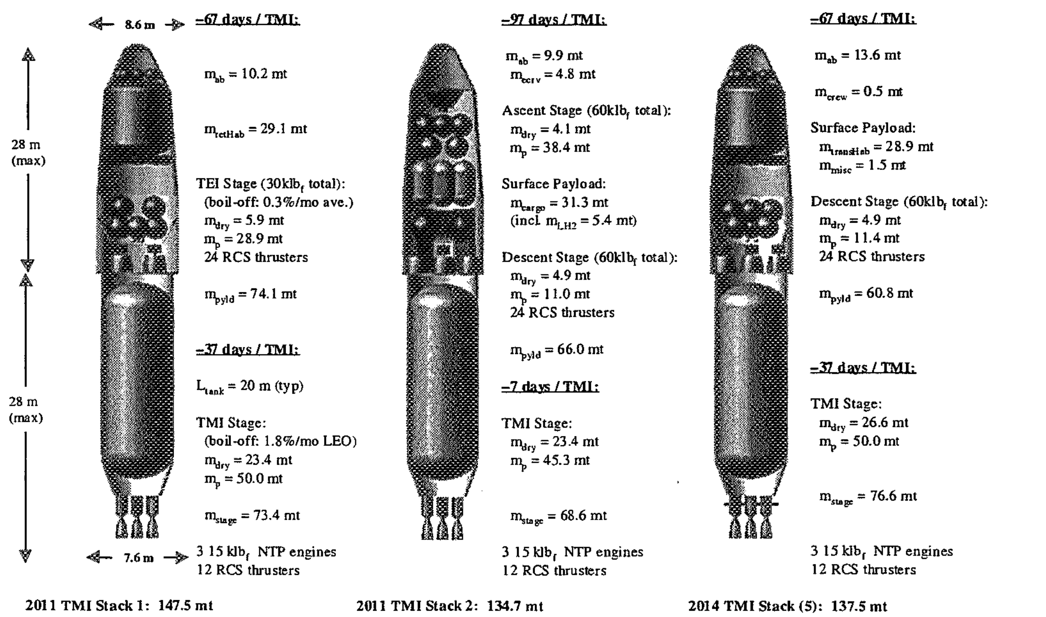
Stationary Power Sources (100+ kWe)

- Multi-year life (7 years)
- Solar and Nuclear Power Generation Options
- 30 kWe Habitats
- 30-60 kWe Regenerative Life Support
- 50 kWe In-Situ Resource Utilization

Mobile Power Sources

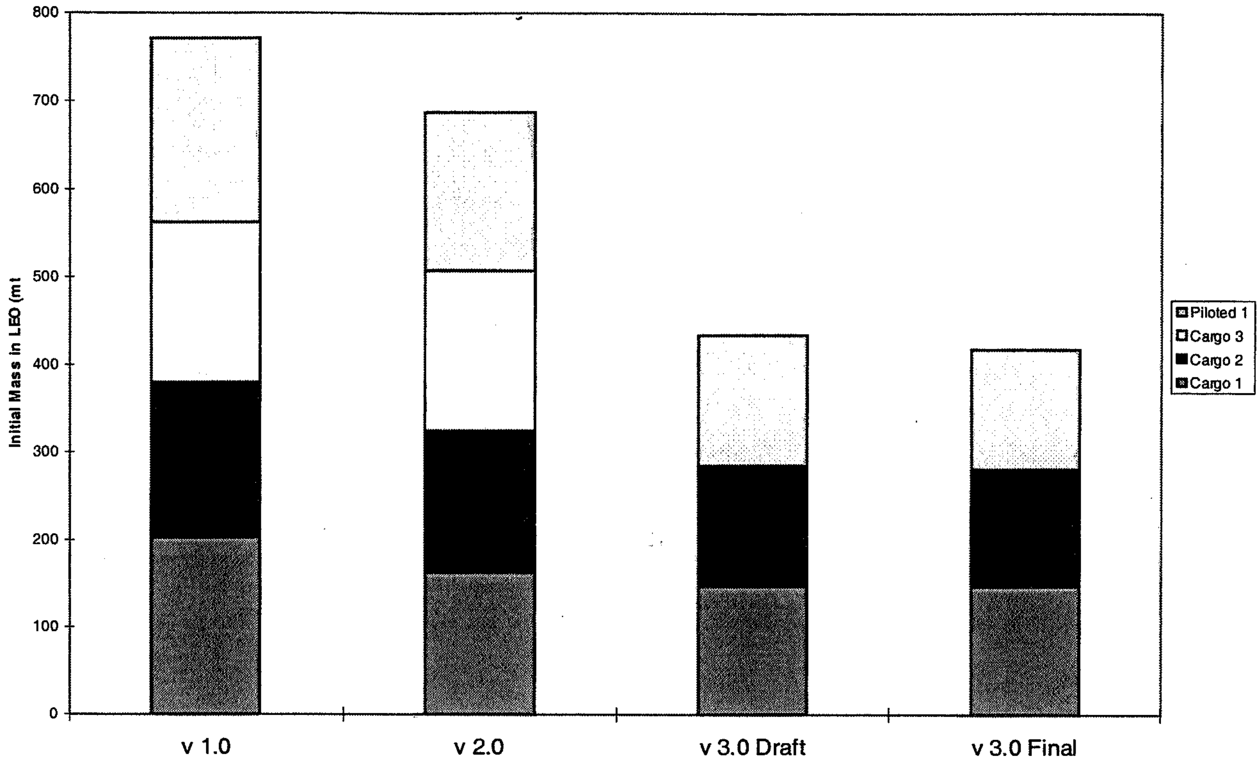
- Power Sources Include: Dynamic Isotope, Photovoltaic with Regenerative Fuel Cells, Advanced Batteries, and Internal Combustion
- 10 kWe for pressurized rovers
- 10 kWe for universal power cart
- 4 kWe for unpressurized rovers
- 50-100 W for EVA suit

Launch Packaging for Version 3.0



Larry Kos / MSFC / PD32
Ena Nishimuta / MSFC / PD23
v3.5, 1/21/98

DRM Mass History



Version 3.0 Mass Summary

Flight 1: ERV

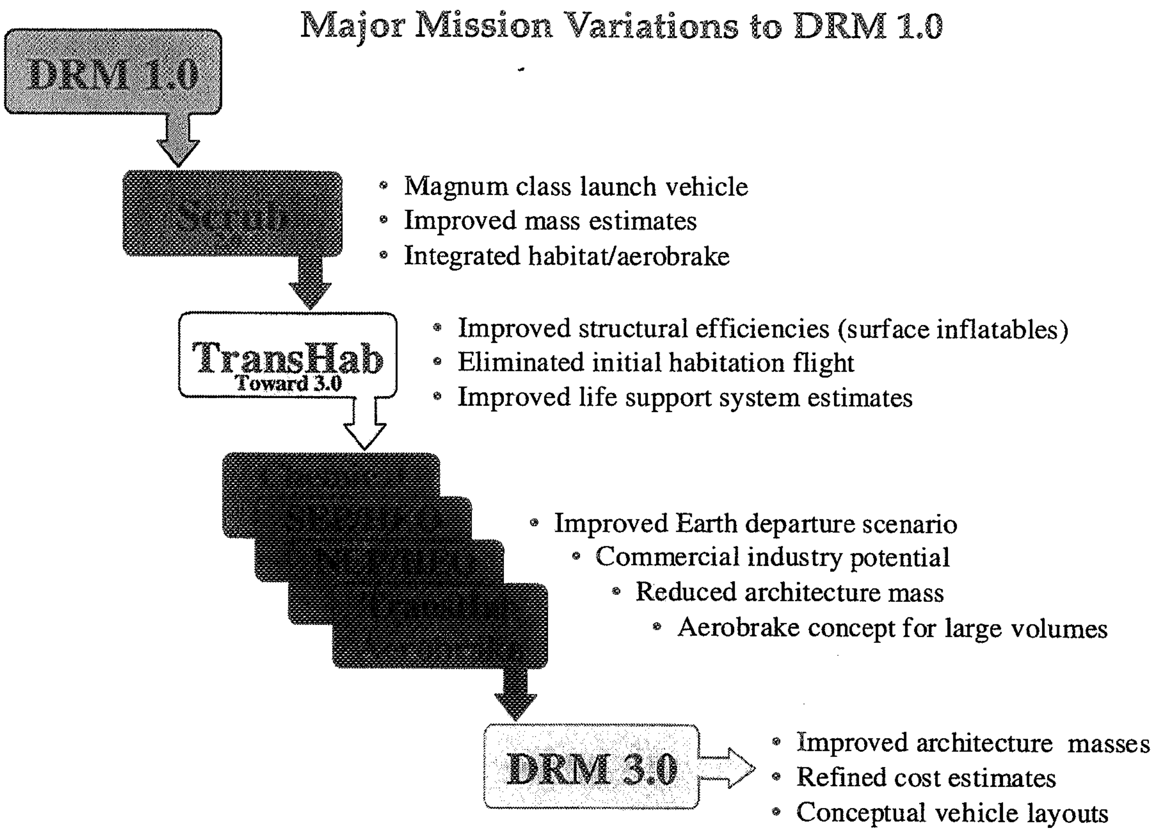
	Reference Version 1.0	Final Version 3.0
Earth Return Vehicle	56 mt	29 mt
TEI Stage	5 mt	6 mt
TEI Propellant	52 mt	29 mt
Aerobrake	17 mt	10 mt
TMI Stage	29 mt	23 mt
TMI Propellant	86 mt	50 mt
TOTAL IMLEO	**246 mt**	**147 mt**

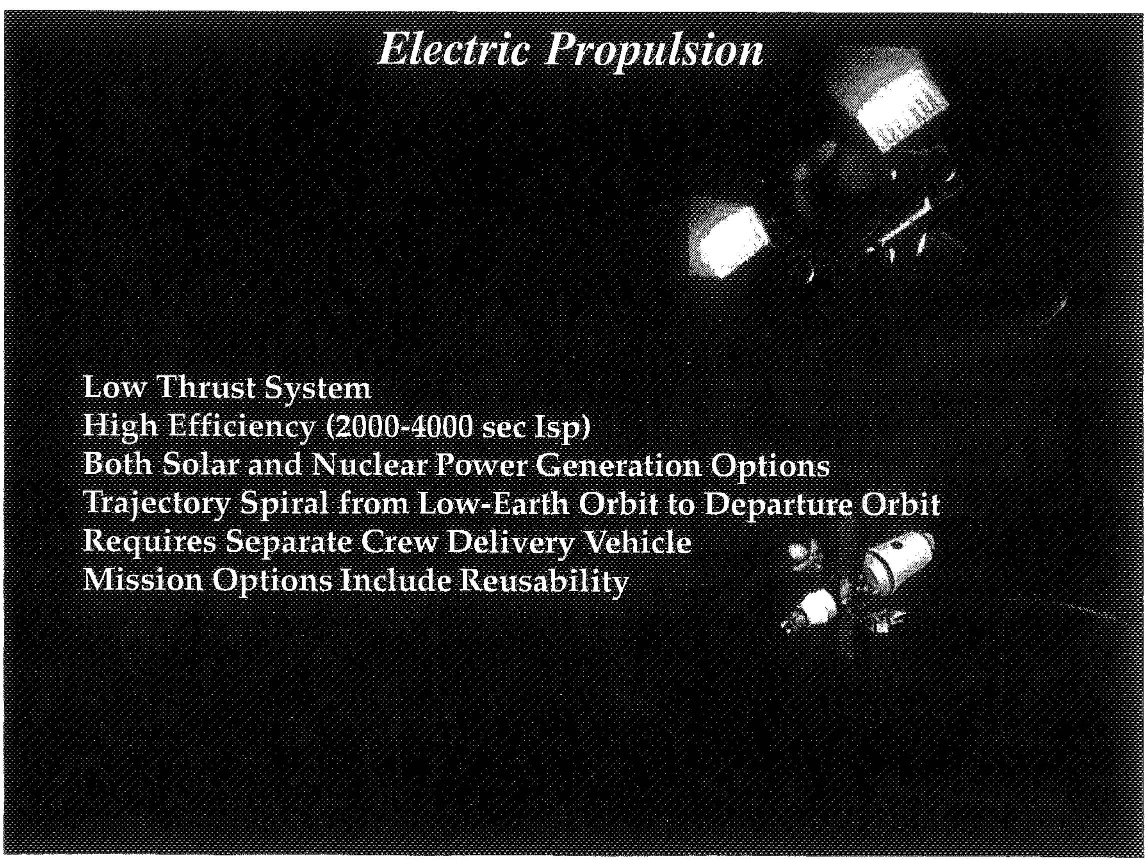
Flight 2: MAV

	Reference Version 1.0	Final Version 3.0
Ascent Capsule	6 mt	5 mt
Ascent Stage	3 mt	4 mt
Payload	48 mt	31 mt
Descent Stage	5 mt	4 mt
Descent Propellant	12 mt	11 mt
Aerobrake	17 mt	10 mt
TMI Stage	29 mt	23 mt
TMI Propellant	86 mt	45 mt
TOTAL IMLEO	**205 mt**	**134 mt**

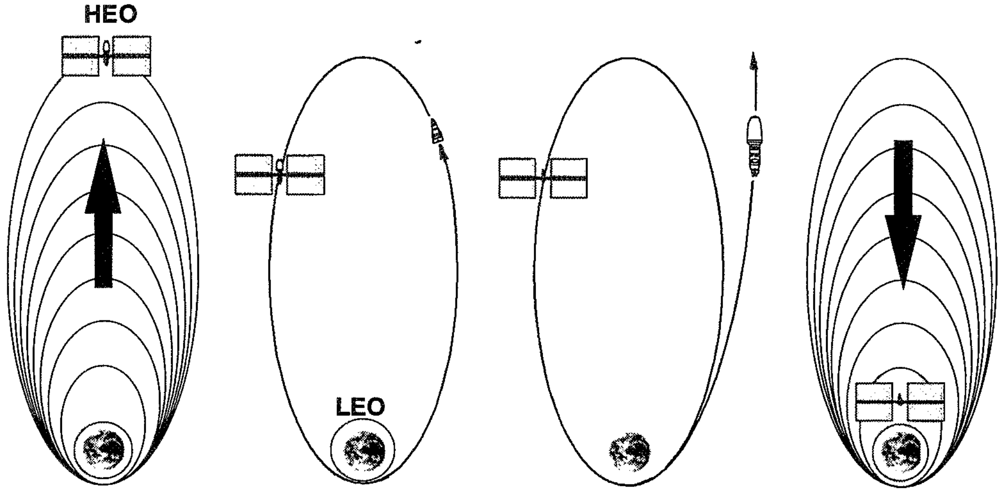
Flight 3: Piloted

	Reference Version 1.0	Final Version 3.0
Habitat	53 mt	29 mt
Payload & Crew	2 mt	2 mt
Descent Stage	5 mt	5 mt
Descent Propellant	12 mt	11 mt
Aerobrake	17 mt	14 mt
TMI Stage & Shielding	32 mt	27 mt
TMI Propellant	86 mt	50 mt
TOTAL IMLEO	**208 mt**	**137 mt**


Major Mission Variations to DRM 1.0
DRM 1.0
Scrub
• Magnum class launch vehicle
• Improved mass estimates
• Integrated habitat/aerobrake
TransHab
Toward 3.0
• Improved structural efficiencies (surface inflatables)
• Eliminated initial habitation flight
• Improved life support system estimates
• Improved Earth departure scenario
• Commercial industry potential
• Reduced architecture mass
• Aerobrake concept for large volumes
DRM 3.0
• Improved architecture masses
• Refined cost estimates
• Conceptual vehicle layouts


Electric Propulsion
Low Thrust System
High Efficiency (2000-4000 sec Isp)
Both Solar and Nuclear Power Generation Options
Trajectory Spiral from Low-Earth Orbit to Departure Orbit
Requires Separate Crew Delivery Vehicle
Mission Options Include Reusability

Electric Propulsion Earth Departure

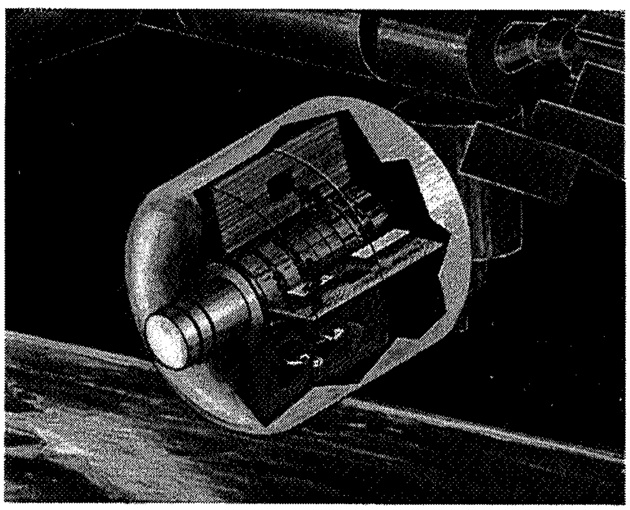


Electric Propulsion (EP) space tug performs low-thrust transfer for Mars-bound cargo to High Earth Orbit (many months transfer)

Crew delivered in "small" chemically-propelled transfer vehicle - X-38 derived (few days rendezvous time)

Remainder of trans-Mars injection performed by chemically-propelled system

Space tug returns for refueling and next assignment (faster or more efficient return since no payload present)

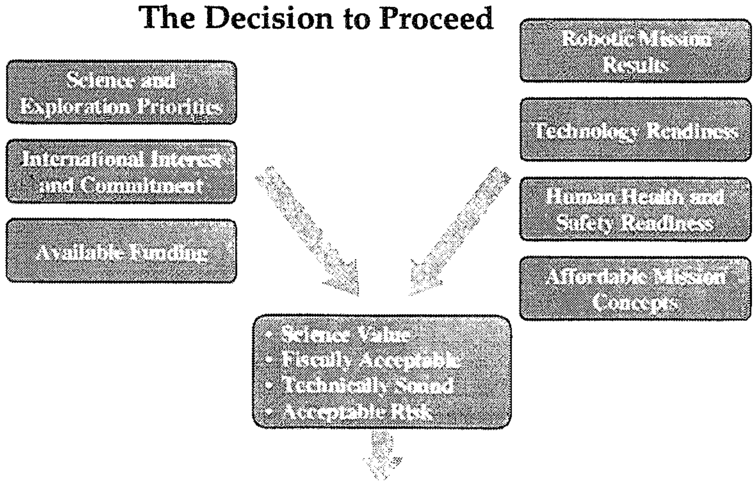


TransHab at ISS

Mars TransHab

- **JSC Engineering Directorate investigated the use of inflatable structures for human Mars missions**
- **Significant improvement in:**
  - **Structural efficiencies**
  - **Advanced life support system design**
- **Advancements incorporated into Mars mission definition (surface)**

The Decision to Proceed



Enable an affordable Mission to Mars

EVA ROADMAP: NEW SPACE SUIT FOR THE 21st CENTURY

Robert Yowell
NASA Johnson Space Center
EVA Project Office

Regenerable CO_2 Removal
- Swing Beds (Currently not practical in Mars atmosphere)
- Liquid and solid amines - absorption of CO_2
- Biologic process - carbonic anhydrase
- Laser ionization - requires high power laser
- Cryo freeze out of CO_2 - would be practical with use of cryogenic O_2 PLSS

PLSS Oxygen Systems
- Use of Cryogenic oxygen produced from in-situ manufacture
- Breathable Oxygen produced "real-time" from martian atmosphere as astronaut walks
- Stored gasseous oxygen (non-regenerable, finite supply)

EVA Power Supply
- Batteries - must reduce weight, increase power, reduce recharge time (current shuttle EMU battery requires 22 hours of recharge for 8 hour EVA)
- Fuel Cells - fully regenerable, recharge quicker than batteries

PLSS Thermal Control Systems
- Radiator cooling system which uses low quality water (current EMU sublimator uses 8 lbs of high quality purified water for each PLSS - sublimator is designed to work in a vacuum environment - not on Mars surface)
- Heat exchangers/Heat pumps

Systems Engineering and Architecture
- PLSS packaging/modularity - component miniaturization
- Ease of maintenance and replacement of components
- Commonality of component parts with life support systems in habitat, pressurized rover, etc.

Space Suit Systems
- Stronger, lighter weight suit materials
- Highly mobile suit with flexible joints
- Power assisted joints, gloves

Human Considerations

- Improved biomedical sensors and monitoring
- Improved astronaut comfort in suit (thermal, muscular, etc.)
- In suit food/drink
- Waste management

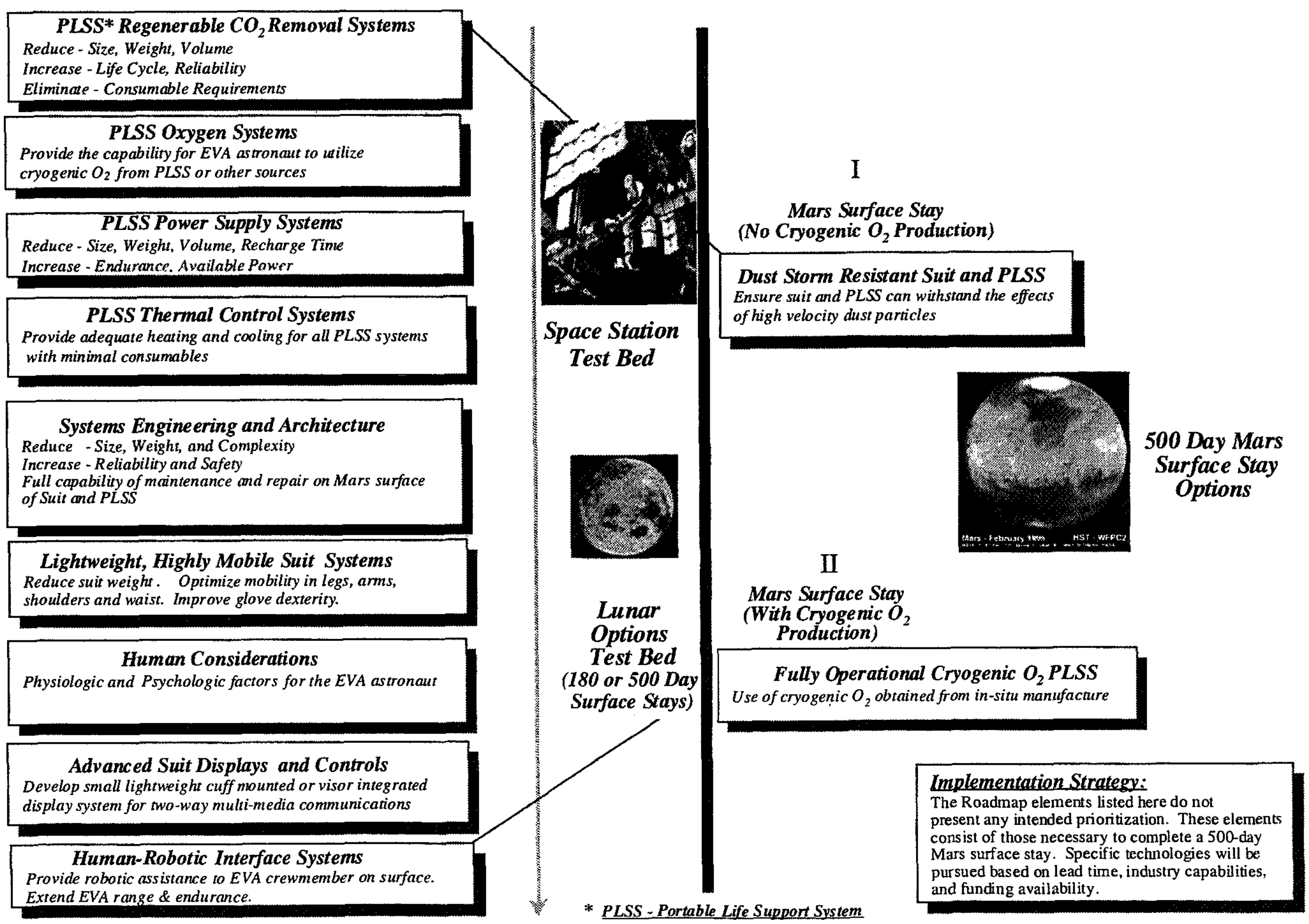
Displays and Controls

- Smaller suit sensors
- Improved suit/PLSS caution and warning (failure indentification, rapid reconfiguration)
- Robust two-way voice and video communications. Improved display technology (Heads Up/Retinal)
- Voice recognition command systems

Robotics Interface

- Small, self-propelled EVA caddies (provide back-up PLSS and/or PLSS recharge capability)
- Unpressurized and pressurized rovers
- Telerobotic command and control interface

EVA Research and Technology Roadmap



CREW HEALTH AND PERFORMANCE ON MARS

Charlie Stegemoeller
NASA Johnson Space Center
Human Space Life Sciences Programs Office

Human Space Life Sciences Programs

JSC is lead center for Human Operations in Space, including:

- Space Medicine
- Biomedical Research and Countermeasures
- Advanced Human Support Technologies
  - Advanced Life Support
  - Advanced Human Engineering
  - Advanced Environmental Monitoring and Control
  - elements of Advanced EVA

Human Space Life Sciences Program Office (HSLSPO) coordinates these critical human research support functions for JSC as Lead Center.

Background

HSLSPO determines critical research areas to assure human health and performance capability to explore and develop space.

Mars Design Reference Mission is benchmark for determining content and direction of mid- and long-term research activities.

Near-term focus continues on tasks and techniques to expand human performance on Shuttle and ISS missions.

Elements of Human Health and Performance (HHP)

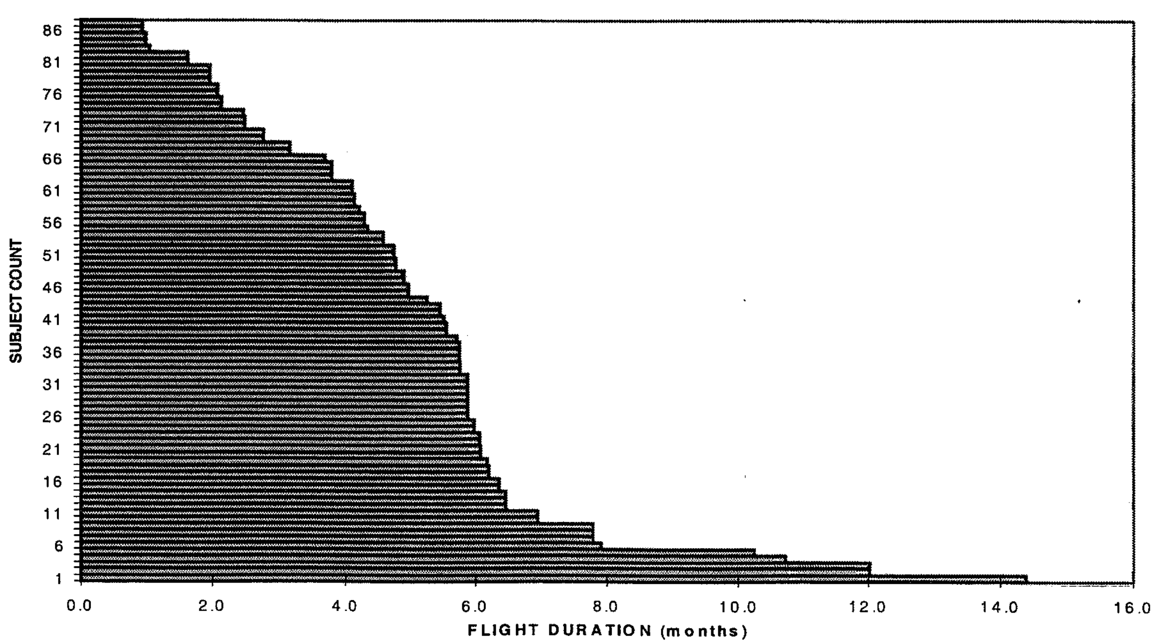
- Advanced Life Support (supply atmosphere, water, thermal control, logistics, waste disposal)
- Bone Loss (fractures, renal stones, joints, discs, osteoporosis, drug reactions)
- Cardiovascular Alterations(dysrhythmias, orthostatic intolerance, exercise capacity)
- Environmental Health (monitor atmosphere, water, contaminants)
- Food and Nutrition (malnutrition, food spoilage)
- Human Performance (psychosocial, workload, sleep)
- Immunology, Infection and Hematology (infection, carcinogenesis, wound healing, allergens, hemodynamics)
- Muscle Alterations and Atrophy (mass, strength, endurance)
- Neurovestibular Adaptations (monitoring and perception errors, postural instability, gaze deficits, fatigue, loss of motivation and concentration)
- Radiation Effects (carcinogenesis, damage to CNS, fertility, sterility, heredity)
- Space Medicine (in-flight debilitation, long term failure to recover, in-flight mis-diagnosis)

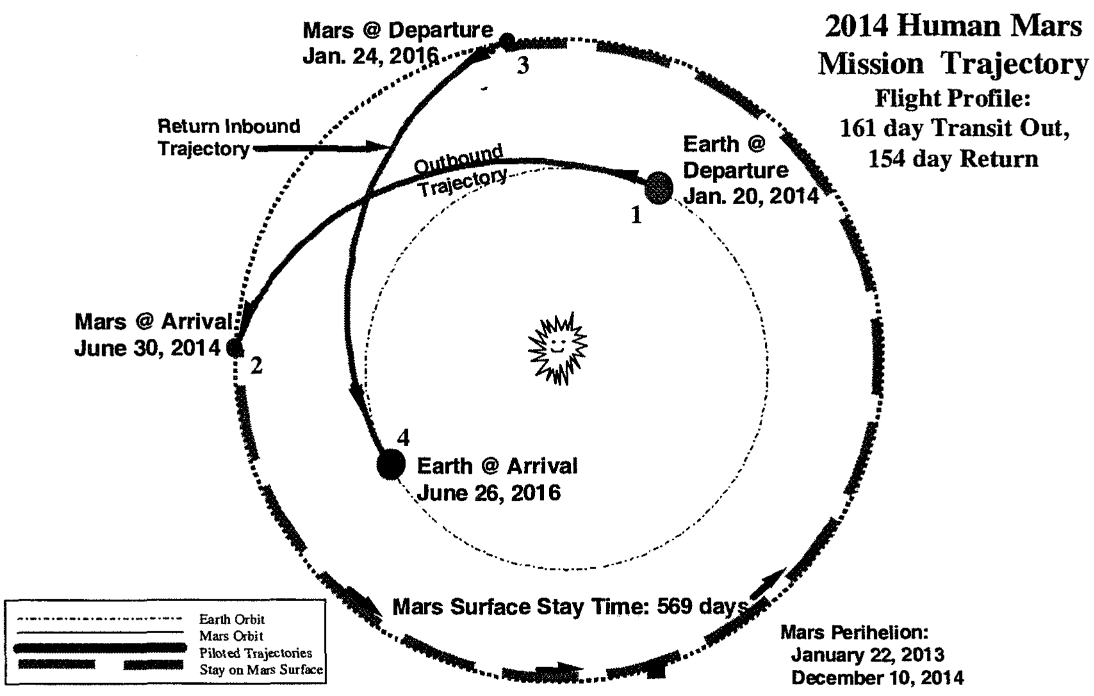
Why Mars?

Mars design reference mission requires most rigorous life sciences critical path of any crewed mission in foreseeable future.

Mars DRM	Current Experience and ISS Requirements
• 30 months round-trip	• longest flight to date: 14 months ISS tours: 3-6 months
• four g-transitions: 1g to 0g; 0g to 1/3g; 1/3g to 0g; 0g to 1g	• two g-transitions: 1g to 0g; 0g to 1g
• two episodes of high (up to 5) g-load: Mars aerobrake; Earth aerobrake	• one episode of low (1.5-2) g-load: Earth aerobrake (via Shuttle)
• high physical demands of Mars surface EVA, possibly daily	• orbital EVA; regular daily exercise
• exposure to spacecraft, terrestrial and extraterrrestrial toxins	• exposure to spacecraft and terrestrial toxins only
• largely autonomous; ground support limited to trending	• access to real-time ground support

Human Space Flight Experience Greater Than 30 Days (as of 1 Jan. 98





Physical Challenges to HHP: Gravity and Acceleration

	Earth Launch	Transit	Mars Landing	Mars Surface	Mars Launch	Transit	Earth Landing
G-Load	up to 3 g	0 g	3-5 g	1/3 g	TBD g	0 g	3-5 g
Notes	boost phase, 8 min.; TMI, minutes	4-6 months	aero-braking, minutes; parachute braking, 30 sec.; powered descent, 30 sec.	18 months	boost phase, minutes; TEI, minutes	4-6 months	aero-braking, minutes; parachute braking, minutes
Cumulative hypo-g	0		4-6 months		22-24 months		26-30 months
G Transition	1 g to 0 g		0 g to 1/3 g		1/3 g to 0 g		0 g to 1 g

Impacts of Extended Weightlessness on HHP

Physical tolerance of stresses during aerobraking, landing, and launch phases, and strenuous surface activities

- Bone loss
  - no documented end-point or adapted state
  - countermeasures in work on ground but not yet flight tested
- Muscle atrophy
  - resistive exercise being evaluated
- Cardiovascular alterations
  - pharmacological treatments for autonomic insufficiency
- Neurovestibular adaptations
  - vehicle modifications, including centrifuge
  - may require auto-land

"Artificial Gravity" as Countermeasure to Weightlessness

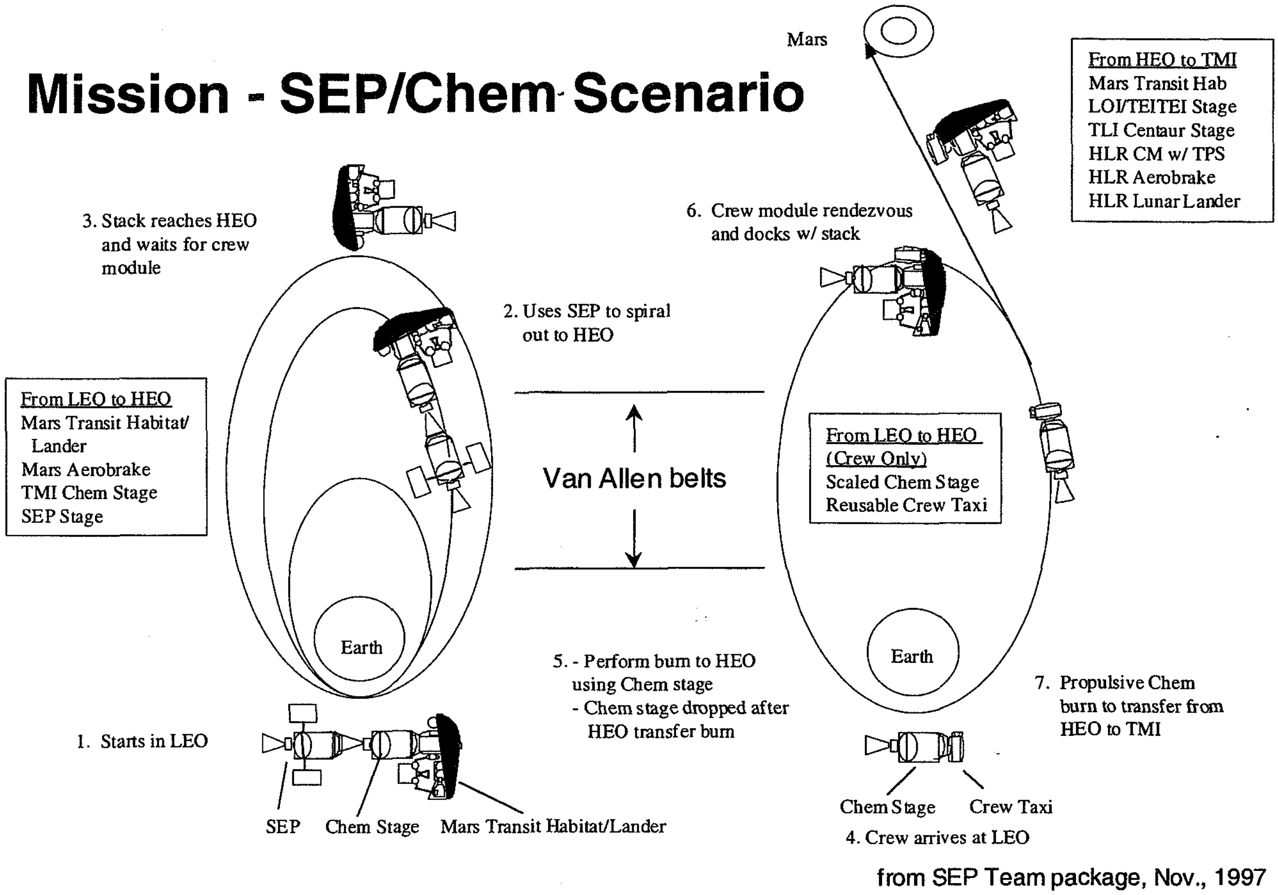
Question: Can AG preserve physiological function on long-duration missions?

Implications:

- Can Mars DRM afford weight, power, cost of AG?
  - dual systems for 0 g and AG phases of transits?
- How will NASA validate approach?
  - ISS small-animal centrifuge not available before CY 2003
  - larger centrifuge not currently planned

Physical Challenges to HHP: Radiation

	Earth Launch	Transit	Mars landing	Mars Surface	Mars Launch	Transit	Earth Landing
Source	van Allen (trapped radiation) belts	GCR (quiet Sun); SPE (active Sun); nuclear power reactor		GCR (quiet Sun); SPE (active Sun); nuclear power reactor		GCR (quiet Sun); SPE (active Sun); nuclear power reactor	
Exposure	SEP option: 3 passages or more	4-6 months		18 mon.; shielded by Mars' bulk and atmos.		4-6 months	
Cum. Exp.	hours-days		4-6 months		22-24 months		26-30 months



Peak Physical Challenges for HHP: Mars Surface Phase (Post-Landing through Pre-Launch)

<u>Assumption</u>

Mars surface gravity
- too low to be beneficial (bone integrity, etc.)
- too high to be ignored (g-transition vestibular symptoms)

<u>Challenges</u>
- physical
  - g-transition (first few days only?)
  - prolonged exposure to 1/3 g
  - high-intensity surface activity
  - EMU hypobaric environment
  - 70 kg EMU (partially self-supporting)
  - surface trauma risk
- no real-time MCC support
  - crew highly autonomous
  - Earth monitoring for trend analysis only

Peak Physical Challenges for HHP: Strategy for Mars Surface Ops

Background: anecdotal evidence suggests only ~50% of Russian Mir crewmembers are ambulatory with assistance immediately after landing, increasing to nearly 100% within hours

Assume: only 3 out of 6 Mars crewmembers ambulatory immediately after landing

Strategy: start with initial passive IVA tasks, then progress to strenuous EVA tasks
- first 1-3 days limited to IVA reconfig of lander/habitat, surface recon
- then, first EVA(s) in vicinity of lander (umbilical instead of PLSS?)
- next, use unpressurized rover for early, shorter excursions
- after a week or more, extended excursions possible

HHP Mars Surface Stay Requirements

Autonomous
- Medical care
- Nutrition
- Psych support
  - meaningful work
  - communications capability (surface, deep space)
- Habitat Facilities
  - exercise
  - workshop
  - recreation

Life Sciences on Mars Surface

Periodic (monthly?) health checks:
- bone integrity
- cardiovascular/cardiopulmonary function
- musculoskeletal fitness
- blood work

Assessments will also serve as applied research:
- probably longest period away from Earth to date
- probably longest exposure to hypogravity (1/3 g) environment to date

Space Medicine Issues

Based on US and Russian space flight data, and US astronaut longitudinal data, submarine experience, Antarctic winter-over experience, and military aviators:

Significant Illness or Injury = 0.06 per person per year (or PYE)
- requiring emergency room (ER) visit or hospital admission
- by US standards

For DRM of 6 crewmembers and 2.5 year mission, expected incidence is 0.90, about one person per mission

Subset requiring intensive care support (ICU) = 0.02 per PYE
Expected incidence is 0.30, about once per three missions

Space Medicine Issues:
Space Flight Incidence of Illness and Injury

Common (> 50%incidence)
- skin rash, irritation
- foreign body
- eye irritation, corneal abrasion
- headache, backache, congestion
- gastrointestinal disturbance
- cut, scrape, bruise
- musculoskeletal strain, sprain
- fatigue, sleep disturbance
- space motion sickness
- post-landing orthostatic intolerance
- post-landing neurovestibular symptoms

Incidence Uncertain
- infectious disease
- cardiac dysrhythmia
- trauma, burn
- toxic exposure
- psychological stress, illness
- kidney stones
- pneumonitis
- urinary tract infection
- spinal disc disease
- radiation exposure

data from R. Billica, Jan. 8, 1998

Space Medicine Issues:
Recommended Clinical Care Capability Development

Clinical Care
- imaging capability
- trauma care
- surgical capability
- noninvasive diagnostics
- respiratory care/advanced ventilation
- hyperbaric treatment
- medical informatics, telemedicine
- radiation treatment
- blood substitutes
- urologic diagnosis, treatment
- extended shelf-life pharmaceuticals
- body disposal, palliative treatment
- serological capabilities
- banked autologous marrow

Prevention and Countermeasures
- reconditioning, rehabilitation
- preventive medicine
- recycling of resources
- toxin dust management
- sterile water
- resistive exercise training
- radiation prophylactics
- microbiology

data from R. Billica, Jan. 8, 1998

Human Factors and Habitability

The following require engineering solutions to optimize HHP:
- clean air
- clean water
- waste management
- adequate food
  - long-duration storage
  - grain processing
- particulate analyzer
- microbial analyzer
- clothes washer
- lighting
  - intensity (threshold level)
  - periodicity (circadian rhythmicity)

Conclusions

- The human element is the most complex element of the mission design
- Mars missions will pose significant physiological challenges to crew members
- Some challenges (human engineering, life support) must be overcome
- Some challenges (bone, radiation) may be show-stoppers
- ISS will only indirectly address Mars questions before any "Go/No Go" decision
- Significant amount of ground-based and specialized flight research will be required — Critical Path Roadmap project will direct HSLSPO's research toward Mars exploration objectives

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PREPARING FOR HUMAN EXPLORATION

Bret G. Drake [1] and B. Kent Joosten[2]

Abstract

NASA's Human Exploration and Development of Space (HEDS) Enterprise[1,2] is defining architectures and requirements for human exploration that radically reduce the costs of such missions through the use of advanced technologies, commercial partnerships and innovative systems strategies. In addition, the HEDS Enterprise is collaborating with the Space Science Enterprise to acquire needed early knowledge about Mars and to demonstrate critical technologies via robotic missions. This paper provides an overview of the technological challenges facing NASA as it prepares for human exploration. Emphasis is placed on identifying the key technologies including those which will provide the most return in terms of reducing total mission cost and/or reducing potential risk to the mission crew. Top-level requirements are provided for those critical enabling technology options currently under consideration.

Introduction

Previous studies have identified a wide variety of technologies needed to support the design, development and ultimate implementation of human expeditions beyond low Earth orbit (LEO)[3,4,5]. These technologies span a wide range of needs and technology disciplines which have been focused more or less on specific mission implementations. The current exploration is to identify leading technologies which can radically reduce the cost and risk of human deep space exploration, and to drive out top-level performance requirements for these technologies.

Key technology thrust areas for human exploration are divided into five major categories including: 1) Human Support, 2) Advanced Space Transportation, 3) Advanced Space Power, 4) Information and Automation, and 5) Sensors and Instruments. A broad overview of each of these technology are discussed below. A draft version of human exploration technology goals and requirements have been developed and are currently under review[6].

Human Support

The human support thrust includes research and technology development areas pertaining to the health and human performance of crews in the conduct of deep-space exploration missions[7,8]. Key focus areas for the human support thrust include: Health and Human Performance, Advanced Life Support, Advanced Habitation Systems, and Extra-Vehicular Activity and Mobility.

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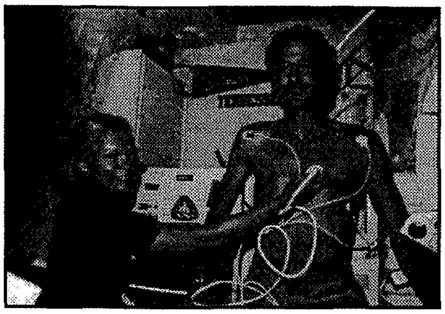
Health and Human Performance



A key element of deep-space exploration missions is ensuring human health and safety throughout all mission phases. Key technology efforts within this area include radiation protection research, zero-g countermeasure development, medical care and environmental health, and human factors (see Table 1).[9]

Human exploration missions beyond low-Earth-orbit, namely to Mars, expose the crew to the harsh environment of deep-space for potentially long periods of time. Of particular importance are the health affects of radiation, both solar particle events and galactic cosmic radiation, and long transit times (on the order of six months) to and from planetary destinations. Understanding the effects of this deep space environment on biological systems, as well as developing countermeasure protocols, are essential for reducing the risks to the crew.

Systems that characterize and enable the prediction of solar radiation events would substantially contribute to the health and safety of future explorers. Such systems might involve a range of technologies, including various sensors (e.g., X-ray detectors, visible light imagers and others), predictive software and associated database systems. In conjunction with such general systems, local sensors (e.g., attached to habitats) as well as personal radiation hazard monitors would improve crew safety. Radiation research to understand the impacts to biological systems from the deep-space radiation environment including the interaction of the habitat structures and materials is critical to the HEDS Enterprise.

Sufficient equipment, tools, and techniques must be in place to support the crew's medical care, environmental monitoring, and systems interface needs during the long-duration isolated missions. Emphasis is being placed on determining potential risks, defining acceptable levels of risk, and developing risk mitigation strategies. Risk areas include medical and medical care, psychosocial factors, air and water contamination, and forward and back contamination including methods of control.

Radiobiology

- Characterization of the deep-space radiation
- Beam line ground reasearch (HZE) to simulate GCR exposure and sutides to understand the effects of HZE expousres on biological systems
- Establish carcinogenesis dose response for HZE radiation
- Develop accurate biodosimetry techniques
- Determine individual variation susceptibility to radiation effects
- Determine feasibility of using pharmacological agents to inhibit radiation
- Examine how biological effects vary with shielding thickness and types
- Establish radiation exposure limits for design and operational use

Zero-G Countermeasures

- Short-arm centrifuge
- Ultra-light-weight, multi-axis head and binocular 3-D video eye movement measurement systems
- Angular and linear whole body acceleration devices
- Dynamic visual acuity test
- EVA free-gas phase monitor
- Ambulatory sensors
- Body composition monitor
- Advanced urine collection system
- Telemetry system for non-invasive cardiovascular monitoring
- Phase plane steerable array

Medical Care

- Wearable or implantable sensors
- Blood component storage
- Non-invasive surgery techniques
- Imaging and telemedicine systems
- More autonomous diagnostic, treatment systems

Environmental Health

- Detection and identification of potential Mars mission contaminants
- First alert capabilities
- Rapid microbial detection
- Minaturized, highly reliable systems requiring less crew time and ground support than ISS systems for operations, maintenance, and data interpretation
- Decontamination capabilities

Human Factors

- Diagnostic tools and countermeasures to monitor and maintain crew performance
- Systems to collect and analyze data on flight systems status
- On-board training concepts, techniques, and procedures
- Light-weight, efficient personal hygiene systems
- Food preservation and processing techniques to increase shelf-life and process raw products grown in-situ

Table 1. Summary of Human Health and Performance Technology Needs.

Advanced Life Support

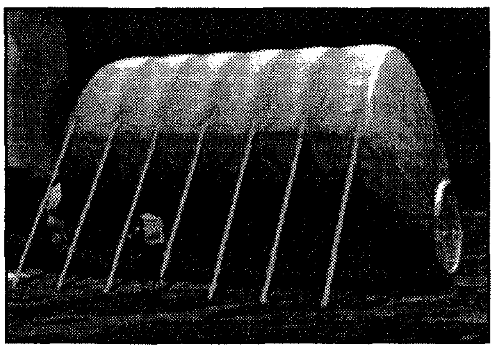
Developing technologies which can significantly reduce the consumables required to support the crew during long-duration is also critical for human exploration. Technologies include air and water loop closure, environment monitoring, solid waste processing, thermal control, and food production.

Advanced sensor technologies to monitor and intelligent systems to control the environmental "health" of the advanced life support system, including air and water, are also needed. Studies have shown that incorporation of advanced biological air and recovery systems can save as much as 25% as compared to previous approaches[10] (Figure 1). Key performance requirements for the advanced life support systems are provided in Table 2.

Advanced Life Support System
- Require essentially no crew time for operations or maintenance
- Provide 99% closure of air and water
- Evolve to provide at least 50% closure of food production for planetary surface crews
- Be capable of utilizing local planetary resources
- Be capable of performing waste processing and recovery of useful resources

Table 2. Summary of Advanced Life Support System Technology Needs.

Advanced Habitation



Structural and materials advancements to provide large livable volumes, both in-transit to and from planetary destination as well as during surface explorations, while minimizing mass are desired for human exploration missions. Advanced inflatable structures which protect the crew from the harsh space environment are actively being pursued.

Key technology thrusts include habitat concepts and emplacement methods (including robotic emplacement), advanced light-weight structures (inflatable versus traditional "hard" shells), and developing integrated radiation protection for crew health and safety. Incorporation of light-weight inflatable structures have been shown to save up to 25% structural mass (Figure 1). Key performance requirements for the advanced habitation systems are provided in Table 3.

Advanced Habitation
- Provide mass savings of at least 40% when compared to conventional designs
- Provide radiation protection withoug significantly increasing habitation system mass
- Be capable of autonomous operations of the integrated systems
- Be capable of performing deployment, assembly, and checkout autonomously and/or robotically

Table 3. Summary of Advanced Habitation Technology Needs.

Extra-Vehicular Activity & Mobility

Advanced technologies which enable routine surface exploration are critical to the HEDS Enterprise. This includes advanced EVA suits and short and long-range surface mobility (rovers) for advanced surface exploration. Systems which provide routine, and continuous surface exploration are key to maximizing mission return.

Key technologies include: advanced materials research which provide enhanced mobility and dexterity while maximizing radiation and puncture protection; low-weight, fast recharge batteries; low-weight efficient thermal control; consumable supply technologies including cryogenic backpacks; humidity control systems; advanced sensors for environmental monitoring including oxygen, carbon-dioxide, nitrogen, temperature, etc.; and advanced avionics such as heads-up displays, communications, and navigation. Key performance requirements for the advanced extra-vehicular activity systems are provided in Table 4.

Advanced Extra-Vehicular Activity
• Weight of the total EVA systems shall be reduced by 40%
• Volume of the portable life support system shall be reduced by 30%
• Be capable of utilizing local planetary resources
• Be robust and capable of protecting the crew from dangers of sharp rocks and objects as well as operating effectively in a dusty environment

Table 4. Summary of Advanced EVA Technology Needs.

During the technology development process, emphasis is being placed on understanding the benefits and leverage of the various options. Benefits can come in the form of risk reduction (to the crew) or through system performance (reduced mass). An example of the performance leverage provided by of some of the human support technologies is shown in Figure 1.

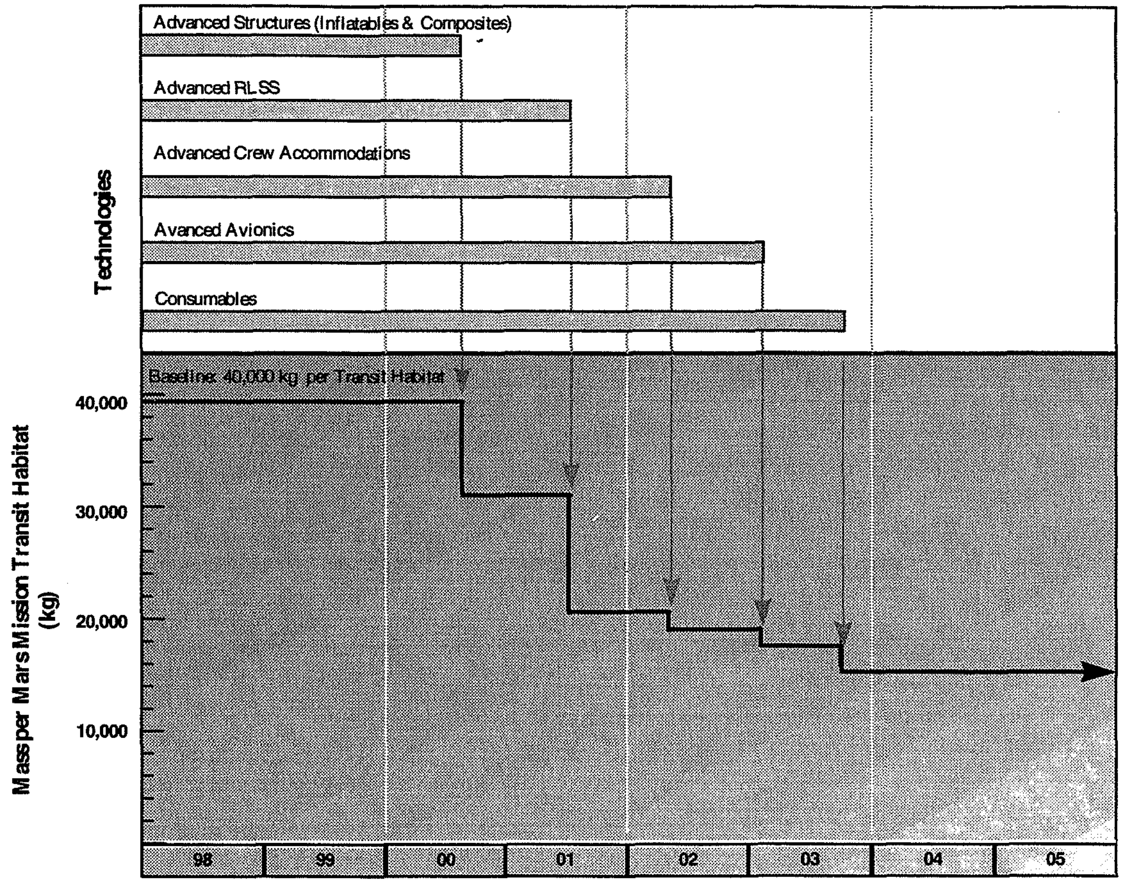
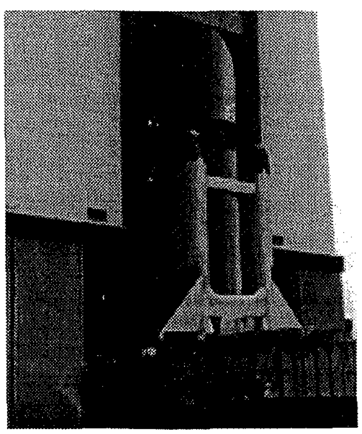


Figure 1. Example Benefits of Human Support Technologies.

Advanced Space Transportation

The advanced space transportation technology thrust includes all technology development areas pertaining to the transportation system architecture and elements of the transportation architecture including propulsion and vehicle concepts to enable routine human exploration. The advanced space transportation technology thrust includes: Affordable Earth-to-Orbit Transportation, Advanced Interplanetary Propulsion, Cryogenic Fluids Management, Aeroassist, and In-Situ Resource Utilization. A summary of the key technology performance requirements for the advanced space transportation thrust is provided in Table 5.

Affordable Earth-to-Orbit Transportation

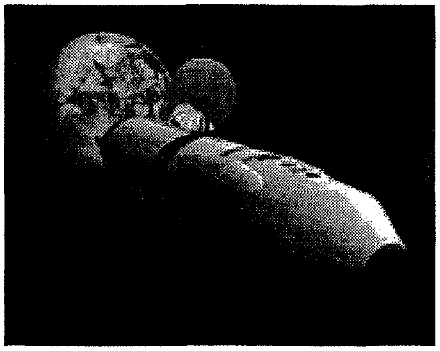


Advances in the earth-to-orbit launch vehicle technology area focus primarily on reducing the life-cycle costs associated with launching large payloads. Key to this technology area are low-cost technologies which can be scaled to a large launch vehicles. Examples include tanks and structures; propulsion systems; shrouds; upper stages; launch vehicle/payload integration; launch operations; and automated on-orbit assembly and checkout.

Cryogenic Fluid Management

Significant technology advances in long term storage and handling of cryogenic fluids will be required to accomplish human exploration missions. Technologies for low heat leak extremely long duration (years) cryogenic storage vessels; boiloff fluid recapture and reliquification both in-space and on the planetary surface; liquification , transfer and storage of the products of in-situ resource utilization processes; long term pressure control; and fluid mass gauging on both zero and low g environments. Though on a smaller physical scale, many of these technologies are needed to improve/enable future science and Earth observation systems which require cryogenic fluids as coolants or working fluids.

Advanced Interplanetary Propulsion



A key element in achieving low-cost human exploration missions is the efficient and cost effective interplanetary propulsion system. Emphasis is being placed on providing quick trips to and from planetary destinations while at the same time reducing overall system size and mass.

Numerous technology options are currently under investigation including: Solar electric and nuclear electric propulsion, nuclear thermal propulsion, all chemical propulsion, and various hybrid combinations of these systems. Advanced propulsion technologies can reduce total mission mass by as much as 55% A comparison of the performance advantages of the various interplanetary propulsion options, as implemented in the current Mars Design Reference Mission, is shown in Figure 2.

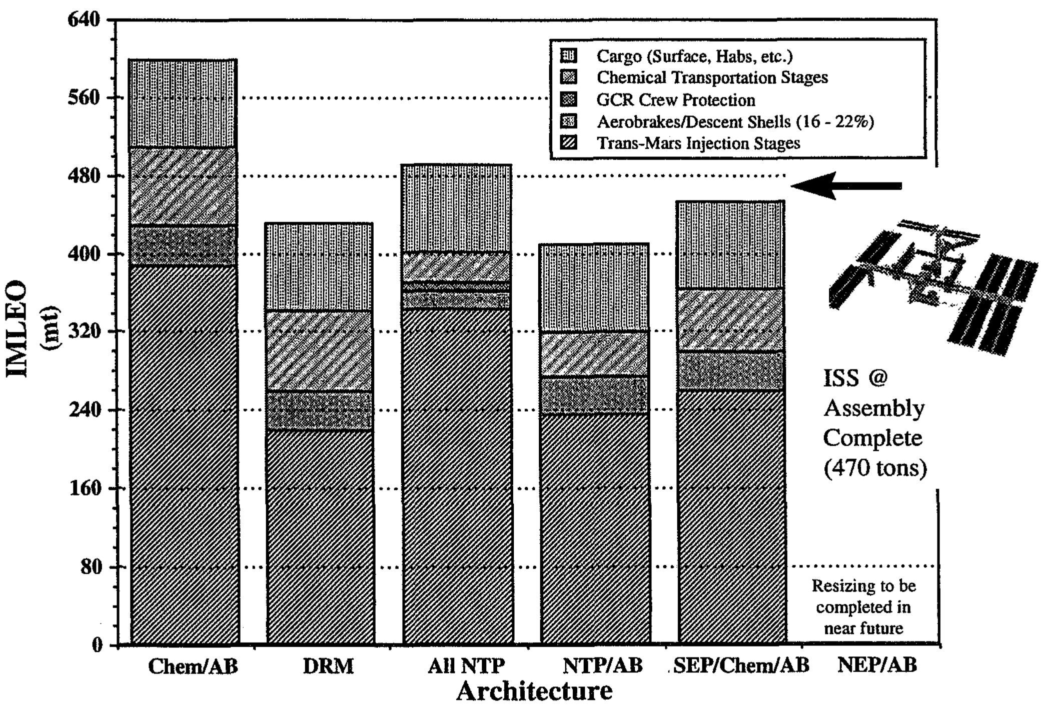


Figure 2. Example Benefits of Advanced Space Transportation Technologies.

Aeroassist

In order to support future human exploration missions, significant advances in aeroassist technologies are required. Utilizing the atmosphere of Mars to decrease the speed of the vehicle and capture it into the orbit of Mars can significantly reduce the overall transportation system mass.

Technology advances in aerothermodynamics; thermal protection systems; guidance, navigation and control; and vehicle design/integration must be accomplished. These technologies provide high leverage in exploration of solar system bodies which have atmospheres (e.g., for human Mars missions aerocapture reduces initial mass in low Earth orbit by as much as 40% when compared with an all chemical propulsion transportation architecture).

ADVANCED SPACE TRANSPORTATION		
Affordable Earth-to-Orbit Transportation		
• ETO system cost goal of delivering payloads to Earth orbit for costs <$1000/pound of payload		
• Deliver on the order of 80 metric tons to Low-Earth-Orbit (28.5° inclination, 407 km altitude)		
• Payload volume on the order of 7-8 m diameter by 28 m length		
Electric Propulsion	High Earth Orbit Departure	Continuous EP Scenario
• Specific Impulse	~2000 seconds	~4000 seconds
• Thruster Power	~50-100 kWe	~250-500 kWe
• Thruster Lifetime	10,000 hours	10,000 hours
Nuclear Thermal Propulsion	Reference Approach	All Propulsive Approach
• Thrust Level	15 klbf/engine	15 klbf/engine
• Specific Impulse	940-960 seconds	940 seconds
• Engine Burn Duration	45-55 minutes total	45-60 minutes total
Aeroassist		
• Transit times shall be no greater than 180 days to and from Mars		
• Aerobrake large volume comparable to a volume 14.9 meters long by 10 meter base		
• Entry speeds up to 8.7 km/sec at Mars		
• Entry speeds up to 14.5 km/sec at Earth return		
• Precision landing at least 1 x 3 km ellipse		
• Be capalbe of supporting external system connections such as power, com., and thermal		
Cryogenic Fluid Management		
• Be capable of storing and maintaining 4-60 metric tons of oxygen, hydrogen, and methane for up to 1700 days in free space		
• Be capable of storing and maintaining 4-30 metric tons of oxygen, hydrogen, and methane for up to 1200 days on the surface of Mars		
In-Situ Resource Utilization		
• ISRU process shall be synergistic with transportation systems, surface power generation, life support systems, and extra-vehicular activity systems		
• Shall be capable of operating autonomously for months/years		
• Propellant production shall provide the following production rates for ascent systems Mars Robotic = 1-2 metric tons Mars Human = 30-40 metric tons		

Table 5. Summary of Advanced Space Transportation Technology Needs.

In-Situ Resource Utilization

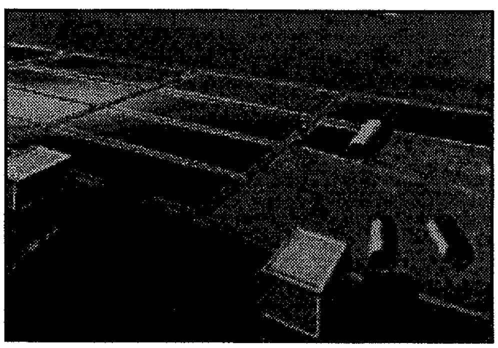
Technologies for "living off the land" are needed to support a long-term strategy for solar system exploration. Utilizing available resources for transportation purposes rather than transporting these resources from Earth is the first step in maximizing the use of local planetary resources.

Technologies for capturing and processing planetary resources to produce ascent stage propellants provides significant leverage for the human missions (20% reduction in initial mass in low Earth orbit when compared with an all chemical architecture in which the ascent propellants are transported from Earth). In-situ resource utilization for future robotic missions can have significant effects for larger science sample returns from the surfaces of solar system bodies.

Advanced Space Power

A key focus of the advanced power systems technology thrust is to develop technologies to provide continuous high power at low cost in order to enable robust exploration activities. The advanced space power technology thrust includes: Advanced Power Generation, Energy Storage, and Power Management. In addition, the advanced space power technology thrust includes all functional areas of human exploration including space transportation, stationary surface power, mobile power (rovers), and human portable systems (EVA). A summary of the advanced space power technology needs is provided in Table 6.

Advanced Power Generation



Technologies which provide high continuous power capability are enabling for robust human exploration. High power generation can enable other high leverage technologies, such as in-situ propellant production, which greatly reduce overall system mass and launch costs.

High power generation enables technologies such as electric propulsion and in-situ resource utilization for reduced transportation propellant mass, and highly closed loop life support and plant cultivation for reduced life support consumables mass. Both solar and nuclear power technologies are under consideration. Key technology areas include advanced solar systems with very low specific mass and cost and relatively high radiation resistance; efficient energy conversion systems for radioisotope and nuclear systems; high temperature materials for increasing system efficiency and reducing system mass; and materials compatibility with planetary environments.

Energy Storage

Advances in energy storage techniques are enhancing across a range of HEDS applications and likely enabling for the practical implementation of large solar surface power systems. Potential HEDS applications with significant electrical energy storage requirements include night time energy storage for solar-powered surface systems, temporary emergency power for surface systems and spacecraft, and mobile rovers and spacesuits. Technology options for addressing these needs include chemical energy storage in advanced batteries and fuel cells, mechanical storage via flywheels, and direct storage within electrical capacitors. Generally desirable characteristics of advanced energy storage options include low mass and cost per unit energy storage, and low or nonexistent restrictions on depth of discharge. Additional specific system requirements include a high storage capacity for rover primary propulsion and surface habitat systems with high night-time power requirements, and volumetric compactness for mobile rovers and spacesuits.

Power Management

Advances in lower mass and increased efficiency power management, conditioning, and distribution technologies are necessary to reduce the overall mass of HEDS power systems. Applications span a broad range of potential powers, from kWe's to Mwe's. Specific needs include the development of reconfigurable fault tolerant power networks, and high voltage processing and distribution for surface transmission and electric propulsion systems.

ADVANCED SPACE POWER		
Electric Propulsion Power Needs	High Earth Orbit Departure	Continuous EP Scenario
• Total Power	~500-1000 kWe	~4 Mwe
• Specific Mass	~10 kg/kWe	~7 kg/kWe
• Operating Lifetime	~1-3 year	~3 years
• Radiation Degradation (solar)	<30%	Not applicable
NTP Power Needs (Bi-Modal)	Reference Approach	All Propulsive Approach
• Total Power	15-25 kWe/engine	15-25 kWe/engine
• Power Generation Time	< 1 hour	4-5 years
Surface Stationary Power		
• Capable of providing continuous power for many years (7 years)		
• Provide 100-200 kWe electrical power for surface systems		
Mobile Power		
• Power sources include: dynamic isotope, photovoltaic with regenerative fuel cells, advanced batteries, and internal combustion		
• 10 kWe for pressurized rovers and power carts		
• 4 kWe for unpressurized rovers		
• 50-100 W for EVA suits		

Table 6. Summary of Advanced Space Power Needs.

Information and Automation

The key focus for the information and automation thrust is to enable robust human exploration by providing the crew with highly intelligent and autonomous systems in the presence of a data-rich environment. The information and automation technology thrust includes: Communications and Networks, Intelligent Systems and Advanced Operations, and the Intelligent Synthesis Environment. Technologies that enable autonomous system health maintenance will be essential to low cost operations for exploration missions. These include advances in artificial intelligence, integration of data from multiple sensors and intelligent signal analysis to enable systems to perform self-diagnosis and operational decision-making. Also, technologies that enable increasingly effective modeling, mission analysis and design are needed for various ambitious HEDS missions.

Communications and Networks

Advanced communications and networks includes technologies for providing fast and reliable data acquisition, transmission, and delivery to remote operations sites; high-bandwidth communications; and robust communications capabilities at exploration destinations.

Intelligent Systems & Advanced Operations

Due to the remoteness of exploration destinations, new advanced operations concepts and technologies are required to account for the long time-delay of communications. The intelligent systems and advanced operations thrust focuses on autonomous system operations for remote operations independent of direct earth-based control and includes technologies such as systems health management and performance support systems for both the flight crew and ground operations personnel. In all systems, advances in mission operations technologies are needed, including automated mission design and planning, automated operations, and increased operability in all systems.

Intelligent Synthesis Environment
The intelligent synthesis environment thrust includes technologies associated with the development of a state-of-the-art simulation based system engineering and analysis environment for all phases of development and execution of HEDS missions. The intelligent synthesis environment integrates remote teams in virtual environments including scientists, technology developers, and project engineers, providing for rapid and efficient systems analysis and integration.

Sensors and Instruments

The sensors and instruments technology thrust includes: Science and Engineering Field Labs, Planetary Prospecting, Environmental and Medical Monitoring, and Sample Curation.

Science and Engineering Field Labs
The focus of the science and engineering field labs technology thrust is to develop advanced technologies to enable in-situ analysis of the planetary environment. Included are technology advancements in areas such as organic chemistry and age dating, electron microscopy, chemical and mineral analysis, imaging, and remote sensing.

Environmental and Medical Monitoring
Sensor and instrument development, particularly in the area of miniaturization, calibration, and portability are key for advanced exploration missions. Sensor technology areas include alarm monitors (fire, toxins, radiation), environmental monitors (food, air, water), human health monitors (EVA suit, IVA, routine check-ups), emergency medical systems, telemedicine, and global monitoring and hazard avoidance (e.g. dust storms).

Planetary Prospecting
The focus of the planetary prospecting technology thrust is primarily on planetary environmental characterization and understanding. For instance, site safety and selection, resource identification and mapping, as well as sample acquisition (including drilling to depth) are included here.

Sample Curation
Key sample curation technologies include long-term packaging and preservation, "witness plate" monitoring, hazards and contamination analysis, and on-site caching and archival.

Micro/Nano Technologies
Micro-miniaturization of advanced analytical sensors and instrumentation, including scanning electron microscopy (SEM), scanning tunneling microscopy (STM) and other approaches would greatly enhance the returns from extended human expeditions to other planetary bodies. Similarly, these technology developments could enable significant improvements in the systems used to assure crew health in the presence of toxins, particulate irritants or related hazards. Similarly, miniaturized biotelemetry sensors and systems are needed for human crew monitoring (clinical), as well as portable clinical laboratory diagnostics systems.

Conclusions

The exploration community is continuing to refine and advance the technologies and mission approaches needed to support future human exploration missions. The primary goal of these efforts is to develop mission architectures, including technology options, which can significantly reduce the cost of human exploration. During the technology development planning process, emphasis is being placed on those technologies which can provide the most leverage in terms of risk reduction and cost reduction.

Acknowledgments

The technology needs and requirements discussed in this paper are the result of a team effort. The authors would like to thank the following individuals for their support and work in development of these data: Dr. John Charles/JSC (Human Health and Performance), Dr. Don Henninger/JSC (Advanced Life Support), Kriss Kennedy/JSC (Advanced Habitation), Mike Rouen/JSC (Advanced EVA), Steve Richards/MSFC (Advanced Space Transportation), Bill Eoff/MSFC (Affordable ETO), Jeff George/JSC (Electric Propulsion), Stan Borowski/LeRC (Nuclear Thermal Propulsion), Dave Plachta/LeRC (Cryogenic Fluids Management), Jerry Sanders/JSC (In-Situ Resource Utilization), and Bob Cataldo/LeRC (Advanced Space Power).

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POWER SYSTEMS FOR HUMAN EXPLORATION MISSIONS

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Power system options were reviewed for their appropriateness to meet mission requirements and guidelines(1). Contending system technologies include: solar, nuclear, isotopic, electro- chemical and chemical. Mission elements can basically be placed into two categories; in-space transportation systems, both cargo and piloted; and surface systems, both stationary and mobile. All transportation and surface element power system requirements were assessed for application synergies that would suggest common hardware (duplicates of the same or similar design) or multi-use (reuse system in a different application/location), wherever prudent.

GENERAL REQUIREMENTS

Power systems, defined as a life critical function, falls under a fail operational/fail operational/fail safe (FO/FO/FS) functional redundancy risk approach. A power system strategy incorporating redundant, back up and dual-function systems are utilized to satisfy this mission risk approach. Also the adopted mission abort philosophy is to utilize the Mars Base as a "safe haven" since a significant infrastructure of shelter, power, life support and consumables, return flight propellants will already exist.

Thus, a 600-day supply of life support gases and water, along with the ascent vehicle propellants (CH_4 and O_2), will be generated and stored before committing to the piloted mission scheduled for the following opportunity, some 750 days later. A significant requirement on the power system will be a design that can be self-deployed or telerobotically deployed within a short period of time. The initial power system output is therefore dictated by the total energy needed to produce and store the cache of life support and propellants and the available operating time. Of the 750 days between missions, only 480 days are available to produce power based on 210 days of transit and 60 days for robotic deployment of surface systems.

TRANSPORTATION SYSTEM REQUIREMENTS

The mission transportation elements that require power are: Transit Habitat (TH), Mars Transfer Vehicle (MTV), Mars Lander (ML), Ascent Vehicle (AS), and Earth Return Vehicle (ERV).

Power requirements for the six person crew Transit Hab for both nominal and "power down" emergency mode are shown in Table 1. The life support system (LSS) is a major constituent of the 30 kWe. The LSS is based on a partially closed air and water system design that performs the following functions: CO_2 reduction; O_2 and N_2 generation; urine processing; and both potable and hygiene water processing. The derated "emergency mode" value is based on the LSS operating in an open loop mode and reductions in non-critical operations. A TH is used for both outbound and inbound flights. However, the outbound TH's are landed on Mars and become part of the Base's living quarters. The Earth return TH is sent on the previous opportunity aboard the ERV and remains in transit and Mars orbit for almost 5 years.

TABLE 1. Nominal and emergency transit habitat power estimates

ESTIMATED MARS TRANSIT HABITAT POWER REQUIREMENTS (kWe)			
ELEMENT	MODE		NOTES:
	NOMINAL	EMERGENCY	
LIFE SUPPORT SYS. (LSS)	12.00	8.00	OPEN LOOP IN EMER. MODE
THERMAL CON. SYS. (TCS)	2.20	2.20	
GALLEY	1.00	0.50	EMERGENCY VALUES:
LOGISTIC MODULE	1.80	1.80	DERATED FROM NOMINAL
AIRLOCK	0.60	0.10	WHERE DEEMED
COMMUNICATIONS	0.50	0.50	APPROPRIATE
PERSONAL QUARTERS	0.40	0.00	
COMMAND CENTER	0.50	0.50	VALUES ADAPTED FROM
HEALTH MAINT. FAC. (HMF)	1.70	0.00	NAS8-37126, "MANNED
DATA MGT SYS	1.90	0.80	MARS SYSTEM STUDY"
AUDIO/VIDEO	0.40	0.10	
LAB	0.70	0.00	
HYGIENE	0.70	0.00	
S/C UTILITY POWER	5.00	5.00	
TOTAL	29.40	19.50	

The spacecraft base power load for vehicle avionics, communications, and the propulsion system is estimated at 5 kWe. This value is also assumed for cargo only vehicles.

The MTV uses a nuclear thermal rocket (NTR) for the trans-Mars injection propulsion only and an aerobrake (A/B) for Mars orbit capture and entry. The baseline power system for the NTR-A/B configured MTV is photovoltaic arrays and regenerative fuel cells for energy storage. Figure 1 shows a power vs. time profile for the Mars transit.

The array is designed to produce the required 30 kWe in Mars orbit (worst case 1.67 AU). The energy storage system is sized to provide power before and after Mars orbit capture during the following maneuvers: attitude control, array retraction, orbit capture, array extension and orbit eclipse, as shown in Figure 1. It is currently assumed that the TH can be safely "powered down" to 20 kWe during these mission phases to save RFC mass and volume. The RFC and array remain with the TH/lander and are utilized on the surface.

Based on the size of the energy storage system, eclipse power and the available power from the array, it will take 7 orbits before the RFC is fully charged. The RFC delivers power when the array is retracted during entry, descent and landing. The RFC can deliver 20 kWe for 24 hours after landing and is the prime power source for the lander/TH and crew. The RFC could also provide power for moving the habitat from the landing site to its final emplacement location, assuming no solar array deployment. The ERV solar array/RFC will become part of the back up power system for the habitats upon final emplacement.

Another option under consideration is the "all NTR" concept, where the propulsion system is also used for the Mars capture and trans-Earth injection maneuvers. The reactor therefore, would be configured to produce power as well as propulsion. Power would be required to maintain LH_2 boil-off to acceptable levels, thus the NTR engine in the power-mode would produce 40 kWe; 30 kWe plus 10 kWe for propellant refrigeration. Only refrigeration power is needed while in Mars orbit, however full TH power would be required for Earth return.

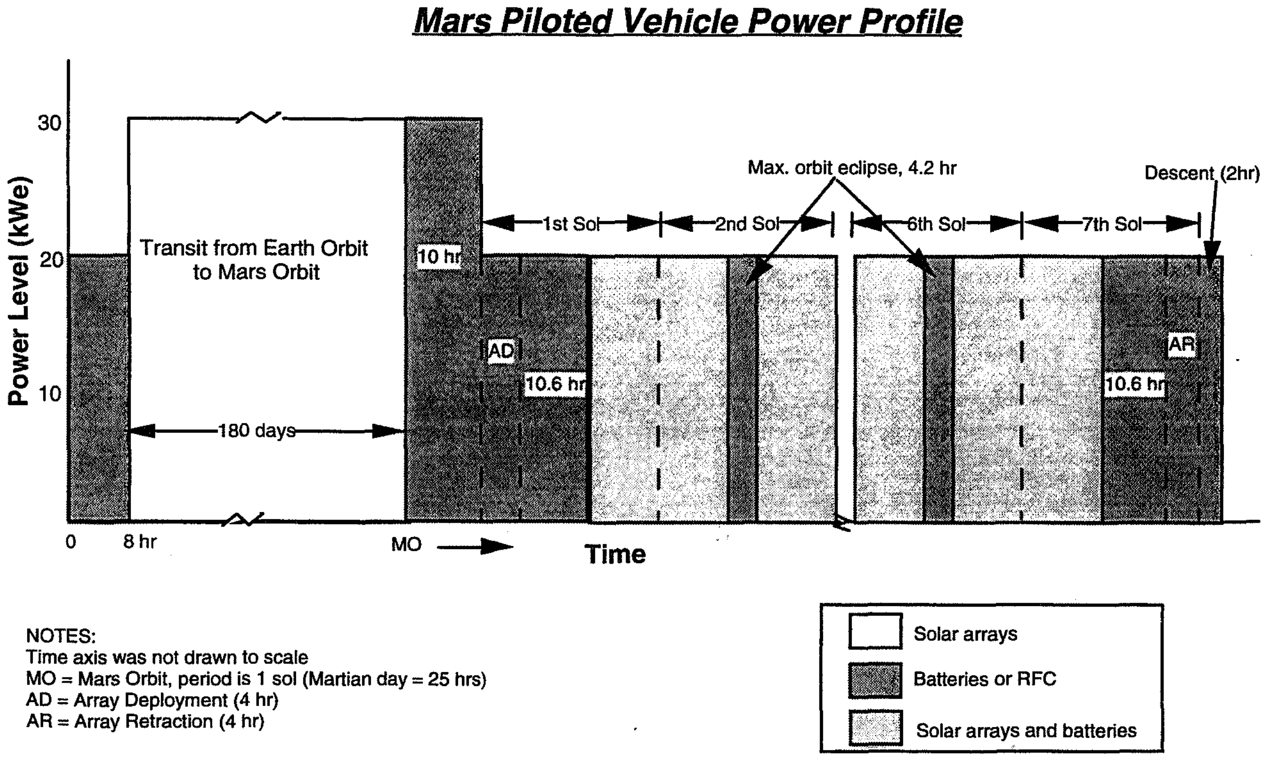

FIG. 1. MTV Power Profile

SURFACE SYSTEMS REQUIREMENTS

Significant design requirements are placed on all the surface equipment delivered on the initial cargo flights. Each system must be deployed to their respective locations and function autonomously for almost two years. These two requirements could greatly impact the design and selection of the power system. Crew safety and well being demands reliability and robustness in all surface elements. Risk is also mitigated by backup and redundant systems or systems that can perform multiple functions.

Habitation, Life Support And Propellant Production And Operations

A particular challenge to the power system and other surface assets is their deployment and set-up on the planet surface. The power system, LSS cache plant and propellant fuel plant must be deployed without direct human intervention. They therefore must be self-deployed or most likely deployed in a supervisory, tele-operated mode from Earth. For example, a command will be given for a "safe" maneuver depending on vision capability and line of sight limitations, then an operator will wait for conformation of the completed task. This sequence could take up to 40 minutes (speed of light delay) plus the actual time to perform the task. This could be a significant design factor the power system.

To best determine the type and design of the power system, an estimated power profile, was determined and is shown in Figure 2.

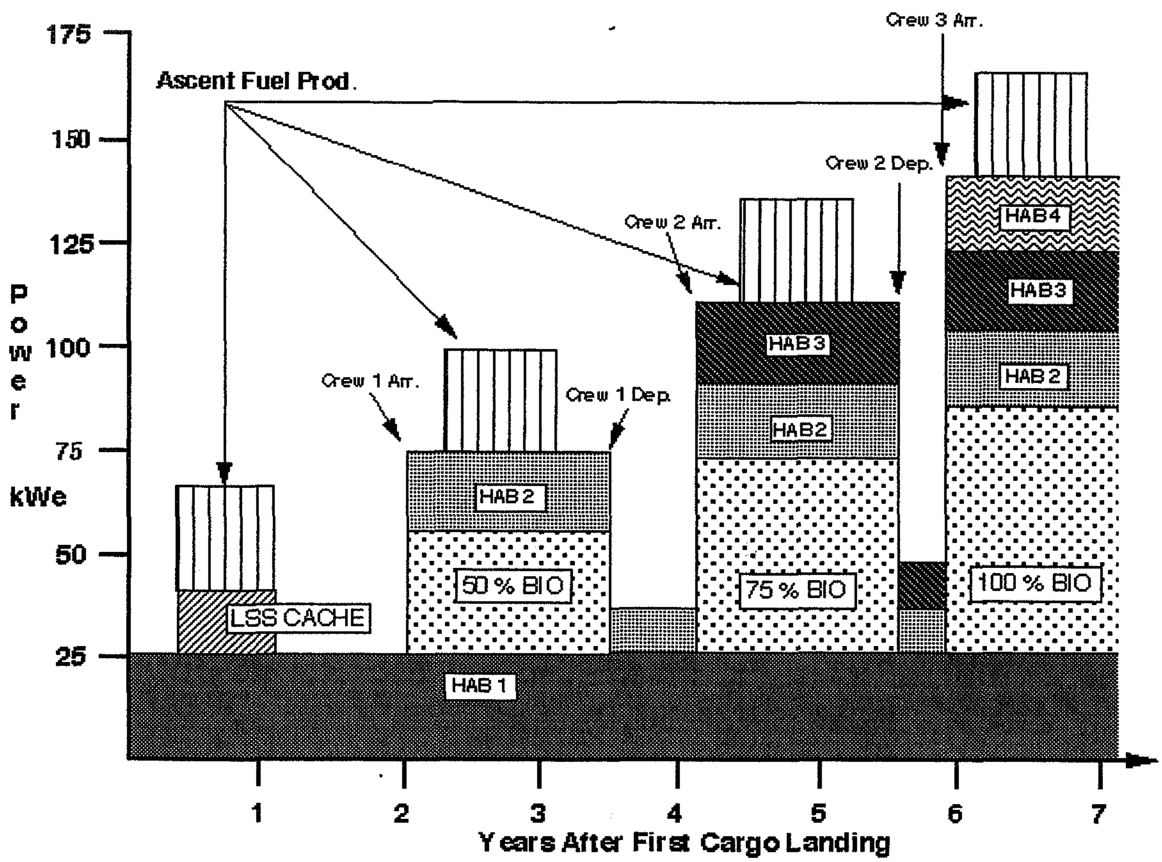

FIG. 2. MARS SURFACE POWER PROFILE

Figure 2 shows the estimated power levels and time sequencing for the various surface elements. The power system must be one of the first elements deployed because it must provide power to produce the life support cache and ascent vehicle propellants, prior to the first crew launch. Approximately 370 days will be available to produce the required cache. However, this will be reduced by the time to deploy the power system. With an estimated power system deployment time of 30-60 days, about 320 days remain for producing these products. The initial 60 kWe power level was determined by the required energy and production time. Power levels approach 160 kWe as the outpost reaches full maturity of increased habitation volumes and life support capability.

Two types of power systems were evaluated to meet the evolutionary power requirements of the base; nuclear and solar. Table 2 shows estimated mass, volume and area. A brief description of each system follows.

The nuclear power system is configured for remote deployment and is integrated with a mobile platform. The entire system is tele-deployed from the landing site (trailing distribution cables) to a site about 2 km from the base. No assembly is required, however, deployment of the radiator panels, either self-deployed or with the aide of a rover arm, is necessary. It is planned to utilize the pressurized rover (or its power cart) for this task. Power from the rover will be used for startup heating (eliminating batteries) and obtain operating conditions. The nuclear power system will be capable of delivering the full base needs of 160 kWe. A second system is delivered and deployed to satisfy the fail-ops mission requirement, but will not be turned on unless required. The mass of this system is higher than technically achievable because of the low temperature design parameter selected for Mars surface application.

TABLE 2. Surface power system options characteristics

MAIN POWER SYSTEM	TYPE	MASS (MT)	VOLUME (m^3)	AREA (m^2)
160 kWe	NUCLEAR- SP-100 type, low-temp, stainless steel, dynamic conversion, 4-Pi shielding	14	42	321 radiator area
120 kWe	SOLAR- tracking, O.D. = 0.4	19.6	341	6,400 array area 45,000 field area
	SOLAR- non-tracking, O.D. = 0.4	33.5	686	13,000 array area 39,000 field area
BACKUP (40 KWe)	SOLAR- tracking, O.D. = 6.0	14	390	7,600 array area 53,000 field area
	SOLAR- non-tracking, O.D. = 6.0	26	816	16,000 array area 48,000 field area
EMERGENCY	USE PRESSURIZED ROVER POWER SYSTEM (SEE TABLE 3)			

A solar power system requires array panels to supply the main base load and recharge the energy storage for nighttime operations(2). The system was sized to produce required power at winter diurnal cycles, at the equator. The backup habitat power system was designed to operate at "worst case" global dust storm conditions, or an optical depth (O.D.) equal to 6.0, since these conditions could be present at the Base when an emergency power situation arose. The ISRU plant was not considered a life critical function and therefore designed to produce full power at an optical depth of 0.4 or a "clear Mars sky." Both sun tracking and non-tracking arrays were evaluated. The sun tracking array total land area is greater that the non-tracking because of the required panel spacing needed to eliminate shadows from one panel upon the other.

Optical depth, or the intensity of the Sun reaching the surface of Mars, has a significant impact on system size and mass. For example, if the entire 160 kWe were solar generated, the array field would encompass about 11(O.D. =.4) to 40 (O.D. =6.0) football fields. In addition, the the need for prompt telerobotic emplacement of the array panels and interconnectiong cables would present a significant challenge. Dust erosion, accumulation and wind stresses on the array panels raise power system lifetime issues. However, use of the "in-space" array and fuel cell power system is anticipated for the habitat emergency/backup power systems, which could be stowed until needed.

The power management, transmission and distribution masses (@ 95% eff.)have been included in each of the system sizing estimates. Transmission cable masses were calculated using 500 V due to the Paschen breakdown limit associated with Mars' atmospheric pressure.

Surface Mobility

Another application needing power is rovers. Three types of rovers have been identified, long-range pressurized, local unpressurized and long range robotic. Several options, including regenerative fuel cells, combustion engines and isotope for powering these rovers were evaluated.

Requirements for the long-range pressurized rover are as follows: a crew of 2-3, 500 km range, 5 days out-10 days at site-5 days back. Power estimates for this rover is 10 kWe.

TABLE 3. Rover Power System Characteristics

Power System	Mass (MT)	Volume (m^3)	Area (m^2)	Mass (MT)	Volume (m^3)	Area (m^2)
	Regional Rover			Local Rover		
Dynamic isotope	1.1	10	33	0.5	4	16
Photovoltaic/RFC	2.8	66 (RFC-4) (PV-62)	1,275	recharge by refueling		
Primary Fuel Cell	6.5	29	13	.160	1	6
Methane ICE	12	36	n/a	.160	0.4	n/a

It is anticipated that the pressurized, regional rover or its power system would be used to assist in the deployment of the main power system, situate future habitat modules, and serve as back-up, emergency power when required. It is desirable that the rover power system be mounted on its own cart. This would add considerable versitility to its use when the rover is not on a sortie. Table 3 shows the estimated mass, volume and array or radiator area for the four power system options listed.

The dynamic isotope power system (DIPS) was chosen for its low mass and significantly lower radiator size compared to the photovoltaic array area. The ^{238}PU isotope has a half life of 88 years and can be the same design as the flight proven RTG. However, the quantity and cost are issues to be addressed and could be justifiable for a sustained base occupancy. The isotope fuel would be reloadable into other power units in the event of a failure, thus preserving its utility for subsequent missions. Another feature of isotope fuel is that it does not need to be recharged and is always ready as a back-up, emergency power source independant of solar availability or atmospheric conditions. For example, this flexibility is utilized in providing power for the positioning of each crewed transit habitats from their landing sites to the main habitation locale. The small amounts of radiation emited (primarily alpha and gamma rays) by ^{238}PU is mitigated by a small heat source end cap shield and distance ($1/d^2$ attenuation) to the crew.

Methane is a possible fuel for the rover since the propellant plant could produce additional fuels, given extra hydrogen is brought from Earth. Methane could be used in an appropriately designed fuel cell. The reactant water would be returned and fed through an electrolizer to capture the hydrogen. However, once you have electrolized the water into H_2 and O_2, which the fuel cell acually uses to operate, it is not prudent from an energy utilization standpoint to make methane again. Although the issue of storing and maintaining reactants on the rover would need further study. A methane burning engine could be used to operate the rover, however, combustion materials would need to be collected to reclaim the H_2.

The photovoltaic/RFC power option seems impractical for the regional rover due to the large array area. The arrays were sized to provide required power output during a local dust storm, anticipating suspended operations during the global dust storm season.

The local rover is unpressurized like the Apollo LRV. It would function to transport the crew 10's of kilometers, 3 hours out and back, and 4 hours at the site. The primary fuel cell would meet the local rover rquirements at less mass than other options. The power system design characteristics assumes refueling after every sortie.

SUMMARY

A power system strategy was adopted that satisfied mission requirements for power availability and reliability by utilizing several different technologies and functional redundancy of several elements. The power system selected for surface operations is a SP-100 type reactor system capable of producing 160 kWe. This option was selected based on its high power capability at reduced mass and volume, less deployment issues and its insensitivity to changes in operating environment, i.e., latitude, atmospheric sunlight attenuation, seasonal variation of day/night ratio. The selection of nuclear power for this mission is a major concern due to its historic socio-political nature. In addition, DOE's SP-100 and other space nuclear power programs have been terminated.

Back-up, emergency power is provided by the MTV photovoltaic/RFC power system. This is the same system used in Mars transit and provides power during descent. taken to and the isotope power system of the regional rover. This strategy maximizes power availability with the least amount of hardware through functionally redundant componets.

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IN-SITU RESOURCE UTILIZATION (ISRU) DEVELOPMENT PROGRAM

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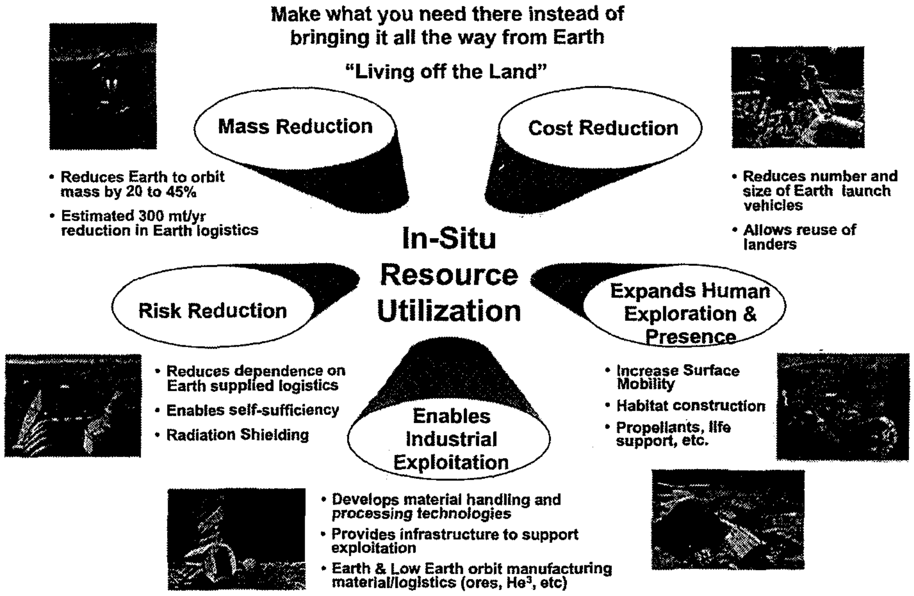
Why In-Situ Resource Utilization (ISRU)?



Resources and ISRU Products

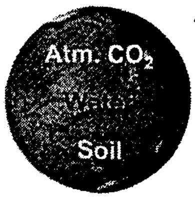
Regolith
- Oxygen (45%)
- Silicon (21%)
- Aluminum (13%)
- Calcium (10%)
- Iron (6%)
- Magnesium (4%)
- Other (1%)

Water
- 0.5 to 1% at poles?

Solar Wind
- Hydrogen (50 - 100 ppm)
- Helium (3 - 50 ppm)
- He^3 (4 - 20 ppb)

Soil*
- Silicon Dioxide (43.5%)
- Iron Oxide (18.2%)
- Sulfur Trioxide (7.3%)
- Aluminum Oxide (7.3%)
- Magnesium Oxide (6.0%)
- Calcium Oxide (5.8%)
- Other (11.9)
- Water (?)

*Based on Viking Data



Atmosphere
- Carbon Dioxide (95.5%)
- Nitrogen (2.7%)
- Argon (1.6%)
- Oxygen (0.1%)
- Water (parts per million)

Lunar Resources & Products

- Lunar regolith contains 45% oxygen by mass that can be used for propulsion , power generation, and crew breathing
- Lunar soil could be used for crew radiation protection
- H_2 and He (including He^3) from the solar wind are available at very low concentrations (parts per million) for fuel production and fusion reactors on Earth
- Aluminum, iron, and magnesium can be used in construction
- Silicon can be used to produce solar cells for power generation
- Ice in the lunar regolit can be used for life support or to make propellants for propulsion and power generation

Mars Resources & Products

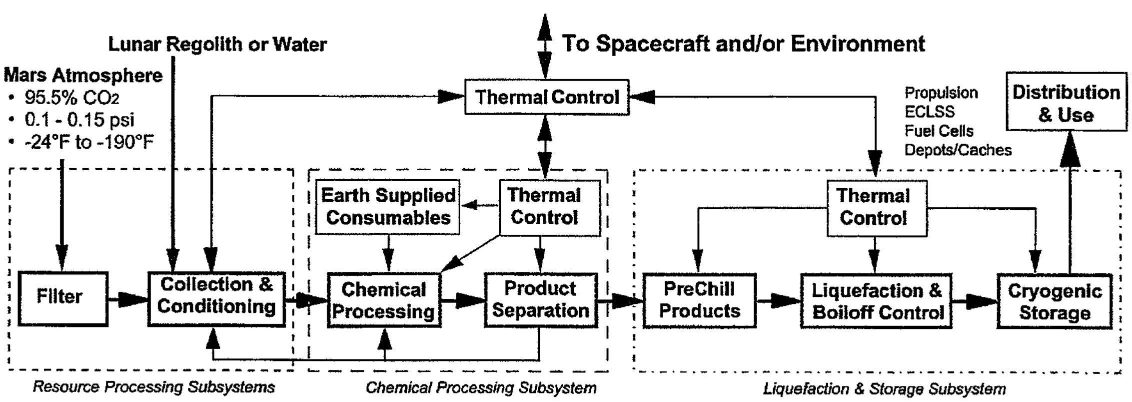
- The atmosphere contains >95% carbon dioxide that can be used to make oxygen and fuels
- Atmospheric nitrogen (N_2) and argon (Ar) can be used for life support, experiment carrier gases, inflating structures, purging dust from hardware, etc.
- Water in the atmosphere and in the soil (if available) could be extracted for use in life support, propulsion, and power generation
- Further information is required to determine how best to extract and use Mars soil based resources, especially water content

ISRU Term Definitions

- **In-Situ Resource Utilization (ISRU)**
  - Covers all aspects of using or processing local resources for the benefit of robotic and or human exploration. Examples:
    - > Using dirt/regolith for radiation shielding
    - > Making structures/habitats and solar cells from processed resources
    - > Making propellants or other consumables
- **In-Situ Consumables Production (ISCP)**
  - Is a subset of ISRU that covers all aspects of producing consumables from local resources
  - Consumable products/needs include:
    - > Propellant for ascent, hoppers, or Earth return
    - > Reagents for fuel cells
    - > O_2, H_2O, and N_2 for Environmental Control & Life Support System (ECLSS) backup
    - > Gases for purging or inflating habitats/structures
    - > Heat for spacecraft/habitat thermal control
- **In-Situ Propellant Production (ISPP)**
  - Is a subset of ISCP that covers all aspects of producing propellants from local resources for the benefit of robotic and or human exploration
  - ISPP requires the least amount of infrastructure to support and provides immediate benefits to mission plans

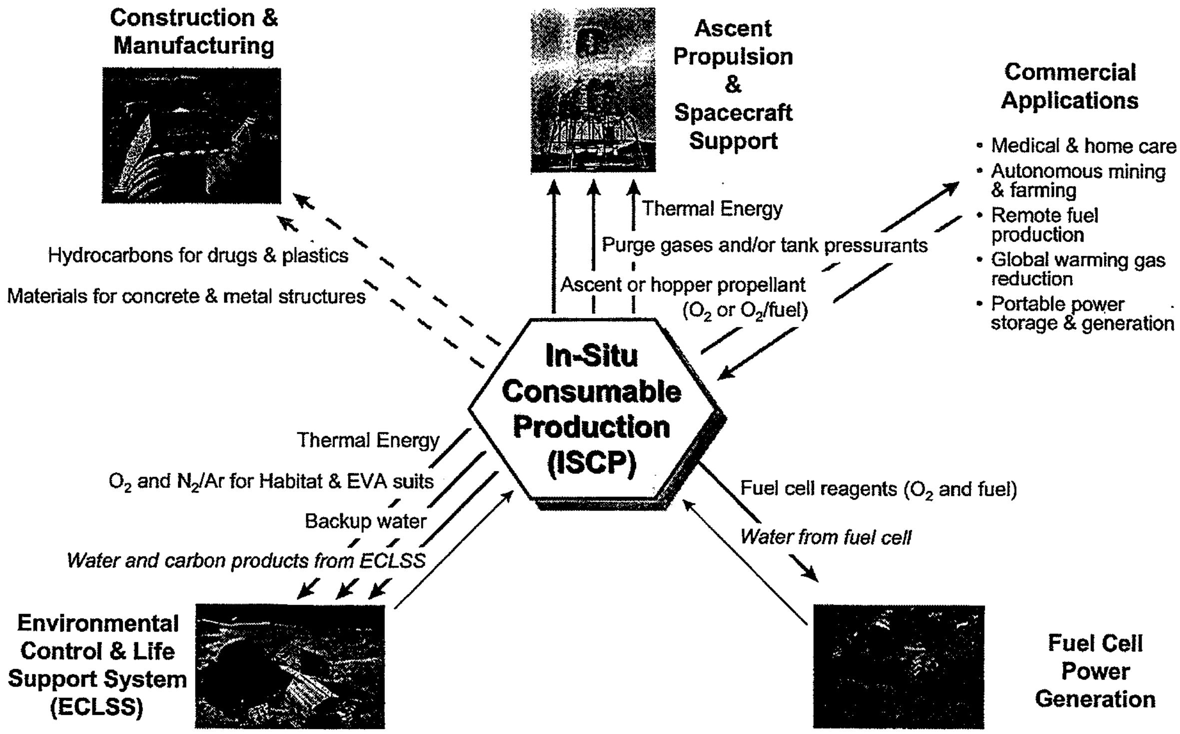
Note: Most work performed to date is specific to ISPP at this time

ISCP Process Diagram



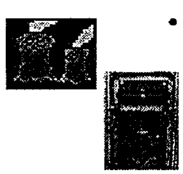
- *Resource Processing Subsystems*: Collects and prepares in-situ resources for use in process subsystem
  - Filtration, and collection & conditioning using adsorption beds or compressors for gas resources
  - Shoveling, mining, sorting, sifting, and grinding for solid resources
- *Chemical Processing Subsystems*: One or more chemical reactions and reactant/product separations to change the collected resource into usable products.
  - The Chemical Processing Subsystem defines the ISCP products, Earth consumable needs, and the system complexity and power characteristics for the ISCP plant
- *Liquefaction & Storage Subsystems*: Many in-situ products are gases. To efficiently store large quantities of these in-situ products, liquefaction and storage as a cryogenic liquid is required

Possible Consumable Interaction



ISCP Development Challenges

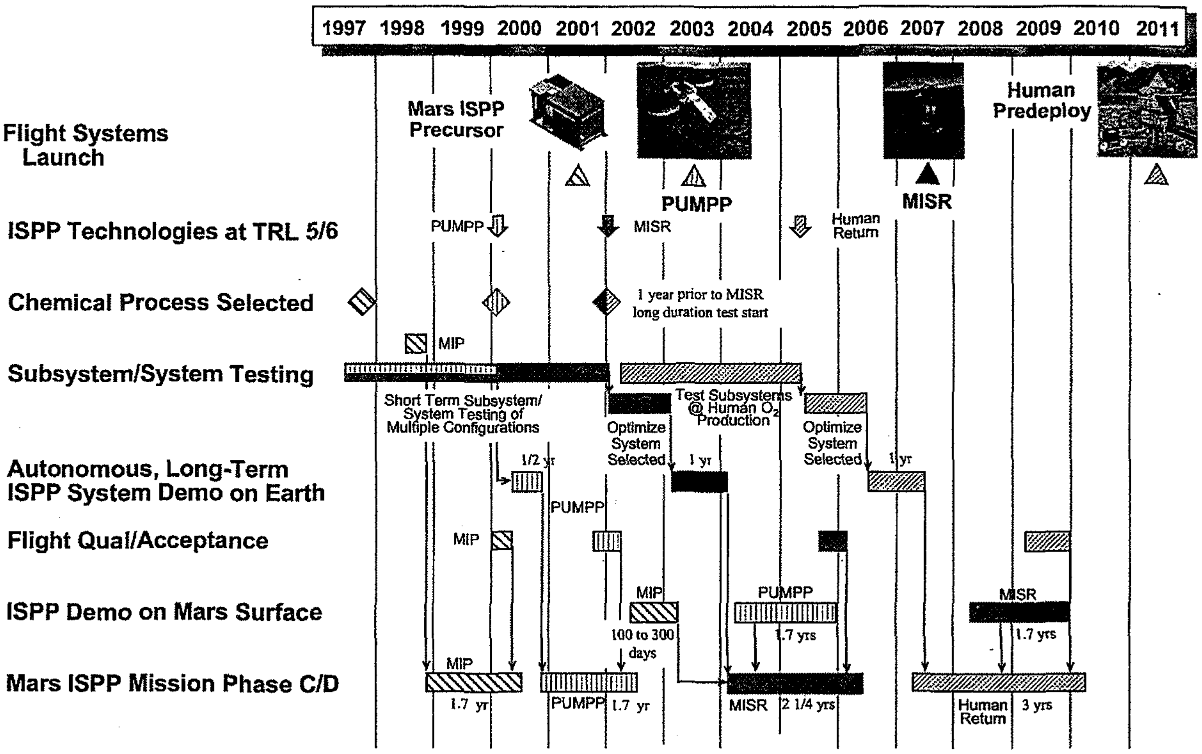
- **Chemical Process Development**
  - Chemica/separationl conversion efficiency
    - > Earth supplied consumable limitations
  - Thermal integration and management
  - Complexity
- **Operational Environment/Surviviability**
  - Autonomous control & failure recovery
    - > No crew for maintanance
    - > Non-continuous monitoring
  - Environmental compatibility [dust, temperature]
  - Long-life operation [months to years]



- **Support System Development**
  - Power
    - > Advanced solar cells or RTG's for robotic
    - > Nuclear power for human
  - Product liquefaction and cryogenic storage [months to years]
    - > Earth supplied Hydrogen

- **Cost**
  - Technology/system synergism between Moon and Mars
  - Technology/system synergism with other systems [ECLSS, fuel cells]
  - Commercial viability of technology

Top-Level Mars ISPP Development Plan

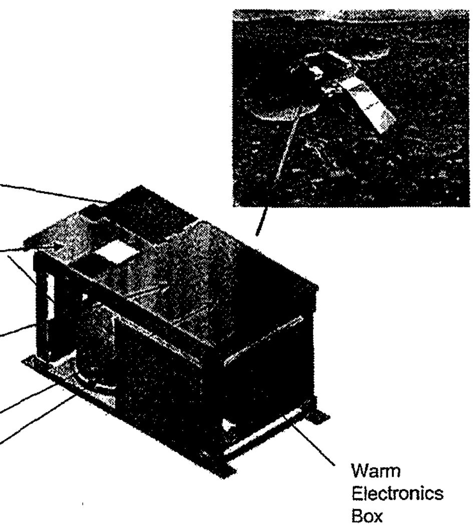


Mars ISPP Precursor (MIP) Flight Experiment

MIP will incorporate five experiments from three NASA institutions; Johnson Space Center (JSC), Lewis Research Center (LeRC), and the Jet Propulsion Laboratory (JPL). JSC is also reponsible for integrating the experiments into the MIP flight demonstration unit

The five MIP experiments are:

- **MAAC - Mars Atmosphere Acquisition and Compression (JPL)** Demonstrate the ability to collect and compress Mars atmospheric carbon dioxde
- **MTERC - Mars Thermal Environment and Radiator Characterization (JPL)** Provide data to determine the effective sky temperature and the long term effect of the Mars environment on radiator performance
- **MATE - Mars solar Array Technology Experiment (LeRC)** Characterize advanced solar cell performance and obtain data on Mars surface environments that can impact future solar cell designs
- **DART - Dust Accumulation and Repulsion Test (LeRC)** Demonstrate techniques to mitigate dust accumulation on solar cells (tilting and electrostatic repulsion) and characterize dust properties and deposition rates
- **OGS - Oxygen Generator Subsystem (JSC)** Demonstrate the production of oxygen from Mars atmospheric gases in the Mars environment



MIP Design Characteristics

- **Mission Design Life = 300 Mars days (sols)**
- **Mass = 7.5 kg**
- **Dimensions = 40 cm L x 24 cm W x 25cm H**
- **Average Power; Day = 15 Watts*, Night = 3 Watts**

* When producing oxygen; 9 Watts average without oxygen production

Mars ISCP Technology Development Coordination

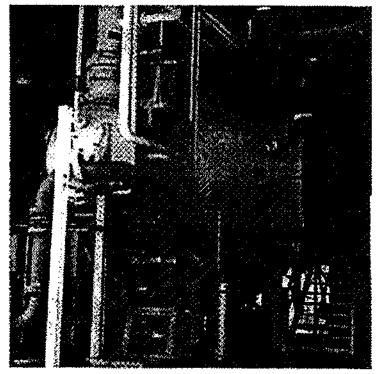
	Gov't/Industry	SBIR/ACRP	Univ.Partners & Grants
Resource Collection & Conditioning	• MIP CO_2 adsorption pump experiment (JPL) • MISR scale CO_2 adsorption pump (LMA/JPL) • Low-power CO_2 adsorption pump (ARC)	• Φ I water vapor adsorption pump (Adroit Sys)	• GSRP - water vapor adworption material (Univ. of Washington/JSC/JPL)
Chemical Processing	Sabatier/Water Electrolysis (SWE) • SWE breadboard (LMA/JSC) • Methane conversion (JPL) • CO tolerant H_2 separation (JPL) • Methane pyrolysis (HS/LMA) Zirconia CO_2 Electrolysis (ZCE) • ZCE cell stack (AS/JPL) • Methanol/HC production breadbaord (JSC) Support Hardware • COT sensor, separator, and pump evaluation (JSC) • Autonomous control & failure recovery (JSC/ARC/KSC)	Zirconia CO_2 Electrolysis (ZCE) • Φ II - O_2 extraction/separation (Nanomaterials Research) • Φ I - O_2 generation from Mars CO_2 (NexTech Materials) Reverse Water Gas Shift (RWGS) • ACRP - RWGS & ethylene breadboard (Boulder Center Science & Policy) • Φ II - RWGS & methanol breadboard (Pioneering Astronautics) • Φ I - Hydrocarbon fuel reactors (Pioneering Astronautics)	Zirconia CO_2 Electrolysis (ZCE) • Radio Frequency CO_2 dissociation (Old Dominion/JSC) • ZCE cell stack development (Univ. of Arizona/HS/JSC)
Product Liquefaction & Storage	NASA Cryogenic Working Group • Pulse-tube cryocooler (NIST/JSC) • Cryogenic storage architecture (JSC)	• Φ I - Pulse tube cryocooler (Mesoscopic Devices)	• H_2 transport to Mars study (Utah State Univ/JSC/JPL)

Mars ISRU System Technology (MIST) Objectives

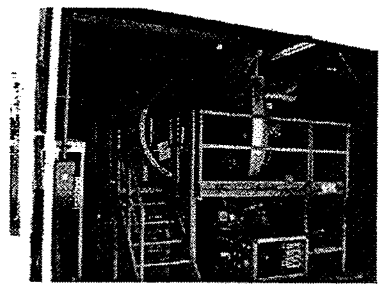
- Characterize technology and subsystem performance for mission modeling and technology funding planning
  - Advance multiple ISRU process options to same TRL for design flexibility
  - Verify performance/benefits/risks associated with different process options
- Raise individual subsystem/component TRL by:
  - Providing low-cost testing for industry/university partnerships
  - Funding key technology development efforts
  - Work w/ industry, universities, and other government organizations to focus ISRU development and testing
- Reduce risk/concerns for sample return and human missions utilizing ISRU
  - Development and demonstration of autonomous control and failure recovery hardware, operations, and logic
  - System level testing to understand subsystem interaction
  - System level testing to optimize processes
  - Long term testing to verify component/system operation robustness
- Demonstrate environmental suitability of ISRU components/processes/systems
  - Mars pressure, temperature, and atmospheric composition
  - Continuous versus day/night production cycles
  - Loads & vibration
  - Life cycles and contamination sensitivity

MIST Facility Overview

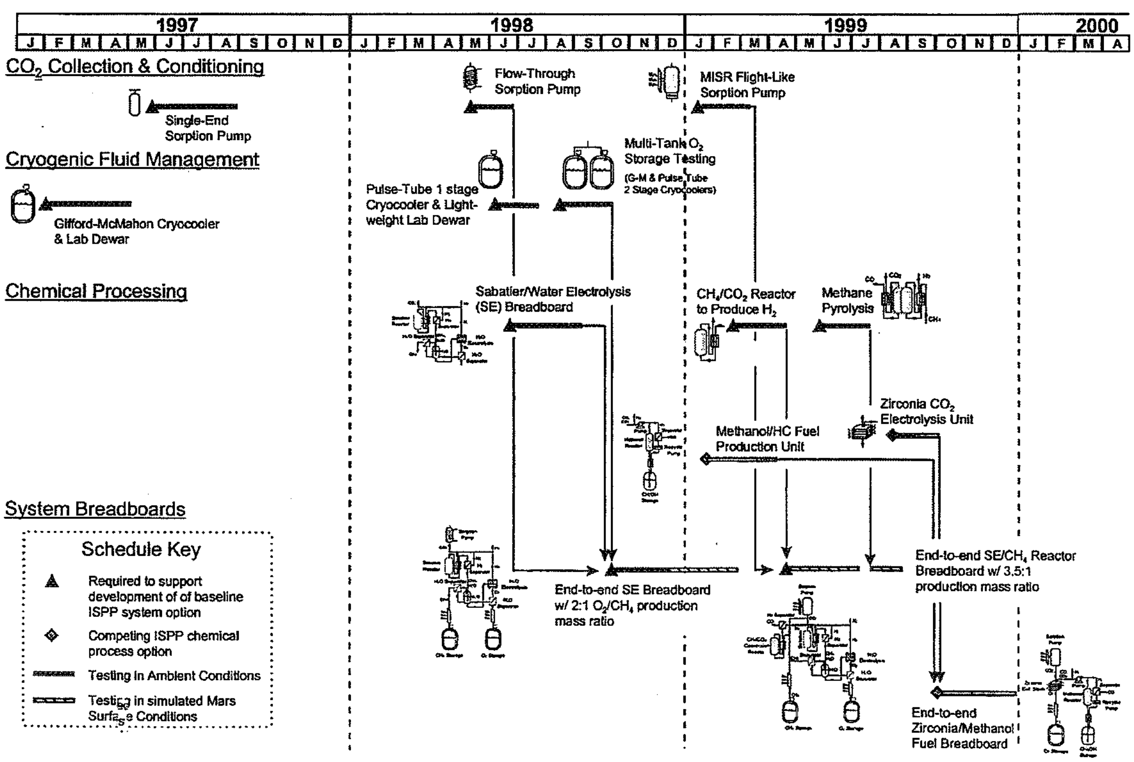
- Building 353
  - Ambient test cells for subsystem and system testing
  - 20 ft dia chamber for Full Mars environment testing
    - > Atmosphere (CO_2, N_2, or Mars mixture), pressure, & temperature
    - > Designed for hazardous operation testing (explosion and fire hazards)
    - > Solar flux & dust conditions
  - Office area for hardware providers while at JSC



- Building 356
  - 5 ft dia. chamber for Partial Mars environment testing
    - > Atmosphere, pressure, & temperature
      - » -300 to +300F
      - » Vacuum to 10^{-6} torr
      - » Atmosphere at 6.5 torr & 100% CO_2 or N_2, or Mars mixture
    - > Night sky temperature simulation
  - Facility will be used for Mars ISPP Precursor development, qualification, and flight unit testing



Stage 1 Proof-of-Concept Demonstration Schedule



ANALYTICAL CAPABILITIES AND FINDING LIFE ON MARS

Carl C. Allen
Lockheed Martin

- What will we do?
- Where will we do it?

Petrography
Optical and Electron Microanalysis

- Solidification
- Alteration
- Shock

Crystal Structure
X-ray diffraction
Electron diffraction

- Mineral identification
- Alteration
- Shock

Chemical Compositions
Neutron activation
Beam microanalysis
Mass spectrometry

- Rock/mineral compositions
- Alteration
- Trapped volatiles
- Crystallization T, P, fO_2
- Alteration T, P, fO_2

Controlled Melting Experiments

- Crystallation T, P, fO_2

Isotope Dating

- Crystallization ages
- Shock ages

Stable Isotope Studies

- Parent body
- Temperature, chemistry of alteration
- Atmospheric history

Paleomagnetism

- Constraints on core
- Temperature limits on alteration

Microscopy
Optical
Electron
Atomic force

- Cells
- Microfossils
- Biominerals
- Biofilms

Mass Spectrometry

- Detection, identification and location of organic molecules

Isotope Fractionation
Carbon
Oxygen
Sulfur

❖ Indications of life

Biochemical Analysis
DNA/RNA
Amino acids
Cell wall components
Amphiphiles

❖ Life detection
❖ Life identification
❖ Terrestrial contamination

Reproduction and Growth

❖ Life detection
❖ Life identification
❖ Terrestrial contamination

Challenge Studies
Cells
Organisms
Microcosms

❖ Life detection
❖ Life identification
❖ Biohazards
❖ Terrestrial contamination

Mars

❖ Establish geological context
❖ Collect documented samples
❖ Conduct first level analysis
❖ Select samples for return to Earth

Earth

❖ Screen samples for hazard
❖ Conduct highest quality analysis
❖ Document sample histories
❖ Preserve samples for future studies

And much more . . . . .

TRANSPORTATION: DESTINATION MARS

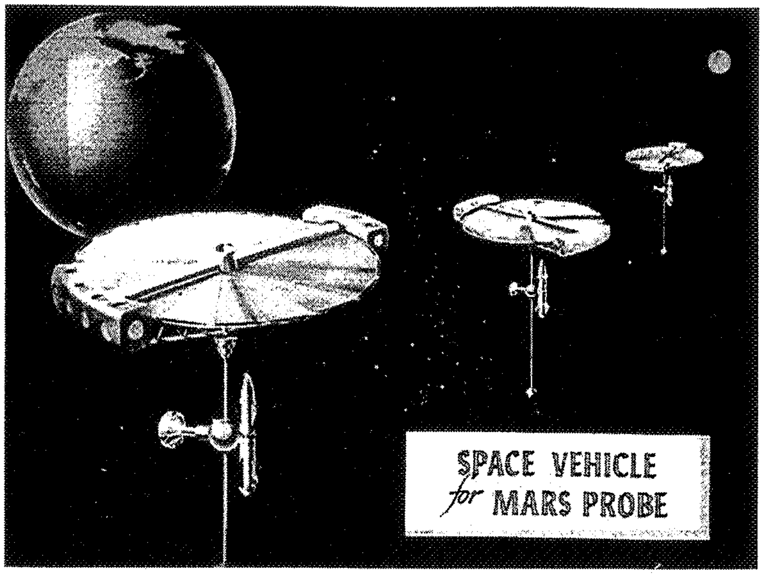
Bill Eoff
NASA Marshall Space Flight Center
Exploration Transportation Office

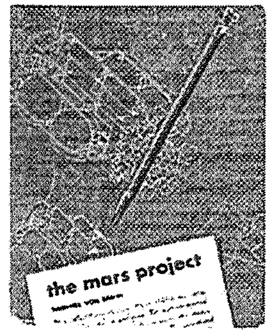
As the agency space transportation lead center, Marshall Space Flight Center has been conducting transportation assessments for future robotic and human Mars missions to identify critical technologies. Five human Mars options are currently under assessment with each option including all transportation requirements from Earth to Mars and return. The primary difference for each option is the propulsion source from Earth to Mars. In case any of the options require heavy launch capability that is not currently projected as available, an in-house study has been initiated to determine the most cost effective means of providing such launch capability. This assessment is only considering launch architectures that support the overall human Mars mission cost goal of $25B. The guidelines for the launch capability study included delivery of 80 metric ton (176 KLB) payloads, 25 feet diameter x 92 feet long, to 220 nmi orbits at 28.5 degrees. The launch vehicle concept of the study was designated "Magnum" to differentiate from prior heavy launch vehicle assessments. This assessment along with the assessment of options for all transportation phases of a Mars mission are on-going.

The Marshall Exploration Transportation Office (RA50), under Mr. Bill Eoff, is responsible for managing the Mars Transportation Study (MTS) in response to the Integrated Mars Mission Study co-chaired by Mr. Doug Cooke, Johnson Space Center and Mr. Norm Haynes, Jet Propulsion Laboratory. Ames Research Center, Kennedy Space Center, Langley Research Center, Lewis Research Center and Stennis Space Center also participant in the study.

Acronyms

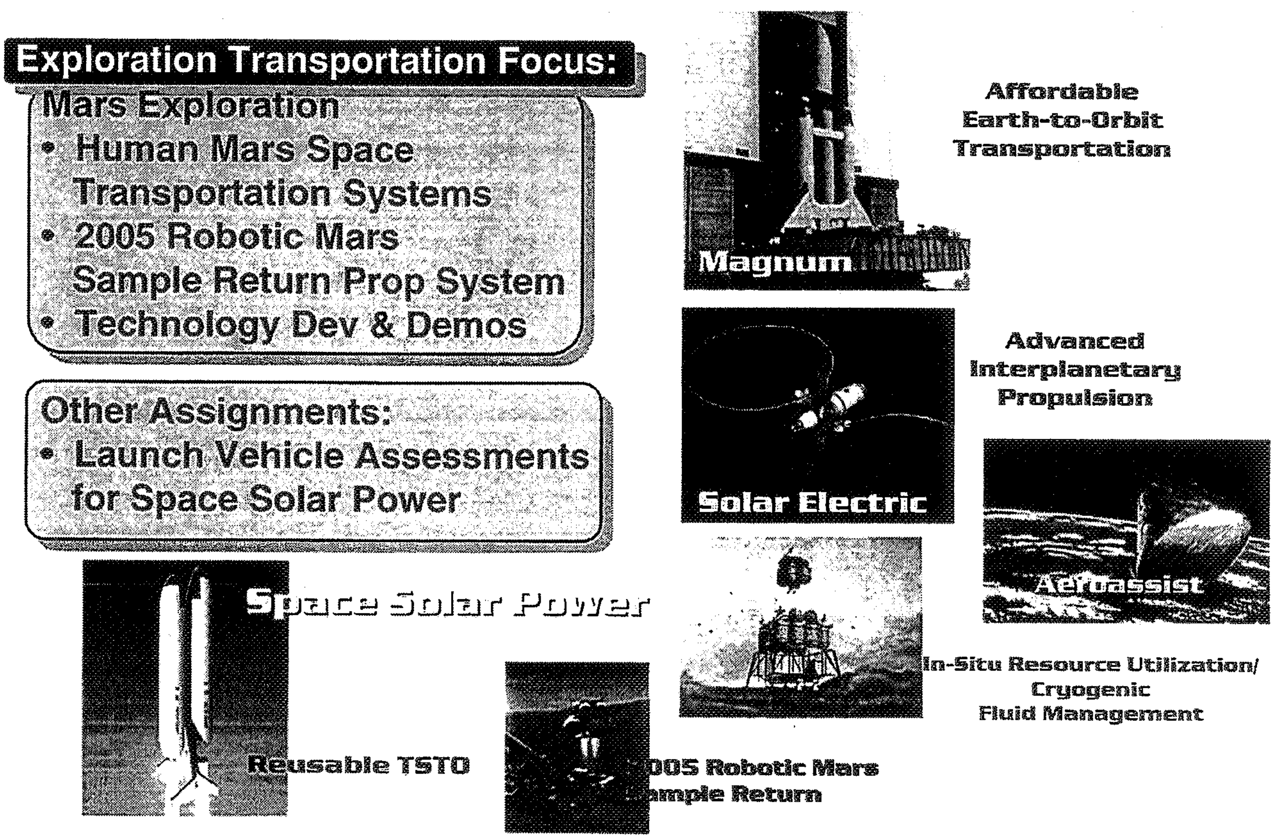
AGS	Advanced Grid Stiffened (Composite) Shroud
AR&C	Automatic Rendezvous & Capture
ASTP	Advanced Space Transportation Program
DDT&E	Design, Development, Test & Evaluation
DRM	(Human Mars) Design Reference Mission
EELV	(USAF) Evolved Expendable Launch Vehicle
ETO	Exploration Transportation Office
ETO	Earth to Orbit
ETP	Exploration Transportation Program
HEELV	(TRW) Highly Evolved Expendable Launch Vehicle
HLV	Heavy Lift Vehicle
HMM	Human Mars Mission
IMLEO	Initial Mass to Low Earth Orbit
ISPP	In-Situ Propellant Production
LCE	(TRW) Low Cost Engine
LFBB	(Shuttle) Liquid Fly Back Boosters
MLV	Magnum Launch Vehicle
MT	Metric Tons
RLV	Reusable Launch Vehicle
SDV	Shuttle Derived Vehicle
SPS	Solar Power Satellite
SSP	Space Solar Power Program
STP	Space Transportation Programs
TBCC	Turbine Based Combined Cycle
TMI	Trans-Mars Insertion
TSTO	Two Stage To Orbit



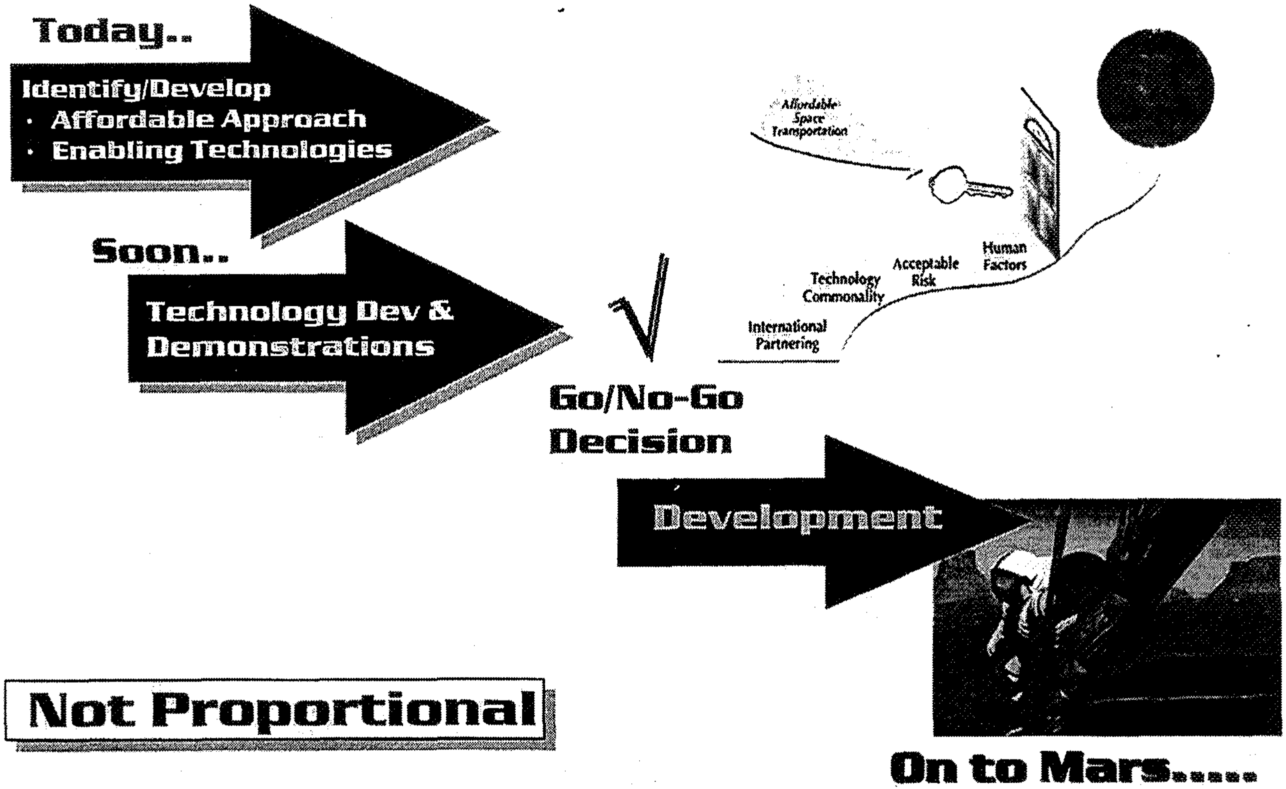


Von Braun proposed a human Mars mission in his 1953 book, the "Mars Project," with ten ships, a crew of seventy and 5.3 million metric tons of fuel.

Exploration Transportation

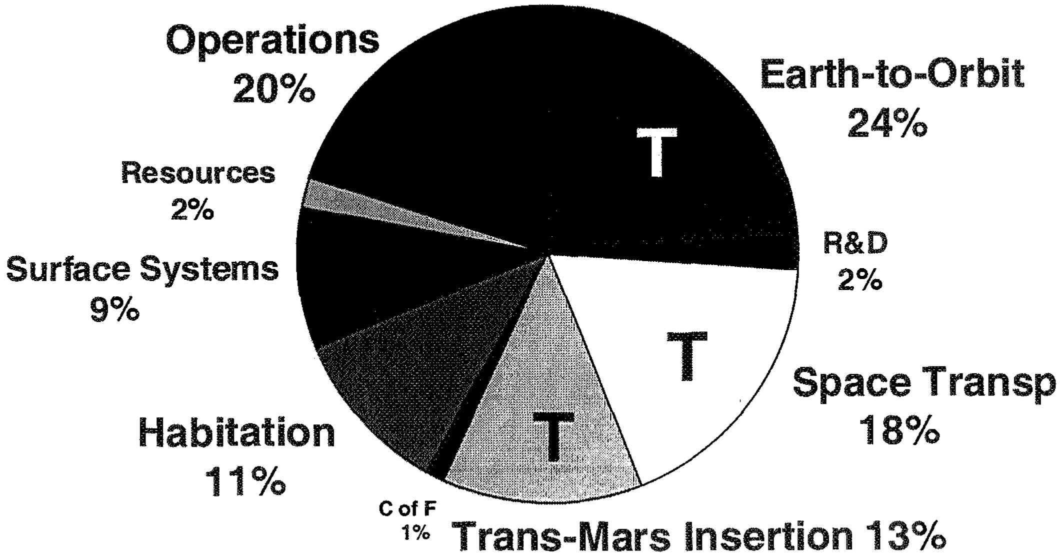


Exploration Transportation



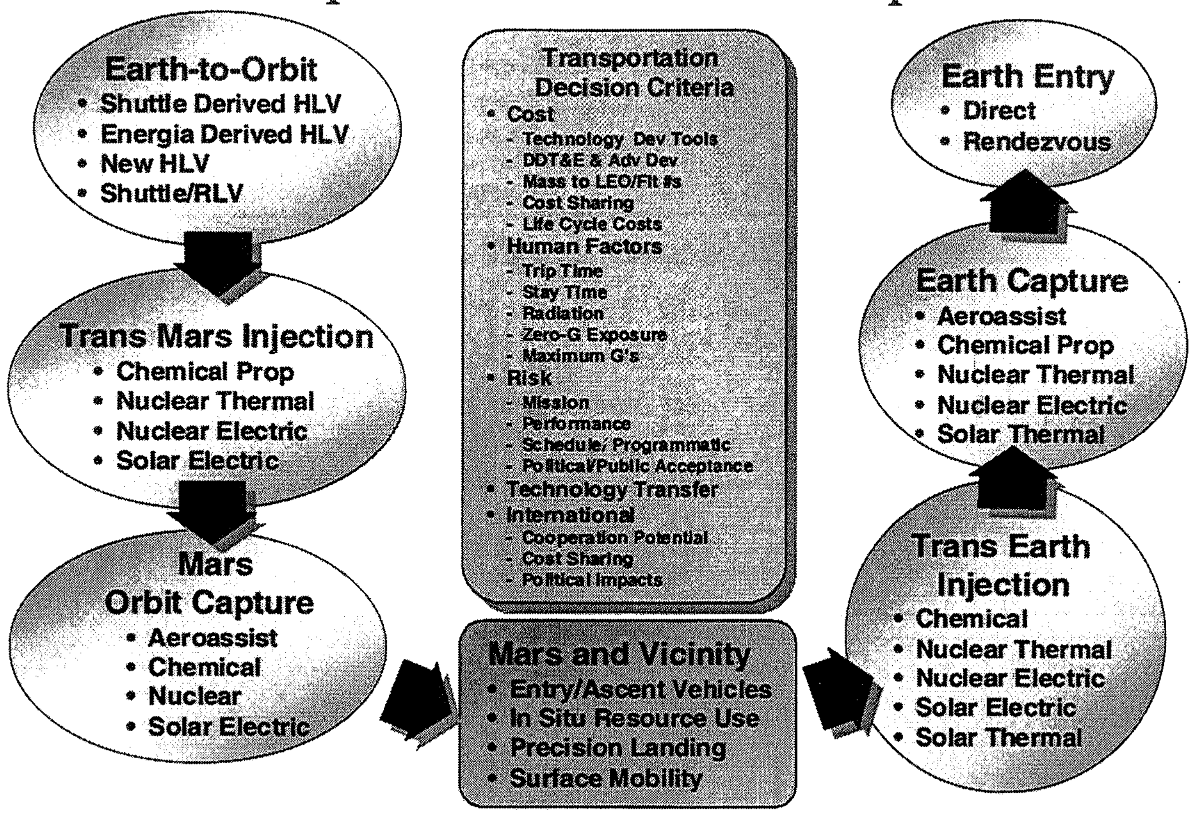
Why Invest in Transportation Technologies?

- Transportation Historically Accounts for >50% Of Exploration Mission Costs.
- Space Transportation Costs Must Be Reduced to Make Exploration Affordable.
- Transportation Technology Investments Are Required to Reduce Costs.



Human Mars Exploration Costs- DRM

Human Mars Mission
Transportation Architecture Options

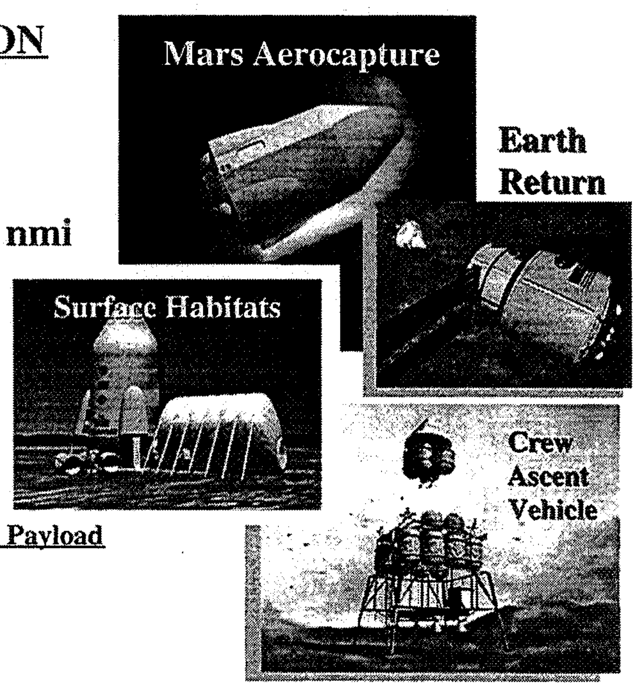


Human Mars Payload Requirements

DESIGN REFERENCE MISSION

- P/L Diameter: 7.5 m/ 24.8 ft
- P/L Length: 27.7 m/ 91.4 ft
- P/L weight: 80 MT/ 176 Klb
- Assembly Orbit: 407 km/ 220 nmi 28.5 degrees
- Launch Rate: 6/ year

HMM ETO Costs Driven by:
- Mass Required in Earth Orbit
- Launch Costs



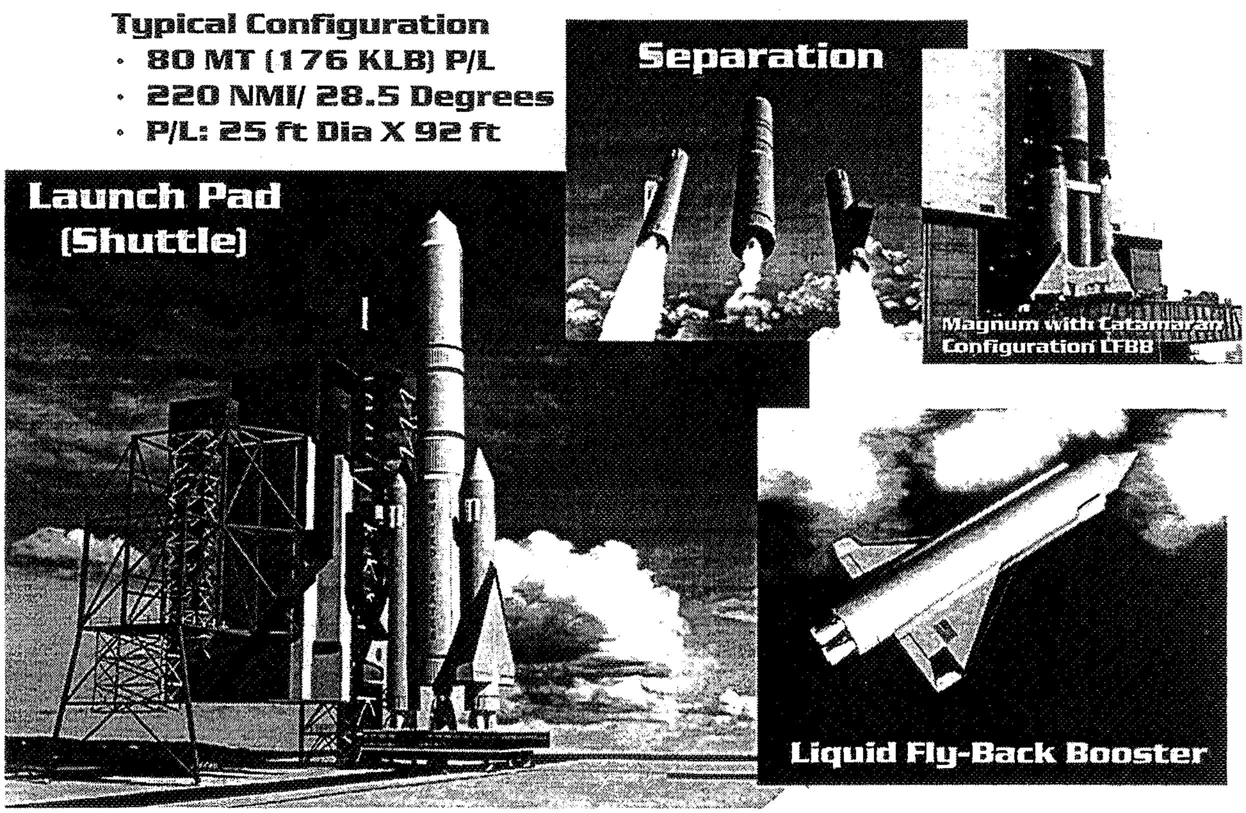
IMLEO (Initial Mass to LEO)		Launch Vehicle Payload
89' 90-Day Study	850 MT	250 MT
93'/94' DRM	850 MT	217 MT
96' DRM	660 MT	100 MT
97' DRM	431 MT	80 MT

200-300 MT → **Affordable Launch Costs**

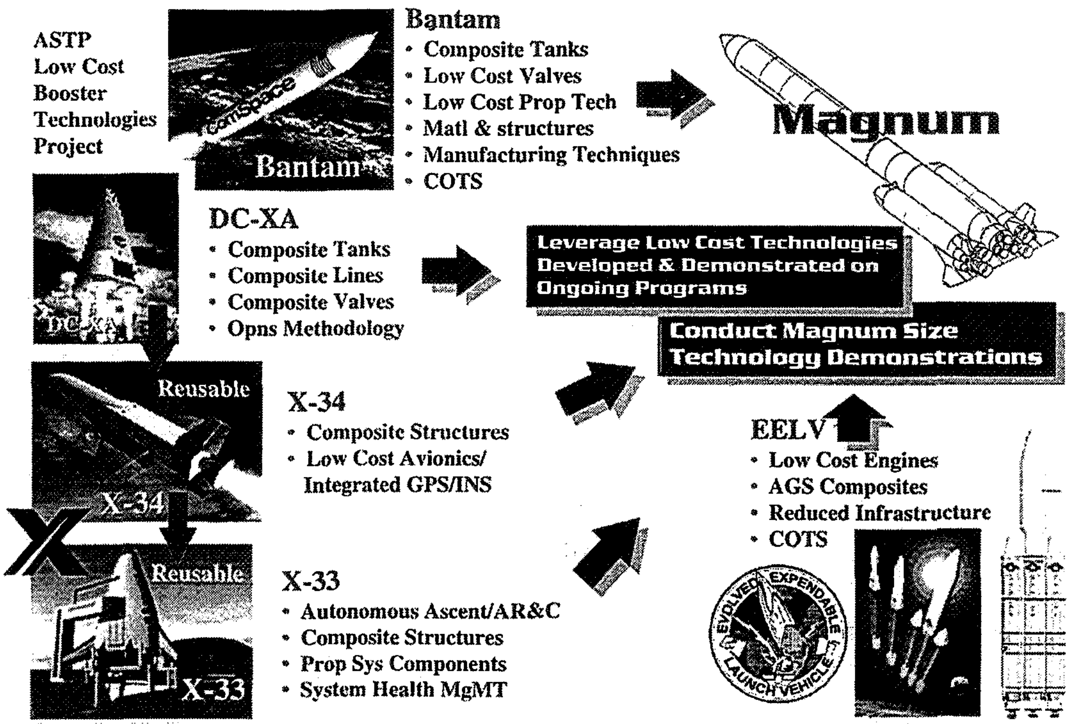
Affordable Earth-to-Orbit Transportation

- Need: Minimize Total Transportation Costs Including In-Space Assembly and Checkout.
- Exploration ETO Could Be Accomplished With RLV/Shuttle; However, Costs of Launch/In-Space Assembly and Checkout Would Be Prohibitive (30+ Launches and Associated Assembly/Checkout Per Human Landing).
- Approach: Each Mars Payload Launched in Two 80 Metric Ton Pieces.
  - Pieces Automatically Assembled On-Orbit.
  - Design Reference Mission Requires 6 to 7 Launches of 80 MT Vehicle for First Humans to Mars.
    - Two Payloads (4 ETO Launches) Required During the First Opportunity (Human Support Cargo/ ISRU).
    - One Payload (2 ETO Launches) Required During the Second Opportunity (Humans).
- Cost Bogey for ETO: $3B to $6B for First Human Landing
  - Technology Investment
  - DDT&E
  - Flight Hardware and Integration
  - Launch Facilities and Operations

Magnum Concept

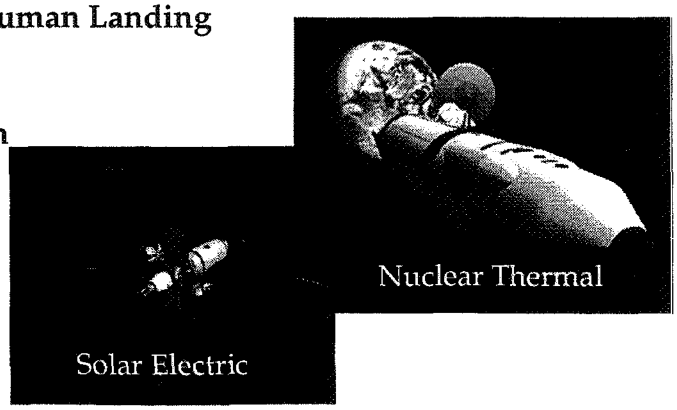


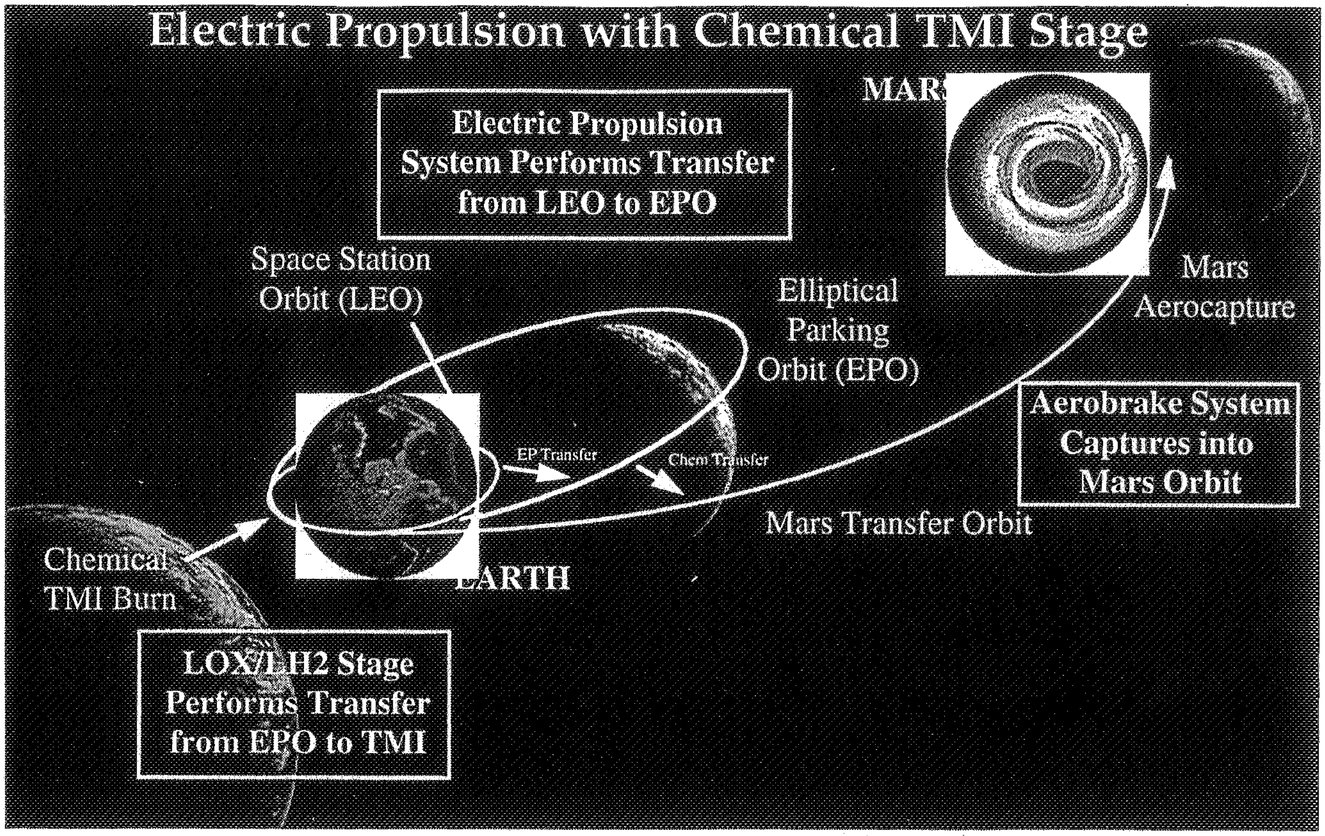
Magnum Applied Technologies



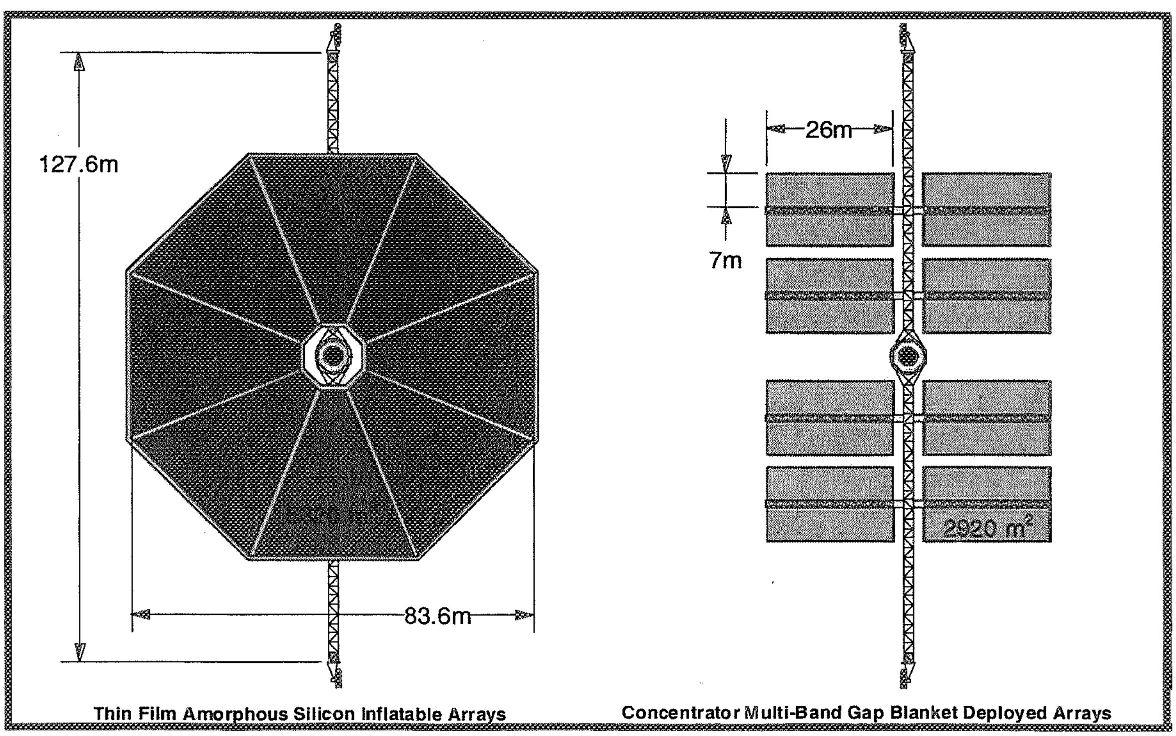
Advanced Interplanetary Propulsion

- Needs:
  - Minimize Total Transportation Costs
  - Develop Affordable Option for Non-Nuclear In-Space Transportation
- Approach:
  - Parallel Nuclear Thermal and Solar Electric Technologies for Trans-Mars Injection (TMI).
    - Downselect by End of 2001
    - Nuclear Thermal Focused on Fuels Improvements, Components, and Test Capability.
    - Solar Electric Focused on High Power Thruster, Components, and Test Capability.
  - Decent/Ascent Focused on Research to Support Use of In-Situ Resource Products.
- Cost Bogey for TIM: <$3B for First Human Landing
  - Technology Investment
  - DDT&E
  - Flight Hardware and Integration
  - Launch Processing



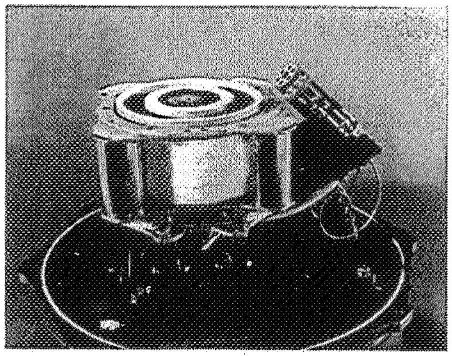


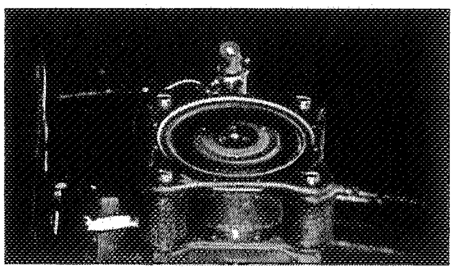
Solar Electric Transfer Vehicle Concepts



Electric Propulsion Technology for TMI

Small Russian Hall Thrusters (1.5 to 4.5 Kw)



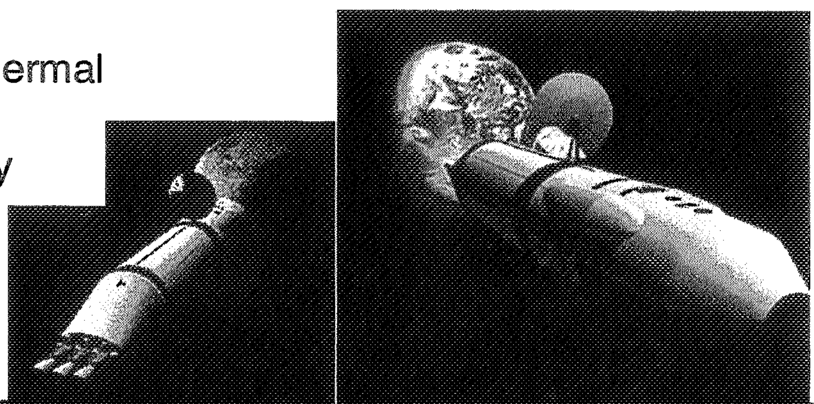


High Power Electric Propulsion for Exploration (50 to 100 Kw)

- High Power Hall Thrusters
  - 25 Kw Russian Thruster Tested and Evaluated
  - 50 Kw Breadboard Using American Technologies
  - 100 Kw Prototype unit
- Power Processing Technologies
  - Light Weight
  - Efficient
- Tankage and Feed System Technologies

Trans-Mars Insertion Option

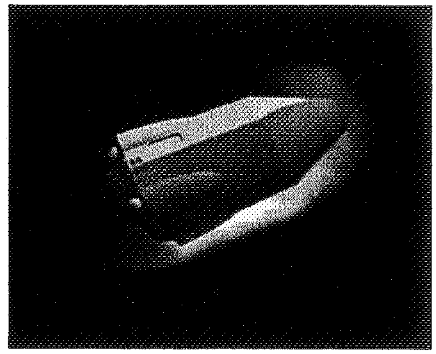
Nuclear Thermal Propulsion Technology



- **Fuel Development, Test and Validation for High Performance Bimodal Operation**
- **Effluent Treatment for Environmentally Acceptable Ground Test Capability**
- **Low Cost Component Technologies**
- **Materials Technologies**
- **Health Management and Instrumentation Technologies**

Aeroassist

- Needs:
  - Minimize Total Transportation Costs
  - Develop Affordable Options for Non-Propulsive Mars Orbit Insertion
  - Develop Affordable Options for Non-Propulsive Crew Return to Earth
  - Support Exploration Beyond Mars
- Approach:
  - Integrated Technology Program Addressing Needs of Human and Robotic Missions
    - Mars
    - Outer Planets
    - Other Solar System Bodies



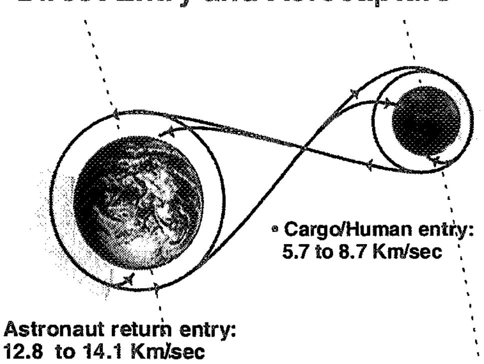
Mars Exploration Program

Aeroassist Benefits & Requirements

Direct Entry and Aerocapture

DRM Requirements & Goals

- Fast human transit drives entry speeds
- 15% mass fractions
- Minimal EVA Assy
- L/D for precision landing
- Biconic/"new" shape



- Aeroassist significantly reduces system complexity and mass of propulsion systems.
- Reductions in mass of vehicles -> Reduced launch requirements or direct increase in payload e.g.., 40 % reductions in IMLEO for Human mission assuming chemical propulsion.
- Aerocapture at Mars gives options for precision landing with reduced entry errors, entry in daylight conditions, or entry after an unexpected dust storm.

Aeroassist Technology
Investment Returns

Aerothermodynamics: Prediction of flowfield surrounding entry vehicle to determine aerodynamic forces and surface heating conditions.

Impact: Reduce uncertainties -> smaller safety factors -> mass & cost decrease

TPS: Protective material system surrounding entry vehicle, designed to maintain specified spacecraft structure and payload temperatures.

Impact: Lightweight TPS -> Smaller launch vehicle & useful payload mass increase

GN&C: Actively control vehicle attitude and trajectory during entry

Impact: Enables precision landing and aerocapture missions

Vehicle Design: Optimized integration of entry vehicle systems to meet mission requirements

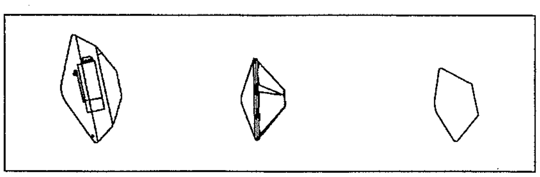
Impact: Drives technology focus & assures project goals are met. Allows design problems to surface before Phase C/D

Investment in Aeroassist Technology will enable exciting planetary missions, allow for larger payloads, and use smaller launch vehicles. It will enable HEDS exploration of of Planetary Bodies with Atmosphere.
"Better, Faster Cheaper"

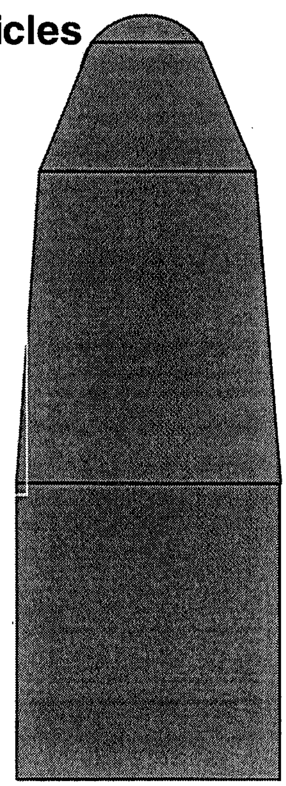
Comparison of Mars Entry Vehicles

	Viking	Pathfinder	Mars 2001	HEDS Biconic
$V_{e,rel}$ (km/s)	4.5	7.65	6.52	5.7 - 8.4
Diameter (m)	3.5	2.65	2.4	8.6
m_e (kg)	981	603	450	65000
Q_o (J/cm^2)*	~1000	~4000	~7000	50000 (est)
q_{max} (W/cm^2) *	25	100	60	1000 (est)

* non-ablating conditions



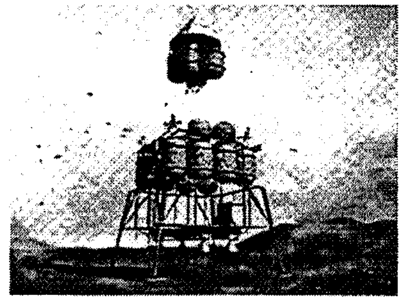
Viking   Mars Pathfinder   Mars 2001



HEDS Biconic

Concerned NASA technologist

In-Situ Resource Utilization



- Needs:
  - Minimize Total Transportation Costs
  - Develop Affordable Options for In-Situ Propellant Production (ISPP) from Mars Resources
- HEDS Approach:
  - Integrated Technology Program Addressing Needs of Human Missions
  - Phased Precursor Demonstrations of ISPP on Robotic Missions (Under Review)
    - 2001: Component Experiments
    - 2003: Small Oxygen Production Capability
    - 2005: BYOP Mars Sample Return Using Cryogenic Oxygen (Fuel is TBD)
    - 2007: Mars Sample Return Using ISPP to Provide Ascent Stage Propellants

Cryogenic Fluid Management

- Needs:
  - Minimize Total Transportation Costs
  - Cryogenic Fluid Storage for Long Periods In-Space and on the Martian Surface
  - ISPP Product Liquification, Transfer, and Storage
  - Minimum Propellant Boiloff Losses (Goal is Zero Boiloff)
- HEDS Approach:
  - Integrated Technology Program Addressing Needs of Human Missions as Part of ASTP CFM Program (STT Project)
  - Phased Precursor Demonstrations of Mars Surface Liquifaction, Transfer and Storage on Robotic Missions
    - 2003: Small Oxygen Production Capability
    - 2005: BYOP Mars Sample Return Using Cryogenic Oxygen (Fuel is TBD)
    - 2007: Mars Sample Return Using ISPP to Provide Ascent Stage Propellants

    (Note: JPL Carrying Parallel Code S Funded Propulsion Technology Development for Hypergolic Propellant; Downselect in 2000)

Cryo Fluid Management

Mars Human Mission Cryogen Storage Requirements

Mission Phase	Liquid Propellant	Quantity (Mg/m^3)	Temperature	Days of Operation	Operating Environments
TMI	H_2	60/850	20	150	Earth launch, 0-g, TMI burn
Descent	O_2 CH_2	16/14 4.6/11	90 112	500	Earth launch, TMI burn, 0-g, aerocapture, descent
ISRU seed	H_2	4.5/65	20	560	Earth launch, TMI burn, 0-g, aerocapture, descent, Mars surface
ISRU	O_2 CH_4	30.5/27 7.6/18	90 112	1200	Mars surface
Ascent	O_2 CH_4	30.5/27 7.6/18	90 112	1200	Mars surface, ascent
TEI	O_2 CH_4	25/22 7.2/17	90 112	1700	Earth launch, TMI burn, 0-g, aerocapture, TEI burn

Transportation Technology Challenges

Affordable Earth-to-Orbit Transportation

- **Low Cost Technologies Scaled to Large Launcher**
  - Tanks & Structures
  - Propulsion Systems
  - Shrouds
  - Upper Stages
- **Accommodate large-volume payload requirements**
- **Minimum on-orbit assembly costs**
- **Minimum impact to launch facilities**

Advanced Interplanetary Propulsion

- **All Chemical Propulsion Option**
- **Solar Electric Propulsion Option**
- **Nuclear-Thermal Option**
- **Ascent & Descent Propulsion**

Cryogenic Fluids Management

- **Long-Term (1700 days) Cryogenic Fluid Storage**
- **Cryogenic Liquefaction of In-Situ Propellants**
- **Cryogenic Refrigeration**
- **Zero-G Fluid Management**

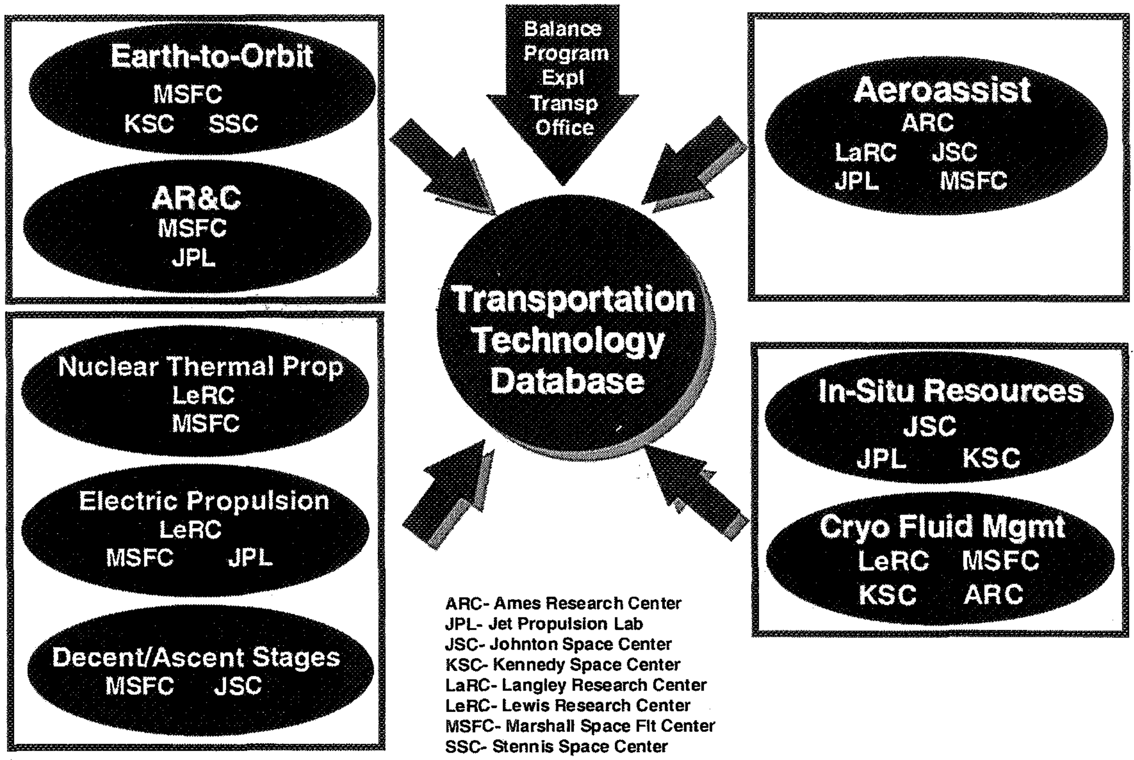
Aeroassist

- **Earth/Mars Orbital Insertion & Direct Entry**
- **Advanced Thermal Protection Systems**
- **Mars Atmospheric Modeling**
- **Guidance & Navigation for Precision Landing & Aerocapture**

In-Situ Resource Utilization

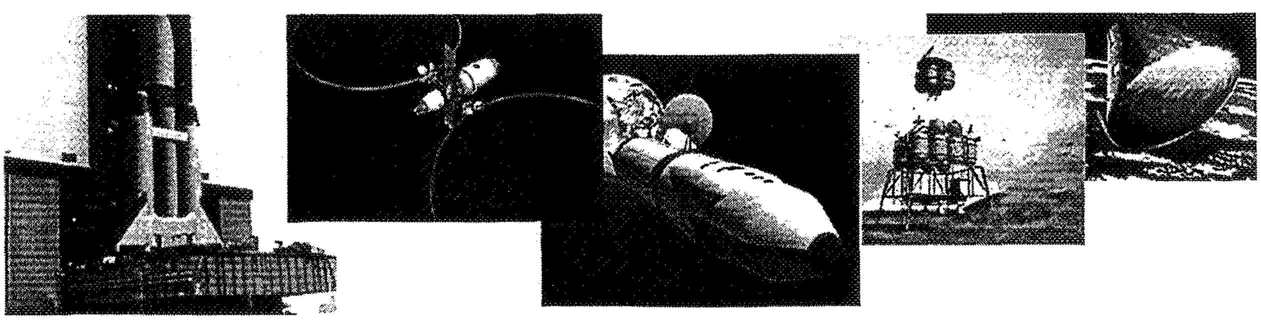
- **Propellant Production from Mars Atmosphere**
- **Human Mars Ascent Propellant**
- **Mars Sample Return Using In-Situ Resources**
- **Lunar Demonstration from Soil**

Exploration Transportation Technology Definition



Transportation Summary

- Human Exploration Is a Key Part of the NASA Strategic Plan
- Transportation Technology Development Is Required for Affordable Human Exploration
- Transportation Technologies Defined by Multi-Center Teams of Technical Experts
  - Anchored by Transportation Architecture Systems Analyses
  - Requirements and Goals Established to Guide Technology Definition
- Exploration Transportation Technology Update to be Performed as a Part of Budget Submission



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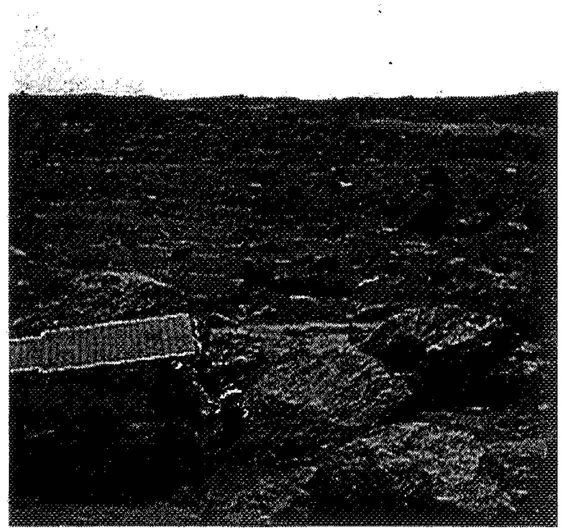
ADVANCED EXPLORATION TECHNOLOGIES

MICRO AND NANO TECHNOLOGIES ENABLING SPACE MISSIONS IN THE 21ST CENTURY

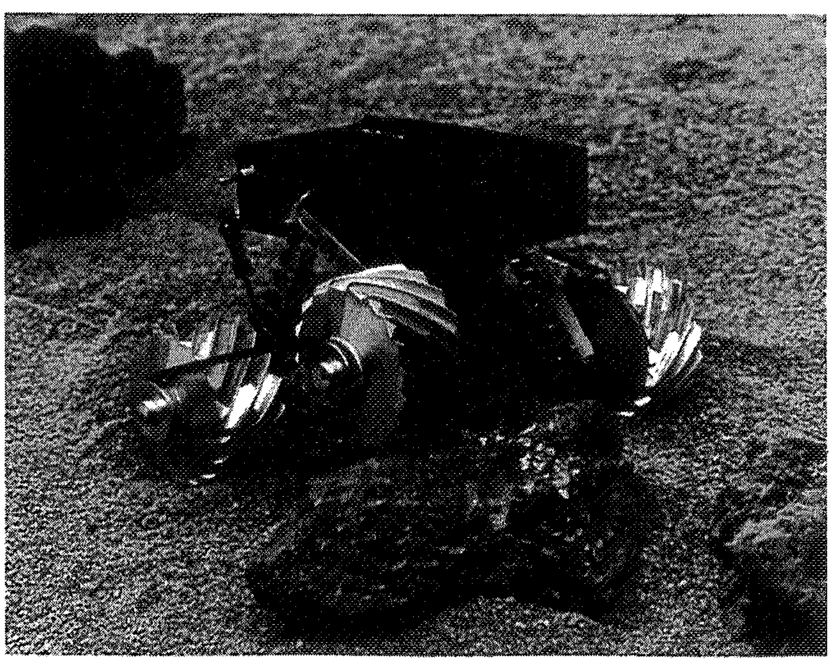
Timothy Krabach
Jet Propulsion Laboratory
Center for Space Microelectronics Technology

- NASA and ISAS have agreed to Collaborate on the MUSES C Mission.
- In Exchange for DSN, Navigation and Recovery Support, ISAS will carry a NASA/JPL Rover to the Asteroid.
- The Rover is enabled by NASA technology investments in robotics.

Pathfinder

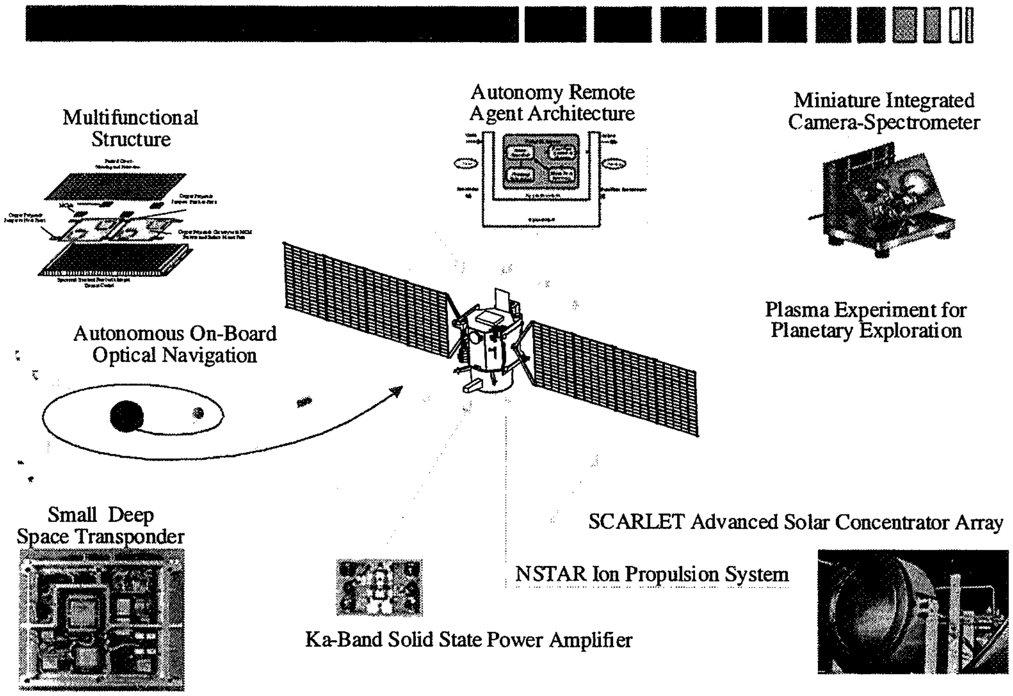


Nano Rover

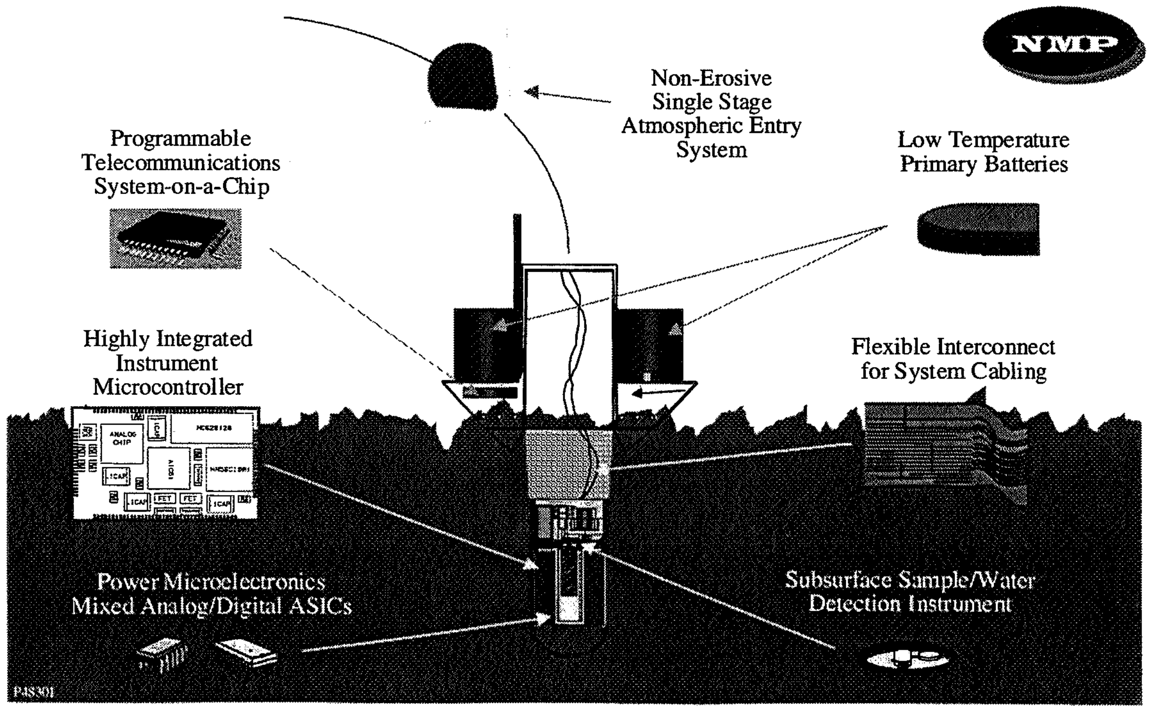


NASA New Millenium Program
Technology Validation through Space Flight

ASTEROID AND COMET FLYBY
DEEP SPACE ONE VALIDATION TECHNOLOGIES



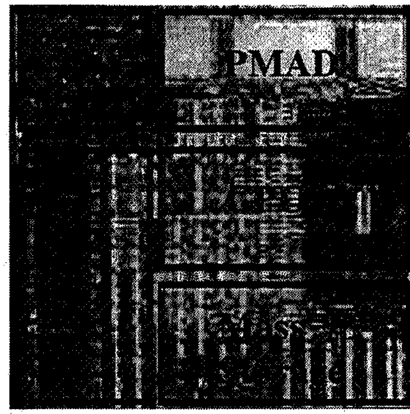
MARS MICROPROBE
DS 2 VALIDATION TECHNOLOGIES



System on a Chip Technical Challenges

•Miniaturization-RF
•Integration-RF
•Integration of optical com.

•Integration of devices and integrated circuits with MEMS.



•Miniaturization
•Passive components
•Low power

•Integration of processors and memory devices.
•Merging of individual designs

General challenges:
- •Different design techniques and design tools (digital, analog, mixed, rf, optical, MEMS)
- •Ultra low power devices and architectures
- •Unified device fabrication technology-SOI CMOS, SOI MOSFET, SOI SI based memories, SiGe
- •Testing of the system on a chip
- •Reliability
- •Intellectual Property related issues
- •Successful partnership with industry for system on a chip fabrication

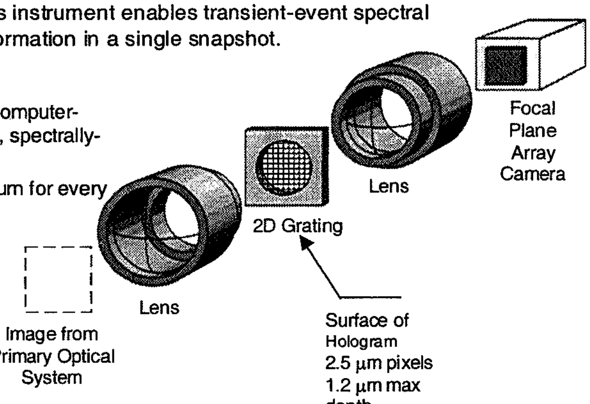
NASA Cross - Cutting Technology Program Examples

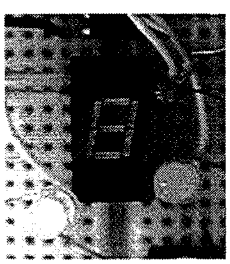
Computed-Tomography Imaging Spectrometer

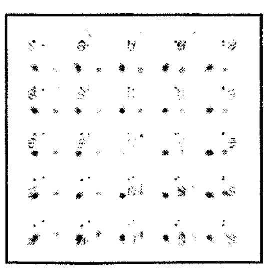
A new concept in imaging spectrometers, this instrument enables transient-event spectral imaging by capturing spatial and spectral information in a single snapshot.

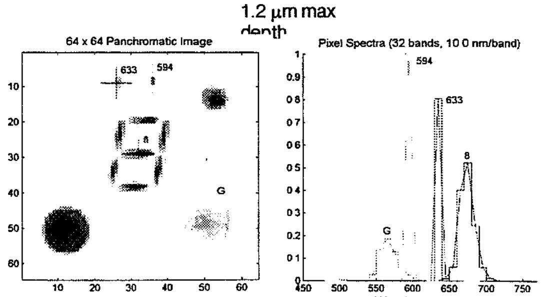
Principle of Operation
- JPL designed and electron-beam fabricated computer-generated hologram splits scene into multiple, spectrally-dispersed images
- Tomographic reconstruction yields the spectrum for every pixel in the scene

Advantages
- Does not employ scanning of any type
- Multiple spatial-spectral data cubes having different dimensionality can be reconstructed from the same frame




Experimental Scene (633 nm and 594 nm laser spots not shown)

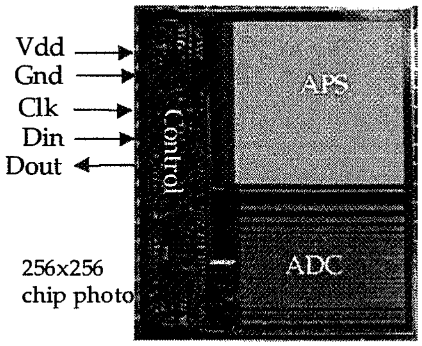

Intensity on Focal Plane Array (Image taken in dark ambient)



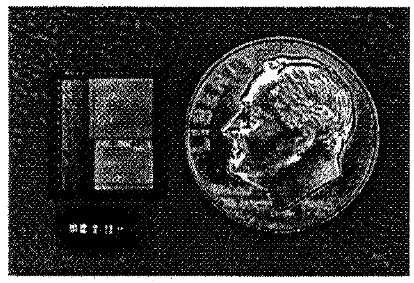
Reconstructed Spatial-Spectral Scene

DIGITAL APS CAMERA-ON-A-CHIP

First fully digital camera-on-a-chip: needs only FIVE wires for operation

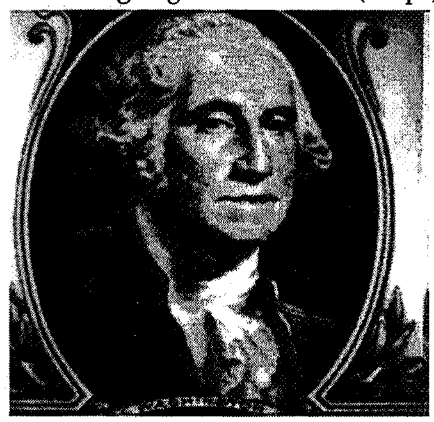


256x256 chip photo

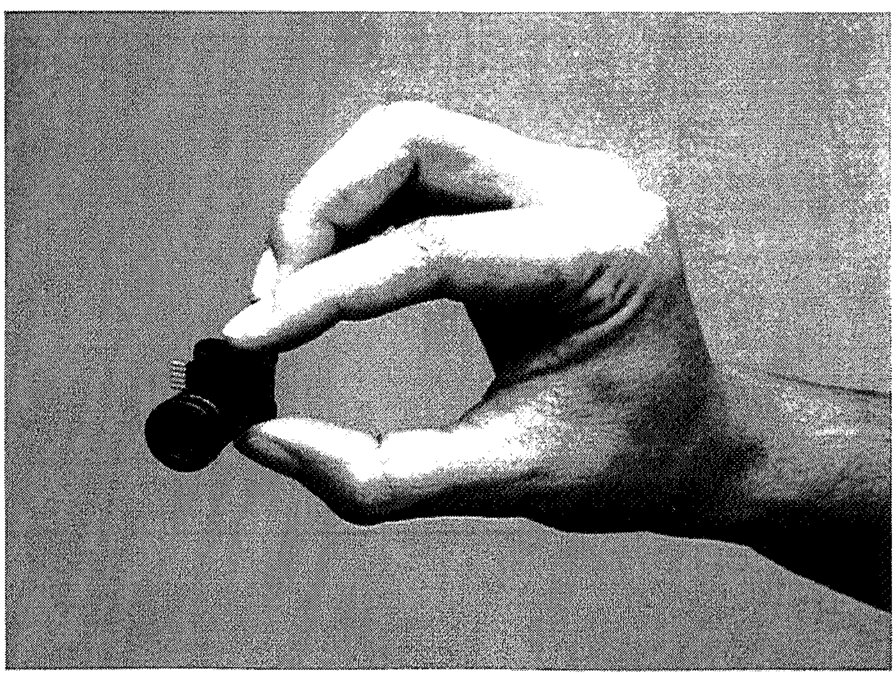


- ⇨Fully **digital** interface
- ⇨Requires **single** bias supply (5V)
- ⇨Fully **programmable**: resolution, speed, electronic pan & zoom, exposure, and data-reduction
- ⇨**256** Column-parallel **ADC**
- ⇨On-chip bias generation
- ⇨Total chip area: **9.7 mm x 8.9 mm**
- ⇨Supports parallel or serial interface
- ⇨Provides on-chip **offset correction**

picture of "george" at video rate (30 fps)



ULTRA-LOW POWER, MINIATURIZED FULLY DIGITAL, 256 x 256 APS CAMERA



Palmcorder size QWIP Infrared Camera

Low Cost Camera for Scientific, Defense, and Commercial Applications

Detector Technology	=	QWIP
Focal Plane Array Size	=	256 x 256
Spectral Bandpass	=	8 - 9 mm
Optics	=	f1.3 Ge
Output	=	Standard Video-analog
Power Requirements	=	5.5 Watts
Battery Life	=	3 hours from Sony camcorder battery
Weight	=	2.5 pounds
Dimensions (with 50 mm lens)	=	5.3 in. x 9.7 in. x 2.5 in.
NEDT	=	30 - 50 mK
MRTD	=	10.5 mK
Instantaneous Dynamic Range	=	1024 (10 bits)

COMPARISON WITH HAND HELD CAMERA

WEIGHT – X4 LESS
VOLUME – X 4 LESS
POWER – X10 LESS

MEMS
(Micro - Electro - Mechanical System) Technology for Space

Silicon Micromachined Microgyroscope

Present Gyroscope Technologies

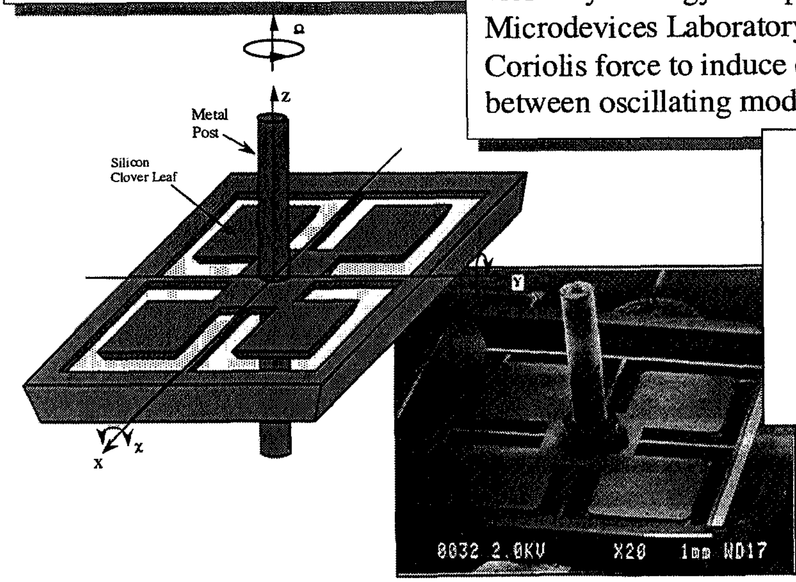
- Too Expensive
- Too bulky (volume, mass)
- Too high power consumption
- Limited Lifetime

Concept

The JPL/UCLA silicon micromachined vibratory microgyroscope fabricated at the Microdevices Laboratory depends on the Coriolis force to induce energy transfer between oscillating modes to detect rotation.

JPL Advantages

- Inexpensive
- Compact
- Low power consumption
- Non-wear/Long lifetime
- Negligible turn-on time
- Large dynamic range



NASA X-33 Advanced Technology Demonstrator
JPL Avionics Flight Experiment (AFE)

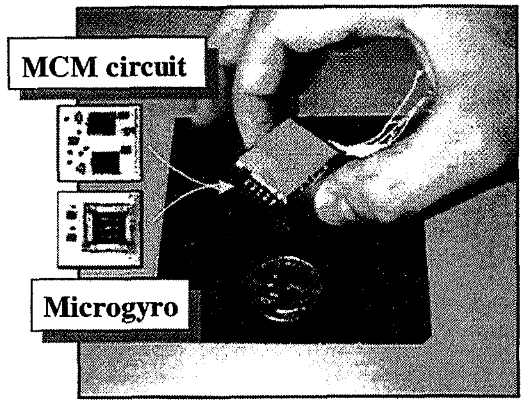
Present Performance:

1) ~17-29deg/hr bias stability,
   ~1.5 deg/root-hr ARW.
2) Electronics packaged in MCM format

Predicted Performance Goals:

1) Bias stability: 1-10 deg/hr.
   ARW: <0.1 deg/root-hr.
2) Operate at matched frequencies condition.
3) Improved electronics.
4) Package: 3 yrs operation.
5) Qualification: shock,vibration,thermal.

MICROGYROSCOPE

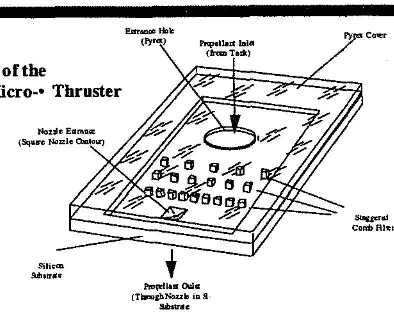


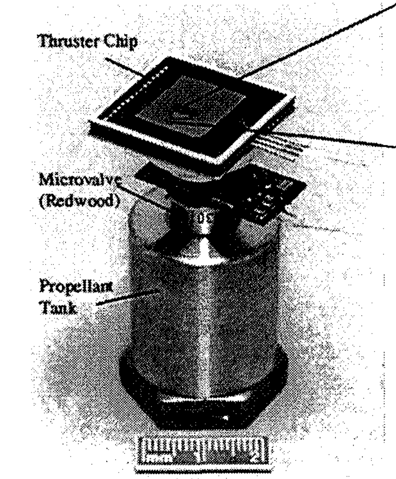
Subliming Solid Micro-Thruster

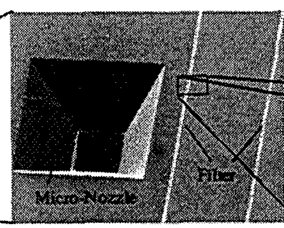
Principle of Operation:

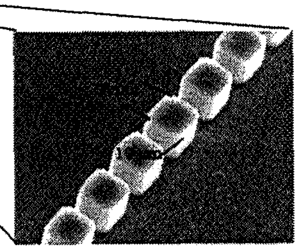
- Store propellant (ammonium salt) in solid form.
- Propellant sublimes when heated, building up pressure in tank (~10-15 psia)
- Vent gaseous propellant through micro-valve, micro-filter and micro-nozzle assembly to produce thrust.

Concept of the Subliming Solid Micro-• Thruster









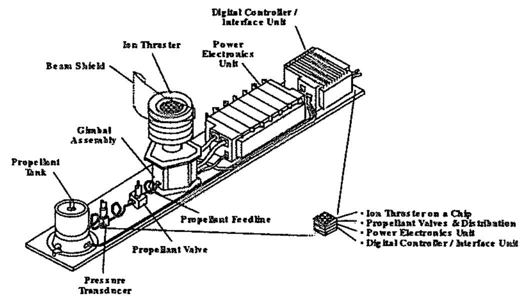
Benefits:

- Phase-change thruster concept, reduces leakage problem.
- Very small thrust and I-bit capability for microspacecraft attitude control through the use of MEMS technologies.
- Benign temperature and pressure conditions compatible with MEMS materials.

Performance Goals:

- Isp : 50-75 sec
- Thrust: 0.5 mN
- Power: < 2 W/mN
- Mass: few grams
- Size: 1 cm^2

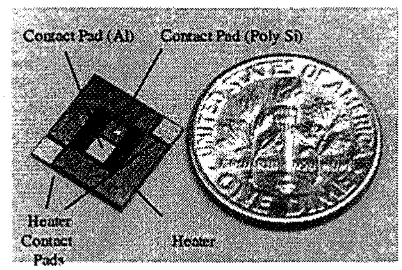
Micro - Ion Thruster



Principle of Operation:
- Create micro-sized plasma to generate ions to be accelerated in micro grid accelerator system.
- Study feasibility of radio-frequency (RF) inductive coupling, cold cathode technology or hollow cathode discharges for plasma generation.
- Pursue miniature conventional and MEMS based approaches for micro-grid accelerator fabrication.

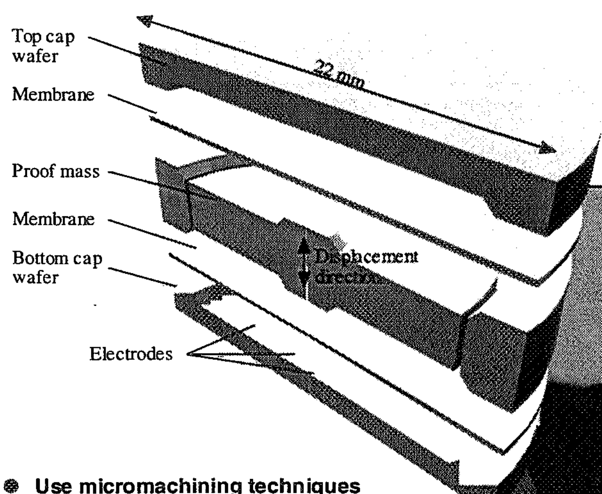
Benefits:
- Many interplanetary missions require large velocity increments, demanding large propellant masses using conventional propulsion technology.
- Ion engine technology provides high specific impulses,requiring less propellant for the same mission.
- Fuel-efficient micro-ion engine technology enables micro-sized spacecraft for demanding interplanetary missions.

Performance Goals:
- Isp: ~ 3000 sec
- Thrust: μN to mN
- Power: < 10 W
- Mass: few grams (MEMS)
  tens of grams (conventional)
- Size: 1-3 mm dia (MEMS)
  1-3 cm dia. (conventional)



Grid Breakdown Test Chip

Micromachined Silicon Seismometer



- Use micromachining techniques (etching and photolithography) to produce tightly toleranced structures
- Continuous 10 μm membranes used as springs to maximize robustness
- Sandwich structure distributes mass/spring structures vertically rather than laterally - produces most compact geometry
- Coupled with ultrasensitive position transducer for 1 ng/√(Hz) resolution

SAW Dewpoint Microhygrometer

Features of SAW Dewpoint Microhygrometer

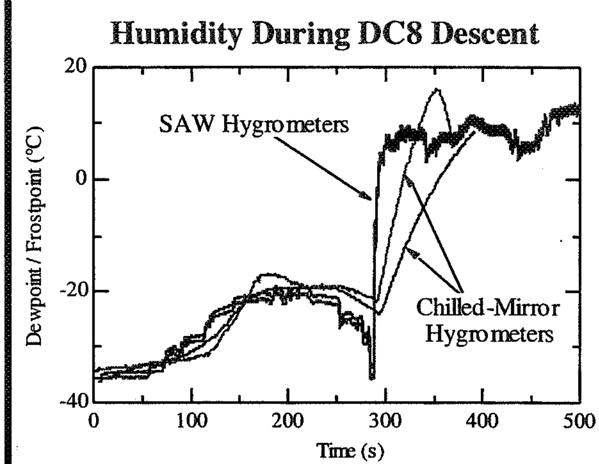
- 100x higher sensitiviy and >10x faster response compared to chilled mirror dewpoint hygrometers
- Reduction in size, mass, and power

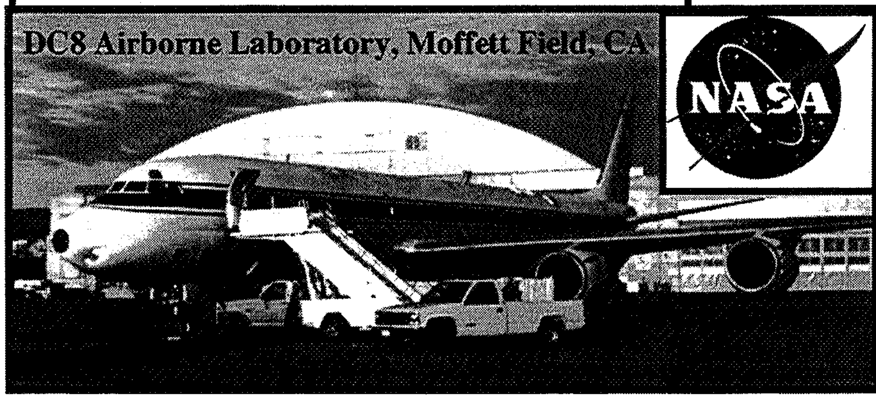
Applications of Microhygrometer

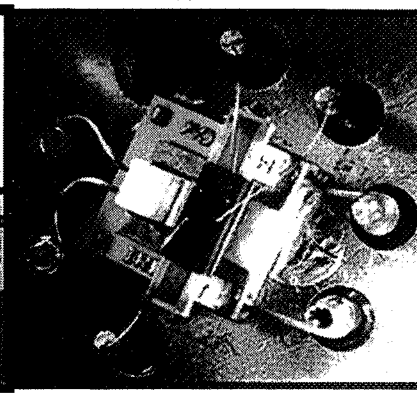
- Humidity in Earth and planetary atmospheres: Micro weather stations, Airplanes, Balloons, UAVs
- Environmental and process monitoring in space: Shuttle, X33, RLV, Space Station

Flight Tests for NASA Code YS

- NASA DC8 Airborne Laboratory (FY'95)
- Balloon-borne reference radiosonde (FY'97)



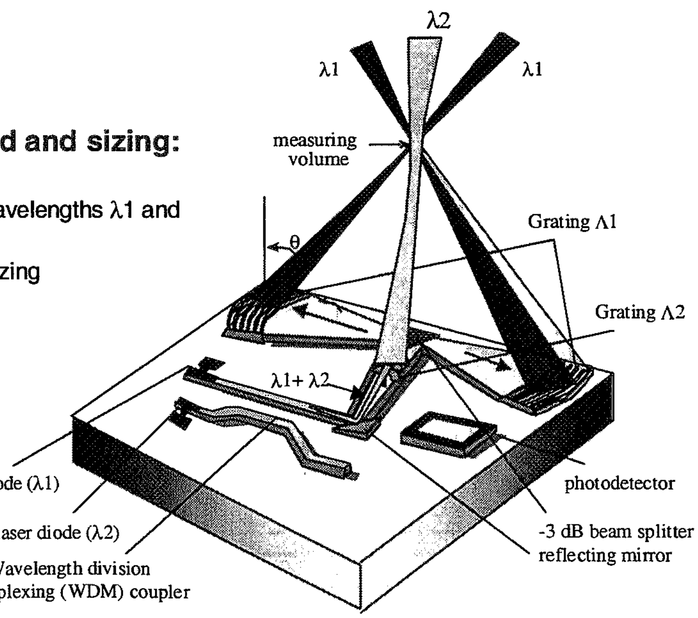




Micro Laser Doppler Anemometer

A wind sensor for particle speed and sizing:

- Combining LDA and Imax technique
- Two DFB lasers emitting at different wavelengths λ1 and λ2
- beam λ1 for speed and beam λ2 for sizing



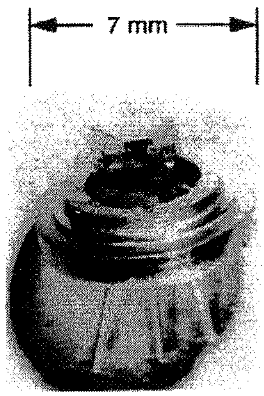
A JPL Innovative Integrated Micro Laser Doppler Anemometer for particle speed and sizing sensor

NASA Applications

- Mars surface dust particle characterization
- Planetary boundary layer wind sensor

JPL Tunable Diode Laser (TDL) Sensors

New generation of TDL's operating at specific wavelengths to perform in-situ gas monitoring of Earth and planetary atmospheres



Typical laser diode package for instrument use

Instrument features

- High Sensitivity
- Gas discrimination
- Corrosion resistant
- Robust
- Low mass
- Low power consumption

Applications

- Measurement of atmospheric species
- Medical (breath analysis)
- Mine safety monitors
- Toxic gas monitoring

The Mars Volatiles and Climate Surveyor (MVACS) mission (1999 launch)

MVACS will carry four TDLs

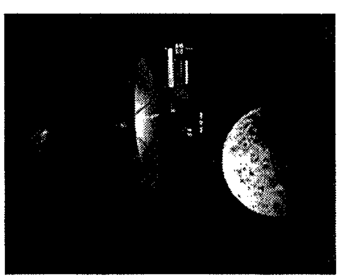
- Metrology package to measure water content of Mars atmosphere
- Thermally Evolved Gas Analyzer (TEGA) package to measure volatile contents of the soil

REMOTE EXPLORATION AND EXPERIMENTATION

HPCC

Vision:

Move Earth-based Scalable Supercomputing Technology into Space



Background

- **Funded by Office of Space Science (Code S) as part of NASA's High Performance Computing and Communications Program**
- **Started in FY1996**
- **Guidelined at $102M over 8 years**

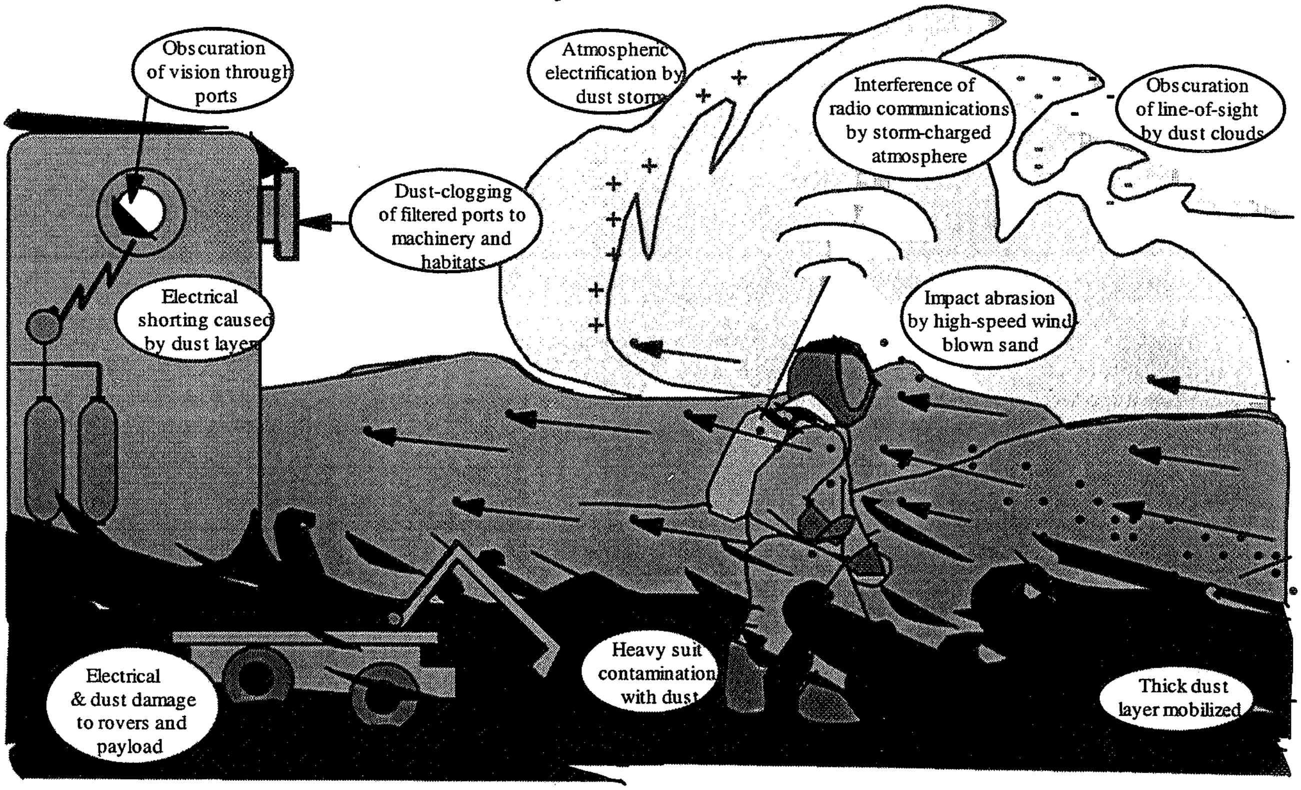
REE Impact on NASA and DOD Missions by FY03

Faster - **Fly State-of-the-Art Commercial Computing Technologies within 18 month of availability on the ground**

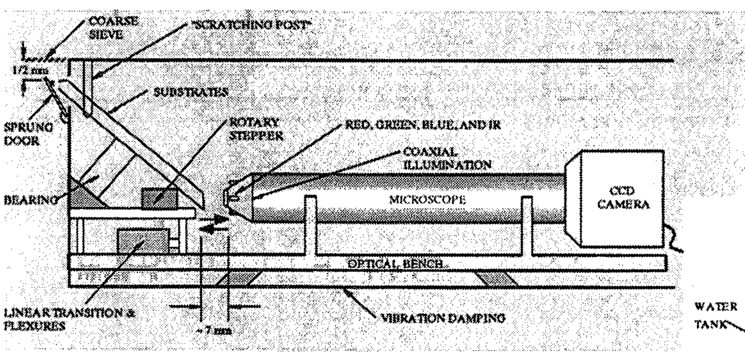
Better - **Onboard computer operating at > 300MOPS/watt scalable to mission requirements *(> 100x Mars Pathfinder power performance)***

Cheaper - **No high cost radiation hardened processors or special purpose architectures**

Interaction of Dust & Soil with Human Explorers

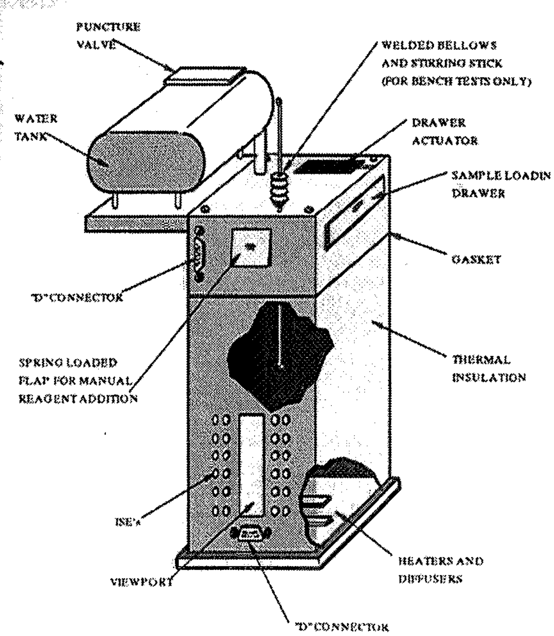


What's in MECA?



An imaging facility to observe the size, shape, and hardness of dust and soil which clings to selected targets. Particles such as quartz and asbestos can cause abrasion and lung damage. An Atomic Force Microscope (AFM) complements the optical microscope.

A Wet Chemistry Laboratory (WCL) to measure what happens when the Martian soil is exposed to water in the human environment. The WCL measures pH, dissolved ions, and potential toxins.



Also

- **An Electrometer to measure Triboelectric Charging in the dry, irradiated Martian environment**
- **Material patches to measure wear and adhesion**

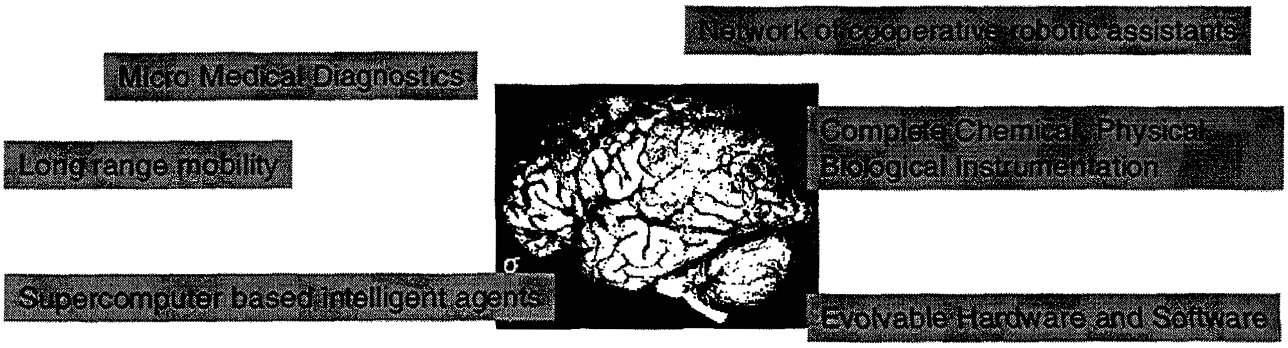
CSMT Board of Governors, 1/27/98

Summary

Advanced Technology insertion is critical for NASA

- **Decrease mass, volume, power, and mission cost**
- **Increase functionality, science potential, robustness**

The Next Frontier



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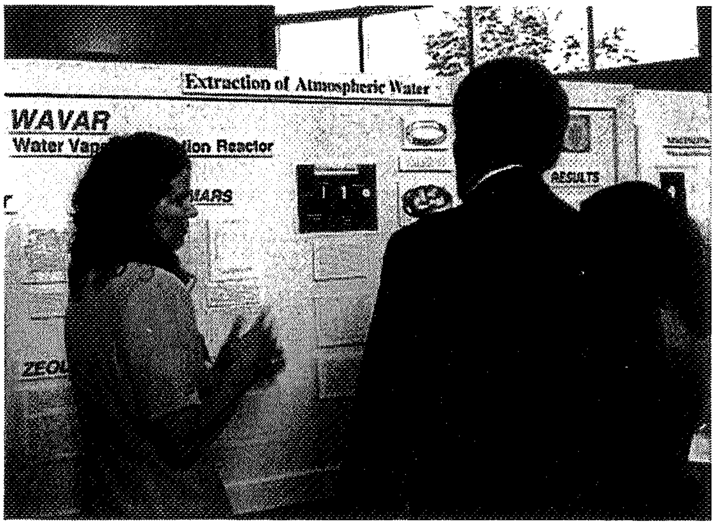
University Design Studies



University of Texas at Austin

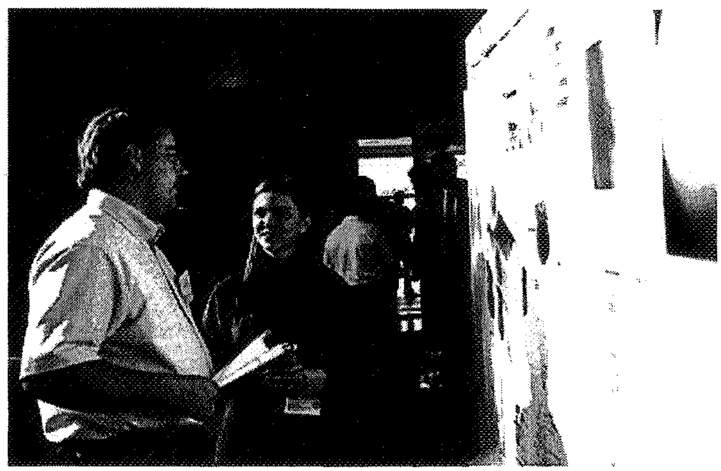
University of California, Berkeley

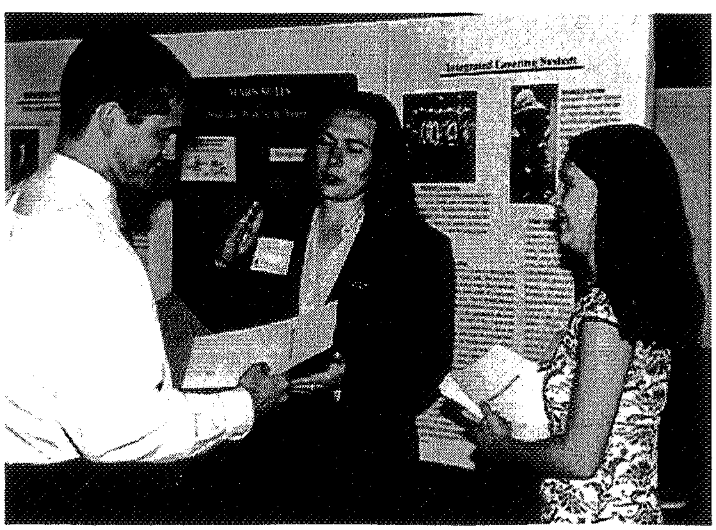
Texas A&M University

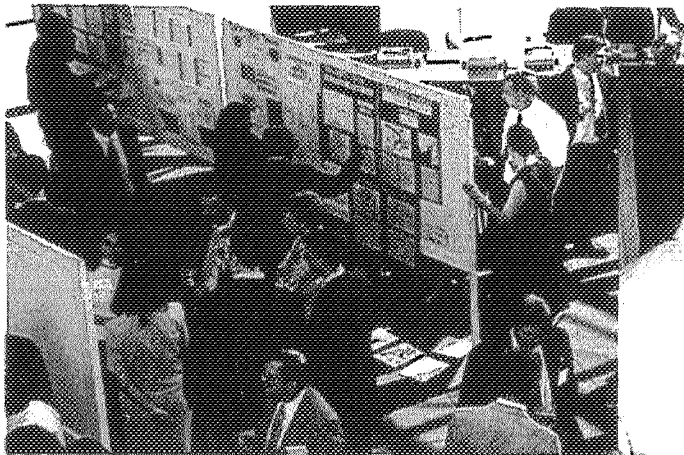
University of Washington

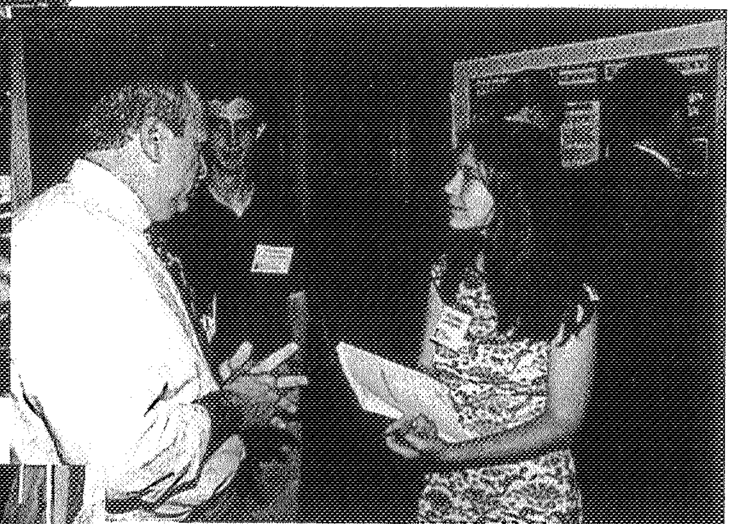
Wichita State University

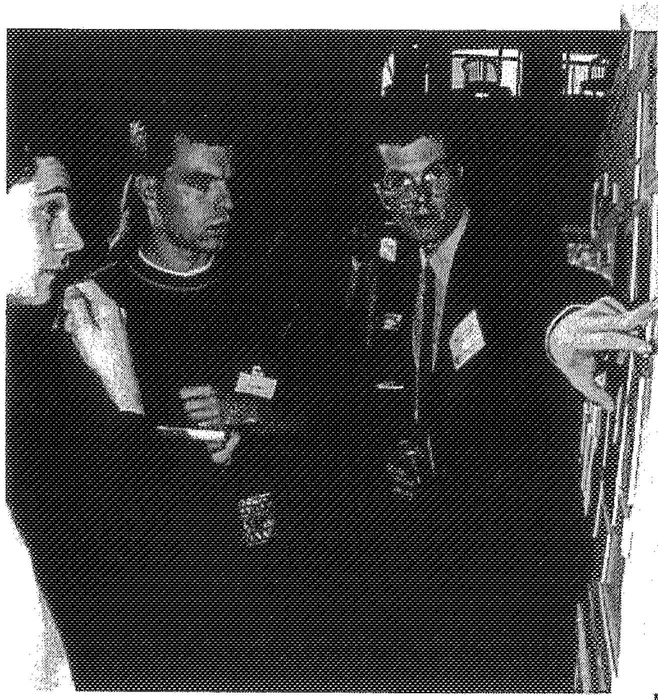
University of Maryland

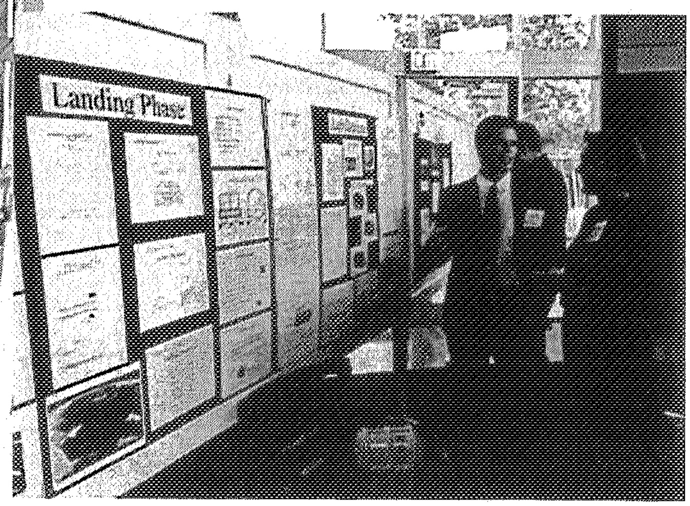








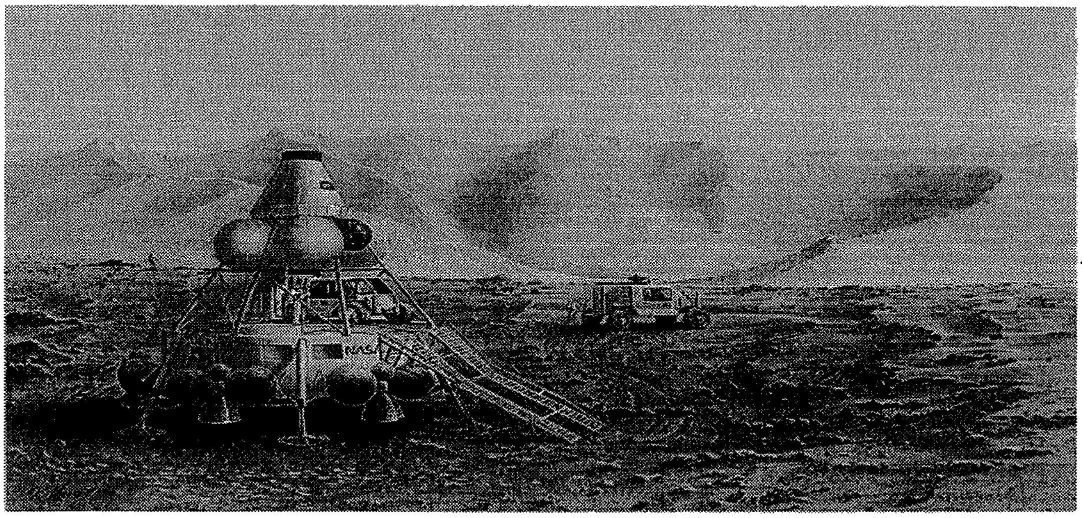



Landing Phase


WAVAR
ZEOLITE

Flag and Footprints Mission to Mars

Preliminary Design Review Two



Source: Martin Marietta: V1-1990

Submitted to:

Dr. Wallace T. Fowler
Dept. of Aerospace Engineering
and Engineering Mechanics, The University
of Texas at Austin

Submitted by:

Space Mission Innovations

Design Team:
George Chi, Greg De La Rosa, Jenna Harsch, Robert Jenkins, Sean Wagner, Jordi Zaragoza

Project Advisors:
Dr. Wallace Fowler, Dr. Hans Mark

Abstract

SMI has developed a preliminary guideline for a flag and footprints manned mission to Mars. The manned mission is a split mission where the return and ground supplies will be sent on a cargo spacecraft. The crew spacecraft will leave on a high-energy trajectory once the cargo spacecraft has arrived in the prescribed orbit about Mars. The trajectory will be approximately 150-day from Low Earth Orbit (LEO) to the prescribed rendezvous orbit. The crew spacecraft will then dock with the orbiting cargo spacecraft for refuel and resupply. In addition, once safely docked, the crew members will transfer to the Mars Excursion Vehicle (MEV) for transport to the Martian surface. Each vehicle will be equipped with all necessary subsystems. To facilitate the transport of a large payload from Earth to Mars, the cargo spacecraft will utilize Ion propulsion. The Ion propulsion is ideal due to the high I_{sp} characteristics. The crew spacecraft will be propelled with high-thrust RL-10 engines. Due to the smaller mass of the crew spacecraft, the spacecraft will utilize a 150-day high-energy trajectory. The MEV propulsion will be hypergolic. This choice of fuel is due to the reliability and simplicity of use. The crew members will stay on the surface of Mars for 30-days. During the 30-days, the crew will perform a series of scientific and exploratory experiments. To broaden the astronauts range of exploration, the astronauts will have access to three Unmanned Aerial Vehicles (UAV) and one rover while on the surface. The scientific experiments will consist of several soil and rock analyses as well as atmospheric study. Upon completion of the 30-day ground phase, the astronauts will return to the orbiting crew ship for return to Earth. SMI's flag and footprints mission outlines the fundamental systems and general requirements for these systems. SMI feels that with the fulfillment of these fundamental systems, this mission will be a highly desirable and potential candidate for development by NASA.

Executive Summary

This document presents the preliminary design by SMI to provide NASA with a highly desirable manned mission to Mars in the event political interest arises. This Flag and Footprints mission will deliver a manned spacecraft to the surface of Mars within a minimal duration. Additionally, the mission concept will be constrained to use existing technology. Initially, SMI developed concepts for three mission alternatives. Each of these missions offer unique advantages as well as disadvantages. The first scenario investigated by SMI utilizes a single vehicle to conduct the entire mission. The second scenario utilizes the split mission concept and remote rendezvous. The third scenario was also a split mission, but avoided remote rendezvous by using precision landing on the Martian surface. The single vehicle mission was eliminated due to the high fuel requirements to satisfy the designated mission constraints. The other two scenarios offer solutions that greatly reduce the mission fuel requirements. The separation of the cargo and crew phases allows for the feasibility of sending the crew spacecraft on a 150-day sprint trajectory. The primary difference between the second and third scenarios is the remote rendezvous versus precision landing. SMI opted to develop the remote rendezvous mission scenario. The two main reasons for SMI's choice was additional savings in fuel requirements as well as the proven reliability of a remote rendezvous in space. A brief overview of the mission scenario is described in the following paragraph.

The cargo spacecraft will utilize low-thrust ion propulsion to travel to Mars. Once the cargo spacecraft arrives in the determined orbit configuration, the crew spacecraft will utilize RL10 engines to depart Earth and enter a high-energy 150-day sprint trajectory to Mars. Upon arrival at Mars, the crew spacecraft will maneuver into the same orbit around Mars as the cargo spacecraft. A remote rendezvous will be required for resupplying and refueling of the crew spacecraft as well as for access to the Mars Excursion Vehicle (MEV). The astronauts, once docked with the orbiting cargo ship will transfer into the MEV for descent to the surface of Mars. Once on the Martian surface, the astronauts will stay 30 days where they will conduct several scientific and exploratory experiments.

SMI's first goal after identifying the mission scenario was to develop a list of necessary subsystems for all the vehicles. The subsystems SMI identified are as follows: Power Systems, Communications, Guidance/Navigation/Control, Propulsion, Environment Control and Life Support System, Thermal Protection System, and Radiation Shielding. This is just a preliminary list and SMI expects that this list will expand as the mission develops. All of these systems play an integral part in the success of the mission. Specific details surrounding each of these subsystems is detailed in Section 4.0.

In addition to identifying the necessary subsystems for the mission, SMI had to investigate methods to develop the trajectory for the crew and cargo spacecraft. The trajectory parameters include launch site and date, initial parking orbit, time of flight, necessary plane changes, Mars orbit insertion, parking orbit regression. SMI utilized these parameters to develop trajectories and launch dates for both the cargo and crew spacecraft. Due to lack of time, actual numerical solutions were not accomplished.

The technical aspects of the project have been broken up into researching and developing specifications for the cargo spacecraft, crew spacecraft, Mars excursion vehicle, and launch vehicles. For each vehicle, the team developed trajectories, necessary subsystems, preliminary mass and size analysis of subsystems, propulsion and fuel requirements for each vehicle.

Each of the mission vehicles will be assembled in LEO. This is due to the size and quantity of supplies necessary for a mission of this nature. Vehicle components will be placed in LEO by a series of launch vehicles. SMI is considering three launch vehicle alternatives. The three launch vehicles are the Titan IVb, the Shuttle, and the Proton rocket. Each of these were selected for their proven reliability and high payload capacity. Each launch vehicle offers unique capabilities and these capabilities will govern the configuration for which the vehicle components will be placed in LEO.

The cargo spacecraft will utilize ion propulsion rockets to transport from Earth to Mars. The initial escape from Earth has not yet been determined. There are two methods for escaping Low Earth Orbit(LEO). The cargo spacecraft can either utilize a high-thrust rocket to propel the craft outside the Earth's sphere of influence or the cargo spacecraft can use the low-thrust ion propulsion the entire time. Using the high-thrust escape will reduce the cargo mission length by up to two years(see Fig. 6.1). The disadvantage of the high-thrust escape is the cost associated with the amount of fuel required. Using low-thrust propulsion the entire time greatly extends the mission time, but reduces the cost and fuel requirements significantly. After the cargo spacecraft escapes Earth's gravitational influence, the cargo will be propelled solely by ion propulsion. Upon arrival at Mars, the cargo spacecraft will autonomously maneuver into a stable Low Mars Orbit(LMO). Once in orbit, the cargo spacecraft

will notify Earth so that the crew ship may depart. The cargo spacecraft will be equipped with all surface equipment, included the MEV. In addition, the cargo spacecraft will transport all return supplies and fuel for the crew spacecraft. Initial mass estimates are identified in Table 6.1. The cargo spacecraft, once assembled, is estimated to have a mass of approximately 1,100,000 kg. Approximately a 100,000 kg of the cargo weight is appropriated for the MEV. SMI's conceptual drawing of the cargo spacecraft, without the MEV, is depicted in Figure 6.3 and 6.4.

After notification of the orbit injection of the cargo spacecraft, the crew spacecraft will depart on a high-energy sprint trajectory to Mars. The time of flight to reach Mars is approximately 150 days. The primary propulsion system to be utilized by the crew spacecraft is a RL10 engine. The crew spacecraft will dock with the orbiting cargo ship to refuel, resupply, and allow the astronauts to enter the MEV for transport to the surface. The crew spacecraft will provide supplies for the 150-day TOF to mars and all necessary subsystems for survival of the crew. Table 7.4 identifies a list of subsystems identified by SMI and their respective estimated masses. The assembled crew spacecraft is roughly the same mass as the cargo spacecraft with one major difference. The primary mass of the spacecraft is comprised of fuel. After completion of the surface mission, the crew will depart Mars on a similar high-energy 150-day trajectory to Earth. SMI's conceptual design of the crew spacecraft is depicted in Figure 7.5 and 7.6

Figure 8.3 depicts SMI's proposed descent phases for the MEV. Upon departure from the orbiting cargo spacecraft, the MEV will enter the atmosphere at proper enter angle. The heatshield will be used to avoid any damage of the MEV from aerodynamic heating. Once in the atmosphere, the MEV will eject the heatshield and deploy a series of parachutes. Retro-engines will be used to provide a soft landing on the Martian surface. The primary source of propellant will be hypergolic due to the proven reliability and simplicity. Initial mass estimates and subsystem requirements are identified in Table 8.2. Once on the surface of Mars, the crew will initiate the ground phase of the mission. A conceptual design of the MEV is depicted in Figures 8.4 and 8.5.

The astronauts will be responsible for conducting several experiments while on the surface of Mars. The experiments range from soil analysis to remotely piloting Unmanned Aerial Vehicles (UAV) for detailed resolution of the Martian surface. The primary goal of the ground phase is to explore as much of the surface as possible in the limited time allotted. In addition to the UAV's, the astronauts will have a rover to extend the range of exploration and sample collection.

Upon completion of the 30-day ground phase, the crew will depart in the designated ascent vehicle (see Fig. 8.5). Once in orbit, the ascent vehicle will dock with the orbiting cargo spacecraft, and the crew will transfer back into the crew spacecraft. The crew spacecraft will then depart from Mars on a 150-day high-energy return trajectory to Earth. To avoid the high fuel requirements to obtain a new orbit about Earth, the crew will utilize an Apollo style capsule to reenter the Earth's atmosphere and splash down on the surface.

Due to time constraints and limited manpower, a few tasks were not investigated. SMI did not develop any abort mission scenarios for the manned mission to Mars. We recognize the extreme importance, but felt other details of the mission were more critical. In addition, many of the general requirements of the subsystems were not determined. The subsystems general requirements are key to developing detailed analysis of the spacecraft design and layout. Furthermore, many key phases of the vehicles trajectories need refining for precise launch date and TOF determination. SMI hopes that future teams will develop the concepts outlined in this paper.

This semesters work has focused primarily on the development of a skeleton for the manned mission to Mars. Having a strong mission concept will allow for future groups to develop the critical details. This report identifies critical areas of the mission as well as potential solutions for these details. SMI feels that with the fulfillment of these critical areas, this mission will be a highly desirable and potential candidate for NASA.

Presentation Overview

- Problem Statement
- Mission Description
- Mission Overviews
- Crew Spacecraft Details
  - Trajectory Analysis
  - Subsystems
  - Mass Analysis
- Reliability Statement
- Future Work
- Questions

Introduction

- Project Motivation
  - New Millennium people are more open to ideas
  - Scientific Advancement
  - Human Nature to Explore
- Project Background
  - Update of Previous Mission From '91
  - No new technology to increase reliability
  - Limited science to reduce complexity

Problem Statement

To provide NASA with a highly desirable Manned Mission To Mars in the event Political Interest arises

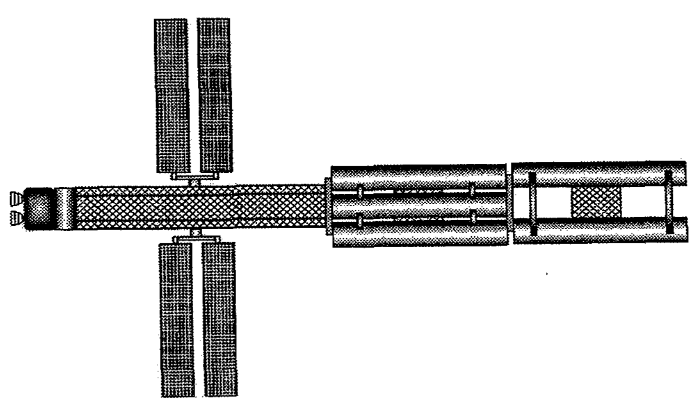
Mission Description

- Split Mission
- Cargo Spacecraft
  - Will Utilize Low-Thrust Ion Propulsion
- Crew Spacecraft
  - Will Utilize High-Energy 150-Day Sprint Trajectory
- Remote rendezvous
  - Required for Resupplying and Refueling of the Crew Spacecraft
- Mars Excursion Vehicle (MEV)
  - Provide Crew with Transportation to and from the Surface of Mars
- 30-Day Ground Phase

Cargo Mission Overview

- Spacecraft is designed to deliver surface exploration equipment and return trip supplies
- Cargo spacecraft equipped with a Mars lander loaded with exploratory equipment and supplies
- Cargo spacecraft sent on low energy trajectory
- Ion propulsion
- Crew module will dock with the cargo spacecraft for supplies, refueling, and lander usage

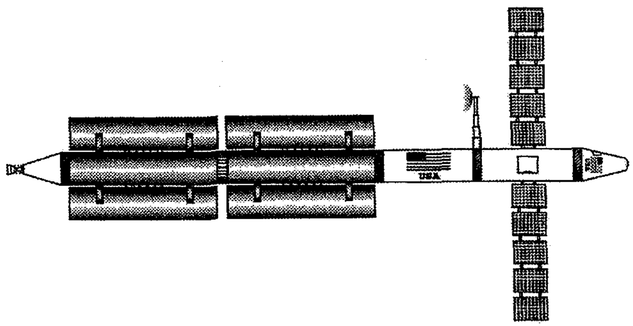
Cargo Spacecraft Conceptual Design



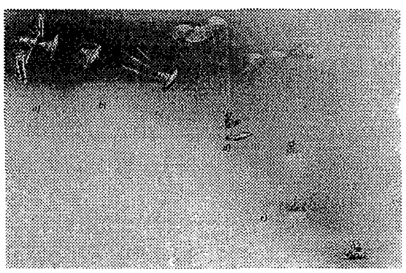
Crew Mission Overview

- Manned Spacecraft
- Spacecraft is a Transfer and Return Vehicle
- Cryogenic Propulsion (LOX/LH2)
- Spacecraft Sent on a High Energy "Sprint" Trajectory
- Spacecraft will Dock with the Cargo Spacecraft to Resupply, Refuel, and Access Lander

Crew Spacecraft Conceptual Design



MEV Mission Overview



- MEV separates from cargo spacecraft and enters Martian atmosphere
- Parachutes are deployed to slow fall and heatshield is jettisoned
- Parachutes jettisoned, legs of MEV extended, and retro-engines fired for final deceleration
- MEV touches down

Ground Phase Mission Overview

- One month stay
- Perform UAV experiments
  - Set up all equipment
  - Determine areas of interest
  - Remotely pilot the aircraft
- Perform observatory/science experiments
  - This has yet to be determined
- Collect Martian samples for analysis at Earth
  - This has yet to be determined

Crew Spacecraft Details

TRAJECTORY ANALYSIS

- Trajectory Utilizing Lambert Targeting
  - Requires Only the Present Location, Arrival Destination, and Time of Flight
  - ΔV's can be Easily Determined
- Approximately 150 days (1 way)
- Arrive in Low Mars Orbit (LMO)
- Conduct Rendezvous with Cargo Spacecraft

Trajectory Analysis: Sample Optimized ΔV's:
(Source: Tim Crain's Web Page)

Year 2007: 150 Days

	Launch	Arrival	Combined
Departure Day	275.0	328.0	295.0
Arrival Day	60.0	113.0	80.0
ΔV (km/s)	4.397	3.226	9.027

Year 2008: 150 Days

	Launch	Arrival	Combined
Departure Day	1.0	1.0	1.0
Arrival Day	150.0	150.0	150.0
ΔV (km/s)	13.66	5.033	18.693

Year 2009: 150 Days

	Launch	Arrival	Combined
Departure Day	311.0	365.0	333.0
Arrival Day	96.0	150.0	118.0
ΔV (km/s)	4.445	3.778	10.113

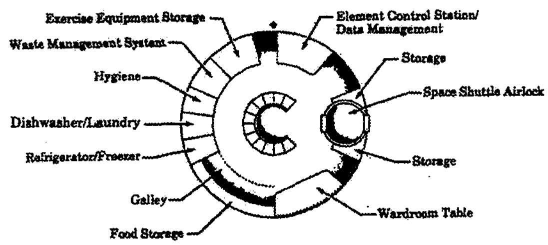
Subsystems

- Propulsion
  - Pratt & Whitney RL-10 A-4-1's
  - LOX/LH2 Propellant
  - Max. Thrust (vac.) 22,300 lb.
  - Isp 451 sec.
  - Special Features:
    - Multiple Starts in Space
    - Expander Cycle provides Self-Starting Capability

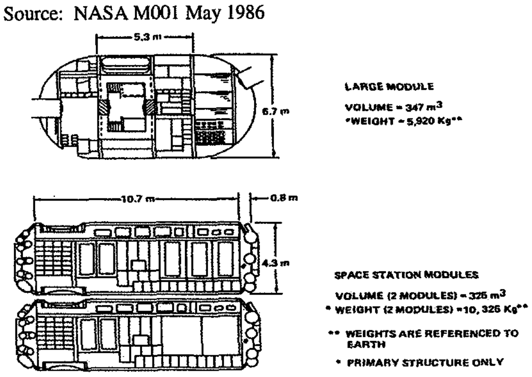
Source: Pratt & Whitney Co.

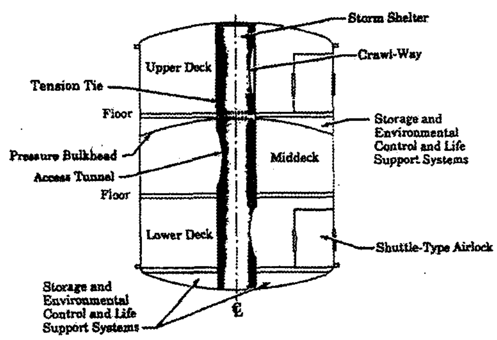
Subsystems

- Crew Modules
  - 3 or 5 Crew Members
  - Multiple Sections
  - Multiple Decks



Source: NASA M001 May 1986





Subsystems

- Environmental Controls and Life Support Systems (ECLSS)
  - Food (pre-packaged, no vegetation)
  - Hygiene (shower)
  - Exercise Equipment (bicycle or treadmill)
  - Water and Waste Management (recycle)
  - Space Suits
  - Temperature and Humidity Control
  - Atmospheric Pressure and Composition Control

Subsystems

- Radiation Shielding
  - WHY?
    - Protection Against Solar Flares and Galactic Cosmic Rays
  - HOW?
    - Place Matter Between the Crew and Radiative Rays
    - Aluminum Shielding, Water, Propellant
    - Existing Equipment
  - EFFECTS?
    - Cell Damage, Vomiting, and Nausea

Crew Mass Analysis: Mars Crew Transfer Vehicle

Spacecraft System	Specifications	Mass (kg)
RCS/Attitude Control	Gyro/Guide Star Telescope	8236.0
Avionics	TBD	1000.0
Radiation Shielding	TBD	9000.0
Crew Module	TBD	25000.0
ECLSS	Standard	14875.0
Earth Re-entry Vehicle	(Apollo Type)	5500.0
Power Systems	Solar/Fuel Cell/Battery	1600.0
Propellant	LOX/LH2	992176.0
Propulsion System	RL-10 (5)	1400.0
Structure	TBD	3977.0
Tankage	TBD	25330.0

Total Vehicle Mass: 1,100,000 kg (~1200 Tons)

Reliability Statement

- Thoroughly Researched
  - Mission Concept
  - Trajectory Analysis
  - Propulsion Systems
  - Remote Rendezvous
  - Preliminary Subsystems
  - Technological Requirements
- More Research Needed
  - Mass Analysis
  - Spacecraft Structural Design
  - Subsystems Power & Volume Requirements
  - Ground Phase

Future Work

- Investigate:
  - Abort Scenarios
  - Science Equipment/Experiments
  - Spacecraft Mass
  - Spacecraft Structural Design
  - Subsystems Power & Volume Requirements
  - Ground Phase
  - Human Factors

Conclusion

Mission Description:

Cargo Spacecraft

Low-Thrust Trajectory to Mars

Cargo Includes: Return Supplies and Fuel, MEV

Crew Spacecraft

High-Energy Sprint Trajectory to Mars

150 Day (1-Way)

Remote Rendezvous

Crew S/C Docks with Cargo S/C in LMO

Crew Transfer to MEV

Conclusion

Mission Description:

- MEV
  - Provide Crew Transportation to Martian Surface
  - Possible Habitat for Crew
- Ground Phase
  - 30-Days
  - For Exploration and Experimentation

NASA DESIGN PROJECTS AT UC BERKELEY FOR NASA'S HEDS-UP PROGRAM

Lawrence H. Kuznetz, PhD.
Instructor, Mars by 2012
University of California, Berkeley

INTRODUCTION	**Lawrence H. Kuznetz, Professor**
INTERACTIVE DESIGN ENVIRONMENT	**Sachin Shah**
SPACESUITS FOR MARS	**Sheyna Gifford/Tatiana Becker**
HYPOGRAVITY COUNTERMEASURES	**Franco Navazio/Connie Yu**
ELCSS	**Donald Beams**
SCIENCE HAB DESIGN	**Gordon Smith**
CREW SIZE	**Alexia Cooper**

BACKGROUND

Missions to Mars have been a topic for study since the advent of the space age. But funding has been largely reserved for the unmanned probes such as Viking, Pathfinder and Global Surveyer. Financial and political constraints have relegated human missions, on the other hand, to backroom efforts such as the Space Exploration Initiative (SEI) of 1989–1990. With the newfound enthusiasm from Pathfinder and the meteorite ALH84001, however, there is renewed interest in human exploration of Mars. This is manifest in the new Human Exploration and Development of Space (HEDS) program that NASA has recently initiated. This program, through its University Projects (HEDS-UP) office has taken the unusual step of soliciting creative solutions from universities.

DESIGN PROJECTS

For its part in the HEDS-UP program, the University of California at Berkeley was asked to study the issues of Habitat design, Space Suits for Mars, Environmental Control and Life Support Systems, Countermeasures to Hypogravity and Crew Size/Mix. These topics were investigated as design projects in "Mars by 2012", an ongoing class for undergraduates and graduate students. The methodology of study was deemed to be as important as the design projects themselves and for that, we were asked by Dr. Mike Duke of LPI to create an Interactive Design Environment. The Interactive Design Environment or IDE is an electronic "office" that allows scientists and engineers, as well as other interested parties, to interact with and critique engineering designs as they progress. It usually takes the form of a website (in our case, http://mars2012.berkeley.edu) that creates a "virtual office" environment. That environment is a place where NASA and others can interact with and critique the university designs for potential inclusion in the Mars Design Reference Mission.

PRESENTATION

UC Berkeley's presentation at the HEDS-UP conference at LPI started with a vision of how the IDE could be used to create a virtual organization tying together universities working on various Mars mission elements. The vision starts with the reasons for using universities to contribute to the design of the Mars reference mission, and continues by demonstrating the benefits of a large-scale space program such as Apollo to the economy, in terms of math/science graduates, patents and technology base. Figure 1 shows the breakdown of the Design Reference Mission into distinct elements that can be disseminated to universities or groups of unversities for study. These universities would have proven expertise in the mission element area. Figure 2 is a prototypical virtual organization chart that would tie the universities together under the auspices of a guiding NASA office such as HEDS-UP and the NASA University Affairs office for the purpose of distributing and critiquing the work on a semester by semester basis. In such an organization, each semester's work would be fed back to the next semester's group of students to provide continuity and improvement. The basis of this approach is that over the course of the months and years necessary for maturation of the design reference mission, these university studies could evolve to serious engineering designs, possibly even flight hardware, at a fraction of the cost associated with traditional government contracts. The talent, free labor, enthusiasm and facilities of universities would be the vehicle used to accomplish such a cost benefit.

Figure 3 displays the "Mars by 2012" demographics. Its purpose is to show how the large and disparate student makeup and design project philosophies provided an analog for the bigger organization. The intent here is to show that the organization created for the class could be used as a model to test the viability of the IDE concept for the larger university model.

In summary, the "Mars by 2012" class, with over 60 students working on 6 different design projects, was deemed a suitable testing ground for the IDE model to see if it could accelerate the design process. The IDE website provided information exchange, links to expert resources, documents, chat room meetings between groups and group leaders, archiving of data, mail and brainstorming sessions, and proposed solutions to the design projects as well as critiques, threaded by topic, date or author.

Following this introduction of our vision for HEDS-UP and the concept of the IDE, each of the individual groups were called to the podium at LPI to present their findings in detail. The order of these presentations were as follows: The Interactive Design Environment, presented by Sachin Shah; Space Suits for Mars, presented by Sheyna Gifford and Tatiana Becker; Countermeasures to Hypogravity, presented by Connie Yu and Franco Navizio; Environmental Control and Life Support Systems, presented by Anthony Beams; Designs for the Mars Habitat, presented by Gordon Smith; and Crew Size and Mix Issues, presented by Alexia Cooper. Summary reports of these presentations, as well as recommendations for future work, are in the sections that follow.

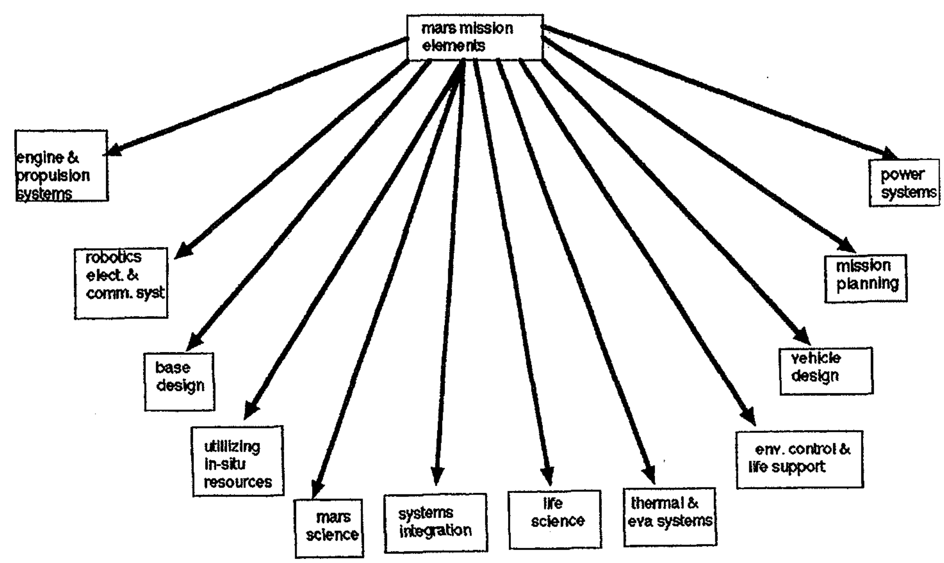


Fig. 1.

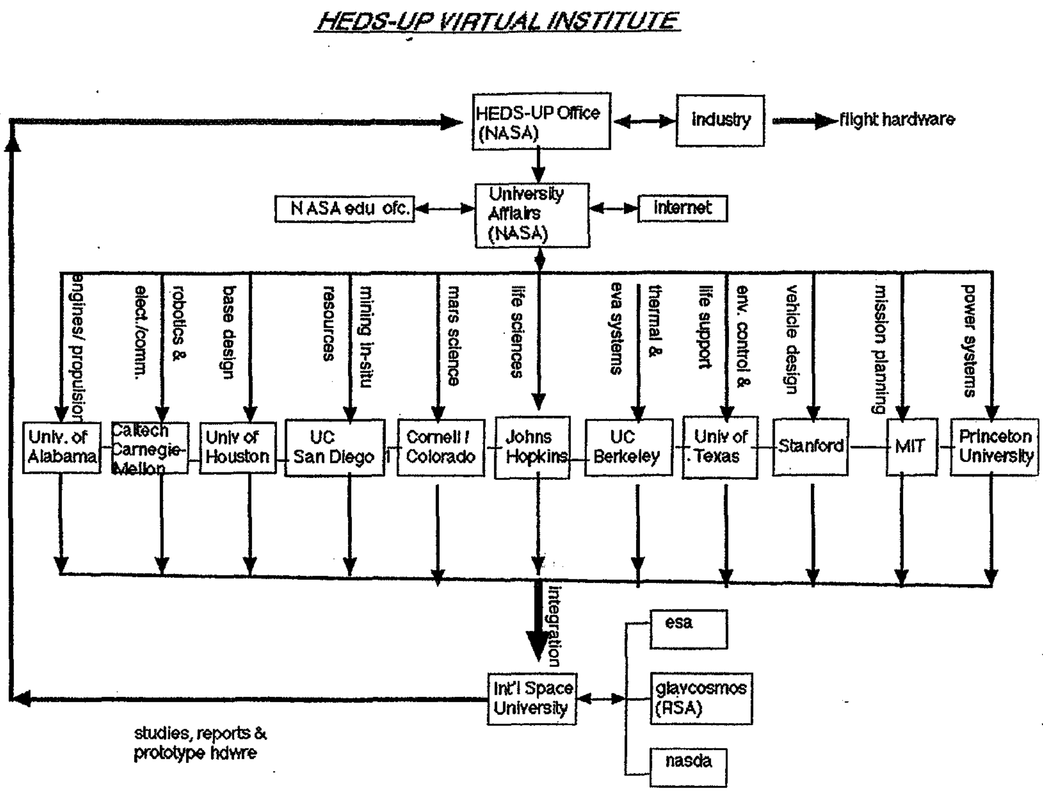


Fig. 2.

UC Berkeley IDS 60...Mars by 2012

- Large class (60 students)
- Undergraduates
- Diverse majors
  - mechanical/civil/electrical engr
  - molecular/cell biology/physics/chem
  - computer science
  - economics
  - architecture
  - other
- Diverse mix
  - 1/3 women
  - 1/3 ethnic/international
- Lectures given by acknowledged experts in field
- Six design projects accompanying lectures
  - Six teams (approx 10 students/team)
    - Spacesuits
    - Countermeasures
    - ECLSS
    - Science Hab
    - Crew size
    - IDE

Fig. 3.

THE INTERACTIVE DESIGN ENVIRONMENT

IDE Team Members: Yuan-Juhn Chiao, Cora Estrada, Mike Goff, Billy Martin, and Sachin Shah

When we were assigned the task of creating the Interactive Design Environment at the beginning of the semester, the IDE team had one question: What is an IDE? After months of research we discovered the IDE is essentially the central processing plant of the virtual institute, a collection of tools designed to facilitate the exchange and development of ideas between and within the various groups. The IDE is, if you can imagine, the hub of a wheel, with each tool acting like a spoke, supporting the rim which consists of the various groups (e.g. Space Suit, Habitat, etc.). Once we figured out what the IDE is, we needed to figure out what it should do and what it needed to do. In order to help convey our vision of the IDE, I shall now take you on a metaphorical journey.

Pretend it is your first day at work. What are some essential questions you will have? Well, the first thing you are going to need to know is: who are your team members? Who are the people you are going to be working with? To find the answers to these questions, you turn to the IDE. Using the "Profiles" tool, you can easily find introductions and pictures of all of your team members, along with vital contact information and areas of expertise.

So you know who you are going to be working with; now it is time to get started. But what is it you are going to be doing? In the real world, your boss would now drop a stack of research material on your desk and say: catch-up. However, in our virtual world, you simply click on the link that leads you to the "Documents" section. Here you can find a variety of hyper-documents to update you on the history and current status of the project.

All right, you are now all caught-up. But what if you have questions? To whom can you turn to find answers? Who are the experts in your field? The "Contacts" page will reveal all. Here you can find the contact information for the various experts and third-party sources in your project area.

Now, what are your resources? Where can you turn to find primers and help researching your topic? You can find all of these sites under the "Links" page. From the "Links" page you can immediately leap across the web, going directly to supporting sites such as the HEDS-UP page.

Great, you are caught up and ready to start working. One problem: you have no idea what you are doing! That's when your boss comes in and tells you it is time for your section meeting. This is where you will be assigned your task, and find out how your team members are progressing. However, in the virtual world, you don't need to leave your desk. Your team members don't even have to be in the same state! You simply enter the "Chat" section, where you will enter a virtual conference room with your team members.

You've met your team members and you now know your share of the project. But what has already been done? You wouldn't want to repeat what others have already accomplished. So you enter your team's section of the IDE and read about the problem definition and what progress has been made in your area. Here you can also retrieve data posted by other team members or invited third-party support groups.

Now you start thinking: what are some possible solutions to my task? In the real world, you would head to the library, and begin research on possible solutions. However, in our virtual world, you head for "The Collaborative Digital Library." Here you can search for sites with information on your topic, and read reviews of the site by other team members. This way you can get a basic idea of how valuable the site will be to your research without having to load each site.

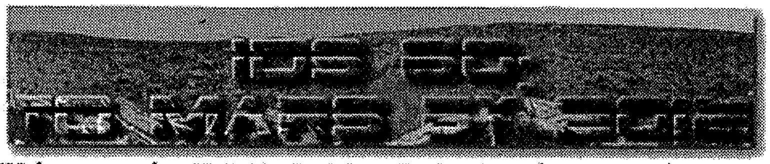
Wow! Only your first day at work and you have already come up with a solution. But you need feedback from your team members. You need to find out what other people think. So you send out an email with your proposed idea to your team address, where it will get distributed to all interested parties. They in return will provide you with feedback. And this entire exchange of ideas can be tracked from within the "Mail Archives" where you can search by subject, date or author, and follow a virtual paper trail of ideas as they develop into tangible solutions.

At this point I would like you to imagine the IDE not as a wheel, but a ship's wheel. And this wheel is what you will use to navigate the virtual institute, through the choppy waters of budget cuts and bureaucracy, and into the wide, open seas of a cheaper, faster, better way.

The purpose of IDE is to help you answer the following questions: Who are my team members? What is the background of the project? Who are the experts in this field? What are my resources? What is my task? What work has been done on my topic? What are some possible solutions? What do other people think?

Site Map

- Home
  - Course Info
  - Guide
  - COOL System
  - Discussions
  - Teams
  - Profiles
  - Documents
  - Links
  - Contact Info



Welcome to the *IDS 60: To Mars By 2012* Spring 1998 Classpage.

A Brief Intro to this Site:

- The site map on your left will serve as your guide. If you are going to be a frequent visitor (i.e. a student enrolled in IDS 60) to this site, you may want to click on the Home link prior to bookmarking this site. This will expand the tree structure partially, allowing you quick excess to the important links.
- The News section below will inform you of any announcements.
- The What's New section below will inform you of any new additions as well as updates to this site.

News:

- 04/22/98: You should make EVERY EFFORT to attend Thursday's (04/23) lecture by **Astronaut Byron Lichtenberg**. Bring your friends! Dr. Lichtenberg will show a not-seen before video of a shuttle launch from inside the cockpit. Byron K. Lichtenberg, 44, was selected as a payload specialist by NASA in 1978. Lichtenberg was born in Stroudsburg, Pa., and has made 3 shuttle flights.
- 04/21/98: After a discussion with Prof. Kuznetz there has been an should nominate best qualified individual. We'll be leaving on saturday morning, may 2 and return on thursday or earlier if you have to. Hotel is covered as is tour of Johnson Space Center. We have been given 30 minutes to talk on monday afternoon as well as another slot of time in round table discussions wednesday. We also need to bring 2 44x44 inch posters for poster presentation in lobby of lunar planetary institute. Use the CNN shoot as a dry run if possible for material your team would like to show. Remember...keep it simple, novel and to the point. - Dr. K

What's New:

- Attention Team Webmasters! Teampage templates are in your respective directories as "teamtemp.html". Please use the template for creating any pages for your team.
- Mars Mid-Term Survey is due Tuesday, April 7th!
- The team coordinators have agreed to meet at 3:00p on Tuesdays before class *and* in the General Chatroom on Thursdays at 9:00p.
- Email lists are active! Students & NASA scientists can send email to the various groups by clicking on the following links:
  Crew Size | Exercise | Habitat | Integrated Design Env. | Life Support | Space Suit
  The messages sent to these lists will get logged and categorized in a searchable format under the Discussions section.

This page was last updated on April 23, 1998.
Site design and graphics by Sachin Shah, created on March 01, 1998.
Site Managed by Sachin Shah, Mike Goff & Alex Cuthbert.

Example home page from UC Berkeley NASA design project showing the interactive design environment.

MARS SUIT DESIGN PROJECT

Mars Suit Design Group Team Members: Sheyna Gifford (team lead), Jamaica Lambie, Tatiana Becker, Minka Ludwig, Elizabeth Yale, Pete Dorman, Chris Spitzer, John Chang, Benjamin Hartshorne, Jeff Marx

In Spring 1998, our research team at UC Berkeley examined new technologies for a space suit to be used in a future Mars mission. Using the Interactive Design Environment created by our IDE group (http://www. mars2012.berkeley.edu), we formulated requirements for this EVA suit and hypothesized design solutions. Our research eventually led us to dense monolithic membranes and the Polymer Technology Group in Emeryville, California. Mr. Robert Ward, the company president, discussed the properties of these membranes with our group for their possible inclusion in spacesuits.

The attractiveness of these membranes is rooted in the fact that they can serve as a pressure bladder, thermal control system and biological contaminant barrier, we believe. If this proves to be the case, they would have great potential for substantive weight reduction of a Mars suit, thereby significantly enhancing the conduct, efficiency and productivity of EVAs on the martian surface.

It is our strong recommendation that these dense monolithic membranes be studied further and that a prototype suit be built to test their merits in the field.

BACKGROUND/RELEVANCE

To date, NASA's space suits have been built for earth orbit's zero (micro) gravity and the Moon's 1/6 gravity. These suits, extremely heavy, thick with insulation and relatively unmaneuverable, perform well in the hostile environments for which they were intended.

It is unlikely, however, that a space shuttle suit or any close relative will prove satisfactory on Mars. The environment of Mars presents a new set of challenges and advantages, radically unlike those for which Shuttle and Apollo suits were designed. In addition, the Mars Design Reference Mission states that important scientific research is one of the two main goals of any human mission to Mars.

Research on Mars will involve a human presence outside the habitat. However, current suit designs will not allow the planetary explorer to be productive in the field. Martian gravity presents the first barrier to the suit designer. The one-third earth g loading, would make the nearly four hundred pound shuttle suits too heavy and unwieldy to "get down in the dirt and work", as NASA-Ames astrogeologist, Chris McKay puts it. The thick layers of the current mechanically pressurized suits are an impediment to meaningful scientific work. They limit joint motion and make small finger manipulations all but impossible. Finally, cross contamination is an issue with them. The suit designer must include a biological barrier in a Mars suit, a feature not required in the sterile environments of the Moon and low earth orbit.

Countering these challenges, the designer has the martian environment working to his or her benefit. Temperatures are more moderate on Mars. Thermal modeling indicates fewer layers of insulation need be used. Mars has seasons so the thickness of suits can be tailored to match them. Astronauts could wear thinner suits in summer, thicker suits in winter. Finally, the designer can allow the martian environment to absorb some of the heat created by the astronaut's activities. It may well be that the suit need not be burdened with the excess mass of a closed loop system.

We believe that a dense monolithic membrane of the type developed by the Polymer Technology Group is a potential solution to the Mars suit conundrum. This membrane, called Biospan, is a dense, non-porous polymer that retains pressures in excess of 8 psi while allowing water vapor to diffuse across the pressure gradient by an active transport process. When combined with an appropriate restraint layer (the nature of which remains a topic for future study), Biospan could serve as a passive, lightweight pressure and thermal control system that maintains biological isolation. The resultant benefits in weight reduction, mobility, dexterity and performance would contribute to more meaningful scientific research, one of the two primary objectives stated in the Mars Design Reference Mission.

OBJECTIVES

The goal of suit design is identical to the goal of the Mars Design Reference Mission: the properly designed suit should make it possible for humans to conduct scientific exploration on the martian surface. Indeed, without functional EVA equipment, exploration will be impossible. *If suits are too heavy, if they don't allow a range of movement for walking, bending, kneeling, and climbing in 1/3 g, a human mission to Mars will be defeated before it begins.*

The objectives in designing Mars EVA suits are very different from the objectives behind the Apollo program. In Apollo, the goal was to get to the moon and back. Engineering was the primary driver, then science. As for suit design, the question of what kind of science can be done was asked after the suit had been built. Those priorities are reversed for a Mars suit. The first question is, what kind of science do we need, the second, how will that influence suit design.

Unlike Apollo, there is no Cold War to compel us to go to Mars today simply because we can. Consequently, we cannot afford to waste the scientific opportunities that wait in the martian deserts. If and when they present themselves, we must take advantage of these opportunities by having an EVA suit that will enhance research.

REQUIREMENTS

Over the course of this semester, our group brainstormed a number of requirements for the Mars EVA suit. Some of these requirements are addressed by the dense polymer technology; others are not. This list follows.

<u>A MARS EVA SUIT MUST:</u>

1. Weigh less than 140 pounds, earth weight, including the PLSS and all accessories
2. Be durable enough to withstand radiation and dust as well as occasional falls to the surface.
3. Be cost effective
4,. Be easy to don/doff
5. Be flexible, especially at the joints, to promote the fullest range of natural movement.
6. Keep the astronaut at a comfortable body temperature, regardless of the martian season or the kind of metabolic workload.
7. Form an effective cross contamination barrier.
8. Be easy to clean, maintain and repair.
9. Integrate with the habitat and the rover

CONCLUSIONS/RECOMMENDATIONS

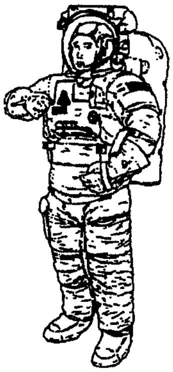
The Suit Design Team has concluded that the internal garment of the EVA suit represents the best source of potential weight savings/ performance gains. The use of the Biospan membrane, supported by a polypropylene insulating layer internally and a silicone rubber-coated heavy duty nylon externally is our choice for that internal garment. Research and testing should be done in several related areas to validate this design.

First we must ensure that the polymer will perform as advertised. We plan to do this in upcoming semesters by contructing an actual suit component such as a torso that can be put through pressure, durability and permeability testing in a lab setting. We would also like to build a glove component so that mobility and dexterity testing can be performed.

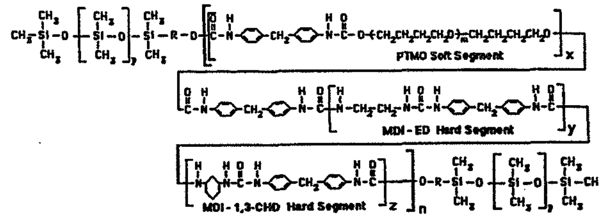
The liquid collection and storage system must also be researched. Once moisture permeates through the polymer membrane layer, it must either be rejected to the atmosphere or collected and stored in the suit. Persistant concerns over the risk of contaminaton make the preferred method liquid storage. However routing perspiration and other moisture (in vapor form) to a central location for condening and storage presents a unique set of problems of their own.

Once the above concerns have been addressed, a prototype thermal control and restraint layer system can be constructed. This work should illuminate any remaining design issues and allow testing of the system as a whole. With proper encouragement from NASA, the university community and industry, we would like to perform that work.

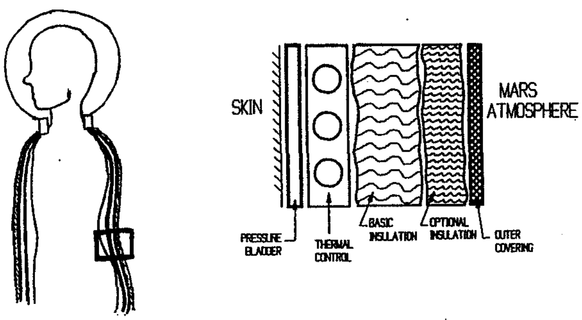
WOULD YOU RATHER GO HIKING



IN THIS SUIT OR THIS SUIT?



Chemical structure of BioSpan-S segmented polyurethane showing polydimethylsiloxane surface-modifying end groups on BioSpan base polymer. From "Development of a New Family of Polyurethaneurea Biomaterials," by Robert S. Ward and Kathleen A. White, The Polymer Technology Group Incorporated, 4561-A Horton Street, Emeryville, California, USA.



SUIT CROSS-SECTION

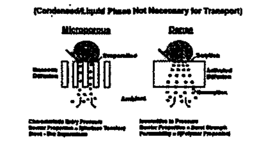
Biospan

1. Hydrophilic
2. Dense
3. High tensile strength

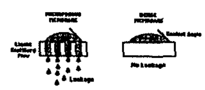
How Biospan Could Replace
LCG & Sublimation System

1. It's hydrophilicity makes this polymer an excellent "sweating suit".
2. Density = "unquestionable" biological
3. Strength = Maintaining structural integrity in the face of all the motion a Martian EVA would require.

Microporous vs Nonporous (Dense) Semi-Permeable Membranes



Effect of Pressure and Contamination on Liquid Barrier Properties of BBFs



Physical Property Comparison: PTG vs Conventional Polyurethane

	PTG-PU	Typical PU
Tensile Strength [psi]	4300	5000
Initial Modulus [psi]	500	2200
Ultimate Elongation [%]	1100	800
MVTR [g/M²/24 hr][1]	18000	2700

1. 0.5 mil unsupported film / Inverted Cup MVTR

EXERCISE COUNTERMEASURES

Exercise Countermeasures Team Members: Crispin Barker, Brett Bondi, Sian Geraghty, Anoop Ghuman, Jason Kintner, Dr. Franco Navazio, Lanny Rudner, Connie Yu

NOTE: Countermeasures based on rotational devices to implement artificial gravity were considered but were not the focus of our research since we did not want to reinvent the wheel. Significant work has already been done in this area pointing to the complexity and expense of implementing such systems, and their potential safety concerns.

There are many physiological problems associated with space travel. Our responsibility in the Exercise Countermeasures Group of the Mars by 2012 class at the University of California, Berkeley, was to research and brainstorm solutions to them. Perhaps the most insidious problem facing astronauts on a mission to Mars will be bone demineralization. Most bone loss occurs in the weight bearing bones, especially the heel and legs. Paradoxically, there is actually an increase in bone mass in the head and hands! One prospective solution we investigated was to increase overall bone mass through an increase in vitamin D. Vitamin D is important in bone formation. It has been found that whales maintain a hypervitaminosis D condition that may help to maintain an adequate skeletal system in the sea. The sea is a neutrally buoyant environment and whales are mammels living in what amounts to a zero gravity world. They have a human-like skeletel structure but maintain bone mass in spite of their low gravity environment. Perhaps hypervitaminosis D plays a role in their homeostasis. (Another theory may be that whales create an "artificial gravity" loading in their neutrally bouyant world by breaching. If true, the frequency and intensity of their breach patterns may be useful in establishing an analog for the duty cycle of impact devices or rotational frequency in artificial gravity in spacecraft.)

Two other methods we looked at to decrease bone demineralization are electromagnetic stimulation and implants. Electromagnetic stimulation devices have been shown to help fracture sites. Nanoimplants that release bone morphogenetic hormone have been shown to slow the rate of osteoporosis in highly susceptible bone demineralization areas such as the heel. Both electromagnetic stimulation and nonoimplants can specifically be targeted to a problem area such as the lower extremities. They also have the benefit of being lightweight and portable, always a concern in the design of spacecraft.

The primary focus of our research was exercise countermeasures. Sian Geraghty brainstormed four different systems that provide stress to the skeletal system through impact or other means. The virtual suit resists the astronaut's movements while he or she is moving through a virtual reality display working every muscle group in the body. Bouncercise and Space Balls provide an element of fun to the exercise routine, always a concern on a thousand day mission where exercise and other routines can become tedious and unmotivating.

Another type of impact/fun exercise we looked at is partner exercise. These strengthen muscle groups as well as group dynamics without increasing the mass of the spacecraft from unnecessary exercise machines attempting to do the same function. as the astronauts use their partners as a source of resistance.

Jason Kintner's designs looked at modifying existing exercise machines using virtual realtiy to again, break the monotony of the exercise routine. One aspect of his design that is of particular interest is the shoulder bar over the stair climber device. The shoulder bars can be adjusted to provide a downward force on the astronaut so that the impact of walking may be similar to that of walking on Mars or Earth. The body loading can also be made comparable to what an astronaut may experience when wearing a Mars EVA suit. Using such a device, an astronaut's skeletal system can be preconditioned to the environment that it will face leading up to the EVA.

Lanny Rudner designed an impact machine for exercises that help maintain the muscles of the stomach, back and arms. While it looks big, imposing and too heavy to fit in a spacecraft, the concept is adaptable to a lightweight, space-saving design (next semester's work). The main points of interest in this machine are the shoulder bars and bungee harness attached to the floor. The bungee cords are attached to a belt fitted around the crewman's waist. When the astronaut jumps, it provides resistance to the jumping action, thereby working the leg muscles. The belt also keeps the crewperson rooted to the floor so that the second part of the jumping exercise can be carried out. When the astronaut rebounds the floor, the impact on the heels stress the skeletal system,especially the lower bones. The shoulder bars can also be used as a source of pressure for upper body impact exercises.

RECOMMENDATIONS

Next semester, we hope to refine our impact machine designs and continue looking at drugs and whales as topics for study. Another project we intend to study further will be the simulation of the G profile of a Mars mission, in which we brainstorm countermeasures that provide partial 1/3 gravity on earth. This simulation is especially important because the physiological information accumulated for a mission to Mars is thus far purely hypothetical. Of paramount concern is that there has been no bottoming out of bone demineralization rate in zero g to date. The extent to which bones will decalcify in hypogravity is merely an extrapolation of inadequate data.

We look forward to doing more in next year's class. However the extent to which we can actually make a contribution depends upon access to data. As we all know, gigo (garbage in/garbage out) generates woefully unimpressive work. Although we now have a useful tool in the form or our IDE website, it can only help us if we can tap into the right kind of database, such as the Life Science Archive and others. We hope that we'll be able to that with the assistance of NASA and LPI.

COUNTERMEASURES TO PROBLEMS UPON

1. Predeparture Screening of Crew*
2. Departure
3. Flight to Mars (6–8 mos.)
4. Martian Landing
5. Life on Mars (18 mos.)
6. Departure to Earth
7. Return Flight (6–8 mos.)
8. Landing on Earth
9. Post Landing Quarantine and Reconditioning

*Inclusive of the Colia 1 Genotype

COMPLEMENT WITH

Pre- and Postflight Data on Bone Status with

1. Single Energy Absorptiometry*
2. Dual Energy XR Absorptiometry**
3. Quantitative Computed Tomography***
4. Ultrasonography****

*Very precise for forearm and heel

**Very precise for total body assessment with very low dose of radiation

***Good assessment of trabecular bones

****Somewhat less precise but could be used in flight

"The Study"

In 2–3 astronauts with identical controls, measure the pre- and postflight (60–120) of the following variables:

1. Vitamin D Intake
2. UV Exposure
3. Blood Levels of:

Ca^{++}; Inorganic P; Albumin; Vitamin D Binding Protein; Osteocalcin; Hydroxylysine; Procollagen ICP; and 25 Hydroxy Vitamin D

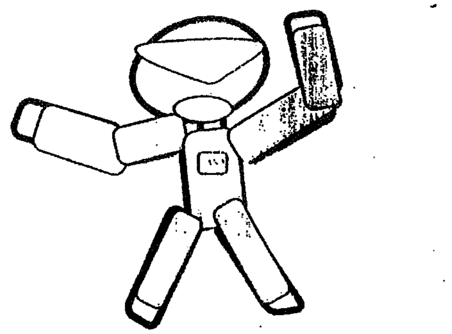
4. Urine Concentration of:

Ca^{++}; Hydroxyproline; Creatine and Deoxypyridoline

FUTURE GOALS

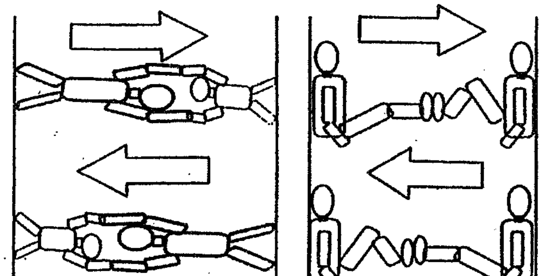
- Simulation of Mars trip
- Test of countermeasures
- Determine intensity and frequency of impact exercises
- Whale study
- Vitamin D tests

Virtual Exercise



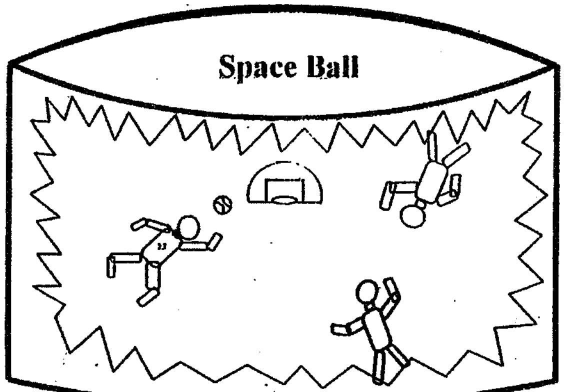
This design combines a full body resistence suit with virtual reality. The virtual reality asks the astronaut to play an endless variety of programs from sport based games like virtual basketball and virtual soccer to obstacle courses and combat games. All of the games require the astronaut to use a wide range of movements to successfully play the game. As he plays he is wearing a resistence suit that meets his every gesture with a force. In playing the game, the astronaut [illegible] against the resistence of the suit to provide a fun and interesting workout

Partner Exercises

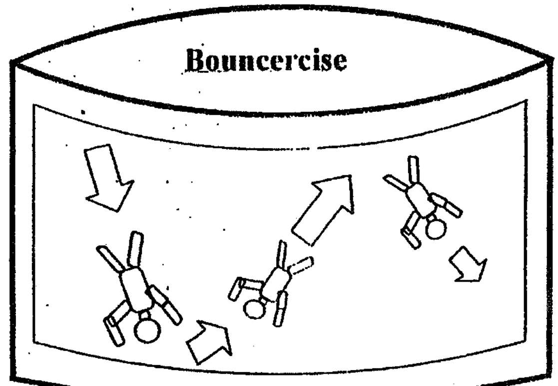


Partner exercises are another alternative to traditional exercise machines. The astronauts use each other's strength as resistence. In this exercise the astronauts brace themselves against a wall and alternate pushing on each other. This builds muscles and provides pressure on the skeleton.

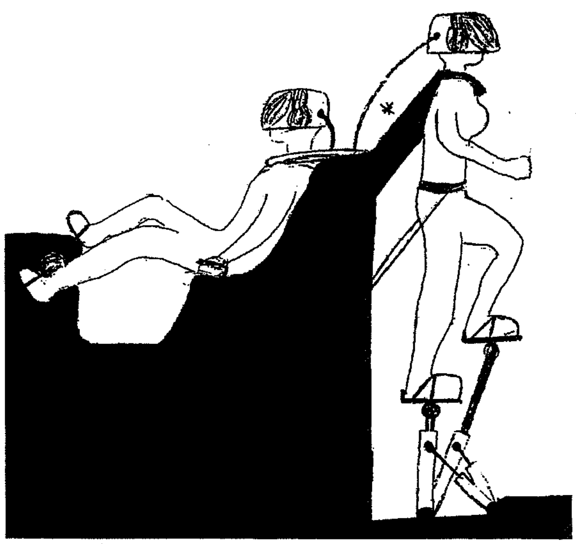
This is a partner exercise that targets the leg muscles.



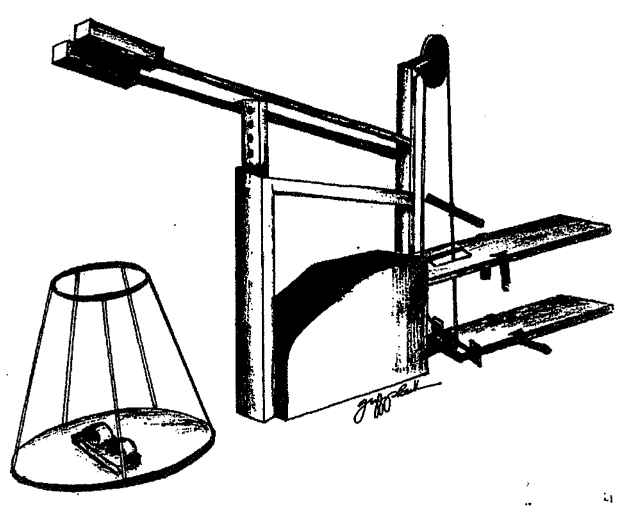
In addition to bouncing, the astronauts can make a game of their exercise. Possibilities include basketball, football and dodge ball. This would promote team unity and better social relationships.



Exercise can be done in space without complicated exercise machines. The astronaut's own force can propel him into walls, and the impact force is an effective exercise for strengthening both arm and leg muscles



Modifying existing exercise machines using virtual reality.



Impact machine for exercises that help maintain the muscles of the stomach, back, and arms.

ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEMS

The Environmental Control and Life Support Systems presentation was divided into two parts. The first was a summary of our observations and recommendations concerning the closing of the life support system loops, and the second, a proposal for an experiment to test the duration of liquid water on the surface of Mars. In this paper I will be describing both and then supplying other information concerning the Life Support Group's recommendations.

One of the problems with sending a six man/woman crew on a 1000 day mission to Mars is that it takes eleven pounds of food, air and water to support each person per day. This translates to a total need of 150,000 pounds of consumables, an unrealistically high weight penalty. To overcome this obstacle, the three types of life support systems: open loop, chemical/physical and closed ecological, should be integrated. By so doing, the 150,000 pound penalty could be greatly reduced.

There are three methods of life support currently used: open loop, chemical/physical and CELLS (greenhouse or closed ecological life support systems). Open loop means all consumables are brought along and used with no recycling, scrubbing or transformation. Chemical/physical are recycling processes used to create consumables such as air and water from human output (i.e., urine reclamation from vapor compression/distillation or Sabatier/Bosch reactions). CELSS (closed ecological life support) are plant-based greenhouse systems that transform sweat, CO_2, urine and metabolic heat into usable consumables, requiring only power after initial setup.

Given the learning curve constaints of one semester, our group decided to focus on the benefits and detriments of each type of system. We charted system pros and cons with an eye towards using them in a mathematical model developed in subsequent semesters. Such a model would have the goal of optimizing economy, weight and power in an integrated system. Our longer term goal will be to utilize this model to develop an evoluationary plan for an integrated life support system on the martian surface from the first three years of human missions.

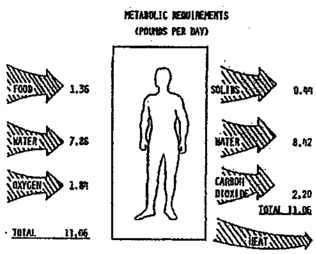
While the specifics of these tasks were beyond our technical abilities given the one semester timeframe, we did create a solution methodology that we felt could generate particulars in subsequent semesters. It is based on utilizing the IDE website discussed earlier to acccelerate information exchange and design ideas.

One conclusion our group arrived at early on was our cause would be greatly helped if we could find and use liquid water on the surface rather than bring it or manufacture it. This led to the second part of our presentation, an experiment to test for the presence and duration of liquid water on the surface of Mars. The idea stems from pressure and temperature graphs that show pressures well above the triple point pressure on the surface and temperatures above the freezing point. If these areas coincide for any length of time, thermodynamics dictate that water must exist in a liquid state. This is important for two primary reasons. First, if liquid water exists on the surface, it reduces the mass, cost, power usage and complexity of the life support system. Second and more profoundly, it greatly increases the probability of finding life (past, present, and hopefully referring). If life indeed does exist, it also creates the need for more emphasis to be placed on contamination, both forward and backward, in mission planning. It was for these reasons that we deemed an experiment to search for liquid water to be of value. As the viewgraph shows, such an experiment would use thermogenics to form ice on the surface on a mirror, then use optics and microwave radiation bombardment (for assessing molecular bond strength) to verify the presence of a liquid/ice boundary rather than the ice/vapor boundary thought to exclusively exist by sublimation alone. The advantage of such an experiment is that it could be ground tested first in a Mars environment simulation chamber such as the one at NASA/Ames. And if it shows promise, it could be implemented on a Sojourner-type rover as part of the Pathfinder series at a reasonably low cost. Our research has shown that the technologies to do this already exist, and it is possible to do it with off the shelf hardware.

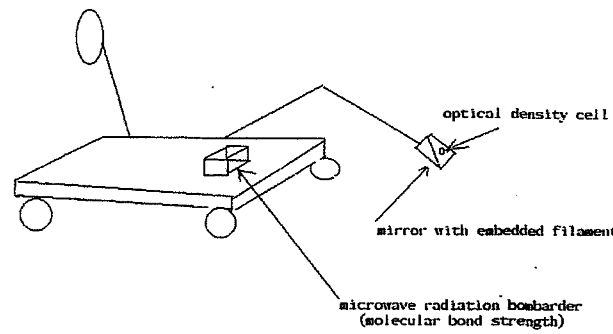
Many contacts and ideas were generated concerning future work of the Life Support Group. These are summarized in the final viewgraph of action items. In addition, joint projects with the University of Washington, and other universities and companies, were discussed at the conference. Many expressed an interest in being connected ito our IDE site. We were also fortunate in being able to visit the Johnson Space Center and see what NASA is doing with life support technologies, especially in the Bioplex facility. Hopefully our research will be able to contribute in some way to the future planning of this facility and its long-term testing of human subjects in Mars mission simulations.

Problem Statement:

- A completely open loop system for a crew of six would require the transportation of 150,000 lbs of food water and oxygen, generating an unrealistic cost for the mission



water/ice experiment



- **Methodology**
  - close Life Support Systems loops
- **Solution**
  - develop and integrate new technologies
    - design software to find best combination of open loop, physical/chemical, biological systems
    - develop communication between biological research institutions
  - continue bio-plex, South Pole , etc. experiments
  - create models showing relationships between ECLSS loops

Action Items

- Locate research topics
  - scaling problems
  - greenhouse technologies
  - recycling technologies
  - solar technology
- Update IDE with ECLSS data
  - expand web page library
  - continue to network connections
  - organize information sources
- Water/Ice Experiment
  - refine experimental design
  - develop Earth based simulation
  - Pathfinder implementation

System Pros and Cons

	Benefits	Disadvantages
Open Loop	• No research needed • Food, water, oxygen guaranteed / safe	• High Cost (Volume/Mass) • Time limited on Mars • Less information gained
Physical/Chemical	• Cost is cut down in long run • Available resources used • Extended stay possible	• More power needed • Start up time extended • Research time may cause initial delay
Greenhouse (closed loop)	• Long term costs will be the least • Possibility of colonization • Self sustaining • Less power 1. Oxygen /Air organically filtered 2. Use of sun as power • Larger work area • Wastes recycled • Extended stay allows for more research	• Start up of system 1. More than one mission is needed 2. Set up time 3. Start up cost 4. Maintenance 5. Resources required for greenhouse • Lack of research • ECLSS extremely fragile

HABITAT SCIENCE LAB

Money is obviously the primary consideration when designing any aspect of a manned mission to Mars. If one has only twenty billion dollars to spend, the habitat will look something like an oversized tin can, such as proposed by Zubrin, with only a tiny wedge in which to perform science (figure 1). If on the other hand one has half a trillion dollars, you can have a spacious facility with more than enough room to perform any science desired (figure 2). Not being privy to the budget of the future, our dilemma at UC Berkeley was how to tackle a design without first knowing the dollars available. Using our IDE website and resources available, our HABITAT group decided to attack the problem by emphasizing the science. That is, determine the scientific goals of the mission, the resources necessary to tackle them, then work from there.

Each experiment on Mars will require equipment, facilities, and manpower, which translates to a dollar value. If the budget is too restrictive, it inhibits not just equipment, but scientific goals. This is the key point. The point of view of our analysis focused on SCIENCE GOALS, not equipment lists. Not enough money means downwardly revised goals.

Our long term objective is to create a math model of a closed loop, iterative design process to solve this problem. While this is unrealistic in the short term of a nine-week semester, it is a reasonable goal in the long term of several semesters.

The vehicle we will use to create our closed loop model will be the IDE or Interactive Design Environment created by our IDE group. The format of our Mars by 2012 class provided us with many excellent sources of information related to our problem through the IDE website. Furthermore, by means of our guest lecture series, we had the opportunity to make contact with Dr. Chris McKay, Dr. Carol Stoker, Mark Cohen and other experts in the field. They have given us the tools to help us determine what we want to look for on Mars, where we need to look, and what equipment we need to include. We have also had access to NASA and NASA-AMES web sites to obtain background habitat designs.

Being students at UC Berkeley enabled us to visit biology, chemistry, and geology laboratories to get a better idea of the weight and volume of the equipment we were considering. Furthermore, through our IDE website, we were privy to many previous studies on Habitats and equipment list. To mention a few, these included the 90 Day Study report of 1990, the LPI/NASA Mars Design Reference Mission and Bob Zubrin's Mars Direct papers. From these sources we were able to ascertain the scientific goals of a mission to Mars. These goals can be divided into two general categories: Laboratory functions dedicated to the presence and long term survival of the human species, and laboratory functions dedicated to the understanding of Mars and its place in the universe, including the search for life. These functions will now be detailed below.

PRESENCE AND LONG TERM SURVIVAL OF THE HUMAN SPECIES

A primary need of the HAB laboratory will be to address crew health needs. This means exercise facilities for preventive countermeasures and equipment for monitoring crew health, especially in response to prolonged isolation, low (hypo) gravity, and radiation. Equipment for monitoring and preventing cardiovascular deconditioning, bone demineralization and immune system suppression will be essential.

The lab should also have facilities for testing of a biological, closed loop, life support system (i.e., a greenhouse). Such a system will eventually be integrated with a turnkey physical/chemical system but its performance must be evaluated beforehand by means of dedicated lab facilities. Determination of crop output from native resources will be critical to the long term goal of human settlement and self sufficiency. As such is it essential that the laboratory place a high priority on monitoring this output.

UNDERSTANDING MARS' PLACE IN THE SOLAR SYSTEM

First and foremost, the Habitat laboratory must have equipment for performing the search for extant and extinct life on Mars. This is one of, if not the most important scientific goals of the mission. Two other goals of the laboratory should be to support scientific studies of the geology, geography and climate of Mars and to provide a testbed for the development of in-situ resource utilization and manufacture.

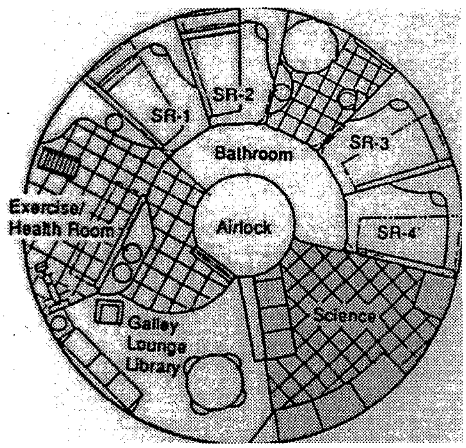
Starting with the scientific goals described above, we researched the experiments needed to achieve them. From these experiments, we then compiled lists of the equipment and facilities needed to implement them and from them, a rough idea of manpower requirements. With these pieces of the pie in place, we were finally in a position to begin prioritizing the scientific goals and experiments. This will be the work of the next phase of the project, since the compilation described above took most of this semester.

LABORATORY EQUIPMENT LIST

The laboratory equipment list is essentially a wish list of the things we would like to see included to perform all the work described above. It is only a partial list since we are still in the process or reviewing data from other sources of information. The task of next semester's team will be to complete this list and begin closing the loop of our design process. The model that does this must take account of constraints such as cost, weight, space and volume. Our goal in this model will be to use the minimum amount of equipment and man-hours to accomplish the maximum number of scientific objectives.

FUTURE GOALS/RECOMMENDATIONS

This semester, being the first in a new program, was a learning process. In summary, what we learned was how to focus on the definition of our problem and the development of a game plan to solve it. The IDE, though suffering through some significant growing pains at first, has reached a point enabling us to store our research, conversations, and thought processes. This will give next semester's teams a head start. It has also been our observation that the primary need of future teams will be increased contact with scientists and engineers in the field and attendance at forums such as the one held at LPI. We hope that the use of the IDE will greatly facilitate these contacts and that NASA takes the next step of making it a standard format that can be used by the government, other university teams, industry and the public.



EQUIPMENT LIST

- Gas chromatograph/Mass spectrometer
- Atomic force microscope
- Ion chromatograph setup
- Gas electrophoresis setup
- Polarimeter
- Beta Counter
- Active seismometer
- Passive seismometer
- Magnetometer
- Gravimeter
- Hematocrit minicentrifuge
- Low gravity centrifuge
- Microcomputers
- Age dating equipment
- Compound microscope
- Dissecting microscope
- Dissection instruments, ie scalpel
- 10 pints O+ blood
- Surgical table
- Surgical equipment, ie scalpel
- Intravenous/vascular access products
- Anesthesiology equipment
- Cardiopulmonary control unit
- Cardiopulmonary breathing unit
- Cardiovascular/Cardiopulmonary interface panel
- Gas analyzer/Mass spectrometer
- Gas tank assembly
- Physiological monitoring system
- Blood holding kit
- Body mass measurement device
- In-flight blood collection system
- Rack mounted centrifuge
- Tracer kit
- Tissue culture incubator

Scientific Goals

- Monitoring the health of crew.
- Search for life or signs of previous life.
- Develop biological life support for future habitation.
- Explore Martian geology, geography, and climate.
- Develop strategies to use in-situ resources for future habitation.

SCIENCE ⇄ MONEY

Sources for IDE Databank

- Dr. Chris McKay
- Dr. Carol Stoker
- Marc Cohen/ NASA-AMES web sites
- UC Berkeley Geology, Chemistry, and Biology labs
- Robert Zubrin
- 90 Day Study and Mars Design Reference Mission
- Where to look.
- What to use.
- Background on habitat design.
- Instruments, weight, volume, cost.
- Mars Direct science lab concept.
- Science lab equipment wish list.

Accomplished Team Tasks

- Determined primary scientific goals and the experiments required to achieve them.
- Compiled instrument, equipment, and manpower requirements.
- Prioritized primary scientific tasks.

Action Items

- Focused problem definition.
- Compiled research.
- IDE record of our progress and achievements.
- Contact information.

Future Team Tasks

- Determine the optimal use of resources to meet space, weight, time, manpower and cost limitations.
- Utilize equipment and tasks common to multiple objectives.
- Create an integrated plan to minimize man-power, time, and energy.
- Develop innovative concepts to minimize cost.

MARS CREW SIZE PROJECT

Mars Crew Size Team Members: Alexia Cooper (Team Leader), Danielle Lee, Homan Yuen (Webmaster), Todd Muehlenbeck, Michelle Cameron, Rudy Provoost, Dan DaSelm, Cliff Sarkin, Molly Friend, Keith Watanabe

INTRODUCTION

The possibility of human beings standing upon Mars by the year 2012 is now greater than ever considering the increases in scientific knowledge and collective advances of various technological fields during this decade. However, it reamins a massive project such that a single country cannot supply all the knowledge, technology, resources, and funding required for completion. A mission to Mars will require the cooperative effort of universities, industries, and governments from the international community. It will be expensive, but the world possesses all the components essential for its success.

Before we can proceed, two important questions must be answered: (1) What will we do on the surface of Mars to justify the multibillion-dollar cost once we get there? (2) How many people do we send to accomplish these tasks and goals? This research proposal will address these two questions through the use of a design project in an interdisciplinary class entitled "Mars by 2012" at the University of California, Berkeley. Information about this class and our on-line discussions may be found at http://mars2012.berkeley.edu/.

BACKGROUND/RELEVANCE

The current NASA design reference for a preliminary human mission to Mars envisions a crew of six. The basis for this number has been largely a matter of conjecture. In a situation where the addition or subtraction of one person can greatly affect the costs and goals of the mission, a "guestimate" is unacceptable. Resources and funds for such a large project would certainly be under a large amount of scrutiny from members of Congress and from critics of the project itself. In light of the monetary and budgetary problems the International Space Station has had since its conception, a thorough examination of the tasks (which directly correlates with the size of the crew) is required in order to obtain the massive support needed.

One cannot make a list of the tasks that are to be completed in transit and on the surface and then assign them to an arbitrary number of people. The mission planning committee must realize that certain combinations of various tasks can minimize the size of the crew. In addition, some tasks can be completed without any or very little human interaction and can save valuable personhours on the surface. Other parameters such as remote operation, safety, and fail-safe systems must also be considered. The more one looks at it, the more obvious it becomes that the factors affecting crew size form a very complicated relationship. This relationship is subject to analysis and it is this analysis that will form the basis of this project.

OBJECTIVES

The goal of the Crew Size Team is separated into two parts. The first part of the project is to compile a list of tasks that are to be completed when the crew arrives on the surface of Mars. After this is finished, a methodology for determining crew size is constructed by analyzing and comparing the type and time required for the list of tasks generated from the first part of the project.

METHODOLOGY

During the first few weeks of the project, we (the Crew Size Team) had brainstormed the various tasks that it thought would be performed on the surface of Mars. That list will not be displayed here for it was incomplete due to the lack of a complete knowledge base at the time of study (and the limited knowledge base of undergraduates beginning such a project). Generalizing the various tasks instead, we decided it was necessary to include the disciplines of planetary geology, biology, chemistry, medicine, and engineering. However, the list is not important because the methodology should not depend on the list it is given; it should be usable given any sort of parameters and conditions.

Initially, our main goal was to summarize our methodology and decision-making process in the form of a single Crew Size Equation expressed by the following polynomial:

$$\text{Crew Size} = cl{*}T^{a} + c2{*}S^{b} + c3{*}A^{c} + C4{*}P^{d} + c5{*}G^{e} + c6{*}I^{f} + c7{*}E^{g} + c8{*}F^{h} + c9{*}IS^{i} + ... + \text{etc.}$$

where cl, c2…cN are constants, a, b, c, d are exponents, and T is tasks, S, safety constraints, A, degree of automation, P, physical limitations of the crew, G, gender constraints if any, I, international constraints, if any, E, ethnic factors, F, funding effects, IS, human factors isolation constraints and so on. Ultimately we decided not to use the above method because of the scarcity of data effecting the constants, exponents, etc.

We next approached the problem from a much more conceptual standpoint by using a flowchart to help with the decision making process. In the flowchart, two main branches dealt with budgeting and skills/tasks. Within these two branches were smaller sub-branches with more detailed scenarios. From this flowchart, we derived two simpler equations in relation to the number of people needed/allowed for the mission. Those equations are displayed on the viewgraph entitled "Crew Size Equations." There are two equations because we could not combine them in a logical sense. This arose from the fact that the total funding and the tasks and workload are both dependent variables. It is at the discretion of the mission planners to decide whether or not the total funding or the amount of workload be the independent variable. There are also several other factors that affect crew size and mix that could have been included in the equation. But dealing with time constraints and our primary goal (to obtain a methodology of determining size), we did not include them. These included psychological, political, gender, and ethnic factors (discussed later in the report).

After obtaining the conceptual crew size equations, we created three situations that displayed how the various ideas came into context. We created sample work shifts for a week for a four-, six-, and eight-person crew. These three sizes were the most popular among the team. We had disliked the idea of an odd-numbered crew for reasons of team dynamics. There could be an odd person out if the crew had paired up psychologically. A two- or three-person team would be ill advised because of safety concerns when dealing with rover excursions. Numbers greater than eight are possible, but having such a large crew would result in a greater financial burden and might not be much more advantageous over an eight-person crew.

In the shift schedule, we assumed that the martian day, although 39 minutes longer, was basically the same length as an Earth day. For the six- and eight-person crew shift schedule, there are 21 shifts of eight hours each. The four-person shift schedule shown on the viewgraph has 28 shifts of six hours each. We had also created a four-person shift schedule with 21 shifts of eight hours each, but it was much less efficient in terms of workload than the 28-shift schedule. Within the weekly schedules are subschedules in which the rovers would be in use. A majority of the hours of the week are in the rover because we believed, as Chris McKay had stated in his lecture to our class, science and exploration could not be done in a stationary base.

In the four-person shift schedule, there could only be two people in a rover because there needs to be two in the base if a crisis situation arises and a rescue is required. This limitation greatly decreases the efficiency of the usage of person-hours. A maximum of only twelve hours work could be completed in a 24-hour period. The explanation for this is as follows: Referring to the first rover time block for the four person crew, one can see that the first shift consists of Member A driving and Member B sleeping. In the next shift, Member A is now working while Member B observes various conditions to make sure everything is in proper order. Members A and B switch roles in the next shift. A crewmember cannot have consecutive work shifts because it could lead to physical and mental exhaustion. Now on the fourth shift, Member A must sleep since sheathe has not had sleep in 18 hours. But since Member A is sleeping, Member B must observe. There has to be at least one person observing every shift to maintain safety (with the exception of the first and last shift of the rover mission in which the person driving is the observer). Consequently, after 24 hours, only a total of 12 hours can be spent performing actual scientific work, the lowest work-hour to total person-hour ratio of the 3 options.

In the six-person shift schedule, there can be three people in the rover because that leaves three people for an emergency situation. The duration of the rover mission is also longer here because there is an extra crewmemberto help work and observe. This creates shifts where two crewmembers can sleep or have recreation time. In this situation, there is now a total of 24 hours of work time per 24-hour period. This is an eight-hour per day increase in work time over the four-person crew. In the eight-person shift schedule, the rover mission duration is even longer. This arises from the fact that there are enough people in the base to perform work and base functions while the excursion crew has three shifts of off-duty to rest and relax.

A summary of the total number of work hours total and per person is displayed in the viewgraph entitled "Work Output by Crew Size." The six-hour shift cycle is only slightly more efficient than the eight-hour cycle for the four-person crew. But when we observed the performance of the six- and eight-person crew, we noticed a marked improvement in the number of total work hours even though the total number of work hours per person did not show a drastic increase. As greater crew sizes are examined and plotted on a graph similar to this, we expected that the curve would level off because of diminishing returns. In the viewgraph entitled "Performance by Crew Size," the findings from the example work schedules are summarized. Although the eight-hour shift for the four-person crew had a longer maximum rover travel time, the total work hours was smaller than the one for the six-hour shift. And again, the six- and eight-person crews had drastic increases in total work hours and substantial increases in maximum rover travel time.

CONCLUSION/RECOMMENDATIONS

At the conclusion of the semester-long research project, the Crew Size Team decided that a six-person crew would be the optimum choice. As stated before, the crew must contain at least four members. Odd-numbered crew sizes are not preferred because of the situation in which members will pair up as confidants, leaving one person alone. A four-person crew would not be as efficient as a six, eight, or higher number crew. Since funding is one of the major influential factors in a mission to Mars, keeping the costs down would be advantageous to its success and popularity among various governments. Adding two people to an four-person crew (with six-hour shifts) would increase the total amount of work hours by 77.8%. However, adding two more people to a six-person crew only results in a 45.8% increase in total work hours. Each additional person would increase the total budget of the mission by several tens of millions of dollars. This is an example of the Law of Diminishing Returns, thus we chose a six-person crew because it gives more for the money.

That said, there are still many other aspects and factors that were not examined as deeply as we would have liked. Given the time, we feel the original crew size equation is still a valid and logical method of approaching this very complex problem. But factors such as T (tasks), S (safety constraints), A (degree of automation), P (physical limitations), etc., need to be better defined. Within these main factors are subfactors and issues. What kind of tasks, how many skills can a single person be reasonably cross-trained to absorb, how much time should be spent on each task? How much safety should the mission be constrained to, do we want computers and robots that can perform human jobs or use computers just for data storage and calculations? Do we want athletes or normal people? Do we want a coed group, which can lead to sexual tensions, or an all-male group, which can have psychological effects? Which countries will participate and how much control will they have over the overall mission? How do we assign which ethnicities and what number to the crew size and make-up? Where is the funding coming from and how will it affect the mission? As the reader can see, there are a plethora of topics that must be researched and explored. We have only laid the groundwork for a methodology here.

In conclusion, the mix of the crew has yet to be dealt with seriously. Crew size and composition, contrary to many mission designs, is a very important aspect. One cannot whimsically say five, or six, or even fifty without examining the consequences, limitations, and advantages. Crew size and composition are the factors in determining the actual crew and the actual crew determines mission success.

Crew Size Equations:

C_F = Crew size # determined by budget
F = Total budget
P = Price per person
S = Economies of scale (dependent upon C_F)

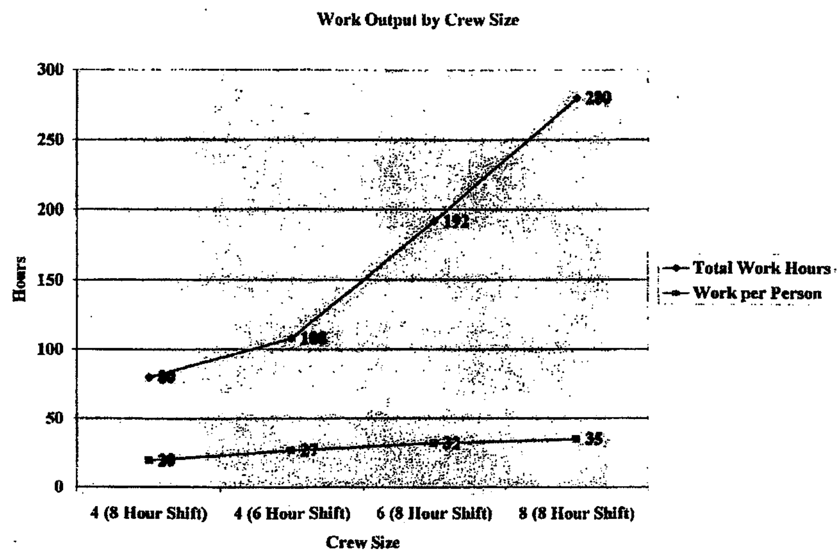
$$C_F = \frac{F}{P-S}$$

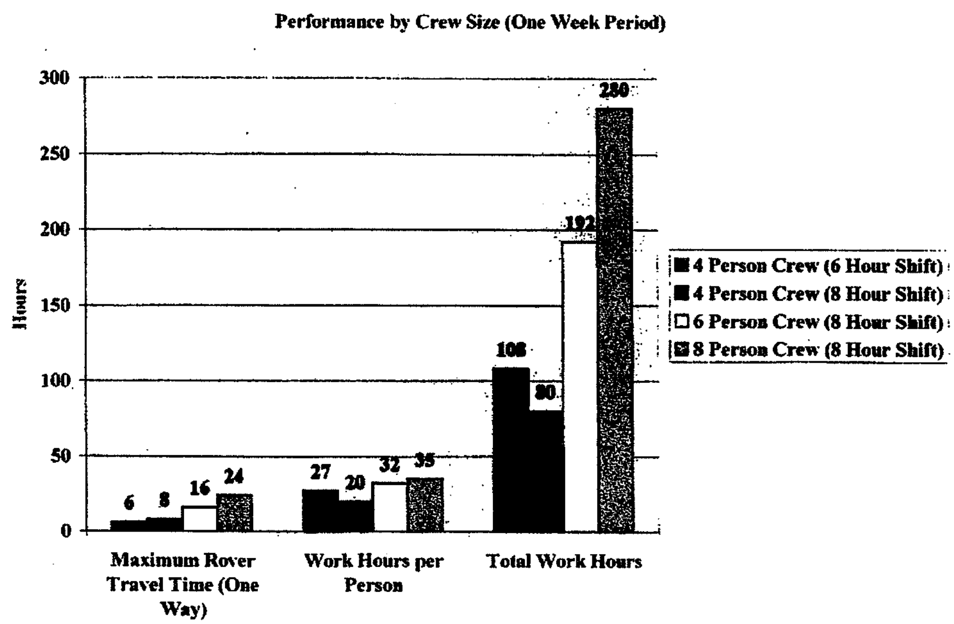
$$C_W = \frac{\sum_{i=1}^{l} B_i + \sum_{j=1}^{m} E_j + \sum_{k=1}^{n} L_k}{W}$$

C_W = Crew size # determined by workload
B_i = Number of hours for a certain base task
E_j = Number of hours for a certain field/enviroment task
L_k = Number of hours for a certain lab task
W = Total number of hours of a person can work a day

If $C_F > C_W$:
Assuming W remains a constant, adjust Bi, Ej, and Lk accordingly until $C_W = C_F$.
If $C_W > C_F$:
Assuming P and S remain a constant, attempt to increase F or adjust Bi, Ej, and Lk accordingly (or any combination of the two) until $C_W = C_F$.

There are two additional factors which set boundary ranges for crew size:
Psychological Factors and Political Factors


Work Output by Crew Size
300
250
200
150
100
50
0
Hours
280
192
108
80
20
27
32
35
Total Work Hours
Work per Person
4 (8 Hour Shift)
4 (6 Hour Shift)
6 (8 Hour Shift)
8 (8 Hour Shift)
Crew Size


Performance by Crew Size (One Week Period)
300
250
200
150
100
50
0
Hours
6
8
16
24
27
20
32
35
108
80
192
280
4 Person Crew (6 Hour Shift)
4 Person Crew (8 Hour Shift)
6 Person Crew (8 Hour Shift)
8 Person Crew (8 Hour Shift)
Maximum Rover Travel Time (One Way)
Work Hours per Person
Total Work Hours

SYSTEM STUDY OF A SURFACE HABITAT AND A TRANSIT VEHICLE FOR A MANNED MISSION TO AND FROM MARS

Texas A&M University

By: Tony Brown, Brian Hebert, Colin Hestilow, Jeff Rogers, Starlee Sykes
Edited by: Joshua McConnell

Executive Summary: The continued technology advancement over the last several decades has provided the impetus for ambitious individuals to look towards exploration and possible settlement of the frontiers that exist beyond the boundaries of Earth.

NASA has expressed a need for the development of a system to provide life sustaining functions for the duration of a three phase mission to and from Mars, including a 500 day expedition on the surface. A preliminary design for a Mars habitation and transportation system was developed to fulfill the need expressed by NASA after down-selecting from several conceptual designs. The design team assigned to this task was divided into subteams responsible for key function groups. These function groups are avionics, power and mobility, environmental controls and life support (ECLSS), and structures. This systems report gives an overview of the total system with attention given to each of these key functional groups. For further information and detail on a specific functional group, refer to the individual reports for that function group.

The problem definition section of the report includes the need statement and need analysis, from which the specific need is expressed and the key system constraints imposed. The major functions resulting from the need analysis were that the habitation and transportation system must provide transportation, meet the constraints imposed by the shuttle, provide habitation needs, and allow for a Martian surface expedition. Following the function structure are the functional and performance requirements, which allocate specific numbers and constraints to particular concepts of the need. Calculations as well as assumptions are involved in the process of determining system performance requirements.

The system description contains basic drawings of the system and a description of major interfaces. A failure modes and effects analysis and a summary of component costs of the system are also included.

Note from the editor: This report is an excerpt of a Systems Integration Report submitted by the authors for their senior Mechanical Engineering design course at Texas A&M University. This report was the result of the first semester of study in a two semester design series. Contributing to this report were 12 students broken into four areas of study; systems integration/avionics, structures, power/mobility and life support/thermal systems. A complete copy of each of these four reports can be obtained by contacting Aaron Cohen in the Mechanical Engineering Department at Texas A&M University.

Need Statement: Provide accommodations for a six person crew research mission to Mars. Sustain the crew for a 500 day surface stay and return them to Earth safely.

Need Analysis: The transportation and habitation system design will be launched in currently available launch facilities to low earth orbit (LEO) fully outfitted. The three-stage mission includes a 200 day journey to Mars, a 500 day expedition on Mars, and a 200 day return trip. The system will be implemented in multiple launches with each launch configuration designed to fit within the payload bay of the Space Shuttle. Its payload capacity implies volume and weight constraints. This includes an available volume of 4.7 m diameter by 15.7 m usable. In addition, the weight of the module cannot exceed 24,400 kg. The system must be lightweight and strong enough to carry itself and all required outfitting to orbit. The module must maintain functional and structural integrity during launch, The living space should be maximized to provide a healthy atmosphere for six occupants. Basic human needs should be provided for including exercise, nutrition, hygiene, medical treatment, entertainment, and sleep. This includes a climate control system and an advanced regenerative life support system (ECLSS) that provides 100% self-sufficient air/water without re-supply. Life sustaining requirements of air and water include circulation, thermal control, sanitation, and pressurization. Liquid and solid wastes must be recycled or disposed of. Food must be supplied to meet the nutritional requirements of six crew members for the duration of the mission. Power requirements for all internal components are considered in the design. For the flight to and from Mars, power must also be provided for the module. Since the module is required to be self sufficient, methods and tools for needed repairs are to be readily available.

Transportation needs include communications, controls, shielding, and effectively meeting time constraints imposed by the mission profile. Communication systems must be available for both long range and short range communications between the crew and communication between the module and Earth. Guidance navigation control and instrumentation systems for avionics must be imposed. The module must include a meteoroid and orbital debris (M/OD), thermal, and radiation protection system. The module must interface to a hard structure for boost from LEO to high earth orbit (HEO), trans Mars injection, and Mars deceleration.

The module must also be able to adapt to the Martian surface and provide safe habitation for the crew during the 500 day surface expedition. This involves accounting for the change in gravity, pressure, and atmosphere. A power system for use on the Martian surface must be supplied. In addition, all previously discussed life sustaining requirements must be met.

FUNCTIONAL REQUIREMENTS / PERFORMANCE REQUIREMENTS

Functional Requirements	Performance Requirements	Source
TIME RESTRICTIONS		
Travel Time to Mars	200 Days	Mars Ref. Mission Webpage, 1-8
Travel Time from Mars	200 Days	Mars Ref. Mission Webpage, 1-8
Time on Mars	500+ Days	Mars Ref. Mission Webpage, 1-7
COMMUNICATION		
Equipment	Mass = 1361 kg	Mars Ref. Mission Webpage, 3-82
Downlink	Ka-band (33.60 to 33.80 GHz)	Mars Global Surveyor Project Plan
Communication time window	4.5 hour DSN Window	Mars Global Surveyor Project Plan
CONTROL		
Avionics	Power 5 kWe (including communications and propulsion system)	Mars Ref. Mission Webpage, 3-93
Guidance	Must determine corrective state vector and attitude	Assumption from Dr. Cohen
Navigation	Must measure attitude and state vector	Assumption from Dr. Cohen
Control	Must control attitude and system interfaces	Assumption from Dr. Cohen
Airlock Interface	Must have a complete seal, pressurize from 0-103.421 kPa	Assumption/Shuttle Ref. Manual - Airlock Support
Power Supply Interface	Must be rated for similar voltage, power, and current	Assumption
Propulsion Interface	Must have thermal protection	Assumption
Braking System Interface	Must reduce momentum to avoid critical impact	Assumption
AIRLOCK		
People Capacity	Must hold 2 astronauts simultaneously	Shuttle Ref. Manual - Airlock Support
SHIELDING		
M/OD Protection Requirements	Stop average 1 cm diameter meteorite travelling 7 km/s	JSC Speaker
Radiation Shielding Requirements	No more than 3% increase risk to cancer due to cosmic radiation	Mars Ref. Mission Webpage, 3-13
Thermal Shielding Requirements	Maximum Temperature on entry must be less than 32.2 deg C	Shuttle Ref. Manual
SHUTTLE CONSTRAINTS		
Structural Integrity of Module Interface to Shuttle	Must withstand vibration and gravitational forces	Calculation
Release Mechanism of Module Interface	Must release avoiding damage	Design Assumption
Attachment Method	Must attach and maintain integrity	Design Assumption
Payload Weight Capacity	24,400 kg	Space Shuttle General Description, pg. 278
Payload Diameter (usable)	4.7 m	Space Shuttle General Description, pg. 278
Payload Length (usable)	15.7 m	Space Shuttle General Description, pg. 278
Payload Weight Distribution	Must balance around the center of gravity	Calculation
ECLSS - Environmental Control and Life Support System		
Air Quantity	0.80 kg O2 per person per day / 3.49 kg N2 and 4.08 kg O2 lost per day	Shuttle Ref. Manual Webpage (Cabin Pressurization)
Air Distribution	80% Nitrogen, 20% Oxygen	Shuttle Ref. Manual Webpage (Cabin Pressurization)
Tank Capacity	0.42 m^3	Calculation (ECLSS System)
Air Pressure	O2 at 19512.2-23097.4 Pa	JSC 38571
Air Volume	4.48 m^3	Mars Transhab
Air Weight	800kg	Mars Transhab
Air Contaminant Tolerance	Max CO2 levels at 1.8 kg/m^3 and particles filtered at 50 kg/m^3	A Case for Mars, Zubrin
Air Circulation	3 air changes per hour, 15-40 feet per minute	JSC 38571
Water Quantity	159.6 kg H2O/day recycled potable and wash water	A Case for Mars, Zubrin
Water Volume	1.61 m^3	A Case for Mars, Zubrin

FUNCTIONAL REQUIREMENTS / PERFORMANCE REQUIREMENTS

Functional Requirements	Performance Requirements	Source
Water Weight	962kg	Mars Transhab
Water Circulation	Prevent bacteria growth, circulate 5-20% of volume/hour	Assumption
Water Temperature	Chilled 7 - 13 deg C, Ambient 18 - 24 deg C, Hot 38 - 104 deg C.	Shuttle Ref. Manual Webpage (Crew Equipment)
Waste Water Quantity	29.08 kg/person-day	JSC 38571
Waste Water Volume	1 tank - 74.8 kg, 90.2 cm length, 39.4 cm dia., 17.9 kg dry	Shuttle Ref. Manual Webpage (Supply and Waste Water)
Potable Water Volume	1 tank - 74.8 kg, 90.2 cm length, 39.4 cm dia., 17.9 kg dry	Shuttle Ref. Manual Webpage (Supply and Waste Water)
Potable Water Regeneration	3 fuel cell power plants equals 11.4 kg max per hour	Shuttle Ref. Manual Webpage (Supply and Waste Water)
Solid Waste Quantity	3.08 kg/person-day	JSC 38571
Solid Waste Volume	2.38 m^3	Mars Transhab
Habitation Humidity	25-75%	JSC 38571
Habitation Thermal Power	2.2 kWe	Mars Ref. Mission Webpage 3-93
Habitation Temperature	Air Temp. 18.3 - 26.7 deg C	Shuttle Ref. Manual (Cabin Air Revitalization)
Module Pressurization for Cabin	68.9 kPa - 103.4 kPa	Shuttle Ref. Manual Webpage (ECLSS 1 of 5)
Module Pressurization for Airlock	0 to 101.4 kPa Variable Pressure Capacity	Shuttle Ref. Manual Webpage (Airlock Support)
INTERNAL POWER		
Lab Equipment	0.7 kWe	Mars Ref. Mission Webpage, 3-93
Health Maintenance Equipment	1.7 kWe	Mars Ref. Mission Webpage, 3-93
ECLSS Power	14.2 kWe	Mars Ref. Mission Webpage, 3-93
Attitude, Avionics, Propulsion, Braking Control	5.0 kWe	Mars Ref. Mission Webpage, 3-93
Airlock Control	0.6 kWe	Mars Ref. Mission Webpage, 3-93
Communications Power	0.5 kWe	Mars Ref. Mission Webpage, 3-93
Personal Quarters	0.4 kWe	Mars Ref. Mission Webpage, 3-93
Audio/Video	0.4 kWe	Mars Ref. Mission Webpage, 3-93
Hygiene	0.7 kWe	Mars Ref. Mission Webpage, 3-93
Galley	1.0 kWe	Mars Ref. Mission Webpage, 3-93
Logistic Module	1.8 kWe	Mars Ref. Mission Webpage, 3-93
Command Center	0.5 kWe	Mars Ref. Mission Webpage, 3-93
Data Management System	1.9 kWe	Mars Ref. Mission Webpage, 3-93
HEALTH		
Laundry Generated	27.7 kg laundry/day	Calculation
Personal Items	cleanliness, health, and emotional needs (0.3 m^3/man allocated)	Assumption
Food Volume	1200 kg food/man/200 days	A Case for Mars, Zubrin
Food Quantity	Supply 11.3 kJ per crew member per day	Shuttle Ref. Manual Webpage
Kind of Exercise Equipment	Must provide complete body workout (ex.Treadmill and/or "flexrod")	Shuttle Ref. Manual Webpage/Infomercial
Pharmaceuticals	General and emergency care	Assumption
Medical Equipment	General and emergency care	Assumption
Sleeping Space	1 m^3	Calculation
COMMUNITY SPACE		
Entertainment Area	10% of total volume	Assumption
Cockpit Work Area	20-40% of total volume	Assumption
Lab Work Area	20-40% of total volume	Assumption
REPAIR NEEDS		
Spare Parts	Mass = 3000 kg	Mars Ref. Mission Webpage, 3-82
Geological and Lab Tools	Mass = 2370 kg	Mars Ref. Mission Webpage, 3-52
Internal Tools	Mass = 500 kg	Assumption based on mass of other repair needs

FUNCTIONAL REQUIREMENTS / PERFORMANCE REQUIREMENTS

Functional Requirements	Performance Requirements	Source
SURFACE EXPEDITION		
Mobile Rover Exploration Range	500km radius of exploration, 10 day trip	Mars Ref. Mission Webpage, 1-23
Mobile Rover Mass	3992 kg	Mars Ref. Mission Webpage, 1-23
Mobile Rover Capacity	2-4 people	Mars Ref. Mission Webpage, 1-23
Space Suit	Air tight thermal shield / radiation shield	Assumption
Transportable Power Supply	6+ year lifetime (Nuclear Power Generation 10 kWe)	Mars Ref. Mission Webpage, 1-22
Surface Power Supply	15+ year lifetime (Nuclear Power Generation 160 kWe)	Mars Ref. Mission Webpage, 1-13, 1-22
Mars Gravity	3/8 gravity	Mars Ref. Mission Webpage, 1-22
Mars Atmosphere	gases, dust storms	Mars Ref. Mission Webpage, 1-22
Mars Temperature	Max. 25 deg C. but much colder usually	Mars Ref. Mission Webpage, 2-10
Mars Radiation	No more than 3% increase risk to cancer due to cosmic radiation	Mars Ref. Mission Webpage, 3-13
Descent Vehicle Constraints	59000 kg of Cargo (for current vehicle)	Mars Ref. Mission Webpage, 1-21
Mars Surface Pressure	Approximately 1.013 kPa	Mars Ref. Mission Webpage, 2-10
Mass of Surface Habitat	15694 kg (Must be landable)	Mars Ref. Mission Webpage, 3-77
Volume of Surface Habitat	Comparable to transportation habitat volume	Design Calculation

System Description: *Mission Profile.* The Mars habitation and transportation system is designed to be implemented using four space shuttle launches. Figure 1 illustrates the mission profile. The systems contained in the first three launches will be pre-deployed to the Martian surface and their systems will be verified prior to launching the crew in the fourth launch. The first launch will contain the nuclear power system, rover, water, and the plant growth system. All of these systems are for use on the Martian surface during the 500 day research mission. The second launch will contain a near duplicate of the habitation module to be used in transit from Earth to Mars. This module will also be utilized during the surface stay.

The third launch will place the unmanned transportation and habitation module in Low Earth Orbit (LEO). The structure will pressurize and expand in LEO. While in LEO, the power, avionics, and life support systems will be activated and a diagnostic check will be performed on all systems. Solar panels will be expanded and engaged to replace auxiliary battery power. Power must be supplied to communications, guidance navigation control (GNC), and instrumentation in order to guide the module to High Earth Orbit (HEO). The air and water supply system will be activated and tested to insure an acceptable living environment prior to the crew rendezvous in HEO.

After the crew rendezvous in HEO, the module will begin transit to Mars. During transit, the structure will provide a safe habitable environment for the crew. The module is designed to be entirely self sufficient and functional without re-supply or external intervention. The external structure will provide protection against meteorite and orbital debris (M/OD) and will provide hard points for attachment of solar panels and interface with the crew capsule. The internal structure will provide volume for habitation with space allocation taking into account physical and psychological well being of the crew as well as efficient placement of functional components for optimal system operations. The solar power system will maintain power supply at 30 kW for the duration of transit to and from Mars. The environmental control and life support system (ECLSS) will maintain pressurization of the module and supply daily air, water, food, and waste disposal for the crew. The avionics system will provide GNC and communication with Earth throughout transit.

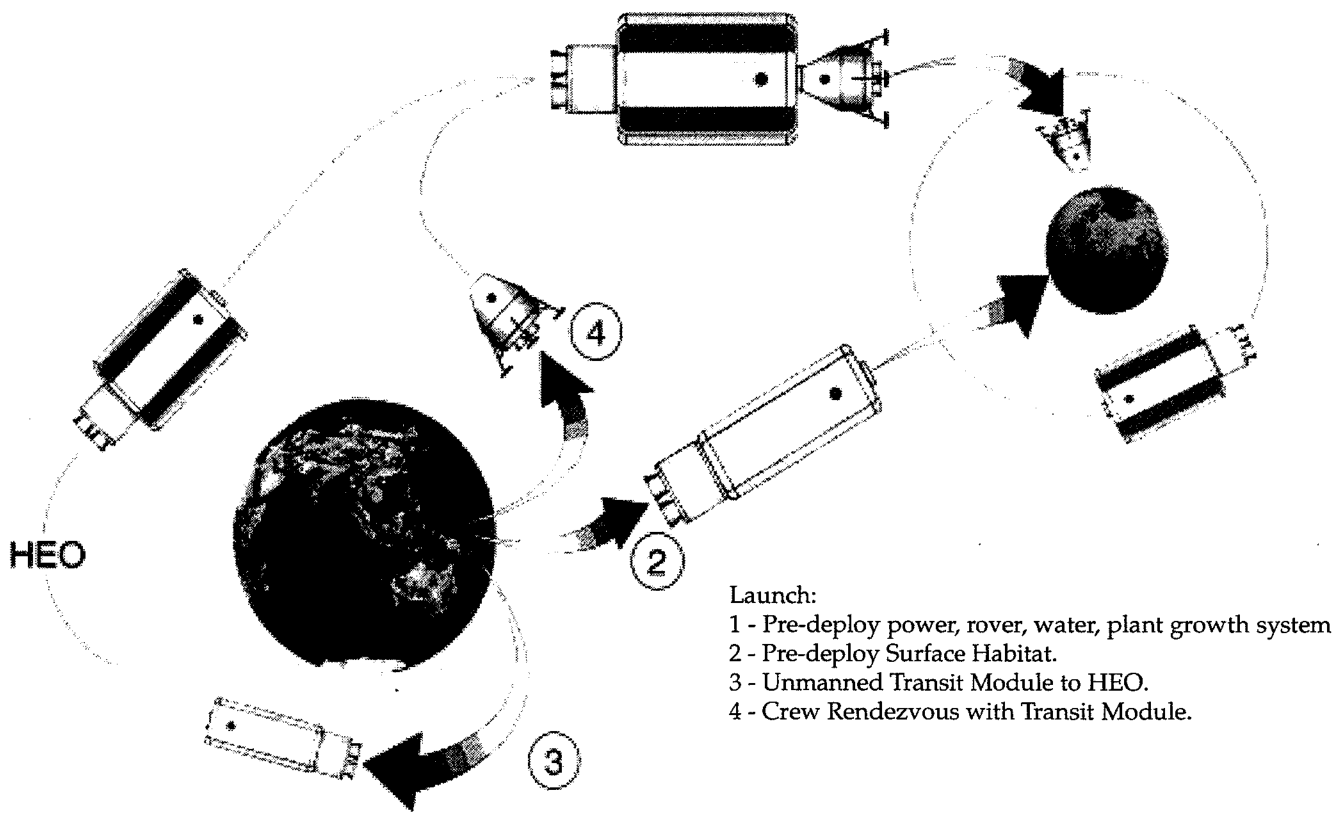


Fig. 1. Sequence of Events.

After Mars orbit capture, a landing capsule will be used to transport the crew from the Mars orbit to the Martian surface. This capsule will enable the crew to rendezvous with the pre-deployed expanded surface habitation module. The transport module will remain in Mars orbit in order to be utilized for the return trip. The surface module will provide a secure living environment for the crew while on the Martian surface. Power on the Martian surface will be supplied by a pre-deployed nuclear power system. This system is designed to provide a minimum of 125 kW to support all systems used for this phase of the mission. The avionics system will provide control and functionality checks of all systems. Communications will be available between all Mars based systems and with Earth. The life support system will be used to pressurize and maintain a livable environment in the surface module and to provide daily food, air, and water for the crew.

At the conclusion of the 500 day research mission, the crew lander will be utilized to return the crew to the orbiting transportation and habitation module. The systems used in the module for the return trip will be identical to those used in transit from Earth to Mars. The return trip will take approximately 200 days.

Structure: Figure 2 shows how the unexpanded transportation and habitation will be packaged within the shuttle payload bay. The unexpanded module is approximately 4.6 m (15 ft) in diameter and approximately 11.3 m (37 ft) in length. Once the propulsion system is attached to the module the total length is 15 m (50 ft). Note that this is well within the limits of the size constraints of the shuttle payload bay. Also, it is important to note that the propulsion system was not within the class scope of the design. Figure 2 also shows the packaging of the secondary solar panels at the front of the module. The secondary solar panels are necessary for supplying the necessary 6 kW from LEO to HEO in order to power up the avionics systems within the module. The thrusters that are located at the bottom of the module demonstrate two of the eight sets of four that are located 90° from each other on the top and the bottom of the module. The windows located at the top of the module are for the astronauts' convenience. Windows tend to be an important issue with the astronauts, especially for such a long duration of time as the Mars mission will require.

Once the module is jettisoned from the shuttle into LEO, it expands to a diameter of 7.9 m (26 ft). The expanded module is depicted in Figure 3. Its expansion is guided along expansion rails located at the top and bottom of the module. The expansion mechanism is constructed of rack and pinion gears with guide rails. The expansion is caused by the pressure differential from the inside of the module and the vacuum of space. The pressure inside the module is kept at a minimum 68.9kPa (10 psi). This is an optimal pressure considering the number of EVAs that are required by the astronauts once on the Martian surface. This pressure minimizes the time required to de-breathe the astronauts from 68.9kPa (10 psi) to the space suit's pressure of 34.45kPa (5 psi). The module expands due to the pressurization of the soft shell.

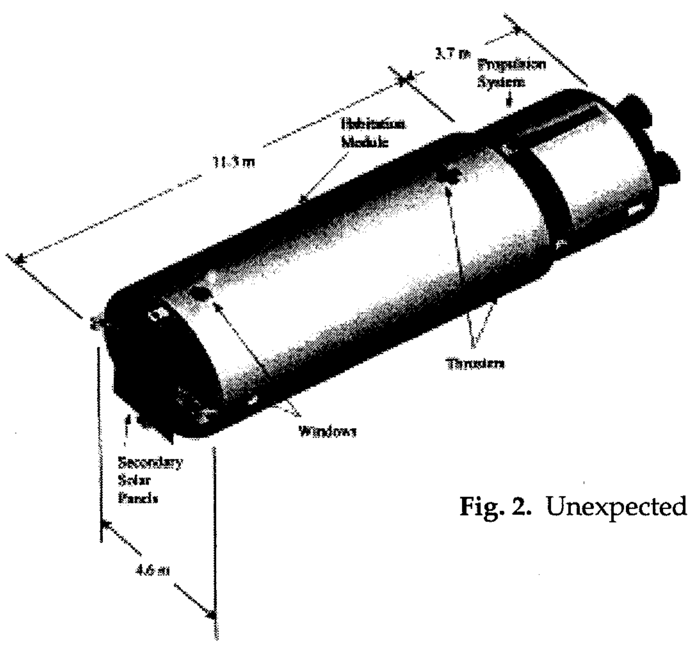


Fig. 2. Unexpected Habitation Module.

The soft shell is made up of a flexible Kevlar and Mylar material. Redundancy is built into the soft shell by multiple bladders layers providing M/OD protection. The hard shell is composed of a Carbon-Carbon matrix with Kevlar and Aluminum layers. There will also be four vertically fastened Aluminum I-beams providing for the necessary structural support on the Martian surface. Figure 3 also shows the airlock positioned at the top of the module. The airlock is made up of a Carbon-Carbon composite attached to an Aluminum layer. This material selection provides for an excellent resistance to the stresses that will be caused by the constant pressurization and depressurization that will occur within the airlock. The airlock serves the purpose of docking and separating of the crew lander with the module, as well as the entry and exit into the module by the astronauts. The basic dimensions of the airlock are 2.1 m (7 ft) in diameter and 2.4 m (8 ft) in length. This the necessary size in order to fit two fully equipped astronauts that fully outfitted in space suits. Figure 5 simply shows the expansion of the secondary solar panels on the expanded transportation and habitation module.

Figure 3 shows the interface of the crew lander with the module in HEO. The lander has the primary solar panels attached on the front such that they will interface with module, providing the necessary 30 kW required for the transit to and from Mars. Note that the lander was not within the scope of the design project; however, the present X-38 crew lander was used for the design. Once the lander has docked with the module, the crew will be able to transfer into the module through the airlock as mentioned previously. Figure 3 simply shows the module's configuration with the attached lander as it will appear in transit to Mars. It is also important to note that the module boosters, provided by the propulsion system, will be used for forward propulsion, while the lander boosters will be used for retro.

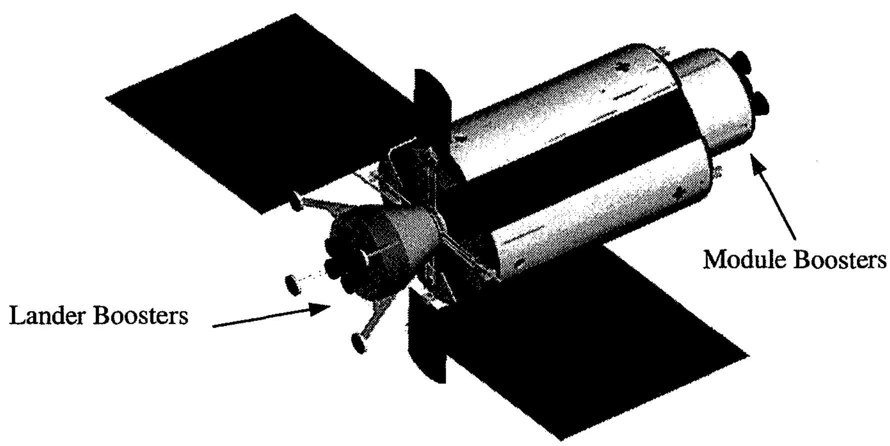


Fig. 3. Expanded Habitation Module Interfaced with Propulsion and Lander Systems.

Once the lander has jettisoned from the transportation and habitation module, which stays in HMO, the lander aerobrakes into the Martian atmosphere. Using parachutes and retro boosters, it will interface with the pre-deployed habitation module that is already operational on the Martian surface. Figure 4 shows the configuration of the habitation module and the lander that will be used for the 500 day stay on the Martian surface. Note that the landing mechanism will be further researched in the fall semester in order to provide the necessary support for the module on the Martian surface.

The basic dimensions for the structure of the internal core are depicted in Figure 5. Each floor is approximately 2.5 m (8 ft) high. The internal core provides for the main structural support on the Martian surface. It is composed of a graphite epoxy attached to an Aluminum matrix. The floors are the same diameter of the unexpanded module while packaged within the shuttle. The floors are constructed of the graphite epoxy material. An integrated fiber cloth will expand outward with the outer shell providing for the added floor space of the expanded module. Note the access pathways located on the different floors such that the astronauts can move from floor to floor.

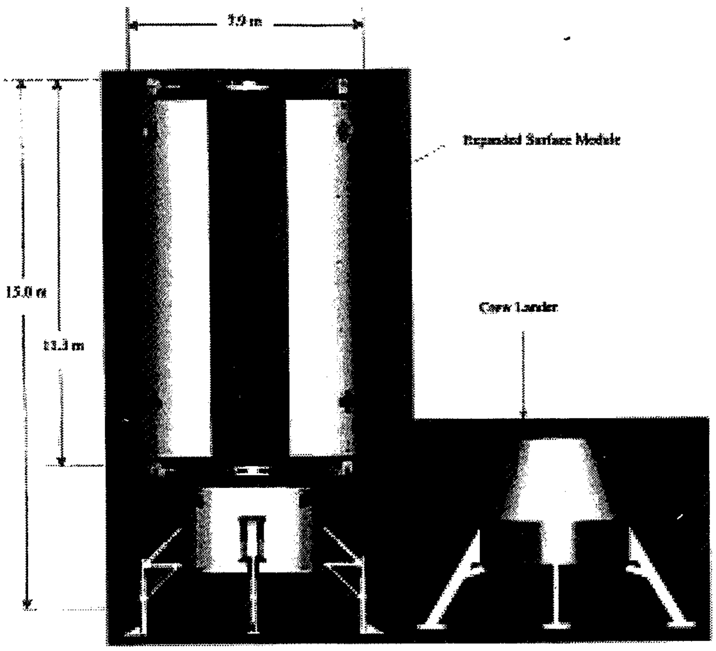


Fig. 4. Crew Interface at Martian Surface.

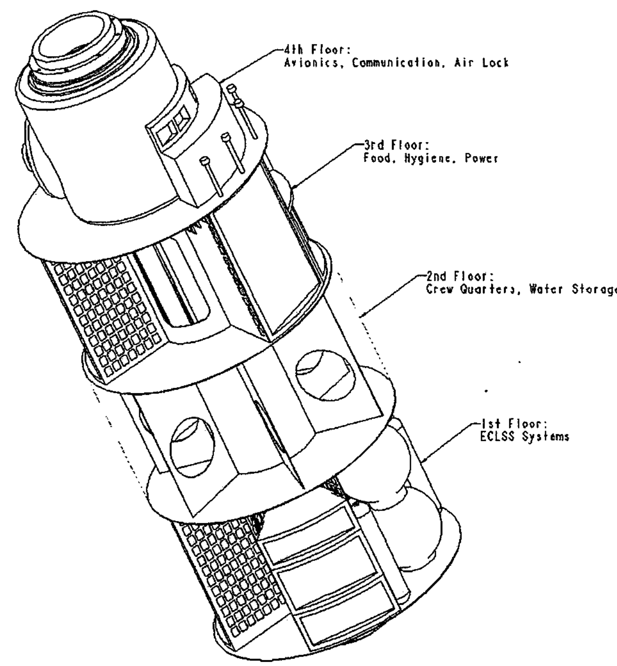


Fig. 5. Location of Systems with Respect to Floors.

Figure 5 shows the internal core and the interfaces between all of the subsystems with respect to the separate floors. The 1st floor provides for the interfaces of the life support systems. This includes the O_2 and N_2 storage tanks, water, O_2 and CO_2 processing units, and atmospheric control systems. The 2nd floor is partitioned into six compartments consisting of the crew quarters surrounded by the water storage system. The crew quarters include such components as beds and showers for the astronauts. The 3rd floor interfaces the food storage and preparation, hygiene facilities, and the power systems. Note that the mass of dry food is approximately 1850 kg (4070 lbs). This is the amount of food for 500 days. The astronauts will consume approximately half of this supply on the trip to Mars. This is noted due to the fact that space that is opened due to food consumption will be used for the 2000 Martian samples that will be returned to Earth. This is assuming a 1g to 500 g (.0022 – 1.1 lb) sample size; thus, filling the weight that was lost due to food consumption for the return trip to Earth. The power system includes storage, converters for AC and DC power, and the distribution into the other subsystems. The 4th floor consists of the avionics systems and the airlock. The avionics systems includes the instrumentation for the module as well as the control systems for the subsystems located throughout the module.

Figure 5 shows an assembly drawing of the integration of the internal core with all of the subsystems – structures, power, avionics, and ECLSS. The purpose of this drawing is to help explain the location of the water storage and life support systems on the first and second floors of the module; thus, creating a lower center of gravity which aides in the stability of the module.

Power: The power that is required for the Mars mission was determined to be 124.9 kW on the surface and 30 kW in transit to and from Mars. Due to the length of the Mars mission and power required, it is necessary to generate power, since it would not be possible to use batteries for the duration of the mission. Solar panels could be used on Mars' surface, but the large distance from Mars to the Sun and the length of the Martian day would require very large solar panels. This is not realistic, because of the large volume and weight this would require. A nuclear power system on the Martian surface is the only practicable solution to the problem, however solar panels can be used in transit.

The surface power system utilizes a SP-100 thermonuclear reactor as the primary source of power and solar panels for backup. For safety purposes, the habitation module must be kept 1 kilometer from the reactor. The nuclear reactor has a seven-year lifetime; hence, subsequent missions to Mars would be able to use the same power system. This would drastically lower the costs of future missions. The SP-100 generates thermal energy, which in turn drives a Stirling engine. The Stirling engine can provide 150 kW per engine. For this mission, two engines would be used. This is done to provide redundancy in the system and allow for future growth. The energy is stored in batteries and sent to a DC power supply. The DC energy is run by a controller, which allocates the energy to the different areas in need of power. These include the module, rover, lander, food production system, and fuel production system. During non-peak operating times, excess energy is sent to batteries and/or dissipated to the atmosphere as thermal energy. The solar panels collect solar energy and send it through a working medium, which generates the DC electrical energy. This energy is then sent through the same system as that generated by the SP-100.

The transit system is based solely on solar power. This is possible, because the transit power requirement is much lower than the surface power requirement, 30 kW as opposed to 124.9 kW. The solar panels are assumed to have 30% efficiency. The size of the panels was calculated based on the surface area required at Mars. Also, the area was increased to provide redundancy in the system. The panels, which consist of Aluminum Gallium Arsenide/Gallium Arsenide solar cells, harness solar energy. This is sent through a working medium and converted to DC electrical energy. The energy is sent to a controller, which distributes it accordingly. For the module, the DC is sent to a converter and transformer before being distributed throughout the module. The DC is also sent to batteries for storage, and excess is dissipated into space as thermal energy.

Avionics: Critical to the operation of the transportation and habitation module is the processing of information related to the performance of all subsystems. This task is handled by the avionics system. The avionics system includes all instrumentation, guidance navigation control, and communication systems. This system composes the main information handling and processing unit of the transportation and habitation module.

The avionics system is decomposed into three subsystems, the instrumentation, guidance navigation control, and communication systems. These three systems are integrated to facilitate manipulation and transferring of data. The integration of these systems allows the main processors to communicate and transfer data as needed. The instrumentation system main processor oversees all other subsystems, including the guidance navigation control and communications systems.

The instrumentation system is built around three main processors working in parallel, one main and two backup processors. These processors operate at 800 to 1000 MHz. These processors coordinate all other activities within the avionics system. These processors monitor the guidance navigation control and communication processors, the ECLSS sensors, crew sensors, structure sensors, power sensors, data manipulation, data storage, and data backup systems. The main processors also send outputs to the ECLSS sensors, generate reports on crew health, and determine power distribution.

The ECLSS, power, crew, and structure sensors read inputs from the various systems and transmit data to the main processor. This data is analyzed by the main processor, which then determines the appropriate response. Data manipulation, data storage, and data backup are also controlled by the main processor. Data manipulation occurs through a human to computer interface. Data storage and data backup utilize a 8868 gigabyte CD ROM tower to store data.

The Guidance Navigation Control (GNC) system is built around two processors, one main and one backup, that operate at 800 to 1000 MHz. This processor receives data from sensors, analyzes these inputs, and transmits data to the actuators. It also transmits data to and receives data from the main processor.

Guidance navigation control sensors include feedback from earth, rendezvous and docking sensors, sun sensors, star sensors, gyroscopic inertial reference units, and feedback from boosters and thrusters. The GNC processor uses the data from these sensors to determine a velocity and position vector, which can then be compared to a predetermined course. Corrections to the course can be made using the thrusters or boosters. Aerobraking equipment is provided for Mars orbit capture.

Cockpit controls are provided in case human inputs into the GNC system are required. All information related to actual and desired position and velocity will be made available to the crew through monitors in the instrumentation system.

The communications system is built around two processors, one main and one backup, that operate at 800 to 1000 MHz. The communications processor receives communication data from video recorders, cameras, microphones, and audio recorders. It may then transmit this data to audio speakers or video screens. This processor may also transmit data to and receive data from the main processor.

Information from outside the transportation and habitation module can be received via either a high gain or low gain antenna. This data is then transmitted by a receiver to the communications processor for routing. Data may also be sent from the module through these same antennas operating through a transmitter.

The entire avionics system uses approximately 7.8 kWe. The entire system will use digital technology to minimize losses due to analog to digital and digital to analog conversion.

Environmental Control and Life Support System: Any manned spacecraft must meet the many needs of the human occupants. This is a difficult task given the inhospitable conditions that lie outside the atmosphere of Earth. The Environmental Control and Life Support System (ECLSS) provides all requirements necessary to maintain crew life and health.

The ECLSS is decomposed by the various tasks it must perform. The Thermal Control System (TCS) controls the heat transfer into and out of the module to maintain a comfortable living environment. The Water Supply and Water Recovery System (WRS) provide clean water for use by the crew. The Atmospheric Revitalization System (ARS) provides the crew with breathable air. A Solid Waste Management System disposes all solid wastes from the module. Food, medical support, and sleep provisions are also provided by the ECLSS.

Thermal Control System: The thermal control system (TCS) consists of a water coolant loop system and an active thermal control system. These systems interact to provide a habitable environment for the crewmembers in the crew living space, laboratory, health maintenance facility and command center in addition to cooling or heating various systems or components.

Water Supply and Water Recovery System: The water supply and water recovery system (WRS) produces potable water for the crew of the habitation module. Water is stored in the storage tank that also serves as a radiation shield during solar activities. The water tank is pressurized to provide directional flow to the water pump that pumps the water to the various outlets in the habitation module. Wastewater that is produced is then treated by the water recovery system. This system utilizes both physical-chemical and biological subsystems to recycle and process wastewater generated by the crew and humidity condensate. The WRS is divided into six major subsystems.

The main water recovery system and the backup water recovery system are 100 percent efficient at recycling wastewater. Water is not lost outside of these systems during each cycle. This efficiency is necessary to reduce the water requirements for long duration missions where resupply is extremely difficult or impossible. For this system, 960 kg of potable water will be stored in the water storage tank initially and the total water amount in the system must be carefully monitored to ensure that there is no significant loss during the duration of the mission.

Air Revitalization System: The atmospheric revitalization system in the module must intake the air from the module and output clean, breathable air for the crewmembers. The atmospheric composition is also monitored to keep the ratio of nitrogen to oxygen at about 80/20. The ARS consists of four main subsystems. The Trace Contaminant Control Subsystem (TCCS) removes contaminants from the air. The Four Bed Molecular Sieve Subsystem (4BMS) concentrates the CO_2 for further processing downstream. The Carbon Dioxide Reduction Subsystem (CRS) uses the Sabatier reaction to convert Hydrogen and CO_2 to methane and water. The Oxygen Generation Subsystem (OGS) uses water to produce Hydrogen and Oxygen.

Solid Waste Management System: An incineration system is used to process solid wastes. The subsystem consists of three major components: a feed system, the fluidized combustion chamber, and the flue gas cleanup system. The feed system consists of a blender and a peristaltic pump. The blender breaks up the waste material. The peristaltic pump then injects the slurry into the combustion chamber. Once in the combustion chamber, the slurry is oxidized using air from the air life support system. A zirconia-based catalyst is used in the combustion system.

Food: In transit to Mars, all food will be supplied. The food will be ready to eat or require minimum preparation. On the surface of Mars, food will be grown. However, all the food requirements for surface will also be supplied to provide redundancy in the plant growth system. It is important to grow food on the surface for several reasons. Mars is being explored and examined to determine its potential for sustaining life. The production of food on the surface will go a long way to prove this objective. Secondly, the food production system is a vital link in the life support system. Not only does it provide nutrient-rich food for the astronauts, it also provides water and acts as a waste filter.

Medical: Even though the astronauts will be extensively screened and monitored for medical problems, the crewmembers will likely need medical care during the mission. The crew should be medically prepared to handle the many conditions.

The following will be provided: physician's instruments, surgery, medical monitoring and medical life support, pharmacy, central supply, medical laboratory, imaging and lighting devices, hyperbaric treatment facility, decontamination equipment, dental equipment, emergency transport equipment, safe haven (and Mars rover) supplies, waste management, and a medical information center (MIC).

The infirmary, including medical equipment, medications, and supplies, is estimated to be 6 m^3 in volume and 2500 kg. During routine operations, the infirmary is expected to draw 0.5 kilowatts of power. During critical care emergencies, the infirmary may require up to 2 kilowatts.

Sleep: Because of the long mission duration, it is important to make sure that the crewmembers are not stressed. Perhaps the best way to combat stress is to insure good sleeping habits. Sleep quality can be maintained by minimizing noise and light, providing a stable temperature and airflow, and allowing exercise during the day.

The habitation module should use lighting to simulate a 24 hour day/night cycle. As the crew gets closer to Mars, the day/night cycle should be slowly adjusted until it matches that of Mars. As the mission progresses, higher light intensities may be needed during the day. The higher intensities help to combat fatigue and increase alertness.

Failure Modes and Effects Analysis: A large system requires the proper function of many components to operate. The Failure Modes and Effects Analysis (FMEA) identifies possible modes of failure for each component and the effect that the failure will have on the operation of th entire system and the particular component. A criticality for each failure may be assigned by determining the effect that the failure will have on the complete system and on the individual component. This analysis helps to identify systems critical to the successful operation of the system. By determining the failure mode, effect, and criticality of a particular component, the proper preventative measure may be determined.

The criticality of each failure mode is defined as follows: (1) Single failure could result in the loss or damage of life. (2) Redundant hardware which, if all failed could result in the loss or damage of life. (3) Single failure which could result in the discontinuance of operation of the module. (4) Redundant hardware which, if all failed could result in the discontinuance of operation of the module. (5) Single failure which could result in the partial discontinuance of the operation of the particular system. (6) Redundant hardware which, if all failed could result in the partial discontinuance of the operation of the particular system. (7) Single or redundant failure which has no effect on the operation of the particular system.

Editor's Note: Only selected systems and components that possessed a criticality of level one were included in this report. See comment from editor after the Executive Summary for information on obtaining the complete FMEA performed.

FAILURE MODE	FAILURE EFFECT	CRITICALITY	PREVENTION
Avionics System			
Guidance Navigation Control			
Feedback From Boosters/Thrusters	Erroneous data	1	Calibration and systems check
Aerobraking	Fails to provide a safe entry	1	Training of correct aerobrake procedure
Instrumentation			
ECLSS Sensors	Fails to return accurate system data	1	Calibration and supply spares for repair
Power Sensors	Fails to return accurate system data	1	Calibration and supply spares for repair
ECLSS Actuators	Erratic operation	1	Periodic inspection
Power Distribution	Partial output	1	Periodic monitoring of system consumption
Power System			
Solar Power System - Solar Collector Unit			
Structural Detachment of Solar Array	Possible Air Leak in Habitation Module	1	Check assembly of solar array before launch
Energy Storage Unit			
Seal Failure	Possible Fire/Explosion	1	Periodically check seals
Tank Ruptures	Possible Fire/Explosion	1	Check tanks for fractures Check tank seals Monitor tank pressure
Overheating	Possible Fire/Explosion	1	Check wire connections
Nuclear Power System – Nuclear Reactor (SP-100)			
Nuclear Reactor Leak	Possible Radiation Exposure to Module	1	Check reactor before launch Diagnostics check before power up Periodic maintenance
Environmental Control and Life Support			
Solid Waste Management System			
Particulate filter fails	Life support systems receive contaminated products	1	Human checks of the filter, Place sensors after the filter to assess air quality
Condenser fails to process the water	Lose water	1	Use as little water as possible in system, Integrate system with other life support systems that use condensers
Carbon filter fails	Trace contaminants enter the air life support system, or the carbon dioxide is not converted to oxygen (lose oxygen)	1	Use two filters in series, clean the filters and check for leaks occasionally
Plant Growth System			
Plants do not grow	Reduction in food supply of astronauts	1	Pre-deploy redundant food supply
Structure			
Module			
Develops leak	Loss of Pressure	1	Provide backup air supply Repair kits
Thermal shields fail	Module burns up	1	Proper design of shields
Module lands too hard	Collapse of structure	1	Avionics problem, they solve
Hard Shell			
MO/D impact	Shell is punctured, Depressurization	1	Provide repair kits
Shell cracks	Loss of pressure and structural integrity	1	Make shell thick enough to withstand stresses
Shell buckles on Martian Surface	Structure collapses	1	Use aluminum supports along length of segments
Soft Shell			
MO/D impact	Shell is punctured, Depressurization	1	Use buffer zones
Hard Shell/ Soft Shell Interface			
Pressure seal fails	Loss of pressure	1	Use double seals
Airlock			
Airlock shell fails	Airlock open to space	1	Strengthen shell with Aluminum
Exterior Hatch fails	airlock open to space; crew cannot leave module	1	Maintain good seals
Interior hatch fails	airlock not usable; crew cannot leave module	1	Maintain good seals
Inner core			
Core collapses	Loss of structural support	1	Strengthen core
Hard Points			
Shuttle Bay points fail	Structure collapse in shuttle bay on surface, mission fails	1	Design hard points properly
Propulsion module attachments	Module does not operate properly	1	Design proper hard points
Solar Panel attachments	No power; Possible structural damage	1	Design proper hard points
Maneuvering thrusters	Aberrant flight	1	Design proper hard points
Docking port fails	Crew cannot dock	1	Design proper docking port

Cost Estimation Analysis: The cost estimation of the individual systems for the overall mission was performed to realize the high expenses of this long-term space mission. The program used to calculate the costs is PRICE (Parametric Review of Information for Costing and Evaluation). This model is a computer aided program for deriving cost estimates of electronic and mechanical hardware assemblies and systems and was developed in the early 1970's for use by the US Air Force, Navy, and for NASA. It was designed especially for estimating avionics and space system costs [7].

This program takes into account the many aspects of engineering and manufacturing in both development and production phases of a final product. PRICE H provides a probable cost estimation based on project scope, program composition, and demonstrated organizational performance while incorporating operational and testing requirements. It also attempts to predict technology costs and use escalation factors to accurately portray inflation [7].

The PRICE model uses a work breakdown structure derived from the system schematics and applies empirical formulas to inputted parameters for each component. The component parameters have input boxes which apply factors inputted by the user to estimate the cost of each component. These factors can be looked up in tables within the program and are based primarily on the complexity of the chosen platform. [7] The platform chosen for this cost estimation was the manned space mission profile.

Each system required a similar work breakdown structure to estimate the individual components of the mission. Detailed cost estimates were performed for the habitation power, instrumentation, rover, life support system, and structure. The work breakdown structure correlates directly to the schematics and can be compared for verification.

Major factors determining costs in the PRICE program include weight considerations and complexity factors for design. These factors were adjusted as best as possible and give a fairly accurate estimates of each system. It should be noted that these are best estimate costs and not concrete estimates.

The following estimates are a breakdown of the individual component costs of each subsystem for instrumentation, power, rover, ECLSS and structures. Figure 6 summarizes the total instrumentation system including component costs for GNC, communication, and integration. This is the individual component cost breakdown separated into development and production phase costs. It should be noted that all costs are in 1994 dollars.

The main processor is the main command and control center for all the instrumentation and processing of pertinent data and interfaces. The guidance navigation and control system (GNC) component has a main function to process the GNC equipment. The sensors assembly includes the redundant systems for the IMU, star tracker, sun sensors, and docking sensors. The effectors system component is a subassembly of the GNC system and includes the thrusters, boosters, and aerobraking. The communication system serves the communications equipment including transmission and data storage. The instrumentation I&T ties all the subassemblies of the instrumentation system together and includes the testing required for operation.

The power cost estimate was done the habitation module in transit, habitation module on the Mars surface, and transportable power on the Mars surface. In transit, the main source of power will be solar and on Mars, it will be nuclear. A purchased cost component of the SP-100 nuclear reactor was inputted for this cost.

The rover was estimated on the PRICE H program using the same manned space platform and assuming it will be open to the Mars environment. It will carry two astronauts in fully equipped space suits. It has an operating time of 78 hours with an approximate range of 1000 kilometers.

The ECLSS cost estimate takes into account the total life support of the crew including water and air regeneration as well as habitation atmospheric requirements. The system must dissipate excess heat, provide acceptable pressure, and clean and circulate the air and water. The food must be produced and stored as well.

The total ECLSS costs were broken down into separate systems for thermal control, water supply and recovery, air revitalization, solid waste management, and plant growth.

The structure of the habitation module is estimated assuming two identical habitation modules. The estimate is broken down by the outer shell, internal core, expansion rails, propulsion unit, and system integration. The outer shell has hard shell and expandable shell components for the overall makeup.

The overall cost estimate can be summarized in the following chart. This figure gives the relative system cost estimates compared to one another. Figure 6 shows relative amounts of each subsystem for the overall mission costs. This does not include the launch cost of each shuttle launch. However, it is estimated to cost $500MM for each shuttle launch. With four launches, an extra two billion dollars could be added to the mission expenses.

From these figures, it can be seen that the bulk of the costs are attributed to the power system. This is because of the cost of the SP-100 alone cost $118MM. The structures component seems to be a little low, but more detailed estimates will be done in the final design.

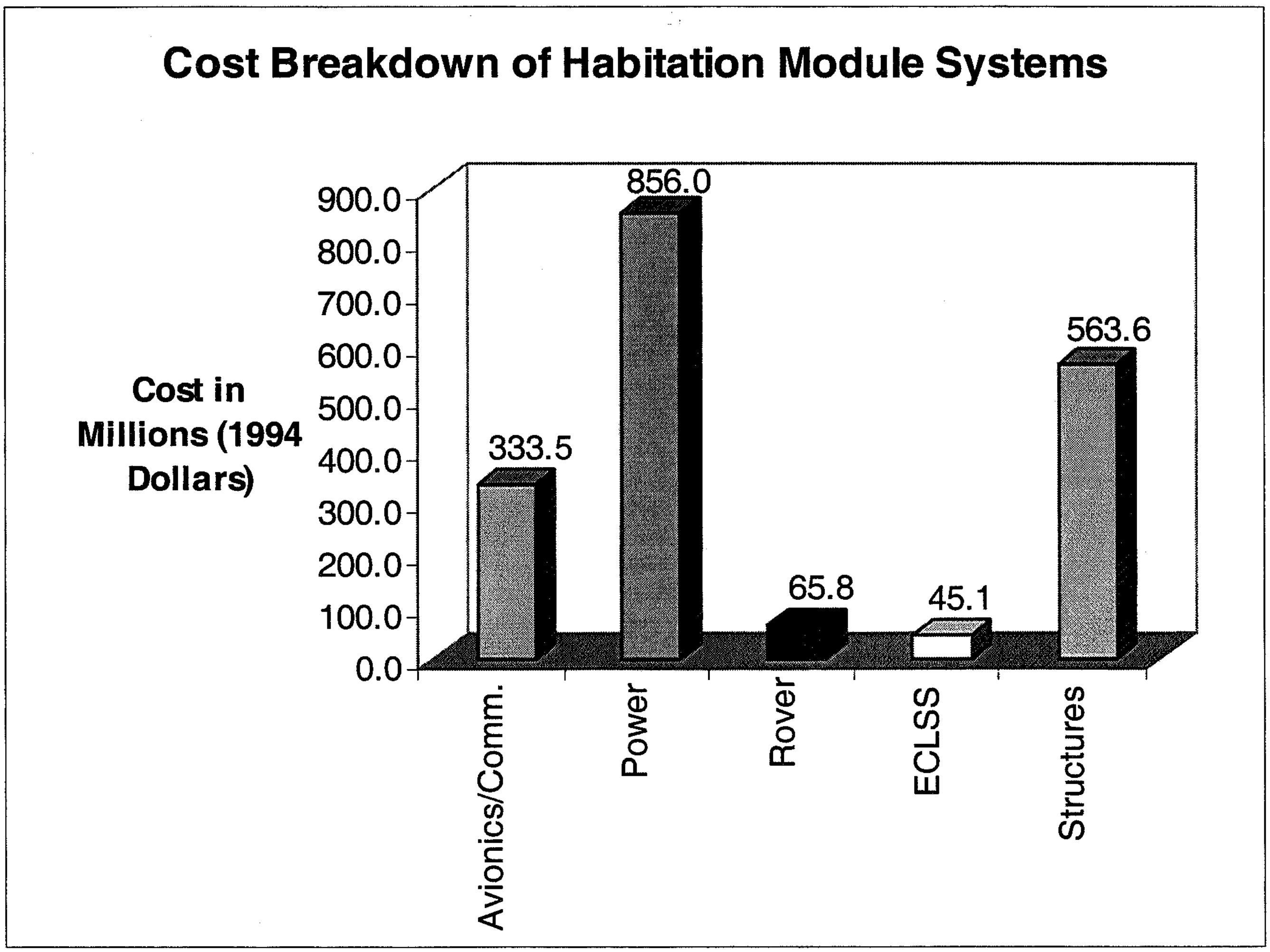


Fig. 6. Relative Cost Amount Comparison of Individual Systems

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Extraction of Atmospheric Water On Mars
for the Mars Reference Mission

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ABSTRACT

The University of Washington has designed an *in situ* resource utilization system to provide water to a life support system in the laboratory module of the NASA Reference Mission to Mars. This system, the Water Vapor Adsorption Reactor (WAVAR), extracts water vapor from the Martian atmosphere by adsorption in a bed of type 3A zeolite molecular sieve. The zeolite 3A adsorbs the water vapor until nearly saturated and is then heated within a sealed chamber by microwave radiation to drive off the water for collection. The water vapor flows to a condenser where it freezes and is later liquefied for use in the life support system. In the NASA Reference Mission, water, methane, and oxygen are produced for life support and propulsion via the Sabatier/Electrolysis process from seed hydrogen brought from Earth and Martian atmospheric carbon dioxide. In order for the WAVAR system to be compatible with the NASA Reference Mission, its mass must be less than that of the seed hydrogen and cryogenic tanks apportioned for life support in the Sabatier/Electrolysis process. The WAVAR system is designed for atmospheric conditions observed by the Viking missions, which measured an average global atmospheric water vapor concentration of $\sim 2 \times 10^{-6}$ kg/m^3. WAVAR performance is analyzed taking into consideration hourly and daily fluctuations in Martian ambient temperature and the corresponding effects on zeolite performance.

1. INTRODUCTION

Current plans to send humans to Mars rest on a mission architecture called the NASA Mars Reference Mission [1]. With concepts derived from Zubrin *et al's* Mars Direct mission architecture [2], the Reference Mission utilizes a strategy known as *in situ* resource utilization, or ISRU, which is defined as the use of indigenous resources at the site of an interplanetary mission for the production of life support consumables and/or rocket propellant [3]. In the Reference Mission, an ISRU process called the Sabatier reaction produces water from seed hydrogen brought from Earth and carbon dioxide from the Martian atmosphere [2]. This water is partially used for life support and the remainder is used for the production of rocket propellants.

Water needs on Mars in the Reference Mission require the production of 23,200 kg of water for life support from 2,600 kg of seed hydrogen imported from Earth [4]. This cache of water is intended to supply the water needs of three missions and is produced entirely by an original ISRU plant landed with the first cargo flight two years prior to the arrival of the first crew. While simple in principle, the importation of seed hydrogen to Mars is extremely challenging due to the need to cryogenically store liquid hydrogen for extended periods of time. A cryogenic hydrogen system having a boil-off rate of 0.5% per day requires leaving Earth with 7,008 kg of liquid hydrogen in order to reach Mars with 2,578 kg after a 200-day journey. This does not include boil-off that occurs on Mars. To make boil-off amounts tolerable, a presently unobtainable evaporation rate on the order of 0.1% per day needs to be attained. With such a rate, delivering 2,600 kg of liquid hydrogen to Mars requires leaving Earth with 3,200 kg. NASA's current plan for liquid hydrogen storage rests on super-thermal cryogenic tank research that will maintain liquid hydrogen with no boil-off using active refrigeration [4], however, the mass and power required for this alternative may ultimately prove to be prohibitive.

Initially the Mars Reference Mission is completely dependent on seed hydrogen for water; however, as pointed out by its architects, a source of indigenous water is needed for the long term success of human Mars exploration. The purpose of this study is to examine how an ISRU concept called the Water Vapor Adsorption Reactor, or WAVAR, might be incorporated into the Reference Mission to meet this indigenous water need.

WAVAR is a process conceived and developed at the University of Washington's Department of Aeronautics and Astronautics under the guidance of A.P. Bruckner [5]. It obtains indigenous water by extraction from the Martian atmosphere. The atmosphere of Mars is the most highly characterized and global water source on the planet [6-8]. Both seasonal and daily cycles have been observed and the amount of water vapor has been found to vary strongly with latitude. The column abundance of water vapor was determined as a function of latitude for a period of nearly 1½ Mars years (~1000 days) by the Viking Orbiters [8]. The amount ranged from less than 1 *pr* μ*m* (precipitable micrometers) at high southern latitudes in midwinter to 100 *pr* μ*m* at high northern latitudes in midsummer. The seasonal variation of local humidity at the two Viking Lander sites was found to be in the range of $\sim 1.8 \times 10^{-7}$–2×10^{-6} kg/m^3 at VL-1 and $\sim 4 \times 10^{-10}$–3×10^{-6} kg/m^3 at VL-2 [9]. More recently Pathfinder measured a column abundance of ~10 *pr* μ*m* [10]. These numbers appear to indicate an extremely dry atmosphere compared to Earth's, but on the average, the atmosphere of Mars is holding as much water as it can on a daily basis, i.e., 100% relative humidity at night throughout the lowest several kilometers, at most seasons and latitudes [11]. The global average of atmospheric water is 0.03% by volume [6], corresponding to saturation at about 200 K, i.e., a concentration of $\sim 2 \times 10^{-6}$ kg/m^3. At the north polar regions during summer the concentration may exceed 10^{-5} kg/m^3. For this study the humidity data of Ryan *et al* at VL-1 and VL-2 were used [9]. In addition, hypothetical sites near the north pole and elsewhere showing enhanced humidities were also used, as described later.

Key to the WAVAR concept is the use of a molecular sieve adsorbent called zeolite, a strongly hydrophilic crystalline alumino-silicate commonly used in industrial dehumidifiers. As illustrated in Fig. 1, the WAVAR process is conceptually very simple. Martian atmosphere is drawn into the system through a dust filter by the fan. The filtered gas passes through the adsorbent bed, where the water vapor is removed from the flow. Once the bed has reached saturation, the water vapor is desorbed from the bed, condensed, and piped to storage. The design has only seven components: a filter, an adsorption bed, a fan, a desorption unit, a bed rotating mechanism, a condenser, and an active-control system.

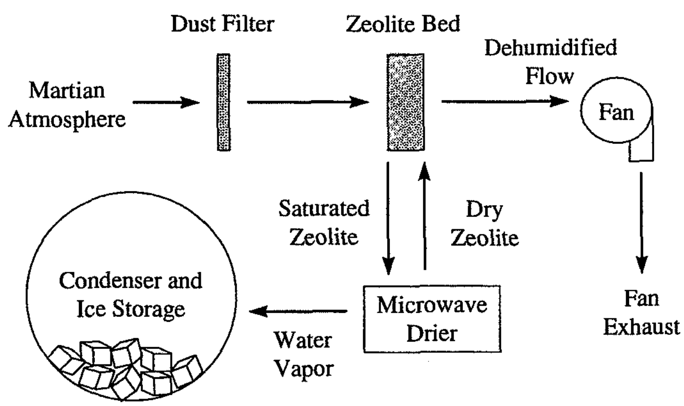

Fig. 1. The WAVAR process.

The WAVAR fan has to move a low humidity (~0.03% by volume), low temperature (~210 K), low pressure (~5 torr) gas, deal with frequent off-design operational periods, and work continuously and reliably for long periods of time (500-600 sols typical surface stay for low-energy Mars transfers). Because the flow will already be rigorously filtered to minimize fouling of the adsorption bed by Martian dust, abrasive wear on the fan can be kept to a minimum. The motor used for the WAVAR fan must operate over a range of loadings because of the variable nature of the ambient density [12].

Adsorption is a process which removes a species (the adsorbate) from a fluid as the fluid passes through a bed (the adsorbent). The adsorbent in WAVAR is zeolite 3A, a material which adsorbs water vapor but allows the other atmospheric gases (primarily carbon dioxide) to pass through. Section 2 provides further details about zeolites and the adsorption process. In the current WAVAR design, the pelletized adsorbent is packed into a bed placed in a radial flow configuration. This design is discussed in detail in Section 3.

Desorption of the bed is achieved by thermal swing desorption, which involves heating the bed until the thermal energy of the adsorbed molecules is greater than the adsorbent/adsorbate bond strength [13]. Thermal swing desorption is well suited for strongly adsorbed species such as water and can be accomplished either through resistive heating or with microwaves. The use of microwaves for the regeneration of zeolites has been demonstrated by Roussy, *et al* [14], and Whittington, *et al* [15]. The major advantage of using microwave energy over conventional conductive heating is that it provides rapid uniform heating for reduced desorption time and can be tailored to specifically heat water molecules.

The use of WAVAR on Mars has been the topic of past studies at the University of Washington, with most attention focused on its use in robotic sample return missions [5,16,17]. However, WAVAR is a process that is easily scaleable and has been included in one previous human Mars mission study [18]. In the present study, as a starting point for the incorporation of WAVAR into the Reference Mission, the water requirement needed to replace regenerative life support losses is set as a top-level design requirement. For a crew of eight, estimated losses amount to 6.5 kg per sol [19] over a typical surface stay duration of approximately 600 sols. Design of the physical configuration of a WAVAR system to meet this requirement is subject to several constraints. Among these constraints are system mass and footprint limitations, the adsorption capacity of zeolite 3A, the water needed to make up for life support regenerative losses, power limitations, minimization of moving parts, ease of integration into the NASA Reference Mission, and the overall simplicity and maintainability of the system and components.

The WAVAR configuration proposed by Williams, et al [5] was used as a starting point for the design. Redesign and optimization of the WAVAR is focused around four goals. First, the WAVAR must collect 3.3 kg of water per sol to make up for the water lost through life support regenerative processes. The WAVAR arrives at Mars with the laboratory habitat module, and begins operation immediately. The system then collects water for the next two years before astronaut arrival, as well as during the 500-600 sol human surface mission. This total of almost 4 Earth years of operation time reduces the daily water collection requirement by a factor of two as compared to a 500-600 sol operation during the human surface mission only. The mass flow rate of water vapor through the zeolite bed must be high enough to ensure an average net gain of 3.3 kg of water per sol during its operation time, enough to supply the astronauts with the water needed during the nominal surface mission. Second, the power drain of the system must be kept to a minimum. Power requirements are dominated by the need to transport large volumes of air through the filter and the zeolite bed (up to 1×10^9 m^3/kg-H_2O during the driest seasons), and the power required to desorb water from the zeolite. In order to minimize the pressure drops at the filter and bed and the corresponding fan power needs, flow velocities are kept low and the zeolite bed and dust filter are kept as thin as possible. Third, the WAVAR must be sized to fit on top of the current Reference Mission laboratory module to facilitate integration with the Mission and to simplify collection of the water for use in the life support system. Fourth, the mass of the WAVAR system must be less than that of the seed hydrogen it replaces in the current NASA Reference Mission. Table 1 summarizes the major quantitative design restrictions.

Table 1. Summary of quantitative system design constraints.

Characteristic	Restriction	Derived From
Net water gain	≥ 3.3 kg/sol	Mass of water needed daily over four years to make up for 600 sols of life support regenerative losses.
Average power drain	≤ 16 kW	5% of Reference Mission available power.
Footprint	≤ 7.5 m diameter	Habitat diameter is 7.5 m.
System mass	≤ 1200 kg	Reference Mission currently requires 1200 kg of seed H_2 to be launched from Earth for replacement of water lost in life support regenerative processes, assuming an H_2 boil-off rate of 0.5% per day over a 200 day Earth/Mars transit. WAVAR takes the place of this seed H_2.

2. ZEOLITE CHARACTERISTICS

The single most important component of the WAVAR unit is the zeolite bed, since it is what extracts the water from the Martian atmosphere. Zeolites are found naturally on Earth and can also be synthesized for specific functions [20]. Since zeolite is so important to WAVAR, its characterization is critical.

Zeolites are crystalline alumino-silicates with a three-dimensional interconnecting network structure of silica and alumina tetrahedra that contain many micropores (Fig. 2). Since zeolites have a crystalline structure, the pore openings are uniform and therefore permit adsorption discrimination based on the size and configuration of molecules in a system. This is a property unique to zeolites, and forms the basis for the name "molecular sieve." The chemical composition for the naturally occurring sodium zeolite is $Na_{12}[(AlO_2)_{12}(SiO_2)_{12}]\bullet 27\ H_20$, where 27 is the number of water molecules adsorbed per unit cell of fully saturated zeolite [20]. The tetrahedra are formed by oxygen atoms surrounding a silicon or aluminum atom. Each oxygen has two negative charges and each silicon has four positive charges. The trivalency of aluminum causes the alumina tetrahedron to be negatively charged, requiring an additional cation to balance the system. Thus, cations such as potassium, calcium, lithium or sodium are the exchangeable ions of the zeolite [20].

Type A zeolites have two types of void spaces where adsorbed molecules are stored: the outer cages, called β-cages, and, the inner cages, called α-cages (Fig. 2) [5]. The size selectivity takes place at these spots [20]. In both the α- and β-cages the water molecules are held by van der Waals forces [21].

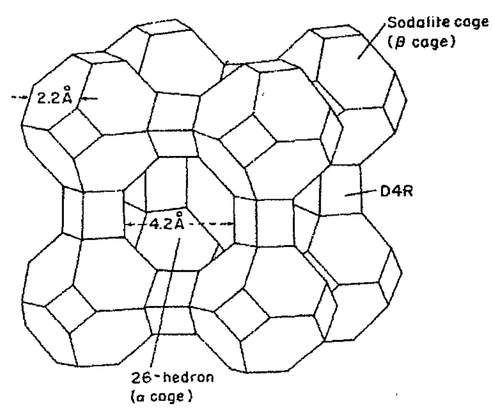

Fig. 2. The molecular structure of zeolite 4A [21]. The SiO_4/AlO_4 structure of the cage is the same for zeolite 3A and zeolite 4A. The substitution of larger potassium ions for the smaller sodium ions reduces the apertures of windows and cavities.

By controlling the ratios of cation exchange and the cation used, it is possible to synthesize zeolites containing different crystal structures. This property can regulate the pore diameter of the zeolite cavity and therefore selectively adsorb molecules of specific sizes.

For the WAVAR, a zeolite must be chosen that adsorbs water molecules but not the other species in the Martian atmosphere. The major constituent of the Martian atmosphere is CO_2 (95% by volume) and is the primary species to be excluded. As can be seen in Fig. 3, the only zeolite that can exclude CO_2 is the K type, which is a zeolite with most of the naturally occurring smaller sodium cations replaced by larger potassium cations. This reduces its average pore size to 3 Å which excludes the 3.3 Å size of CO_2 but accepts the 2.65 Å size of water [20]. Therefore, zeolite 3A was chosen to be the adsorbent for the WAVAR unit.

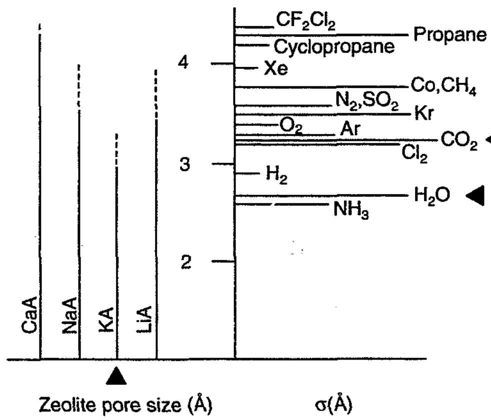

Fig. 3. Chart showing a correlation between effective pore size of various zeolites in equilibrium adsorption over temperatures of 77 K to 420 K (range indicated by ---), with the kinetic diameters of various molecules as determined from the L-J potential relation [20].

Zeolite Capacity

An important parameter of zeolite 3A is its capacity for water. Capacity is defined as the mass of water adsorbed per unit mass of dry zeolite. As can be seen in Fig. 4, the capacity of zeolite 3A varies strongly with both the ambient vapor pressure of water and the temperature. These data were obtained from a chart published by W.R. Grace Davison Molecular Sieves [22], having isotherms down to 253 K. The isotherms down to 170 K, represented by dashed lines, were obtained by logarithmically extrapolating the available data. These low temperature isotherms will need to be experimentally confirmed.

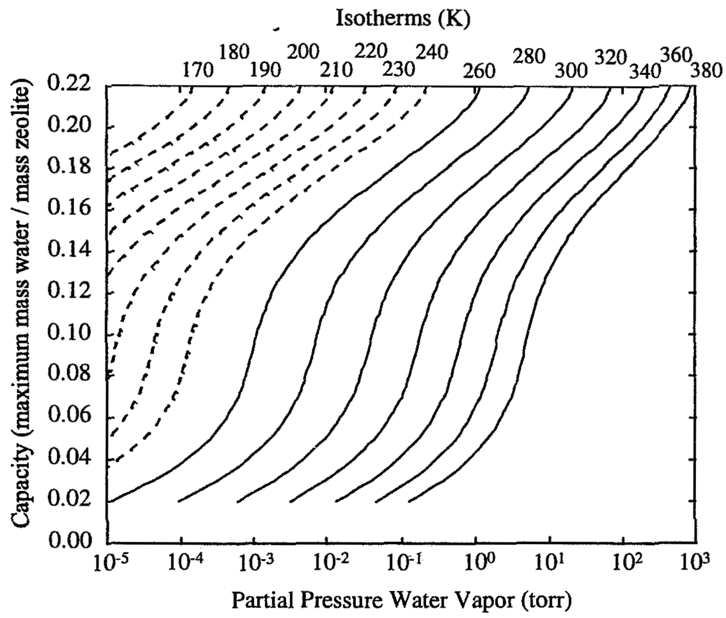

Fig. 4. Isotherms for capacity as a function of water partial pressure. The curves are from W.R. Grace Davison Molecular Sieves [22]. Dashed curves represent logarithmic extrapolations.

During a typical Martian day the temperature varies significantly and thus so does the water capacity of zeolite. Figure 5 shows the diurnal temperature variation on Sol 1 at the VL-1 site and the corresponding variation in the water adsorption capacity of zeolite 3A. As can be seen, the diurnal capacity fluctuation is large, which poses a problem for continuous running of the WAVAR unit. If it continued adsorbing through one of the low points in capacity (maximum ambient temperature), the zeolite would desorb down to what the maximum capacity was during that time. The condition in which the zeolite is loaded beyond its capacity due to a temperature drop is termed super capacity. During super capacity periods, the zeolite bed must be thermally isolated from the Martian ambient temperature so the zeolite does not heat up and the water prematurely desorb. This scheme is illustrated in Fig. 6, where the instantaneous water loading fraction is plotted over a period of four sols (Sols 4-8) at the VL-1 site. The two curves respectively show the capacity of the zeolite with its diurnal fluctuations, and the actual cumulative loading fraction with the bed insulated and inactive during the high temperature periods (horizontal curve sections). This problem increases the complexity of the WAVAR but it is unavoidable if the adsorption time is more than one sol, which for most places on Mars is the case. Figure 7 shows the holding capacity of zeolite 3A as a function of temperature for different partial pressures. The dependence of holding capacity on temperature and partial pressure is key to the design of the desorption process and will be examined in depth in future studies to determine optimum conditions for the process.

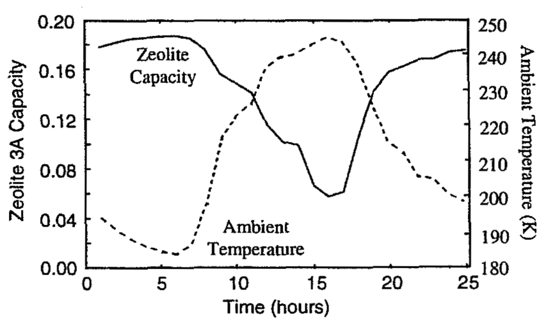

Fig. 5. Typical diurnal temperature variation (Sol 1 at VL-1) and corresponding zeolite equilibrium capacity.

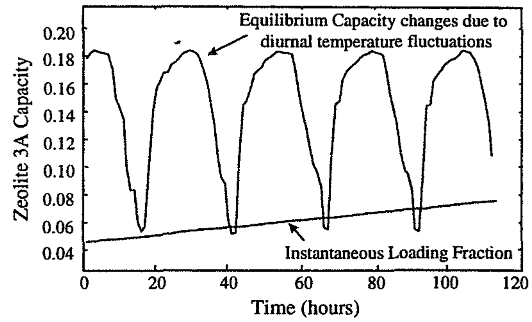

Fig. 6. Simulation results showing times when water capacity of zeolite drops below the current loading fraction, necessitating a method for thermal isolation of the zeolite bed.

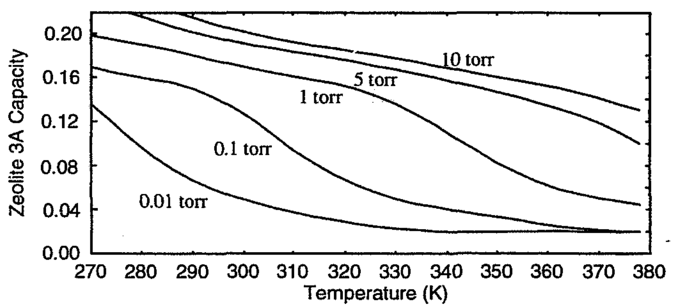

Fig. 7. Simulation showing zeolite capacity vs. temperature at different pressures.

3. SYSTEM DESIGN

3.1 WAVAR Geometry

The WAVAR is designed to minimize fan power requirements by providing a large area of zeolite through which the atmosphere can flow. A WAVAR design that operates efficiently and integrates cleanly with the NASA Reference Mission is shown in Fig. 8. The WAVAR uses a single fan to draw Martian air radially through a curved filter and bed of packed zeolite pellets, both shown in Fig. 9. The zeolite bed is a 180° arc, 10.8 m long, 0.93 m high, and 0.04 m thick, for a total bed flow area of 10.0 m^2 and mass of 240 kg. The annular structure that supports the four zeolite sections rests on rollers that are isolated from the dusty Martian environment. A stepping DC motor drives the rotation of the zeolite bed through a rack and pinion gear system, and a backup motor is available for emergency use.

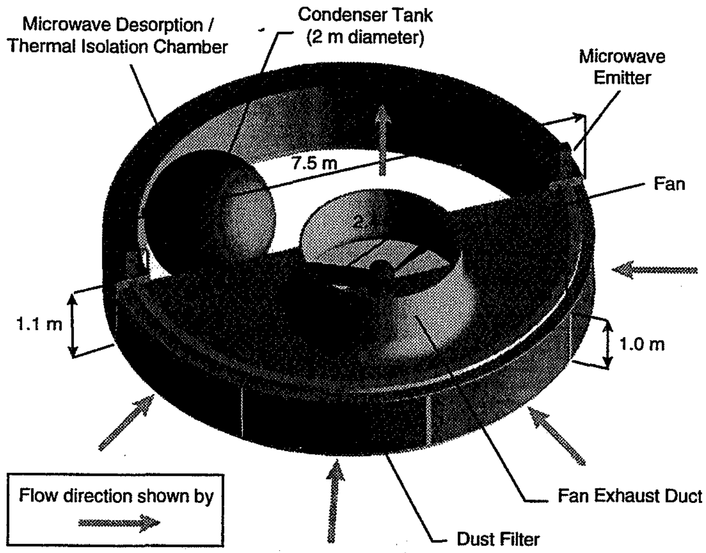

Fig. 8. WAVAR geometry and dimensions.

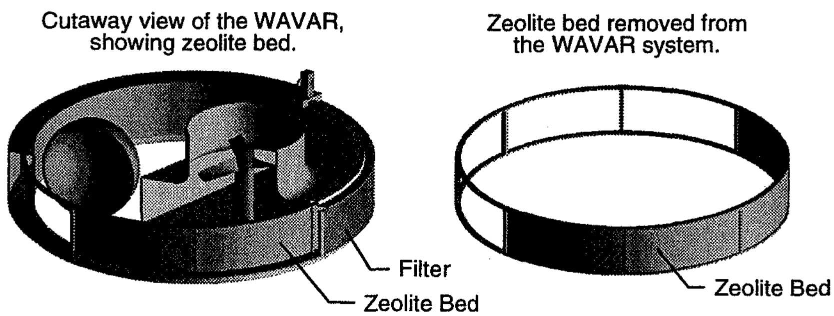

Fig. 9.. Zeolite bed location and shape.

The airtight desorption chamber shown in Fig. 8 is insulated from the temperature fluctuations of the ambient Martian environment, and is used for two purposes. The first use is for thermal isolation of the zeolite bed during the daily super-capacity hold cycle described above. When the bed reaches a super-capacity state due to an increase in ambient temperature, the fan stops and the bed rotates into the desorption chamber, located 180° about the WAVAR's central vertical axis. When the ambient temperature has dropped to beneath the super-capacity temperature, the bed rotates back 180° and the fan engages to continue the adsorption process.

The second use of the desorption chamber is for removal of adsorbed water from the zeolite bed. When a water loading fraction of 0.15 is reached, the zeolite bed rotates into the desorption chamber. During the desorption cycle, microwave emitters are used to heat and desorb the water from the zeolite bed. Initially the released water vapor freezes onto the walls of the desorption chamber, but further heating of the bed warms the walls of the chamber radiatively and sublimates this frost.

A variable-aperture valve links the desorption chamber with the 2 m diameter spherical condenser tank shown in Fig 8. A metal grid covering the valve opening prevents microwave radiation from entering the condenser. After the heating process begins, the valve opens to allow released water vapor to exit the chamber. The condenser is made of aluminum and remains exposed to the low temperature of the ambient Martian atmosphere. When the desorbed water vapor pressure reaches the saturation value, vapor begins to freeze on the cold condenser walls. This freezing maintains a pressure drop from the desorption chamber to the condenser, driving the vapor into the condenser. The rate of vapor transfer from the desorption chamber to the condenser is regulated by the variable-aperture valve to match the freezing rate so as to maintain this pressure difference between the desorption chamber and the condenser. When as much water as possible has been desorbed from the zeolite, the valve between the desorption chamber and condenser closes. The zeolite bed rotates back into the airflow to be cooled and then to continue the adsorption process.

Adsorption, with intermittent hold and desorption cycles, continues for six months. Every six months or when necessary, the condenser is heated resistively to increase the vapor pressure and produce liquid water. A valve at the bottom of the condenser then opens that leads to a heated, pressurized liquid water storage tank within the laboratory module. The condensation and liquid water storage process is diagrammed in Fig 10. Prior to astronaut arrival, the liquid collection cycles are performed remotely. Liquification of the contents of the condenser results in a loss of 4.2 m^3 of habitat atmosphere as the atmosphere bubbles up through the valve into the condenser. This loss of atmosphere is not considered to be a problem because liquification need be performed only once every six months, and habitat atmosphere can be replenished relatively easily.

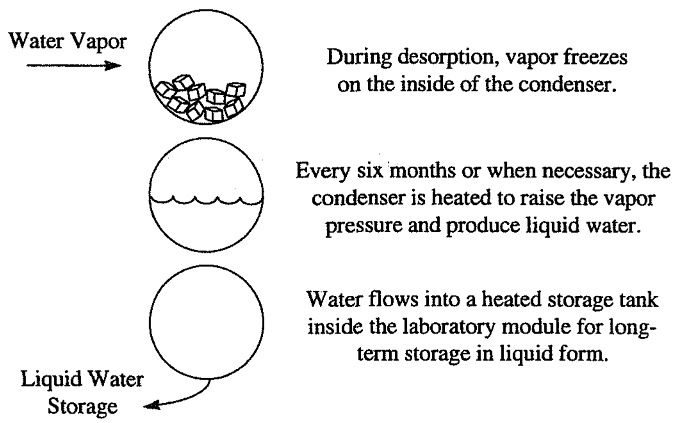

Fig. 10. Condensation and liquid water storage process.

The WAVAR is designed to fit on top of the Reference Mission laboratory module with minor changes to the current configuration. After integration with the existing structural supports on top of the module, the WAVAR increases the height of the module by about 0.5 m at the edges and 1.5 m at the exhaust duct, as shown in Fig. 11.

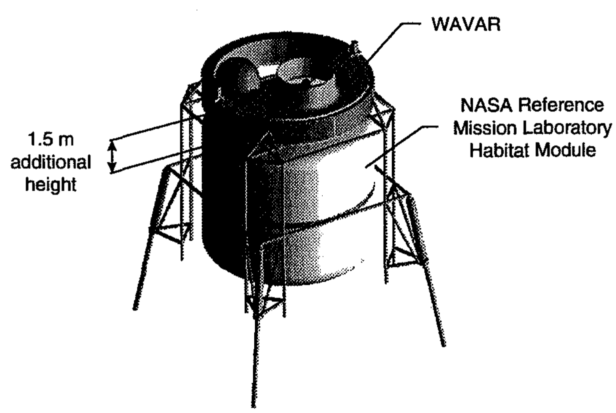

Fig. 11. WAVAR integration with the laboratory module of the NASA Reference Mission.

3.2 Desorption Process

To remove the adsorbed water from the zeolite bed, enough energy must be provided to break the bonds holding the water molecules in the bed. Thermal swing desorption is used due to its ease of implementation. The two types of heating processes considered were microwave and resistive wire heating. Heating by resistive wire is power and mass intensive due to the low thermal conductivity of zeolite. Microwave power was chosen for its controllability, specificity with water, and the relatively low mass necessary for its implementation. When heating the zeolite, there are two main considerations. The correct amount of power must be provided and the zeolite cannot be raised above the damage threshold temperature, ~600 K [23].

During desorption, the zeolite bed rotates into the insulated desorption chamber, where it is heated to 400 K. The desorption chamber is a microwave cavity resonator, and is sealed against the ambient environment for containment of desorbed water vapor. Heating reduces the water loading fraction in the bed to 1.5% (Fig. 7) [24]. Attempting to desorb to a lower percentage would take more power than is justified. The microwaves also heat the walls of the desorption chamber to prevent the liberated water vapor from condensing on the walls. The aluminum honeycomb walls absorb less than 1% of the total microwave power, and this power is input within a skin depth thickness of the walls. The desorbed water vapor enters a condenser and is later stored in the habitat for the astronauts' use, as discussed above.

3.2.1 *Power Requirements*

To desorb the water, the zeolite bed is heated to an average temperature of 400 K. This temperature provides enough energy to break the adsorption bonds, while preventing serious degradation due to thermal cycling over a four-years operational lifespan. The heating process begins with a bed at thermal equilibrium with Mars ambient conditions, i.e., an average temperature of 210 K. Initially, the microwave must provide enough energy to raise the temperature of the water and break the adsorption bonds. The zeolite bed is also heated to 400 K during the process. The heat of desorption of water is assumed to be equal to the heat of adsorption, found experimentally to be 4.19 MJ/kg [24]. The specific heat of water vapor was extrapolated to low temperatures from low-pressure data [25]. Table 2 lists the parameters used to compute the desorption power. The power required for desorption of the water over a four-hour period is:

$$Energy = C_{p\,zeolite} \cdot m_{zeolite} \cdot \Delta T + m_{H_2O}\left(\Delta H + C_{p\,H_2O} \cdot \Delta T\right) = 317\ MJ$$

$$Power = \frac{Energy}{t_d} = 22\ kW$$

Table 2. Constants assumed for desorption performance calculations.

$C_{p\,zeolite}$	Specific heat of zeolite [20]	3.375 kJ/kg·K
$C_{p\,H20}$	Specific heat of water vapor	1.854 kJ/kg·K
ΔH	Water heat of desorption	4.19 MJ/kg
$m_{zeolite}$	Total zeolite mass	240 kg
m_{H20}	Total water mass	36 kg
$T_{desorption}$	Maximum temperature	400 K
$T_{ambient}$	Mars ambient temperature (avg.)	210 K
ΔT	$T_{desorption} - T_{ambient}$	190 K
t_d	Desorption cycle time	4 hours

3.2.2 *Microwave Heating of Zeolite*

Microwaves are electromagnetic (EM) waves operating in the gigahertz (GHz) frequency range. Water has a maximum absorption at 2.45 GHz; therefore the microwave operates at this frequency, similar to microwave ovens found in most kitchens. When heating a dielectric material with microwaves, certain considerations are needed in the design of an efficient, low mass system. The microwaves must penetrate throughout the volume of the bed, the power absorbed by the zeolite and water should be a substantial amount of the input power, the radiation impinging on the surface should be uniform, and the system that delivers the radiation should be as loss-free as possible.

As with most materials, zeolite is a dielectric [20]. EM wave propagation through dielectric materials can be represented by an oscillating electric field function that has an exponentially decaying amplitude. The complex dielectric constant, $\varepsilon' - j\varepsilon''$ [26] has a real and an imaginary permittivity term. The real term is the oscillation and the imaginary term is the exponential decay. The exponential decay represents the loss of power due to absorption by the dielectric. The distance from the input face to the location where the electric field is reduced by a factor of e^{-1} is called the skin depth, δ. The fraction of input power absorbed depends on this parameter as well as the bed depth, L.

$$\frac{P_{abs}}{P_{in}} = 1 - e^{-\frac{L}{\delta}}$$

Due to the lack of data on the electrical properties of zeolite 3A, data available for zeolite A was used. In general, ε' and ε'' depend on the frequency, temperature, and water content in the zeolite [20]. The value of ε'' represents the absorption by zeolite and water. At the frequency of interest, the permittivities become dependent on only one variable and become linear. At a water loading fraction of 0.15 and a temperature of 210 K, 40% of the input power is absorbed by a zeolite bed of 4 cm thickness.

Because only 40% of the input energy is absorbed during each pass, the desorption chamber is used as a microwave cavity to create a resonating field so that all the input power is absorbed by the water and the zeolite. Due to the shape and dimensions of the cavity, a specific field distribution resonates at 2.45 GHz. This is quantified by the mode numbers in the radial, azimuthal and axial directions. A waveguide transmits microwave power from the emitter and guides it to the desorption chamber, and an isolator prevents radiation from transmitting back and causing damage to the emitter.

3.2.3 *Microwave Geometry*

A magnetron microwave generator was chosen for its compactness and high power conversion efficiency of around 80%. Two magnetrons are used for redundancy and longevity. Each emitter is capable of supplying enough power for desorption by itself, but both are used simultaneously at half power to reduce wear from thermal cycling and overheating. The magnetrons are thermally isolated from the environment by an aluminum honeycomb shroud. The mass of a 25 kW magnetron is 20 kg, for a total of 40 kg for both. The magnetrons require a total input power from the main power grid of 27.8 kW, with each operating at half capability. In order to irradiate the large surface area of the zeolite in the desorption chamber, a combination of a waveguide and a cavity resonator (the desorption chamber) is used.

The magnetron emits a cylindrical wave from a cylindrical antenna [26]. A rectangular aluminum waveguide directs the transmission wave through an isolator. The waveguide is sized so that the microwave frequency is twice the geometric cutoff frequency of the waveguide. The waveguide cannot propagate EM waves at a frequency below the cutoff frequency. This frequency is obtained by solving Maxwell's equations for closed volumes, and depends only on geometry. The isolator prevents reflected waves from the resonating (desorption) chamber from transmitting back to the emitter by redirecting them into the terminator. The power is then transmitted through a small inlet waveguide and into the resonator. This input excites the resonant frequency of the desorption chamber, which is roughly 2.45 GHz, and the zeolite bed is bathed in radiation for four hours. Due to the geometry of the chamber, the actual resonant frequency will vary slightly from the optimum value. The resonant frequency also excites high mode numbers of 10-20 in the radial and axial directions.

3.3 Materials and Mass

The WAVAR system must have a mass less than that of the seed hydrogen and associated storage systems required to make up for water losses in the life support system of the NASA Reference Mission. Regenerative losses amount to 6.5 kg H_2O per sol [19] while the crew is on the surface of Mars. For a surface stay of 600 sols this amounts to a total of 3900 kg of replacement water, requiring the use of 433 kg of seed H_2 for water production. Assuming a boil-off rate of 0.5% per day in transit to Mars, a launch from Earth of 1200 kg of seed hydrogen would be needed. Taking into account additional boil-off after arrival on Mars, this figure would increase. The aim of this design was to limit the mass of the WAVAR to 1200 kg.

The WAVAR system (Fig. 8) has a support structure made of two tubular aluminum circles spaced apart by tubular aluminum cross members, with the bottom plate of the adsorption chamber made of graphite-epoxy facesheets with Nomex honeycomb core [27]. The top of the adsorption chamber converges to the fan duct, which is made of the same honeycomb sandwich structure. The fan itself is made of graphite epoxy. The air filter, a Filtrete Type G from 3M [28], surrounds half the periphery of the WAVAR. All exterior components are flush mounted to the structural supports to prevent inflow of dust to the system. Inside the filter is the curved zeolite bed. An aluminum rack reinforced with steel facing under the zeolite bed is used with a stepping motor for rotation of the bed into the microwave desorption chamber.

The desorption chamber is completely encased and insulated from the rest of the WAVAR system and the Martian atmosphere. The walls of the chamber are composed of 0.25 mm thick sheet aluminum (inside), 3 cm thick Aerogel-Based Superinsulation and graphite-epoxy facesheets with a Nomex honeycomb core. These layers are illustrated in Figure 12. Aerogel-Based Superinsulation has a very low thermal conductivity, less than 0.1 mW/m-K, and a density of 12 to 35 kg/m^3 [29]. A density of 20 kg/m^3 was assumed for the mass estimate. Desorbed water vapor freezes in an aluminum condenser tank. The mass breakdown of the WAVAR system is summarized in Table 3.

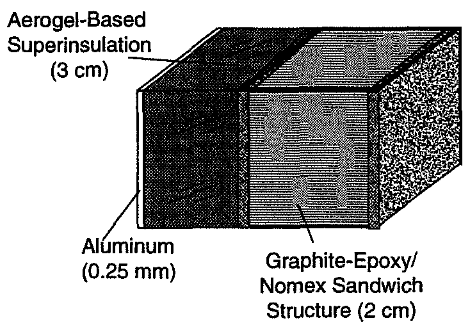

Fig. 12. Desorption chamber wall components.

Table 3. Summary of WAVAR system mass.

Component	Mass (kg)
Structural Supports	60
Adsorption Chamber Floor, Ceiling, and Duct	85
Dust Filter	10
Zeolite Bed	240
Bed Support Structure and Rack	120
Fan	30
Fan Motor (10 kW)	30
Desorption Chamber	150
Bed Rotation Motors (2)	10
Microwave Emitters (2)	40
Condenser Tank	100
Active Control System	10
TOTAL	**885**

4. PERFORMANCE

4.1 Fan Modeling

Achieving a high fan efficiency under WAVAR operational conditions is critical for the minimization of WAVAR power requirements. The design of the fan is driven by the need to efficiently transport large volumes of low density Martian atmosphere at the high velocities required by adsorption design constraints. A fan was designed using momentum-blade element theory, with modifications intended to take into account the rotation induced in the flow by fan rotation. The fan is optimized for operation at an axial flow velocity of 20.6 m/s, corresponding to a velocity at the zeolite bed of 9 m/s.

The 2.4 m diameter WAVAR fan consists of 3 rectangular blades of 0.3 m chord length, as shown in Fig. 13. The fan operates at 500 RPM, corresponding to an angular velocity of 52.4 rad/s. Blade angle of twist varies from 68.63° at the root to 23.47° at the tip, as given by:

$$\beta = -38\ln(0.3r + 0.015) + 16r - 33,$$

where r is the distance from the hub axis in meters and β is determined in degrees.

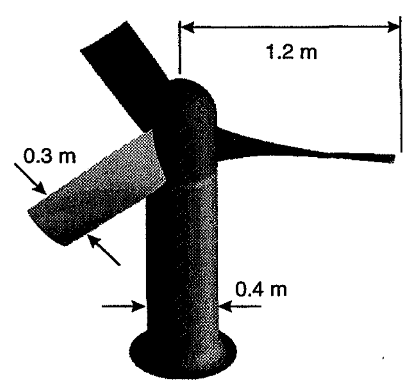

Fig. 13. WAVAR fan as modeled for simulations.

The basic equations of momentum-blade element theory are as follows, and are based on the geometry shown in Fig. 14 [30].

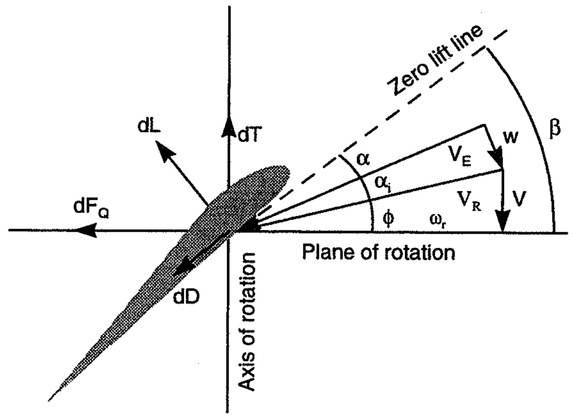

Fig. 14. Notation used for fan blade analysis [30].

$$\lambda = \frac{V}{\omega R} \qquad x = \frac{r}{R} \qquad V_T = \omega R$$

$$V_R = V_T\sqrt{x^2 + \lambda^2} \qquad \sigma = \frac{Bc}{\pi R} \qquad \phi = \arctan\frac{\lambda}{x}$$

$$\alpha_i = \frac{1}{2}\left[-\left(\frac{\lambda}{x} + \frac{\sigma a V_R}{8x^2 V_T}\right) + \sqrt{\left(\frac{\lambda}{x} + \frac{\sigma a V_R}{8x^2 V_T}\right)^2 + \frac{\sigma a V_R}{2x^2 V_T}(\beta - \phi)}\right]$$

$$dL = \frac{1}{2}\rho V_R^2 c C_l dr \qquad dD = \frac{1}{2}\rho V_R^2 c C_d dr$$

$$dT = dL\cos(\phi + \alpha_i) - dD\sin(\phi + \alpha_i)$$

$$dQ = r\left[dL\sin(\phi + \alpha_i) + dD\cos(\phi + \alpha_i)\right]$$

$$P = \omega Q \qquad \eta = \frac{TV}{P}$$

where T is thrust, Q is torque, P is input power, and η is fan efficiency [30].

These equations are sufficient to solve for the fan efficiency if given the blade geometry, rotational speed, and axial flow rate [30]. To determine the axial flow velocity, the following formulation was used.

Given the angle of twist β and the chord length c, the volume swept out by a blade in one revolution is

$$\int_{R_1}^{R_2} dVol'$$

for the differential volume element

$$dVol' = 2\pi rc\sin\beta\, dr\,.$$

For B blades with ω angular velocity, this leads to an average axial flow velocity of

$$V' = \frac{\omega B\int_{R_1}^{R_2} dVol'}{\pi\left(R_2^2 - R_1^2\right)},$$

where R_1 is the hub radius and R_2 is the fan radius.

However, neither this velocity formulation nor momentum-blade element theory takes into account the decrease in axial velocity due to the tangential velocity imparted by the rotation of the fan. In order to approximate this loss, a factor of cos β is applied to the differential volume element *dVol*. With an angle of twist of 90° and slow rotation, this leads to an axial velocity of 0 m/s, as would be expected intuitively. At very small angles of twist, tangential velocity is minimized, also satisfying intuition. At high rotation rates, a factor taking into account α_i may provide a better approximation because of the effects of the induced angle of attack, but α_i in turn depends on the flow velocity. Including the rotational correction factor cos β, the equation for average axial velocity *V* becomes

$$V = \frac{\omega B \int_{R_1}^{R_2} dVol}{\pi\left(R_2^2 - R_1^2\right)}$$

where

$$dVol = 2\pi rc \sin\beta \cos\beta \; dr \, .$$

The choice of a specific airfoil for the fan blades was constrained by the need to operate in the low Reynolds number environment on the Martian surface. For V_R as defined above and blade chord length *c*, the Reynolds number was taken to be:

$$\mathrm{Re}_f = \frac{\rho V_R c}{\mu} \, .$$

The Reynolds number across the fan blades varies linearly with respect to radial position, from 1.09×10^4 at the root to 3.12×10^4 at the tip. At Reynolds numbers on the order of 2×10^4, a sharp leading edge rather than a sharp trailing edge produces more lift [31]. At Reynolds numbers in this regime, a circular arc airfoil with 5% camber provides a high lift to drag ratio [31], so this airfoil was chosen for use in the WAVAR fan. Fourth order curve fits to empirical lift and lift to drag ratio data with respect to angle of attack are shown in Fig. 15.

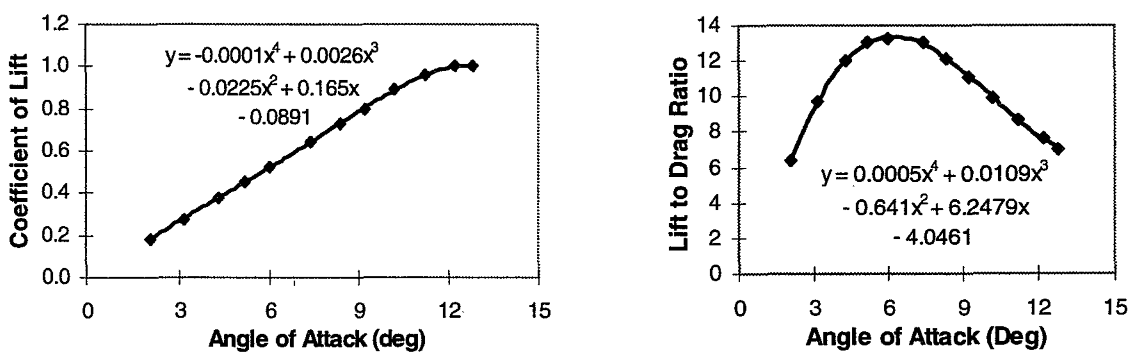

Fig. 15. Curves fit to empirical lift and lift to drag ratio data on 5% camber circular arc airfoil at Re = 2.07×10^4 [31].

An analysis of the WAVAR fan using the velocity equation derived above, momentum-blade element theory, and curve fit data for C_L and L/D leads to a fan efficiency of 76%. The major physical and performance characteristics of the WAVAR fan are summarized in Table 4.

Table 4. Fan calculation constants and results.

Symbol	Value	Explanation
ρ	0.017 kg/m^3	Mars ambient density
μ	1.08×10^{-5} N·s/m^2 [41,42]	Mars ambient atmospheric viscosity
R_1	0.2 m	Fan hub radius
R_2	1.2 m	Fan radius
B	3	Number of fan blades
c	0.3 m	Fan blade chord length
RPM	500 RPM	Rotation rate, revolutions per minute
ω	52.4 rad/s	Rotation rate
$V_{fan\ needed}$	18.2 m/s	Needed for 8 m/s flow rate at zeolite bed
$V_{fan\ actual}$	20.6 m/s	Determined as derived above
η_f	0.76	Fan efficiency

4.2 Pressure Drop Modeling

In order to calculate the power needed to drive the fan, it is necessary to determine the pressure drop of the flow across the filter and the zeolite bed:

$$\Delta P = \Delta P_{filter} + \Delta P_{bed}\,.$$

The pressure drop across the filter is proportional to the flow velocity and is dependent on the type of filter medium [28]. For the pressure drop calculations, a Filtrete Type G filter from 3M was chosen [28]. Filtrete is an electrostatically enhanced non-woven fiber and is available in numerous grades, each having a different filtration efficiency and associated pressure drop. For WAVAR applications on Mars, a Filtrete G-200 will provide at least 95% efficiency [17,28]. Based on Filtrete G-200 data, Coons, *et al*, determined a linear pressure drop correlation across this filter to be [17,28]:

$$\Delta P_{filter} = 127.46\,\rho\, V\,.$$

This relation gives pressure drop in Pascals provided fluid density ρ and fluid velocity V are in SI units. Filtrete has been reported to have a longer life and greater temperature stability than similar media and should be acceptable for the ambient conditions that the WAVAR will encounter on Mars [28].

The pressure drop across the zeolite bed is calculated using the Ergun pressure drop model [32]. The Ergun model expresses the pressure drop across the bed as:

$$\Delta p = \frac{fL\rho(\varepsilon V)^2}{D_p}$$

where f is the friction factor, L is the bed depth, ρ is the average freestream density, ε is the void fraction, V is average flow velocity, and D_p is the pellet diameter. The friction factor is defined as:

$$f = \left[\frac{1-\varepsilon}{\varepsilon^3}\right]\left[\frac{150(1-\varepsilon)}{\mathrm{Re}_p} + 1.75\right]$$

and the Reynolds number based on the average zeolite pellet diameter is:

$$\mathrm{Re}_p = \frac{\rho V D_p}{\mu}$$

where μ is the viscosity of the Martian atmosphere.

The current WAVAR design incorporates a zeolite bed 4 cm deep with a void fraction of 0.4, and a 3 mm average pellet diameter. An average atmospheric density of $\rho = 0.017$ kg/m^3 was assumed, based on an average temperature $T_{avg} = 210$ K and an average pressure $P_{avg} = 5$ torr. The viscosity was curve fit as a function of temperature and found to be 1.08 × 10^{-5} N·s/m² at 210 K [33,34]. These parameters are sufficient to calculate both the filter and bed pressure drops as functions of flow velocity. The resulting total pressure drop as a function of Reynolds number at the zeolite bed, and the power required for fan operation are plotted in Fig. 16.

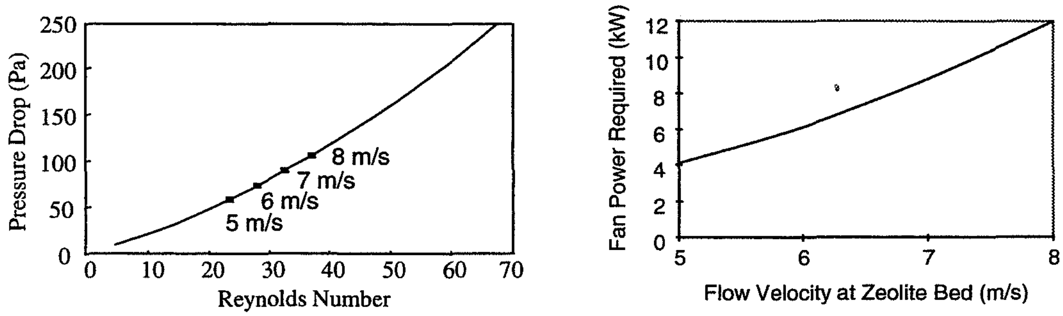

Fig. 16. Pressure drop as a function of Reynolds number at zeolite bed and power required for fan operation as a function of flow velocity at the bed. Pressure drop for the 4 cm deep bed was computed using a linear model for the filter pressure drop [17,28] and the Ergun model for the bed pressure drop [32]. Pressure drops at the zeolite bed corresponding to 5, 6, 7, and 8 m/s flow velocities are indicated.

The goal of the WAVAR is to produce an average of 3.3 kg of water per day, enough to replace the losses due to inefficiency in the life support system of the NASA Reference Mission. To meet this goal, the volume flow rate through the WAVAR must be sufficient to provide this average of 3.3 kg of water per day. Hence, the average atmospheric vapor concentration dictates the necessary volume flow rate through the WAVAR. However, the water vapor concentration depends strongly on temperature and varies with time of day, season, and latitude [9]. Thus it was necessary to find the average water vapor concentration at each of several locations on Mars and to calculate the average pressure drop at each of those locations, based on the average vapor concentration and corresponding volume flow rate. Once the pressure drop values were determined for certain flow rates, they were used to calculate the fan power required to pull the Martian atmosphere through the WAVAR's filter and zeolite bed. The results of these power calculations are discussed below.

4.3 Fan Power

Fan power requirements are determined from the fan efficiency and the pressure drop across the filter and zeolite bed. The fan efficiency and pressure drop are calculated as described above. Fan power is determined from:

$$Power = \frac{\Delta P \cdot Q}{\eta_m \eta_f}$$

where Q is the volumetric flow rate, η_m is the motor efficiency, and η_f is the fan efficiency. Values used in fan power calculations are summarized in Table 5. Results of fan power calculations are shown in Fig. 16.

Table 5. Constants used for performance calculations.

ρ_{amb}	Mars ambient density	1.7 x 10^{-2} kg/m³
--	Zeolite bed void fraction	0.4
--	Zeolite pellet diameter	3 mm
η_m	Motor efficiency (assumed)	0.95
η_f	Fan efficiency	0.76

4.4 Simulation Performance

The primary quantities that characterize the effectiveness of the WAVAR are the total mass of water collected, the power and energy required for operation, and the mass of the WAVAR. In order to characterize the WAVAR's performance under a wide range of Martian atmospheric conditions, simulations were performed that take into account seasonal and diurnal fluctuations in the temperature and vapor concentration, the characteristics of zeolite, and the limitations set on system power by the design constraints.

The energy required by the WAVAR for extraction of a given mass of water depends upon the amount of time that the fan operates and the number of desorption cycles that occur. An initial comparison of WAVAR performance under different atmospheric conditions was carried out with a constant flow velocity through the zeolite bed of 7 m/s, requiring a constant fan power of 8.6 kW. Additional simulations were carried out under different atmospheric conditions with flow velocities of 5 m/s, 6 m/s and 8 m/s, each with a corresponding fan power. The energy required to desorb the water from the zeolite was assumed to remain the same for desorption cycles in all simulations since the loading fraction at which desorption begins is always the same.

Adsorption of water is dependent upon the instantaneous water vapor concentration, the instantaneous zeolite loading fraction, and the instantaneous zeolite capacity, as determined by the zeolite bed temperature. In the simulations it was assumed that all of the water vapor that passes through the zeolite bed is adsorbed.

To simulate variations in the atmospheric water vapor concentration, data from the Viking Landers and Viking Orbiters were used. Since the water vapor concentration data on the surface were inferred [9] and are uncertain, simulations were run using different concentration fluctuation models to obtain an envelope of performance. The only locations for which both temperature and concentration data are available are the two Viking Lander sites. The water vapor concentration inferred by Ryan, *et al* are in good correlation with the MAWD measurements at VL-1 but not at VL-2 [9]. It is possible that the correlation disparities at VL-2 are due to a non-uniform vertical distribution of water vapor [9]. Regardless, both of these sites were used in the simulations.

Since the average concentration measured by VL-1 was below the global average of $\sim 2.0 \times 10^{-6}$ kg/m^3 [6], two additional concentration profiles were assumed in order to obtain an envelope of performance for the WAVAR. First, the vapor concentration for VL-1 was scaled up so that the average concentration was equivalent to the global average. This data set is termed New Houston. Second, the vertical column abundance at the northern polar region is about 10 times that at lower latitudes during the summer [9]. However, during the winter the water column abundance is much lower at the north pole than at lower latitudes, so it was assumed that there is no appreciable water at any time other than summer. The simulation was run using a vapor concentration of eight times that measured by VL-1. The simulation was run for only 145 sols, in an attempt to simulate the high concentration during polar summer and extremely low concentration during other seasons.

The seasonal variations in water vapor concentrations from Viking 1 and 2, New Houston, and the northern polar region are shown in Fig. 17. Extremely low vapor concentrations were also measured during the winter by VL-2. An analysis of WAVAR performance over a full Martian year showed that during the period from Sol 146 through Sol 500 of VL-2, the WAVAR would collect less than 15 kg of water, while still requiring a constant 8.6 kW for operation (with 7 m/s flow rate through the zeolite bed). Therefore, the simulation for VL-2 conditions was only run through Sol 145.

There are no diurnal water vapor concentration fluctuation estimates, but the daily maximum and minimum concentrations are known. The daily maximum is the concentration that Ryan, *et al* [35] reported and the minimum is determined by using the 100% humidity restriction from the Clausius-Clapeyron equation [36] at the coldest part of the night. As described by Ryan, *et al* [9], when the temperature reaches the frost point, an inflection point occurs on a plot of temperature vs. time due to the energy released by water as it freezes. The atmosphere at the time of the inflection point may be assumed to be saturated. From the initial saturation time until when the temperature begins to rise the next morning, water vapor is being forced to precipitate out and is reported to be in the form of fog [9]. As the temperature begins to rise in the morning the fog and/or frost on the regolith returns to the atmosphere as vapor. The actual evaporation/sublimation rate is unknown but is estimated by the curve shown in Fig. 18. The saturation curve is shown along with the concentration from Ryan and the assumed daily variation in concentration.

The assumption that the atmospheric water content follows the 100% humidity level below the frost point is probably pessimistic because as the temperature drops the water vapor precipitates out as fog. This fog would also be adsorbed by the WAVAR. However, since the amount and location of nighttime fog are unknown, simulations at each location are run under both the fog and no-fog assumptions. In the fog simulations, the concentration is more or less constant during the day and night, and is mainly influenced by seasonal effects. In the no-fog simulations, the atmospheric water content during the night follows the saturation curve below the frost point. Sample concentration curves for the fog and no-fog assumptions are shown in Fig. 18. Actual conditions on Mars probably lie somewhere between the fog and no-fog curves at each site.

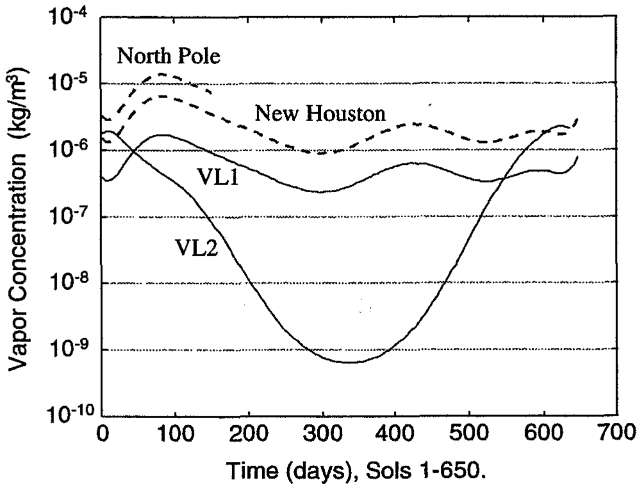

Fig. 17. Seasonal variation of vapor concentration as used in the simulations. Solid lines are actual data, dashed lines are estimated.

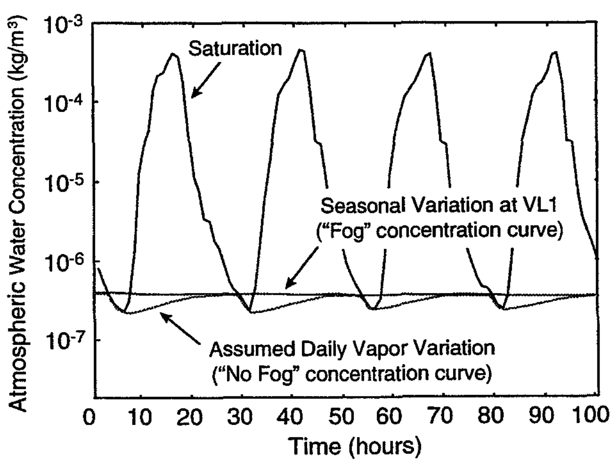

Fig. 18. Five sols of atmospheric water content data used in the VL-1 site simulation.

In the simulations, the desorption cycle was assumed to begin when the zeolite bed reached a loading fraction of 15%. Depending on temperature fluctuations, a loading fraction of over 18% could be achieved but the amount of time spent each day in thermal isolation during daytime capacity dips (daytime temperature peaks) increases at higher loading fractions, reducing the time available for adsorption and thus the mass of water adsorbed each day. A sample plot of the instantaneous amount of water adsorbed in the zeolite bed over one 300-hour period is shown in Fig. 19. The nearly vertical line occurs during a desorption cycle, when the loading fraction of the zeolite drops from 0.15 to 0.015 in only four hours. The wavy pattern is caused by diurnal fluctuations in vapor concentration.

The specific energy required for water collection is calculated by dividing the total energy needed by the total mass of water extracted. The total energy is computed by multiplying the time spent adsorbing by the power draw of the fan and adding the number of desorption cycles times the energy needed to desorb the water from the zeolite bed.

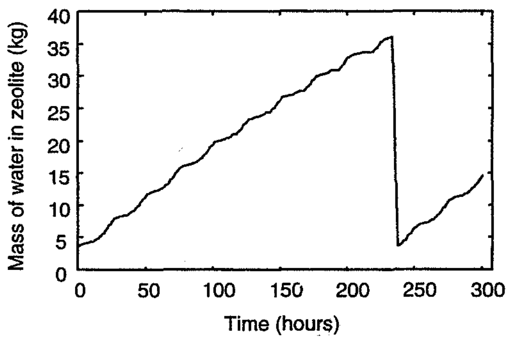

Fig. 19. Sample instantaneous water loading curve.

Tables 6 and 7 summarize the WAVAR simulation results for the four site models under the above-mentioned atmospheric conditions. The simulation at the VL-1 site is for only 333 sols, about ½ of a Martian year, because accurate temperature data are not available for a full year [37]. There is a period from Sol 117 through Sol 133 of VL-1 for which no temperature data are available, so the simulation skips these sols. New Houston concentration and temperature are based on VL-1 data, so the simulation at New Houston also runs for only 333 sols. Since the data used for the VL-1 and New Houston simulations correspond to the first half of the year, during which the vapor concentration is higher than the yearly average (see Fig. 17), the results may not be scaled linearly to obtain yearly results. The simulations for the VL-2 site and the North Pole are for the summer only because the water concentration is too low during the rest of the year for efficient WAVAR operation. The results from New Houston and the north pole represent total yearly returns, because the WAVAR would not be in operation during seasons with extremely low vapor concentration.

Overall performance at each site as a function of flow velocity at the zeolite bed is summarized in Figs. 20-22. Figure 20 shows the mass of water collected by the WAVAR per sol of operation. Figure 21 shows the average power required for WAVAR operation, and Fig. 22 plots the specific energy required. As is apparent from Tables 6 and 7 and Figs. 20-22, WAVAR performance is highly dependent on atmospheric water content.

Table 6. Simulation results under fog assumption with 7 m/s flow rate through zeolite bed.

Site	Number of sols simulated	Total mass of water collected (kg)	Average power during operation (kW)	Mass per sol of operation (kg/sol)	Mass per sol over year (kg/sol)	Specific energy (kW-hr/kg)
VL-1	333 *	1264	8.4	3.79	---	55.2
VL-2	145 †	616	8.7	4.25	0.96 †	52.6
New Houston	333 *	4730	9.8	14.21	---	17.3
North Pole	145 *†	5670	12.1	39.1	8.86 †	7.7

* Accurate temperature data is not available for Sols 117-133 or 351-640 of VL-1, so these sols were not included in the simulations based on VL-1 data.

† Simulations were run only during the summer, but correspond to a full year of operation since at these sites because the WAVAR only operates during seasons with high vapor concentration.

Table 7. Simulation results under no-fog assumption with 7 m/s flow rate through zeolite bed.

Site	Number of sols simulated	Total mass of water collected (kg)	Average power during operation (kW)	Mass per sol of operation (kg/sol)	Mass per sol over year (kg/sol)	Specific energy (kW-hr/kg)
VL-1	333 *	778	8.0	2.34	---	85.9
VL-2	145 †	421	8.5	2.90	0.66 †	74.9
New Houston	333 *	2041	8.9	6.13	---	36.2
North Pole	145 *†	1976	9.6	13.63	3.09 †	17.5

* Accurate temperature data is not available for Sols 117-133 or 351-640 of VL-1, so these sols were not included in the simulations based on VL-1 data.

† Simulations were run only during the summer, but correspond to a full year of operation since at these sites because the WAVAR only operates during seasons with high vapor concentration.

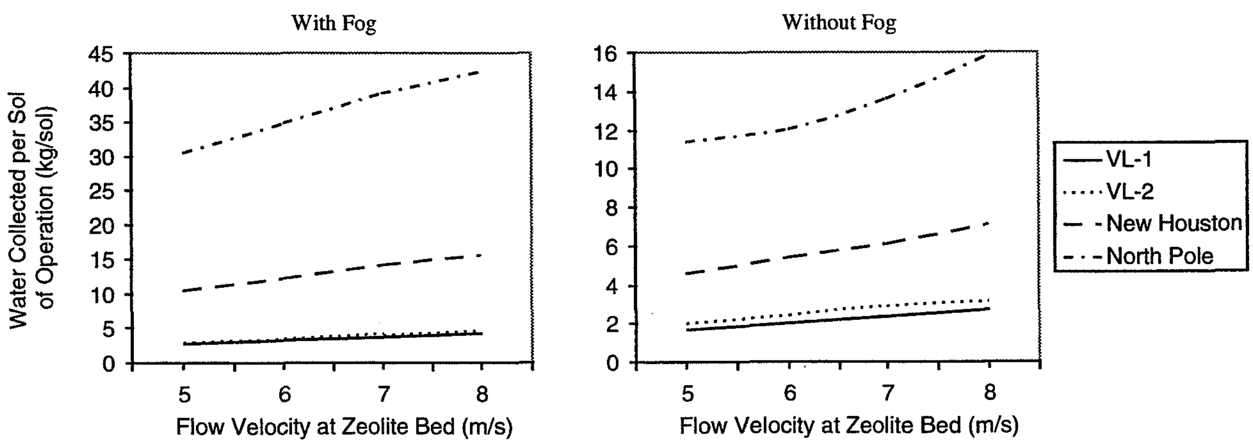

Fig. 20. Water collected by WAVAR per day of operation.

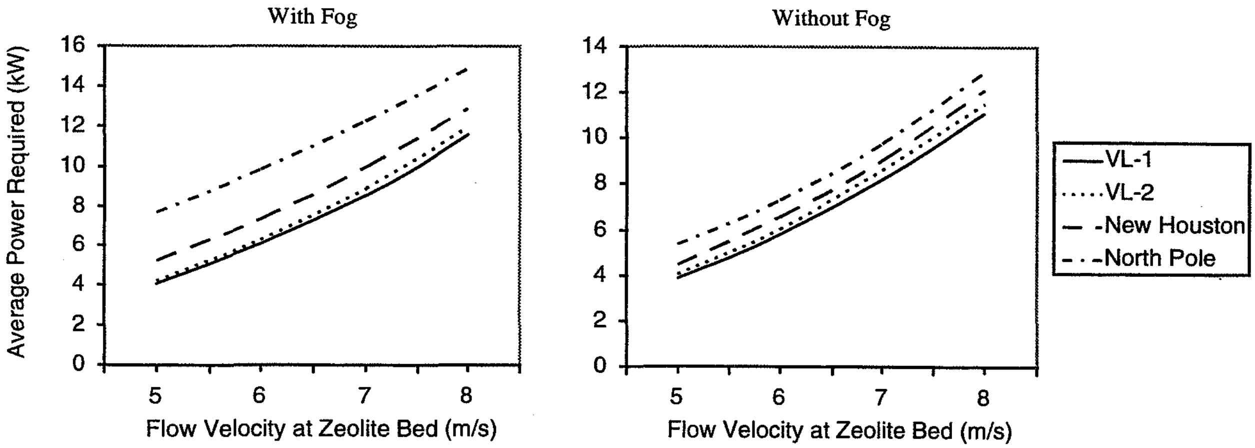

Fig. 21. Average power required for WAVAR operation.

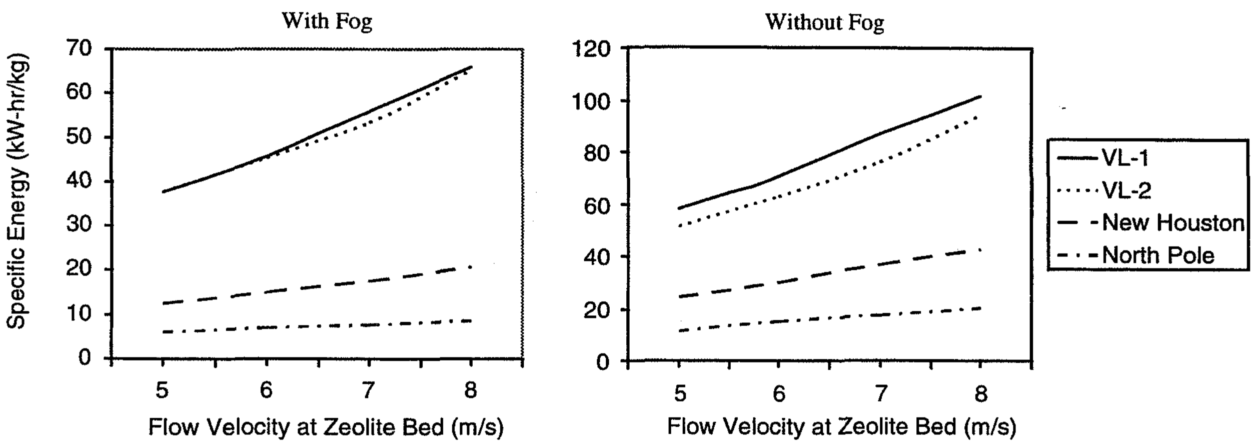

Fig. 22. Specific energy required for collection of water by the WAVAR.

5. CONCLUSION

Results from this study demonstrate that the WAVAR concept is a feasible method for replacing regenerative water losses from the life support system with indigenous water in NASA's Mars Reference Mission. The WAVAR design presented integrates into the Reference Mission in a configuration mounted on the top of the existing laboratory habitat module and has a total dry mass of 885 kg. Simulations show that the design has varying capability under different conditions on Mars. The four conditions simulated in the study are water vapor content and temperature fluctuations at the Viking Lander 1 site, the Viking Lander 2 site, the North Pole based upon Viking Orbiter data, and a hypothetical site called "New Houston" which is a site with daily fluctuation trends based upon those seen at the Viking Lander 1 site but with a average yearly water vapor concentration equivalent to the global average. Simulations were carried out at each site for conditions with and without nighttime. The results of the simulations show that for no-fog conditions the WAVAR meets the design requirements only at the New Houston and North Pole sites. Under the nighttime fog assumption, however, the WAVAR satisfies the requirements under VL-1, New Houston, and North Pole conditions. The low average power required for each of the successful cases suggests that an increase in fan power may be used to increase flow velocity and the rate of water adsorption without exceeding the power constraint of 5% of Reference Mission power. This would be especially beneficial at the North Pole, where an increase in average power to 15 kW increases the daily net gain of water to 42 kg/sol. Low vapor concentrations at the VL-2 site preclude efficient use of the WAVAR regardless of fog assumptions. The most efficient and productive site for WAVAR use is the northern polar region, where the vapor concentration is almost an order of magnitude higher than that measured at the VL-1 site during the summer. Under the New Houston with fog and North Pole with or without fog conditions, WAVAR performance is good enough to consider the complete replacement of seed hydrogen by the WAVAR in the NASA Reference Mission.

The results presented here were obtained using data of varying degrees of reliability. In order to perform a more rigorous simulation, the properties of zeolite 3A under the low pressures and temperatures on the Martian surface need to be determined experimentally. Tests are also needed to determine to what extent, if any, CO_2 blocks the adsorption of water in zeolite under runtime conditions. In addition, direct measurements of diurnal changes in the atmospheric water content at various sites on Mars are needed in order to determine the extent by which fog increases the water available for adsorption during periods of low ambient temperature.

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MARS ANALYTICAL LABORATORY

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Introduction

As mankind continues to explore the solar system, planetary colonization may become an important goal. Permanently manned space stations, bases on the moon, and colonization of Mars will be important steps in this exploration. The colonization and exploration of Mars will be a particular challenge. As mankind one day attempts this colonization, knowledge of the Martian environment and human capacity to live there will become vitally important. The first scientific outposts on Mars will need research laboratories to make discoveries about how we can better live there and use the natural resources of the planet to sustain human life. The design of a laboratory for an existing Martian base is the purpose of this project.

A laboratory on Mars would be very useful to the scientists we send. Some possible focus points for research in a Martian lab are listed below:

- To learn how the human body degrades in the 1/3 gravity condition that exists on Mars.
- To study how to lessen this degradation making long-term stays possible.
- To find ways of using Martian resources to grow food for human explorers.
- To discover ways of using Martian materials to build useful items.
- To explore the current and past geological (seismic, volcanic) activity of Mars.
- To study the past and present history of water on the surface of Mars.
- To study the possibility of indigenous life (past and present) on the Martian surface.

A lab that carries the necessary equipment can address all these focus points. The lab to be designed in this project will be capable of helping scientists study all of these subjects and more. In order to simplify and define the project, some assumptions were made at the beginning of this project. These assumptions are listed below:

- The mission for this project design begins in Low Earth Orbit.
- A heavy lift launch vehicle will be available to lift large payloads into orbit.
- The lab to be designed will not carry astronauts to Mars.
- A small manned habitat will exist on the Martian surface.
  - This habitat will sustain at least six astronauts continually.
  - It will be capable of supplying the life support needs of the lab.
  - It will have a generic 'connection' that the lab can be connected to.
  - The habitat will be set up in a 'trailer park' type configuration with many modules branching off of a large central module.
- The habitat will be located in an area that experiences 'average' Martian weather conditions.

The assumptions listed above enable this problem to be simplified in the following ways:

The first and second assumptions help by allowing the design to ignore the initial stages of the mission. This means that launch from Earth does not have to be considered. If no heavy lift launch vehicle were ever designed, it would require an extremely different laboratory design to effectively launch with the space shuttle.

The third assumption simplifies laboratory design by eliminating the requirement of life support systems for the trip to Mars. A design requiring life support systems would require vast stores of food, water and air reclamation equipment, and heating apparatus. It would therefore be heavier, and also require a shorter trip to Mars, which would be more costly. Once on the surface, however, the water and air reclamation equipment, power source, and heating apparatus would become redundant, therefore being unnecessary. While redundancy will be desired on Mars, having every module provide its own life support needs could make maintenance a problem, and would be very inefficient. Therefore, this module will be one that requires life support from outside sources.

The fourth assumption concerns the habitat that the lab will connect to. The assumption that there will be several astronauts living in the habitat at all times assures the lab will be in use at all times. This enables a lab design that does not require long periods of shutdown. The assumption that it will be able to supply all the life support needs of the lab requires that a large power source, such as a nuclear reactor or a huge solar array, be installed on the Martian surface to supply the necessary power for equipment, heating, ventilation, and air conditioning. It also requires bio-reactors and hydroponics to clean the water as well as filters and the hydroponics to clean the air. The assumptions that the habitat will be set up like a trailer park and that a generic connection will be available enable a mating connection to be designed for the laboratory.

The fifth assumption concerns the weather that the lab will be exposed to. Planning for average Martian conditions enables the design of an HVAC supply system to the lab. If the habitat were in the polar regions of Mars, this assumption would be inadequate, but since at this time it has not been built, its location is unknown, so it will be assumed to be in the middle latitudes.

The scope of this project, therefore, will be as follows:

- A lab will be designed that is capable of supporting scientific investigation on the Martian surface.
- An orbital trajectory will be planned for the transfer of this laboratory to Mars.
- A landing strategy, encompassing all phases of the landing, from atmospheric re-entry to impact will be planned and designed.
- A plan to move the laboratory from the landing site to the habitat and make the connection between them will be made.
- Determine an experimental equipment package that will enable researchers to experiment in the Martian environment.

Orbital Mechanics

The orbital mechanics of an aerocapture system for an unmanned mission to Mars was investigated. A computer code written in FORTRAN 77 was used to develop the orbital transfer mechanics for the outbound trip. It was determined that fast transfers, i.e. departure angles greater than zero, were too expensive in terms of propulsive expenditure despite their shorter trip times. Therefore, as determined from this program, a Hohmann transfer was selected as the most cost effective in terms of energy expenditure for the outbound transfer with a total velocity budget of 5.646 km/s. However, the Hohmann had the longest duration in terms of trip times at 258.9 days. This was deemed acceptable for an unmanned mission.

Another computer program written for MATLAB was used to analyze the aerocapture system. It was determined that at an altitude of 120 kilometers above the surface of Mars, a 240 meter per second reduction in velocity would be needed in order to slow the vehicle into a nearly circular orbit. This yielded a seven pass orbit, with a total maneuver time of 130.7 days. This time in addition to the outbound transfer sums up to 389.6 days or a 12.98 month mission duration with a final, nearly circular orbit eccentricity of 0.0001 and a total propulsive expenditure of 5.986 km/s.

Re-Entry to Mars Atmosphere

This study provides a design of a preliminary lifting entry vehicle for application towards transport of the Mars analytical laboratory from Earth to near the Mars surface. The entry vehicle is required to protect the laboratory from hypersonic impact in space, high heat, and deceleration loads that will be encountered throughout the journey, and provide a economical solution to launch from Earth. By conducting extensive research on hypersonic entry flight, heat protection materials, the use of equations of motion, graphs, a lifting entry vehicle design was created and analyzed. Creating a entry vehicle requires many design considerations which all interact with each other. Assumptions and approximations applied to motion equations provide insight for designing a entry vehicle and the design must consider the hypersonic aerodynamic characteristics and the mission.

Landing Configurations

Multiple runs were made at three different configurations to determine factors of impact velocity, retrorocket burn duration and fuel mass and parachute force exertion.

Configuration #1

As the lab module approaches the Martian surface after atmospheric entry, the module deploys two parachutes at 95,000 m and plummets to the surface front first, deploying two more at 50,000 m. At 40,000 m, two larger parachutes are while the current four are ejected and the lab rotates to a bottom first orientation. At 20,000 m, two additional parachutes of equal dimensions deploy and the module continues to decelerate until an altitude of 2,000 m is reached. At which point, retrorockets providing 55,050 N of thrust fire, slowing the module to a gradual landing. Fuel mass lost during the retrorocket firing phase were not taken into account.

Configuration #2

As the lab module approaches the Martian surface after atmospheric entry, the module free falls in a front first orientation and maneuvers into a bottom first orientation. At which time, retrorockets fire at a force equal to ten times the Mars weight of the module. The rockets fire for a duration of 10 seconds and shut off for a period of 15 seconds. During this shut off period, two parachutes are deployed and the module maneuvers to a bottom first entry. The retrorockets are fired once again at a force equal to 1.5 times the Mars weight of the module close to landing. When the height of the module reaches a distance of one meter above the surface of Mars, the rockets are shut down and the module lands. Again, mass lost due to fuel burn was not taken into account.

Configuration #3

Mass loss due to rocket burn was now taken into account. For this reason, the initial guess of 15,000 kg for lab module weight was increased to 30,000 kg. Starting at a height of 10,000 meters, the lab module free falls to the surface of Mars in a bottom first configuration. The module remains in free fall in this orientation until the retrorockets are fired at a combined force equal to ten times the Mars weight of the module and lands.

Propulsion

The propulsion systems of the Mars analytical laboratory consist of several small maneuvering rockets and four large retro-rockets. The maneuvering rockets utilize a Pressure System, Inc. (PSI) tank (#80255-1) with a hydrazine fuel. The fuel expulsion device is a simple rubber diaphragm. The rockets produce .44 N of thrust each with a mass flow rate of .4 g/s. The throat diameter is .8 mm and the exit diameter is 8 mm. This results in an area ratio of 100.

The retro-rockets are composed of a hybrid liquid/solid fuel system. This system allowed for easy throttling and a shorter start-up time of the system. This system uses a Hydrogen Peroxide liquid oxidizer and a Hydroxyl-Terminated Polybutadiene (HTPB) solid fuel cell. This combination allows for easy storage of the oxidizer on the trip and the rapid regression rate of the HTPB. The fuel cell used a circular grain configuration because of the ease of determining the fuel cell geometry. To compromise for a shorter cell length and a larger cell width, an initial port radius of 5 cm was used. This resulted in a final fuel cell length of 2.3371 m and diameter of .5726 m. The chamber pressure was held constant at 10 MPa so that the pressure term of the solid fuel grain regression rate could be simplified. This is accomplished through the use of a pump. The nozzle throat diameter is .1503 m with an expansion ratio of 27.1. From these results, the exit diameter was determined to be .7819 m. To find the length of the nozzle, a quadratic equation was determined. This equation was $y = 0.1x^2+0.75x+0.07515$. The slope of this line is 41°, which is an acceptable slope for avoiding flow separation and shock waves. These retro-rockets will be controlled by automation and perimeter sensors. If a firing failure occurs, the module will be controlled by the ground crew on the Martian surface.

Landing Gear

Many design requirements must be taken into account when designing the landing gear. The laboratory module will be landed on Mars as close to the habitat as possible without harming it. This distance is assumed to be less than two miles. Therefore, the lab module's landing gear must take the impact loads as well as provide a way to move the lab next to the habitat. This will be accomplished by utilizing a manual or electrical winch along with the 10 meter coring drill. The landing gear will have to be able to support the weight of the lab as well as be able to adjust to level the lab. Also, the lab will need to be able to roll across the soft, sand-like, Martin soil without sinking.

Since the lab will be moved across the Martian soil, large boulders and pits in the ground will be hard to avoid. Six landing gears will be used with independent suspensions and hydraulic systems so individual gears can be raised to go over an obstruction without affecting the others. Also, an individual gear can be lifted off the ground, rotated, and set back down to provide a way to turn the lab.

The landing gear was designed for a landing vertical velocity of 3.0 m/s. At this speed, the lab will encounter approximately 104,000 N per landing gear. With a 0.22 m stroke length, each landing gear will absorb approximately 79,400 N of the total 104,000 N landing force per landing gear. Therefore, the cradle is absorbing approximately 24,600 N at each landing gear location. The material chosen for the landing gear was a Titanium alloy, because of its relatively low density compared to other stronger materials such as AerMet100.

The wheels for the landing gear are aircraft rubber tires with a light Titanium rim. Each landing gear will have two wheels, one on each side for balance. The tire chosen is a 0.2032 m wide tire with a 0.61 m radius. This tire is a high pressure, high load tire with a maximum load rating of 55,000 N. From the Sojourner Rover mission, it was determined that the first 6-8 cm of the surface is virtually dust and below that is unknown. So, it is certain that the lab module will sink at least 6-8 cm into the surface of Mars and maybe even more before the labs tires hit a soil that can withstand the 300 kPa of pressure being exerted on the surface. The total mass for each landing gear including tires and rims is 227 kg and the total mass for the entire landing gear system is 1367 kg.

Pressure Vessel

The pressure vessel geometry consists of a cylindrical mid-section that has a diameter of 4.5 m and is 6 m in length. This diameter allows enough clearance for two floors. Two semi-ellipsoidal end caps, with a semi-major axis of 2.25 m and a semi-minor axis of 1.2 m, are connected on each side of the cylinder. Each end cap has a opening for an airlock at 1 m away from the cylinder along the longitudinal (X) axis. A composite layup is selected for the vessel and for the floors, due to high strength and high stiffness of composite structures. Honeycomb construction is suggested, due to its high bending stress capability and energy absorption capability. The outermost layers of the laminate consists of Kevlar 49 / epoxy woven fabric plies. Then, Scotchply 1002 glass / epoxy and T300 graphite / epoxy plies placed before and after the Aramid honeycomb of 1.905 cm (0.75 in) thick. The laminate configuration, except the Kevlar 49 woven fabric layers, is symmetric around the honeycomb. This will avoid any bending and torsion loads during the cure process. A static structural analysis is conducted, using NASTRAN. The analysis reveals that the laminate failure is critical at the location where the cylindrical portion and the semi-ellipsoidal caps are joined. In addition, the lower half of the cylindrical portion indicates that it is more susceptible to fiber failure than the upper half. Thus, the semi-ellipsoidal caps, upper and the lower halves of the cylindrical section are precured separately and then joined together. The estimated mass of the vessel is about 7500 kg. The manufacturing cost is estimated to be about $ 1,193,151.00, from which 52% is for the material.

Cradle Structure and Radiation Study

The first study performed is that of the design for the cradle structure. The cradle structure is a framework of beams that surrounds the composite pressure vessel. Its purpose is to provide additional support for the entire laboratory module structure as well as to act as the platform upon which many of the various sub-systems, such as the retro-rockets, landing gears, and fuel tanks, are to be mounted. The structural analysis of the cradle was performed by modeling a maximum loading condition on one beam element and allowing a minimum beam tip deflection of 2% in order to find the best combination of beam shape and size. Upon sizing the model beam element, a mass estimate was extrapolated by assuming uniform beam elements. The results showed that utilizing aluminum I-beams of 18.2 cm by 18.2 cm produced the adequate amount of support for the system. Total mass for the cradle structure is estimated to be approximately 5311 kg.

The second part of this study address the radiation protection requirements for the laboratory module. A study was conducted of the various radiation guidelines set by the many agencies, which deal with radiation. These agencies represent the full spectrum of interests from the nuclear power industry to NASA. It was found that NASA's radiation dosage limits are a factor of ten higher than that of the nuclear industry. Also, a brief survey of the expected Martian radiation environment was conducted. It was shown that the amount of radiation received on the Martian surface is expected to be a factor of five less than NASA's dosage limit, but a factor of two higher than that of the nuclear industry. Thus, should NASA's current dosage limit remain applicable for a Mars exploration mission and stay duration is kept low, it was found that no special radiation shield is required for the laboratory module.

Lab Systems

The lab systems design portion of this design project concerns the systems that supply the lab with the necessary life support, power and water for use in the everyday operation of the lab. To accomplish this, the requirements to sprinkle the lab in order to extinguish any fires will be determined and met. Also, the requirements of hot and cold running water will be determined and met. In addition, the electrical power requirements will be determined and met. Then the requirements for heating, ventilation, and air conditioning will be determined and met. Finally, a door will be designed that will accommodate transfer of workers, water, electricity, and heated fresh air. This door will be designed to enable the astronauts to seal it from the inside, while the habitat will have a door that is designed to be sealed from the other side.

The life safety and plumbing requirement were found to be best served by using polybutylene piping at a supply pressure of 53.3 kN/m^2 gage. A 100 watt pump was sized to clear the waste water from the lab. The electrical distribution system was found to require a 60 amp panel, and the electrical usage per day was found to be 90 kilowatt-hours. The HVAC system was designed as a plenum system (air supplied heating), where (4) 26 cm diameter ducts were sized to service the laboratory. The connection was designed from aluminum with a foam core. The masses and costs of the above systems were then calculated and the results are shown in Table 1-1:

	Mass (kg)	Cost
Life Safety	6.21	$ 352.84
Plumbing	8.22	$ 501.77
Electrical	93.94	$ 1,209.00
HVAC	10.00	$ 618.56
Door	278.00	$ 1,234.00
Total	396.37	$ 3,916.17

Table 1-1: Lab systems mass/cost summary.

The system design was kept as lightweight and simple as possible, to make maintenance easy and delivery cheap. The total system design should supply the lab with everything it needs to be a short-sleeve environment for research.

Equipment and Layout

During the design process, the equipment and interior secondary structure (cabinets, tables, counter-tops) was limited to a mass of 5000 kg. Because of this, it would be impossible to take equipment to study all possible scenarios of may be discovered. Most of the equipment for the lab was chosen based on ability to test for many different things as opposed to single specialized purposes. It was assumed that if more specialized equipment was needed, it could be brought on a later mission. With this in mind, a list of equipment was compiled and a mass study performed. The total mass of the equipment and interior secondary structure is approximately 4750 kg including a 10% margin for error.

Since the laboratory will be a permanent structure on Mars, it was designed to be as module as possible. Although the equipment and interior secondary structure mass was limited to 5000 kg, the structure was designed to accommodate 6000 kg. This provides flexibility to add additional equipment brought by later missions.

The laboratory is divided into two levels as shown in Figure 1-1. The 1st level holds mostly planetary science equipment while the 2nd level holds mostly life science equipment.

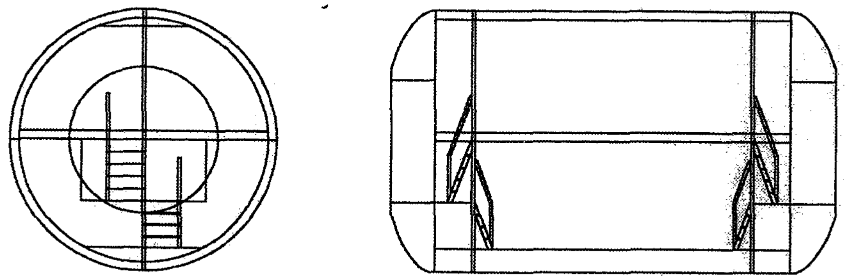

Figure 1-1: Layout of Mars Laboratory

It was not possible to determine an exact interior layout since only volumes (not dimensions) were available for much of the equipment. It was assumed the equipment was cubical based on volume unless exact dimensions were known. Based on this assumption, a layout was designed that took into account the location of power outlets and the comfort of the researchers (Figure 1-2). An estimated center of gravity study was performed to verify the feasibility of the design. Extra supplies sent on the lab during its flight to Mars would be positioned so that the center of gravity is as close to the geometric center of each level as possible.

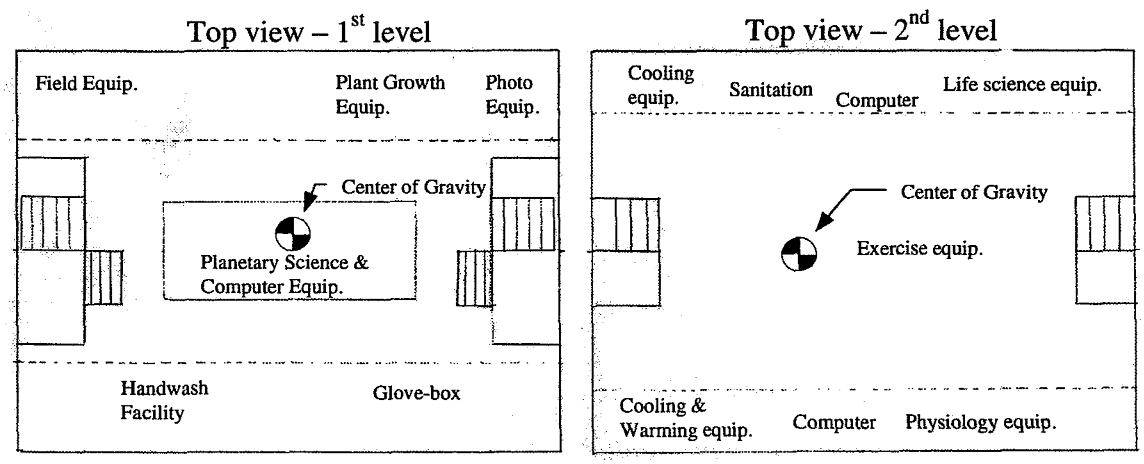

Figure 1-2: Mars Laboratory Equipment Layout & Center of Gravity Location

MERLIN:

Martian Exploratory Rover for Long-range INvestigation

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Abstract

In the days of the Apollo program, it was recognized that it was necessary to cover as much of the surface of the Moon as possible in order to accurately portray the planet's geology. Due to the time and weight constraints of the program, the first few missions covered the surface on foot, with only the last three using battery-powered, unpressurized rovers.

In the future, when mankind colonizes the other planets, the surface stay will be considerably longer, the weight allowances will be much greater, and the science to be performed will be expanded dramatically. All of these factors will cause serious consideration to be given to the idea of a pressurized rover for extended surface excursions.

The following is one possible design for a pressurized rover for use on Mars. It was designed by University of Maryland, College Park Aerospace Engineering students in the second semester of their senior Space Systems Design class. The class was broken down into six groups in order to spread out the workload. The groups were the following: Avionics; Crew Systems; Mission Analysis; Power, Propulsion, and Thermal; Structures and Loads; and Systems Integration.

1. The Reference Mission

As a starting point, the class was given the NASA Mars Reference Mission. This document can be downloaded from the following website: http://www-sn.jsc.nasa.gov/marsref/contents.html.

2. Design Constraints

At the beginning of the semester, the class was given several design constraints. These include the following requirements. The final outcome of the class should be some type of rover for use on Mars. This rover would need to conform in whatever ways we deemed necessary with the NASA Mars Reference Mission. The rover needed to be manned in some capacity. The rover needed to allow for Extravehicular Activities (EVAs) by its crew. Finally, it would need to be able to cover as much of the Martian surface near Olympus Mons, the Tharsis Montes, Valles Marineris, and Lunae Planum as was possible.

It was this last design consideration which made the Martian Rover for Long-range INvestigation's (MERLIN's) design diverge from the vehicle design in the Reference Mission. The rover in the Reference Mission is also pressurized, but is only meant for excursions that are relatively close to base (within a radius of 500 km). Also, this rover did not include very much in the way of on-board science facilities. Below is the region which MERLIN was to explore. The inner circle is the travel radius of the Reference Mission rover and the outer circle is the travel radius needed to fulfill the exploration design constraint (~3000 km). To give the reader an idea of the scope of the exploration area required of MERLIN, a map of the continental United States has been overlaid on the map of Mars. Obviously, this constraint greatly drove MERLIN's design. Not only would MERLIN need to cover a huge expanse of the surface of Mars, it would need to do so with its own fuel, as gas stations are not readily accessible on the surface of Mars.

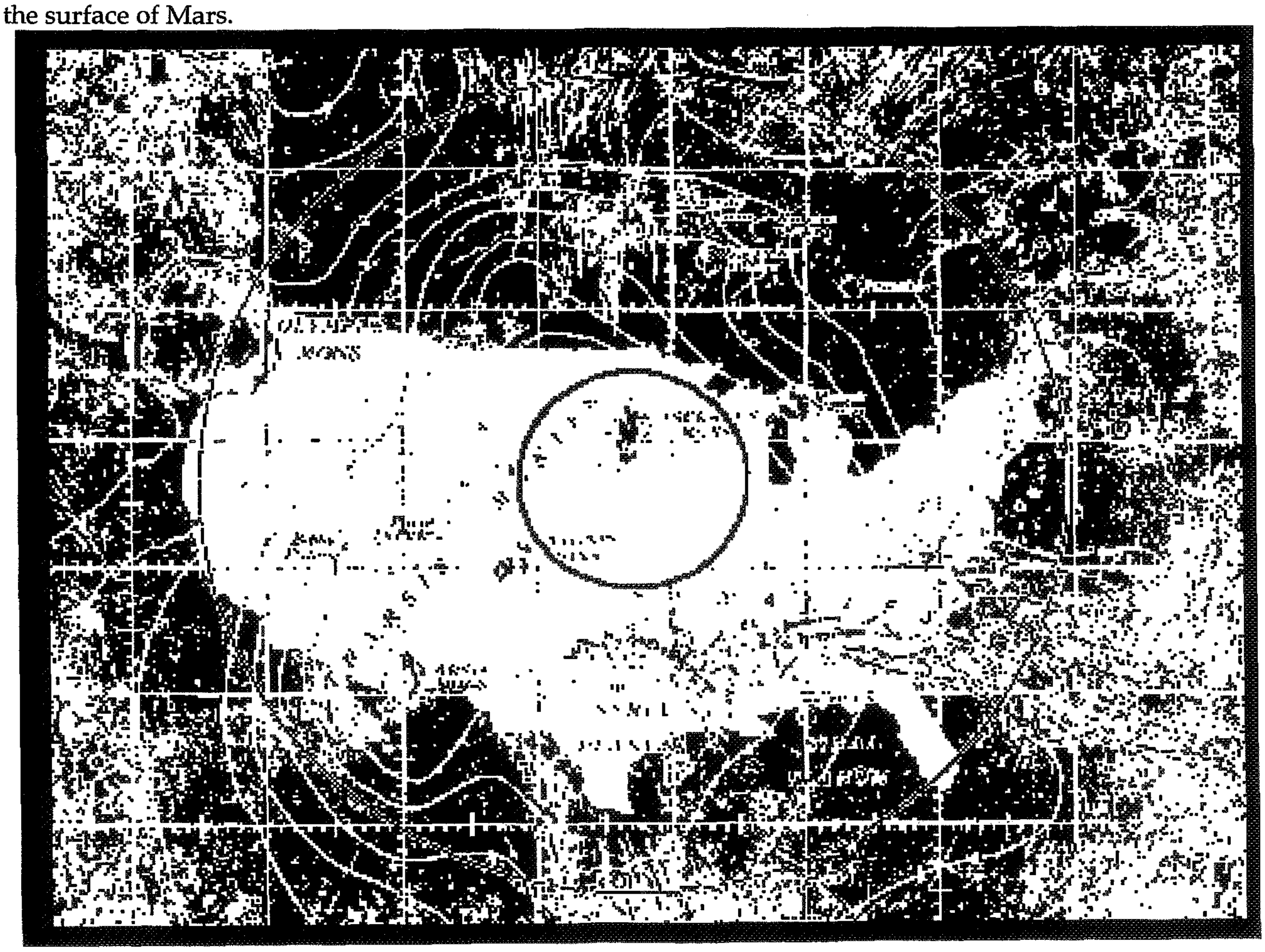

Fig. 2.1. Respective Ranges of MERLIN and Reference Mission Rover.

3. Why a Pressurized Rover?

At the beginning of the semester, many possible designs for a rover were discussed. These included: an airplane, a dirigible, a land-based rover, and a sub-orbital hopper.

3.1. *By Air*

The possibility of a Martian airplane has been discussed numerous times in scientific literature. The main design constraint on a Martian airplane is the extremely low atmospheric pressure of Mars (which averages 800 Pa or 0.12 psi). In order to carry the mass of the required scientific equipment, a planform area of over 15,000 m^2 (almost 4 acres) is necessary. Another major disadvantage of an airplane is that it requires landing strips everywhere it wants to stop. As this mission is the first exploration of the Martian surface, landing strips are not readily available.

Another air-based possibility is a dirigible. This, however, requires a volume of over 900,000 m^3 due to the low atmospheric density in order to lift the required scientific equipment. Both of these possibilities do have some major advantages over the other possibilities to be mentioned later. These designs are not limited by terrain (except in launch and landing), as a land-based rover would be. They also have the ability to see the "big picture," geologically speaking, but since they are limited in their landing sites, they are not flexible enough to be able to stop at an interesting site that had just been discovered.

3.2. *By Land*

Land-based rovers are probably the best understood of all of the options, as they have been designed and built successfully in the past. The main disadvantage of a rover is that terrain does play a major factor in the time it takes to get to each site. While it might take an air-based design a few hours to get to a distant location, it would take a land-based design days or even weeks to get to the same place. A land-based rover would not be able to see the "big picture," but it would have the flexibility to stop at any point and examine an interesting site. A land-based design would be limited severely by its power, propulsion, and life support systems. If unpressurized, the life support system would consist mainly of the astronaut's EVA suits. If pressurized, however, a rover would be able to go farther and would be a safer environment for the crew due to its on-board life support systems.

3.3. *By Space*

Another method for transportation on Mars could be a sub-orbital, ballistic hopper. This would need a specified "landing site," but this site would not need to be a landing strip, merely a flat, boulderless spot near the exploration site. This option would minimize the travel time for the crew, maximizing their safety. It would, however, get the worst of both worlds in terms of seeing the "big picture" or the details, as the choice of landing sites would not be flexible enough to land anytime an interesting site was found, and there would also be a rocket engine where the window would need to be in order to see the scenery. Also, unless one added some type of land-based rover to this design (similar to the lunar rover), the exploration would be limited to the maximum walking distance allowed of the crew once they reached their destination.

3.4. *Conclusions*

The real question in this decision was the level of detail we wished to see on the surface. If one was going from Maryland to California, would they see more of the country by flying, or by hopping in the family Winebago and driving? With this and all of the other advantages and disadvantages in mind, a pressurized, land-based rover was chosen.

4. Science

There are three major science requirements for this mission. These are:

- To understand the history as well as the current state of the planet Mars
- To determine the existence of past or present life on Mars
- To determine the suitability of Mars for long-term human settlement

In order to fulfill these requirements, scientifically interesting sites would need to be chosen. At the selected sites, astronauts will perform EVAs to set up data collection equipment, select samples, and conduct geological and exobiological studies. At some sites, the astronauts will be required to conduct drilling to collect core samples. They will also need to conduct some simple indoor experiments on samples in order to determine which type of samples are worth returning to base camp for further study and which sites warrant further investigation. The sites chosen will also determine what equipment needs to be brought along on each excursion.

4.2. *Areas to be Explored*

As stipulated earlier, the area which was to be explored as fully as possible was the region which included Olympus Mons, the Tharsis Montes, Valles Marineris, and Lunae Planum. The reasons for exploring these areas, and which sites would be explored in each area will be explained below.

4.2.1. Olympus Mons

The first of these sites is Olympus Mons, the tallest known mountain in the solar system. This young shield volcano stands 25 km (15 mi.) high and is around 800 km wide at the base. It also contains an encircling basal scarp which ranges from 2–10 km in height. The immense height of this formation indicates long-term crustal stability of the planet. Of special interest at this site are the basaltic lava flows which are characteristic of shield volcanoes, the aureole deposits, and other surface deposits at the base of the volcano. Basaltic rocks are defined to contain 45–54% silica and often have higher percentages of iron, calcium, and magnesium than other igneous rocks. Aureole deposits, the origins of which are unknown, are lobes of ridged, fractured material surrounding the base of the mountain. Studies of fractured terrain could give clues to seismic activity and the differences in degradation and burial of rocks surrounding the base will suggest the sequence of volcanic activity. Aging of the volcanic material will also aid in determining the age of other surface features. Due to the isolation of this volcano, crater density will be a crucial factor in determining relative age. As part of the determination of planet habitability and search for life, it will also be necessary to determine the distribution of elements and compounds as well as conduct atmospheric studies.

4.2.2. Tharsis Montes

A second region of exploration is the Tharsis Region. This region is characterized by its ridged terrain and three large shield volcanoes. The three volcanoes are Ascraeus, Arsia, and Pavonis Mons. They are only slightly older than Olympus Mons. These volcanoes which range from 9 km to 22 km in height, are smaller than Olympus Mons, but are larger than any terrestrial shield volcano. The scientific interests here are the same as those at Olympus Mons, with the addition of a set of radiating surface fractures. Determination of the origin of these surface fractures will be important in determining the history of the planet and its seismic activity. Studies here will include: atmospheric studies, seismic studies, types and relative ages of rocks, studies on aureole deposits, other surface deposits and lava flows, and the distribution of elements and compounds.

4.2.3. Valles Marineris

The third major region of exploration is the Valles Marineris region. Valles Marineris is a large, complex canyon system which runs along the Martian equator. The entire system is about 4000 km long and as much as 200 km wide and 7 km deep. The system is speculated to have once held water, and possibly life, but its origin is still unknown. The three major regions of interest within Valles Marineris are Tithonium, Hebes, and Melas Chasma. The scientific interest in this region lies in the sedimentary deposits, tectonic features, chemical weathering, and basaltic material. Studies will include: the age, distribution, and composition of sedimentary deposits and clay materials; core drilling; and the distribution of subsurface water. These studies will aid in the determination of the canyon's formation and history and, more importantly, answer questions about whether or not it once held water. In addition, seismic studies will provide historical information on the canyon system. It will also be important to search for any organic remains and life-forming elements or compounds. If organic remains or life-forming elements are found, their ages, distribution, and characteristics will be studied. Atmospheric studies will also be conducted and data will be collected on the equatorial weather of the planet. These studies will ultimately lead to an improved atmospheric model of the planet.

4.2.4. Lunae Planum

The fourth and final region of exploration is Lunae Planum. Lunae Planum is a densely cratered plain with ridges and volcanic material. Studies will include composition and distribution of ridged plain material, volcanic material, craters, and subsurface water. Again atmospheric data will be collected. Another ridged plain area at Fortuna Fossae may also be explored, time permitting. This area is actually located to the west of Lunae Planum, but is included in this section due to its geologic similarity to Lunae Planum.

4.3. *Scientific Equipment*

In order to conduct these studies, MERLIN will need to carry some scientific equipment. Although samples will be returned to the base camp for detailed study, preliminary analysis of surface and subsurface materials will be necessary to save both time and space. Simple detection of elements in samples can help eliminate both the necessity for further in-situ investigation of certain materials and the need to carry them back to base camp. This equipment is described in tables 4.3.1, 4.3.2, and 4.3.3.

TABLE 4.3.1. Geological Equipment

Equipment	Description	Mass (kg)	Volume (m^3)	Power Required (kW)	Set-up Time (hrs)	Work Time (hrs/day)
Mars Geophysics Package (3)	Water detection, determination of local gravity and magnetic fields, mechanical properties and structure of crust	75	0.06	0.025	2	N/A
Marsnet (3)	Seismological stations to be left at sites for long-term seismic activity of planet interior and near surface climate and wind	75	0.06	0.025	2	N/A
Geological Field Package	Field tools to be used during EVA for close examination of field conditions for on-site decision making	45	0.15	2	N/A	4
Differential Scanning Calorimeter	Primary phase identification of minerals and volatiles	20	0.03	0.04	N/A	N/A
Multispectral Imager	Close range imaging	35	0.16	0.024	1	0.2
Binocular Microscope	Preliminary sample examination and evaluation	5	0.01	0.02	N/A	N/A
X-ray Fluorescence Spectrometer	Accurate elemental analysis	2	0.02	0.01	N/A	N/A
Drill Rig	Collect core samples	450	10	5.5	2	1
Mass Spectrometer	Elemental and isotopic analysis to determine absolute ages of rock samples before further investigation	12	0.04	0.016	N/A	N/A

TABLE 4.3.2. Meteorological Equipment

Equipment	Description	Mass (kg)	Volume (m^3)	Power Required (kW)	Set-up Time (hrs)	Work Time (hrs/day)
Surface Atmospheric Package (3)	Measures temperature, pressure, wind velocity and direction, aerosol content	75	0.06	0.025	2	N/A
Mass Spectrometer	Chemical composition of atmosphere	12	0.04	0.016	N/A	N/A
Surface Interaction Experiment	Chemical interactions between atmosphere and surface	N/A	N/A	N/A	N/A	N/A
Ionospheric Sounder	Measures ion composition of upper atmosphere	50	0.3	0.14	4	0.1
Aerosol Laser Ranger	Measures height and content of clouds	40	0.1	0.3	8	0.2

TABLE 4.3.3. Exobiological Equipment

Equipment	Description	Mass (kg)	Volume (m^3)	Power Required (kW)	Set-up Time (hrs)	Work Time (hrs/day)
Incubator	Incubation of Petri dishes for exobiology and life science experiments	3	0.01	0.03	N/A	N/A
Neutron Spectrometer	Analysis and detection of organic material	6	0.00015	0.006	N/A	N/A
Mass Spectrometer	Elemental and isotopic analysis of soil	12	0.04	0.016	N/A	N/A
Thermal/ Evolved Gas Analyzer	Analyzes gases given off by soil	1.9	0.0014	0.014	N/A	N/A
Specific Electrode Analyzer	Identification of solutes of biological significance	2	0.015	0.002	N/A	N/A
Soil Oxidant Survey	Equipment for analysis of oxidants in soil which may be detrimental to the stability of organics	1	0.005	0.01	N/A	N/A
IR Laser Spectrometer	Detects trace gases in soil or air (which may be indicative of biological activity)	10	0.05	0.02	N/A	N/A
Optical Microscope	High resolution sample analysis	6	0.004	0.02	N/A	N/A

This scientific equipment has a total mass, volume, and power requirement of 1114 kg, 11.5 m^3, and 8.3 kW respectively. Without the drill rig this drops to 664 kg, 1.5 m^3, and 2.8 kW respectively. (The drill is not needed for the excursions to all of the sites.) The scientific equipment has a total set-up time of 21 hrs and work time of 5.5 hrs. The number of man-hours per task are summarized in table 4.3.4.

TABLE 4.3.4. Man-Hours Required Per EVA Task

Man-hours	EVA Task
42	Geophysical Experiment/Geological Examinations
42	Geological Observations/Shallow Drilling
50	Geology/Geophysical Experiments/Deploy Science Stations
50	Extended Geology (includes drilling)
184	**Total**

Breaking this down into 8 hr workdays for the crew, and adding time for sample gathering, etc, a time of 14 days was deemed the maximum necessary to complete all experiments at each exploration site.

4.4. *Vehicle Design Impacts*

The science discussed above has a direct impact on the design of the rover. The rover consequently requires an indoor lab to conduct preliminary science experiments on samples. Based on the sizes of the indoor equipment and the work area necessary to conduct lab experiments the lab area was determined to be a 1 m × 1 m square. The equipment must be restrained in storage areas while the rover is in motion but will most likely not be in use unless the rover is stopped. The rover also requires an outdoor cargo area to hold samples as well as the equipment to be used outside the vehicle during EVAs. This area is accessible by a robotic arm which will be used to collect samples in situations where it is impractical to perform an EVA. For the purposes of assisting EVA, the vehicle will require an airlock/dustlock. Additionally, the rover must be capable of carrying the large drill rig, weighing 450 kg and occupying another 10 m^3 in volume, to the previously mentioned areas. The rover will also need the ability to store scientific data on board as well as return that data to base camp.

5. Base Camp Location

Once the sites for scientific exploration were chosen, the next decision was the location of the landing site/base camp. Without this knowledge, the total distance MERLIN would need to travel would be unknown. The base camp location has several requirements. It needs to:

- Be in a location in which it is possible to land.
- Have easy access to all of the scientifically interesting sites.
- Be a possible site for long-term human habitation.

Given all of these factors, the following possibilities were considered (see fig. 5.1):

- Near Gigas Sulci
  4°N 136°W
  A flat area near Olympus Mons.
- Near Fortuna Fossae
  8°N 85°W
  A flat area approximately in the middle of the scientifically interesting sites.
- Near Tithonium Chasma
  0°N 90°W
  Near one of the scientifically interesting sites and the gate of Valles Marineris.
- Near Ascraeus Mons
  6°N 101°W
  Approximately in the middle of the exploration region, and very near one of the scientifically interesting sites.

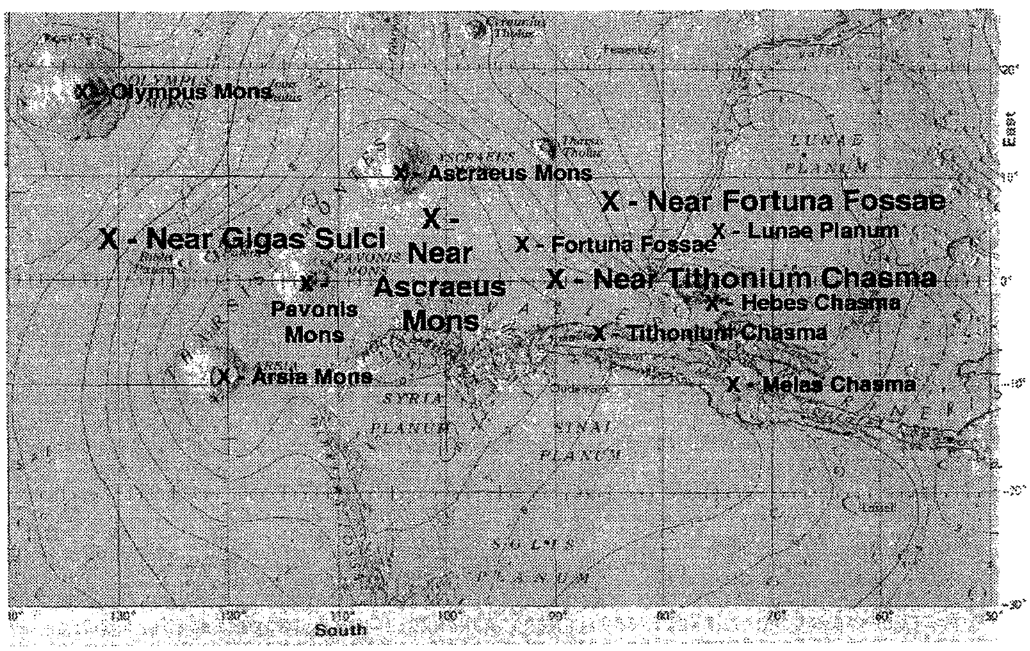

Fig. 5.1. Possible Base Camp Locations and Scientifically Interesting Sites.

Due to its central location and proximity to a scientifically interesting site, the site near Ascraeus Mons was chosen as the base camp location.

6. Mission Scheduling

With the base camp and scientifically interesting sites chosen, the different excursions were decided. These excursions were broken down into two periods — the break-in period, and the working period. All of the different excursions were planned with the following assumptions in mind:

- 500–600 d surface stay
- A maximum of 14 days of science time at each site.
- A minimum of 10 days of contingency time added to each excursion.
- Very conservative estimates of distances were used to account for terrain (35% added to the straight-line distances).

6.1. Break-In Period

When MERLIN reaches the surface of Mars, it will be virtually untested in its actual working environment. In order to ensure that it will perform as expected on the longer excursions, it seemed prudent to schedule a few shorter trips for MERLIN's first few outings. The break-in period consists of two excursions, with a third excursion possible, if deemed necessary.

6.1.1. Break-In Sortie #1

The first excursion would be just a quick trip around the block, so to speak. MERLIN would be driven around the base camp several times, with all systems being tested. No real science return would be expected from this sortie.

Break-In Sortie #2 — Ascraeus Mons

This sortie marks the beginning of MERLIN's scientific explorations. The rover will take its first trip outside of the safety net provided by the base camp. The total distance will be limited, however, since Ascraeus Mons is the closest of the scientifically interesting sites, lying only 500 km from base.

TABLE 6.1.2.1. Break-In Sortie #2

Location	Distance (km)	Travel Time (days)	Science Time (days)	Contingency Time (days)
Base Camp	–	–	–	–
Ascraeus Mons	500	2.5	14	–
Base Camp	500	2.5	–	–
	–	–	–	11
Total Distance (km)	**1000**		**Total Excursion Time (days)**	**30**

6.1.3. Break-In Sortie #3 — Fortuna Fossae

The third sortie is to Fortuna Fossae. This location is on the travel route twice for the trip to the Northeast (Lunae Planum and Hebes Chasma), so it becomes somewhat redundant to take this trip. This is merely a recommended trip, should it be decided that MERLIN is not fully broken in after its trip to Ascraeus Mons.

TABLE 6.1.3.1. Break-In Sortie #3

Location	Distance (km)	Travel Time (days)	Science Time (days)	Contingency Time (days)
Base Camp	–	–	–	–
Fortuna Fossae	650	3.5	14	–
Base Camp	650	3.5	–	–
	–	–	–	14
Total Distance (km)	**1300**		**Total Excursion Time (days)**	**35**

6.2. *Working Period*

Once MERLIN is considered fully functional, it can begin to fulfill its mission goals of scientific exploration. Four sorties were planned which incorporate all seven of the remaining scientifically interesting sites (not including Fortuna Fossae). The longest sortie is 70 days long, and the furthest point MERLIN will get from base is Melas Chasma, which is 2830 km from base along the route through Valles Marineris.

Sortie #1 – Southeast to Tithonium and Melas Chasmas

TABLE 6.2.1.1. Working Period Sortie #1

Location	Distance (km)	Travel Time (days)	Science Time (days)	Contingency Time (days)
Base Camp	–	–	–	–
Gate of Valles Marineris	1260	6.25	–	–
Tithonium Chasma	510	2.5	–	–
Melas Chasma	1060	5.25	14	–
Tithonium Chasma	1060	5.25	14	–
Gate of Valles Marineris	510	2.5	–	–
Base Camp	1260	6.25	–	–
	–	–	–	14
Total Distance (km)	**5660**		**Total Excursion Time (days)**	**70**

Sortie #2 – Northwest to Olympus Mons

TABLE 6.2.2.1. Working Period Sortie #2

Location	Distance (km)	Travel Time (days)	Science Time (days)	Contingency Time (days)
Base Camp	–	–	–	–
Olympus Mons	2750	14	14	–
Base Camp	2750	14	–	–
	–	–	–	13
Total Distance (km)	**5500**		**Total Excursion Time (days)**	**55**

Sortie #3 – Southwest to Arsia and Pavonis Mons

TABLE 6.2.3.1. Working Period Sortie #3

Location	Distance (km)	Travel Time (days)	Science Time (days)	Contingency Time (days)
Base Camp	–	–	–	–
Arsia Mons	2010	10	14	–
Pavonis Mons	1020	5	14	–
Base Camp	1060	6	–	–
	–	–	–	11
Total Distance (km)	**4090**		**Total Excursion Time (days)**	**60**

6.2.4. Sortie #4 – Northeast to Hebes Chasma and Lunae Planum

It is on this sortie that Fortuna Fossae could also be visited. The travel route passes through Fortuna Fossae on both its inward- and outward-bound legs. The science time for Fortuna Fossae could fit easily into the contingency time built in to the mission, or more time could be added without exceeding the limits of MERLIN's consumables supply.

TABLE 6.2.4.1. Working Period Sortie #4

Location	Distance (km)	Travel Time (days)	Science Time (days)	Contingency Time (days)
Base Camp	–	–	–	–
Hebes Chasma	2090	11	–	–
Lunae Planum	450	2.25	14	–
Base Camp	2080	10.75	14	–
	–	–	–	13
Total Distance (km)	**4620**		**Total Excursion Time (days)**	**65**

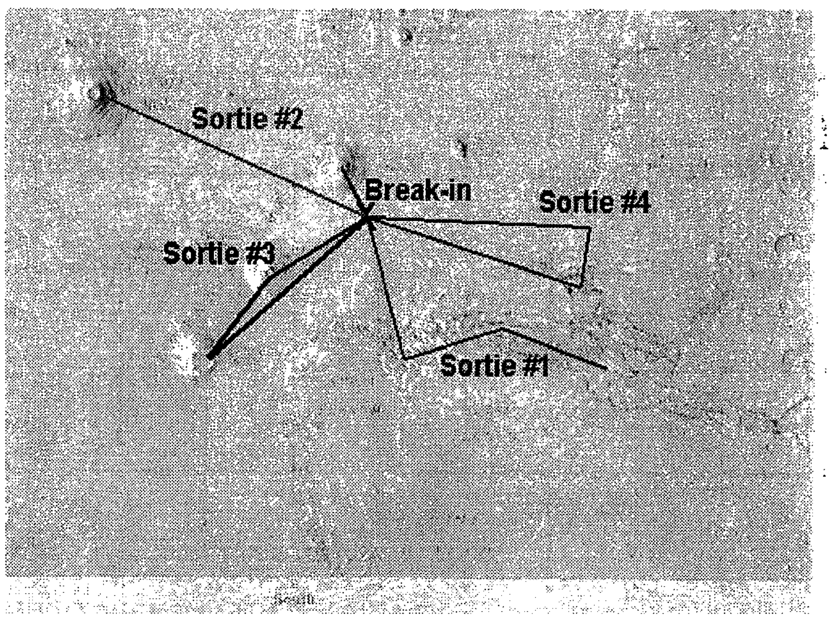

Fig. 6.2.4.1. MERLIN's Sortie Routes.

7. Structures

Now that the basics of the mission have been decided, the actual designing can begin. MERLIN has eight main structural members. These are: the pressure vessel; the front window; the airlock; the undercarriage and main truss; the EVA lift-gate; and the wheels and suspension (see fig. 7.1).

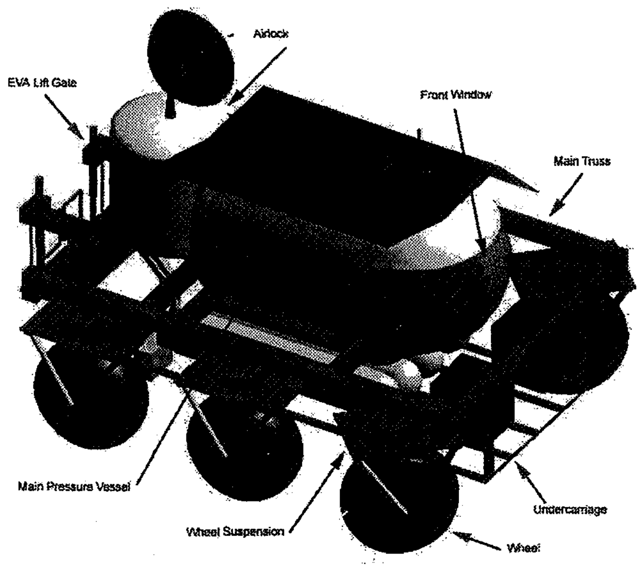

Fig. 7.1. MERLIN's Primary Structural Members

7.1. *Pressure Vessel*

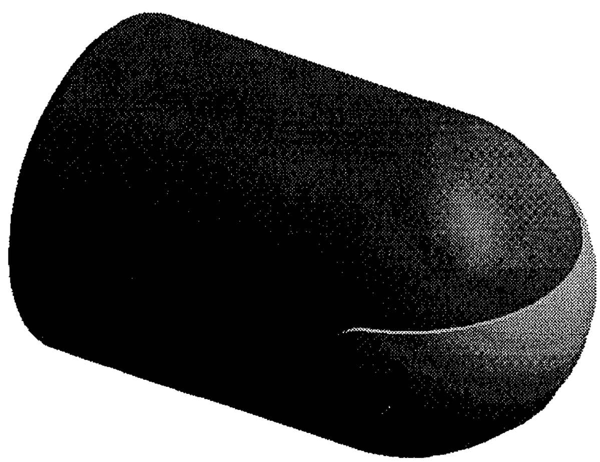

Fig. 7.1.1. Main Pressure Vessel and Front Window

The pressure vessel is designed to encompass the livable interior of the vehicle as well as storage space for major systems (life support, avionics, mission required hardware). The nominal internal pressure, as defined by the Crew Systems team, is 55 kPa, which leads to a required wall thickness of less than 1 mm. The vessel itself is supported from the inside by three circular stiffeners which mate with the cradle of the external truss. The main body cylinder has a radius of 1.8 m, is 3.5 m long, and has a wall thickness of 3 mm. The front endcap, which is hemispherical, has a radius of 1.8 m and a wall thickness of 5 mm. The rear endcap, which is not hemispherical, has a radius of 1.8 m, a height of 0.5 m, and a wall thickness of 5 mm. All of these pieces are made of 6061-T6 aluminum.

7.2. *Front Window*

Also visible in fig. 7.1.1 above is the front window. The window allows for a standing crew member in the cabin to clearly see the horizon while giving members in the control station a clear view of the surrounding area. From the middle of the control station, the window allows for a 180° field of view along the horizon, 15° up, and 60° down. Crew members can see the ground below the front of the truss and between the engines from the control station. The window is made up of panes of 0.5 m^2 (0.71 m × 0.71 m) polycarbonate plastic which is 5 mm thick. Aluminum bands make up the frame which holds the panes together and mounts them to the pressure vessel.

7.3. *Airlock*

The airlock is located outside the main pressure vessel. This is necessary so that when it is depressurized, the structure is not being compressed by the internal pressure of the rover. Both the inner and outer doors are designed to open into the airlock so that pressure assisted sealing can be achieved. Additionally, a series of mechanical latches secure and assist in opening the doors in a manner similar to those currently used for the shuttle airlock. The main cylinder of the airlock has a radius of 1.1 m and is 2.1 m high. The endcaps are 0.25 m high and will be filled with an air-tight, lightweight foam to reduce the volume which must be depressurized. All walls will be 5 mm thick and will be made of 6061-T6 aluminum.

The airlock is designed to allow for two crew members in full EVA suits to exit the vehicle at a time. Two suitcase sized packages can be carried in and out of the airlock to allow for equipment to be to be transferred to and from the rover, as well as to allow for samples to be brought within the vehicle.

A raised grate floor will allow for dust brought in from EVA to fall to a collection area to prevent it from being tracked into the main cabin area of the vehicle. Vacuums, brushes, and other tools will be stored here for the cleaning and maintenance of the suits.

7.4. *Undercarriage*

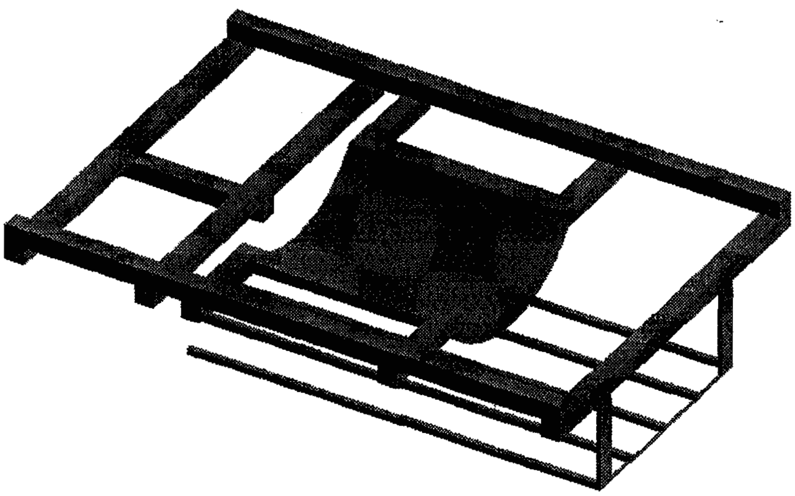

Fig. 7.4.1. MERLIN's Undercarriage

The main truss was designed to be both simple and robust in design. Titanium box beams were selected due to their high strength/mass ratio which is essential in such a critical load bearing structure. The cradle, which makes up the center part of the structure, was designed to avoid point loading on the pressure vessel, thus requiring a high area design. The undercarriage was designed to protect the pressure vessel and fuel tanks from contact with the surface in the event that the rover accidentally bottomed. The rear part of the undercarriage was extended to provide support for the robotic arm and sample storage boxes. The outer frame consists of 10 0.3m × 0.3 m box beams and the undercarriage consists of 5 0.1m × 0.1 m box beams.

FEM analysis revealed a large stress concentration in the center of the cradle. To counteract this effect, and to provide hard-points for mounting objects on the top of the rover, three circular stiffeners were added inside the pressure vessel (not depicted). These stiffeners also aid in transferring the weight of the internal systems of MERLIN outside to the main truss, rather than transmit the forces through the walls of the pressure vessel.
Due to the subsequent design and placement of the fuel tanks and water storage tanks, no support structure was designed to carry them, however their weight was added to the pressure force exerted on the cradle in the

analysis of the truss. Similarly, changes in design of engines (i.e. the addition of a second full size engine) required the removal of the original support structure, which there was not time to redesign. Future work would include the addition of simple supports to correct these missing elements.

7.5. EVA Lift-Gate

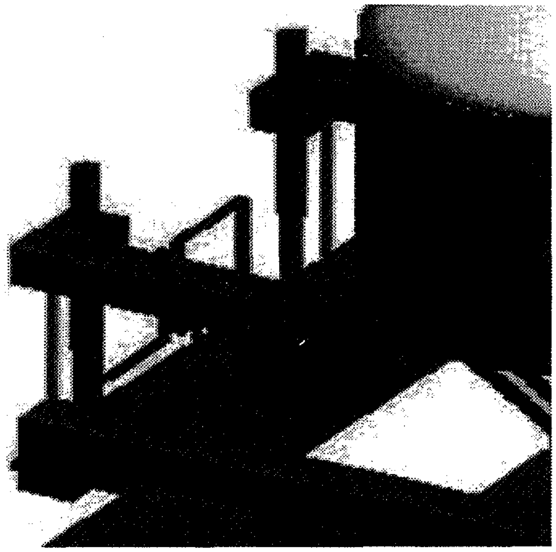

Fig. 7.5.1. EVA Liftgate

The lift-gate idea originated with the tailgate lifts sometimes used on 18-wheelers; a motorized platform that could lift people and heavy cargo easily up to the floor of the trailer. The lift-gate on MERLIN is suspended by four cables (two on each side, only one on either side is visible in fig. 7.5.1) so that it may be raised and lowered via winches. To keep the lift-gate from swinging, two telescoping rods were added. The gate on the lift is actually more of a handrail for the crew as they are raised or lowered. The lift-gate is large enough to take both crewmembers to or from the airlock with any samples they might be transporting.

7.6. Wheels and Suspension

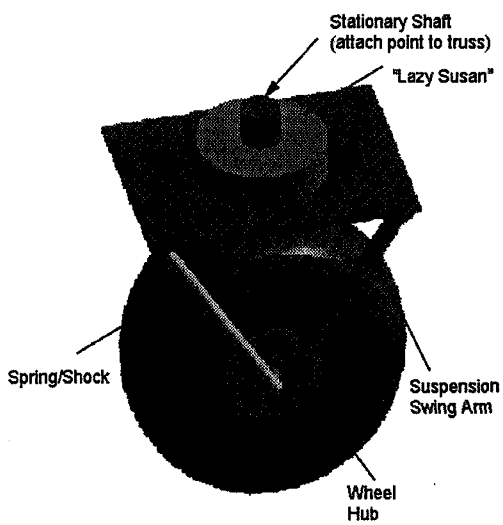

Fig. 7.6.1. Wheel and Suspension

The main design consideration with the wheels was the footprint necessary to keep the rover from sinking into the soft sand surfaces on Mars. On the less cohesive soils, the highest pressure allowable without sinkage was 6 psi. However, more solid surfaces can support much higher pressures and traversing them with a much greater tire contact area than necessary would cause more wear on the tire. To solve this problem it was planned to be able to remotely release some of the pressure when on the soft soil. To re-inflate the tire later, a remotely controlled compressor would use a portion of the CO_2 exhaust from the engine. The wheels have an outer radius of 1 m, and an inner rim radius of 0.375 m. Their pressure can range from 6 to 25 psi.

The suspension system is a modified version of a motorcycle rear-end. The wheels are supported by two bars in the front which are connected to the top plate with a pin joint. The axle of the wheel is supported by these bars and by two springs which are able to rotate in a manner similar to the front bars. This system is fairly simple, while still remaining robust. Springs were chosen with a constant of 27700 N/m in order to have a nominal, flat surface deformation of 10 cm. The swing arm is 2.0 m long and the spring/shock is 1.8 m long giving the wheel a slight offset.

7.7. *Steering*

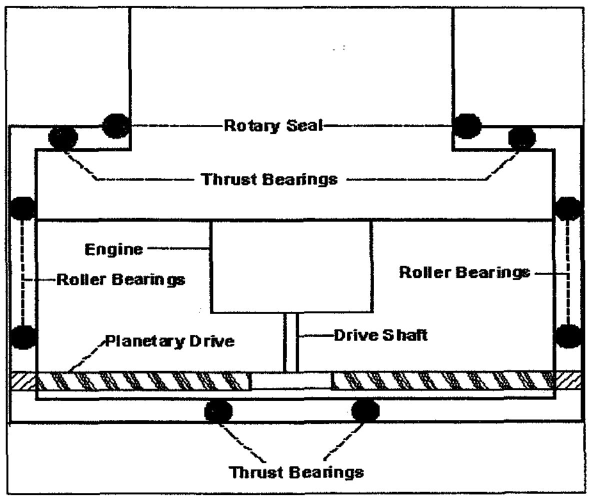

Fig. 7.7.1. Steering Mechanism

The design shown above works as follows: The top shaft is connected to the external rover truss. This point is fixed and does not move. The rotary seals prevent the Martian dust from entering the mechanism and destroying the equipment. The main casing of the design is a cylinder which is affixed to the plate on which the suspension system is mounted to. Thrust bearings at the top and bottom of the cylinder fix the rotating cylinder relative to the shaft that is connected to the truss. An electric motor suspended in the middle of the design rotates a planetary gearing system, consisting of three gears which drive the wheel rotation. Not shown are the power and control wires which run from the upper shaft, through the "Lazy Susan" and down into one of the arms of the suspension to provide power and control to the wheel drive motors.

8. Crew Systems

8.1. *Psychological Requirements*

When there are only six other humans on the planet on which you reside, and your family is (at the closest) almost 79,000 km (50,000 mi.) away, there are bound to be psychological concerns. In order to counteract the loneliness that the crew will feel, frequent communication with family and friends on Earth will be provided through email (voice communication having about a 40 min delay). Also, many forms of recreation will be provided, such as exercise, reading, and watching videos.

Another problem with being in an environment such as that found on Mars, is that all of the people will be confined within extremely close quarters. While humans are known for being able to adapt to many situations, 1.6 m^2 was established as the minimum comfortable personal space required for each person on the rover. This figure was gathered from studies done on submarines and other enclosed spaces which required lengthy stays.

8.2. *Physical Requirements*

8.2.1. Consumables

Each crewmember requires 0.62 kg dryweight/man-day of food and 9.6 kg/man-day of water. The food would be stored in dry form, like that on the shuttle, and rehydrated when eaten. Each crew member will be allowed to change clothes once a week (also similar to shuttle rules), and enough clothes to last for each mission will be brought along to avoid the need of a clothes washer.

8.2.2. Temperature and Humidity Control

The temperature inside MERLIN's cabin should average between 18.3° and 26.6°C, and the relative humidity should stay between 25 and 70% for crew comfort. These numbers were derived from other habitat analogs such as Apollo, Skylab, Shuttle, Spacelab, and the ISS.

8.2.3. Autonomous Driving

A certain level of autonomous driving was added to MERLIN's capabilities when it was discovered that it did not significantly increase the cost, mass, or power required, and it did not overly complicate the avionics system. This would be autonomous in the sense that the crew could set waypoints and desired speed, and then be able to relax in the cockpit. The autonomous driving system would alert the responsible crew member should a problem arise which it could not solve.

8.2.4. Fire Detection and Suppression

A system, again similar to that on the Space Shuttle would be used to detect and suppress fires. Smoke detectors which detect the ionization levels of the air would be used, as would hand-held halon fire extinguishers.

8.2.5. Atmospheric Systems

The Trace Contaminant Control System would be used for the control of airborne contaminants. This system consists of a set of filters that are projected to be fully regenerable in the future. Also required would be 2.76 kg of breathable O_2 and the removal of 3.06 kg of CO_2 per Martian day. A Solid Amine Water Desorption (SAWD) System would be used to scrub the CO_2 from the air and CO_2 electrolysis would be used to produce breathable oxygen (see fig. 8.2.5.1). Fifteen days of backup supplies would be provided. Among these are 90 kg of LiOH canisters for use in removing the CO_2 from the air and 83.3 kg of $Ca(O_2)_2$ which would be used to produce oxygen.

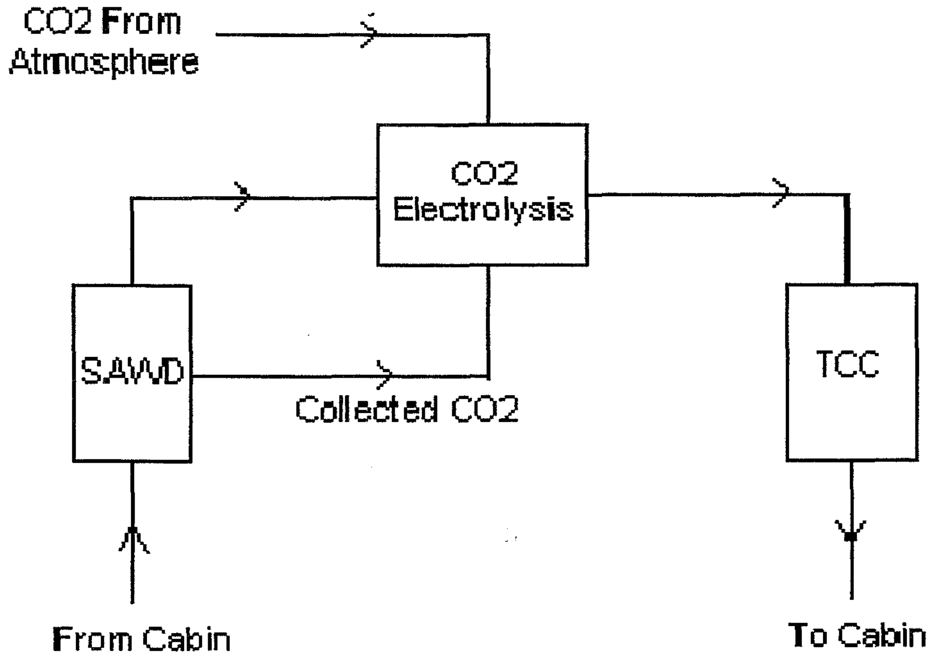

Fig. 8.2.5.1. Carbon Dioxide Removal System

8.2.6. Water Control Systems

A crew of three will nominally need 28.8 kg of water per martian day. This water will be split into hygienic and potable water reservoirs. Water will be reclaimed from toilets, showers, sinks, (see fig. 8.2.6.1) and the cabin air (see fig. 8.2.6.2). It is assumed that water reclamation will occur with a 90% efficiency. Water from the shower and sinks will undergo reverse osmosis, then will pass through a multi-filtration bed before passing through quality monitoring, and being stored in the hygienic water tank. Water from the toilet will pass through a Thermoelectric Integrated Membrane Evaporation System (TIMES) before passing through quality monitoring and being placed in the hygienic water tank. Cabin air will pass through a condensing heat exchanger (CHX), which will return the dry air to the cabin and send the water through quality monitoring to be sent to the potable water reservoir.

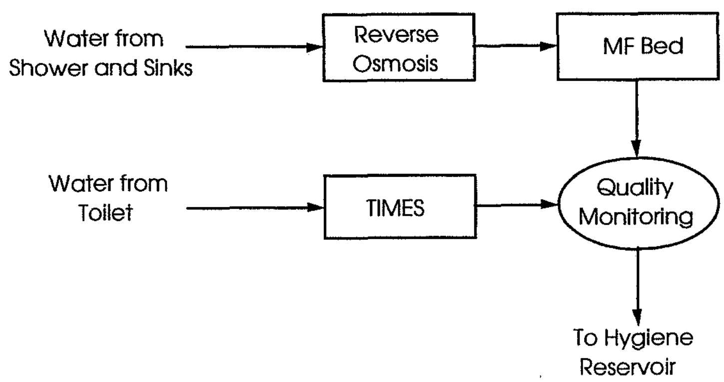

Fig. 8.2.6.1. Water Reclamation System

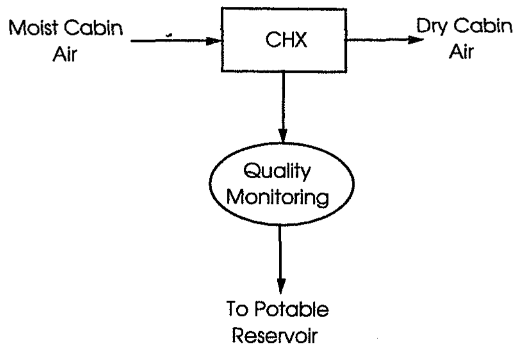

Fig. 8.2.6.2. Humidity Control System

8.3. EVA Support

MERLIN will be able to support two astronauts on EVA simultaneously. Video and suit telemetry will be sent back to MERLIN from the suits. The astronauts will require no pre-breathe due to the interior cabin pressure of 55 kPa. The crew will be able to maintain the suits while onboard MERLIN. The maximum EVA duration will be 8 hours.

9. Power, Propulsion, and Thermal

9.1. Power Requirements

While at rest, MERLIN will have a nominal power requirement of 4.5 kW. This energy will power all of the life support systems (2.0 kW), the avionics (2.0 kW), and will cover any thermal control systems and heat losses (0.5 kW). At times, power will also be needed for such auxillary items as the airlock (7.5 kW), the core drill (5.5 kW), the science equipment (2.5 kW), and the robotic arm (1.0 kW).

When driving, MERLIN will require power for all of the nominal systems, as stated above, as well as power for the engine (90 kW) and water condensers (5 kW).

9.2. Power and Propulsion Systems

9.2.1. Primary Systems

MERLIN will be powered nominally by an internal combustion engine which will run on stored methane and oxygen. The combustion will occur with 40% efficiency at a 2:1 oxidizer-to-fuel ratio. This engine will provide 100 kW of power nominally and 125 kW in peak usage times. Excess power will be stored for later use in NiMH batteries. The engine will only provide power while the vehicle is in motion. At all other times, the secondary systems will be used.

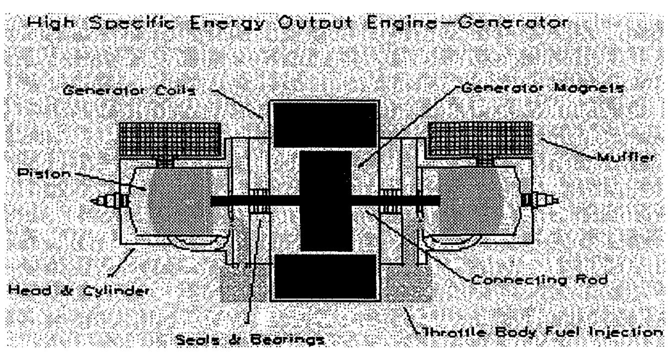

Fig. 9.2.1.1. MERLIN's Engine/Generator

9.2.2. Secondary Systems

While at rest, MERLIN will be forced to rely on its secondary power systems. These include batteries which were charged by the engine while driving, and solar arrays which can be deployed when at rest. The solar arrays will be located on MERLIN's roof and will be stowed while the vehicle is in motion.

9.3. *Thermal Design*

An engine which is only 40% efficient produces a significant amount of waste heat (187.5 kW). This energy will be radiated away from MERLIN through 6 m^2 of radiator panels and 1.7 cm diameter heat pipes which are located on the vehicle's undercarriage. Methane fuel for the engine will pass by the engine prior to combustion to allow it to vaporize. Engine exhaust will be vented through side exhaust pipes.

10. Avionics

10.1. *Computer Systems*

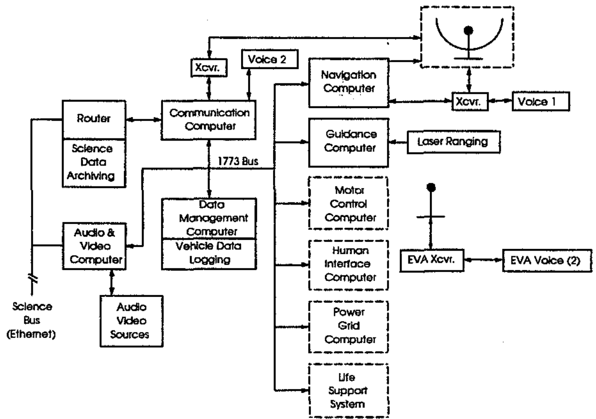

Fig. 10.1.1. Avionics System Block Diagram

As can be seen from the block diagram, the Avionics system is rather complicated. It consists of two main buses — the systems bus, and the science bus. The systems bus is the main bus. It runs over 1773 fiber optic lines. 1773 is a mil spec bus protocol which is redundant by nature. This redundancy provides an added level of safety for all mission critical computer systems. As the science equipment is not necessary to sustain life aboard MERLIN, its systems were kept separate from the systems bus. Since safety is not an issue where science data is concerned, gigabit Ethernet was chosen as the protocol for this bus. This is also advantageous due to its bandwidth and the ease with which it can interface to other systems.

10.2. *Communications Satellites*

The need for constant contact with the base camp while on an excursion is obvious. In order to maintain this contact, it was determined that three communications satellites would be needed. One of these satellites would support high bandwidth operations, like live video feeds, as well as communications and navigation, while the other two would only support communications and navigation. The navigation transponders would have a low bandwidth of 57.6 kbps and a high beam width of 160°. The high bandwidth relay would receive the main data stream at 11 Mbps, but would have a small beam width (20°). These systems would weigh 70 kg (per satellite), and would require 500 W of power. Due to these small requirements, it would be prudent to put these transponders on future Mars orbiters, as well as enough extra fuel to be able to place them in the proper orbits. The high bandwidth satellite would be placed in Mars-stationary orbit, while the other two satellites would be placed in Mars-synchronous orbit at a 15° inclination. These satellites would have 45° of separation to keep them from being co-linear within the orbital plane.

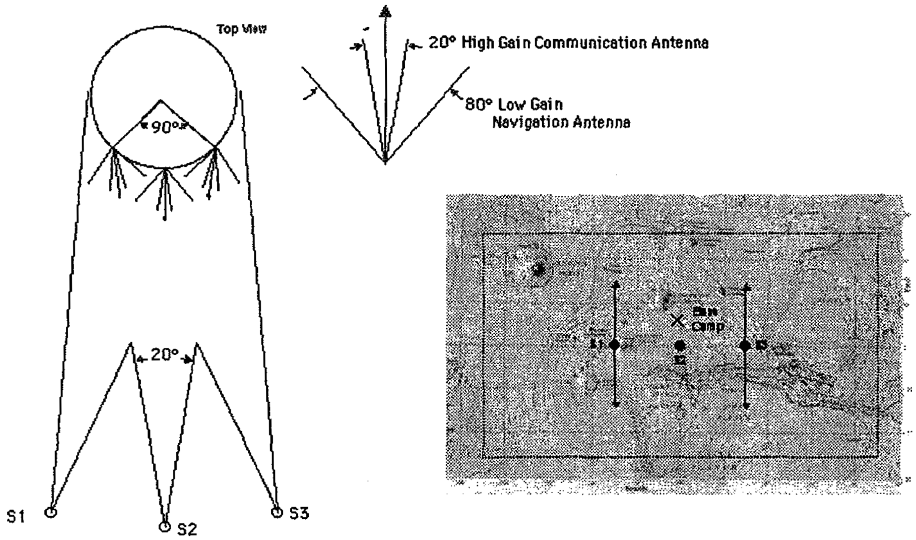

Fig. 10.2.1. Communications Satellite Coverage

11. Miscellany

Two additional systems are necessary for MERLIN's operation — a robotic manipulator, and CRYSTAL BALL.

11.1. Robotic Manipulator

To avoid unnecessary EVA, and to provide some heavy lifting power for MERLIN, a telerobotic manipulator was designed. This manipulator would be placed at the rear of MERLIN, on the starboard side of the airlock and lift gate. It would be within reach of two small sample storage containers. This would allow the arm to pick up rocks, or other samples, which could be carried inside the rover at a later time by an astronaut on EVA. The arm would have five degrees of freedom and would consist of a roll-pitch-pitch-pitch-roll configuration. This would limit the number of possible singularities while allowing a significant amount of mobility within the workspace. In order to be as capable as possible, three end effectors would be required: a claw to pick up rocks, a scoop to pick up soil, and a small core sample drill with which to get 6" diameter, 2' long core samples.

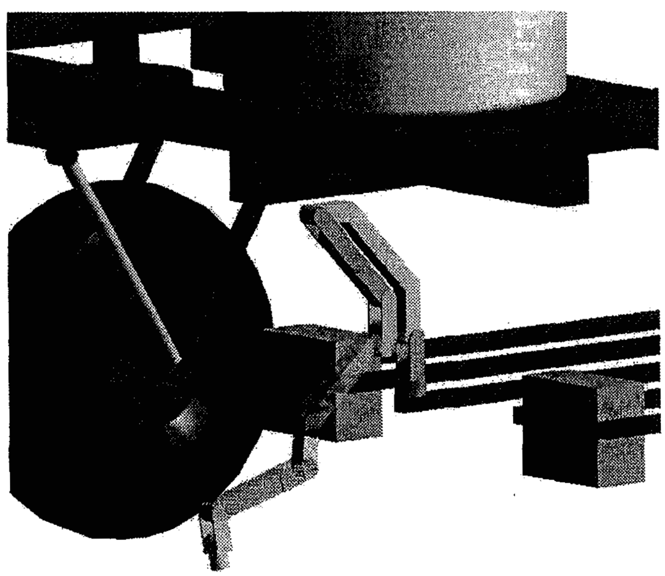

Fig. 11.1.1. Robotic Manipulator

11.2. CRYSTAL BALL

The CRYogenic STorage And Local BALlistic Lander (CRYSTAL BALL) system is basically a network of gas stations on Mars. Each CRYSTAL BALL installation would have about the same configuration as that of the Mars Pathfinder lander, in that it would have the three petals of solar panels, with machinery inside. These would be launched from Earth similarly to Pathfinder, and would be placed at seven locations which would provide the necessary fuel for MERLIN's travels.

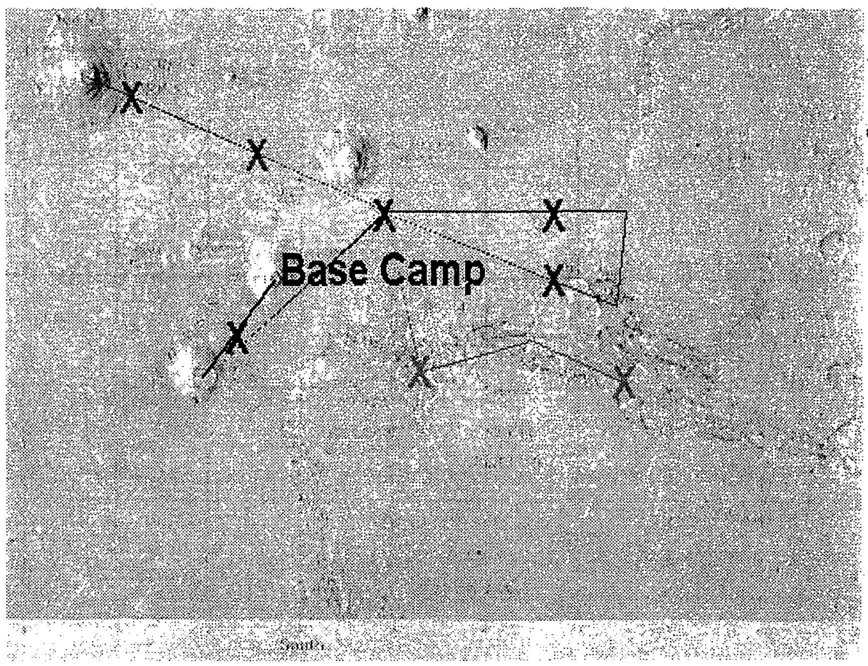

Fig. 11.2.1. CRYSTAL BALL Locations

The fuel and oxidizer would be produced with a Sabatier/Electrolysis Reaction system. The Sabatier rection would produce methane from carbon dioxide (from the atmosphere) and liquid hydrogen (stored). The water by-product from this reaction would then be electrolyzed to produce more seed hydrogen for re-use in the Sabatier reaction and oxygen. These would be stored until needed by MERLIN. Should MERLIN produce excess water (as is expected by the Power, Propulsion, and Thermal group), it will be possible to leave this water at any CRYSTAL BALL location to increase the lifespan of the installation. As they are designed currently, there will be enough seed hydrogen to be able to produce 3000 kg worth of propellants for MERLIN.

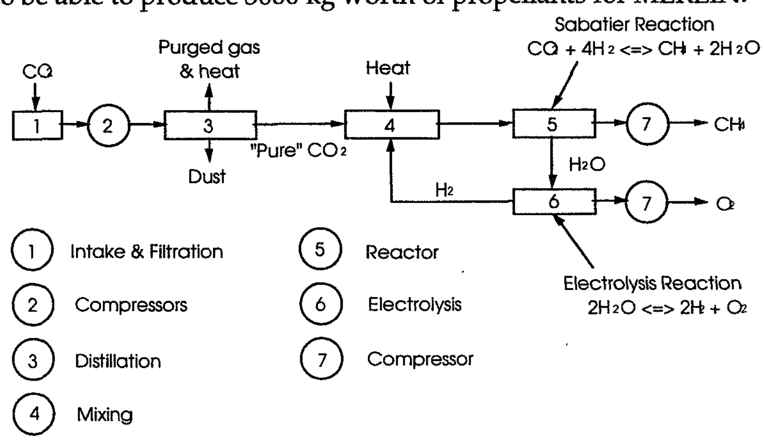

Fig. 11.2.2. CRYSTAL BALL System Block Diagram

12. Conclusions/Recommendations

It is recommended by the senior design class of the University of Maryland, College Park department of Areospace Engineering that the above design be considered as a possible design for a pressurized rover for use on Mars. While this design still contains many flaws, most of the ideas are technically sound and, many times, innovative.

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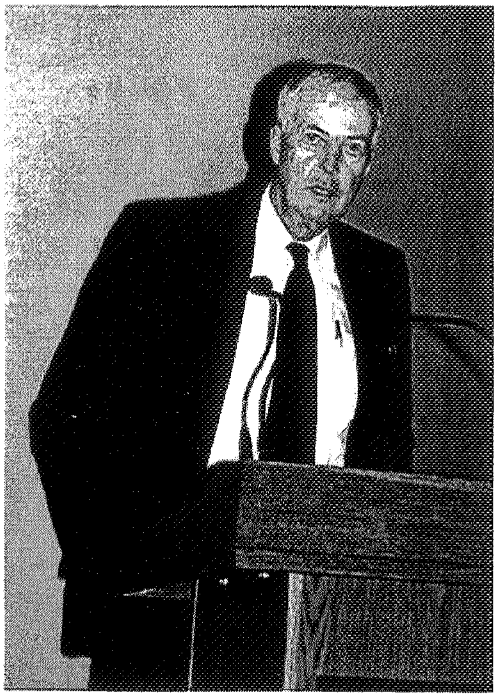
Panel Presentations and Discussion

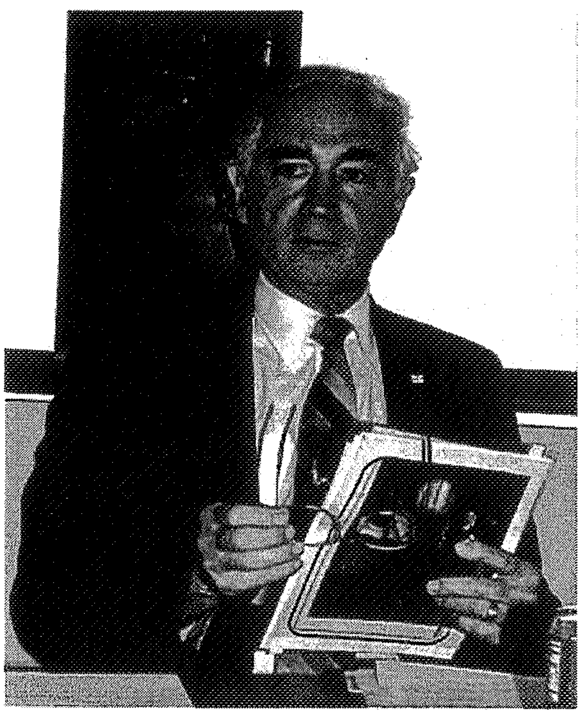
A panel of four aerospace industry representatives discusses the technical readiness for Mars exploration, responding to the question "What do we really need for a human Mars Mission?"

Doug Cooke of NASA/JSC's Exploration Office serves as moderator for the industry panel.



Dr. Joseph Kerwin of Wyle Laboratory Life Sciences discusses human physiology and biomedical issues facing crews exploring the martian surface.

Harvey Willenberg of Boeing focuses on supporting technologies required to enable human missions on Mars.



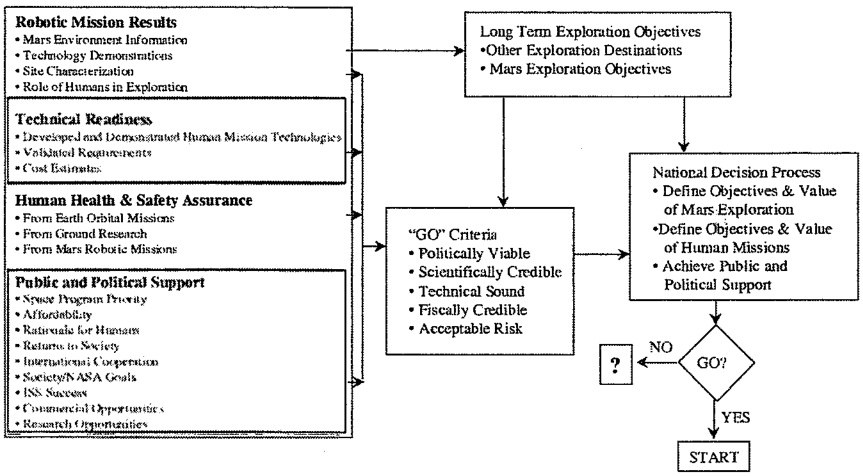
Mike Henry of Lockheed Martin presents his views on optical technologies that might contribute to human surface missions on Mars.

Dr. Eric Rice of Orbitec discusses the impact of using *in situ* resources on Mars, and how small business innovations could contribute to planetary missions.

"WHAT DO WE REALLY NEED FOR A MARS MISSION?" -TECHNOLOGY -

Harvey J. Willenberg
Boeing

The Route to "Go/No Go"



Technical Readiness

- Developed and demonstrated human mission technologies
  - Have we demonstrated the technologies required for a Mars mission?
    - Mission safety and assurance demand multiple technology demonstrations with whatever means are available
    - Include Shuttle, Space Station, and ground demonstrations
- Validated requirements
  - Have we performed precursor missions and simulations to understand the requirements?
  - Do we have the operations experience to assure success?
- Cost estimates
  - Do we have a clear baseline?
  - Is the technology readiness level high enough to accurately estimate costs?
  - Do we have the political support to maintain schedule (and thereby control costs)?

Earth to Orbit Transportation

- Mars Reference Mission requires either 200-225 tonnes to LEO or 110-120 tonnes on a split mission
  - Current capability does not exist
  - Several design concepts evolve from Shuttle Cargo Vehicle or Delta family
- Smaller vehicles require orbital rendezvous, assembly, and checkout of multiple launch payloads
  - Stresses capability of launch operations and propellant storage

Space-based Transportation

- Positive progress being made on solar propulsion - both electric and thermal
  - Technology risks mostly involve scaling up power
- Minimal activity on nuclear propulsion - technology is achievable, but political barriers may be insurmountable
- Earth-return vehicle is a major risk in the reference mission
  - Everything to remain in operating readiness for 4 years
  - Maintain liquid hydrogen for 4 years
  - MAV orbit rendezvous and capture

Mars Landing and Ascent

- The details of aerocapture have yet to be developed
  - Plan for multiple designs and demonstrations before sending crew to aerocapture mission
- Use of propellant generated in situ
  - Adds risk in precision landing
  - Adds multiple non-recoverable failure modes
    - TMI and Trans-Mars coast
    - Failure to capture in proper orbit at Mars
    - Lander disabled during descent
    - Unsuccessful rendezvous with TEI stage

Regenerative Life Support Systems

- Open loop systems not workable for Mars transfer
- Bioregenerative systems are essential
  - Activities underway at JSC, KSC, ARC on bioregenerative life support systems
  - Several years of ISS demonstrations will be required
- Substantial development still required, but ...
- No real technology roadblocks exist

Key Technologies for Human Exploration

Regenerative Life Support Systems
- Loop closure (air, water and food)
- Environmental monitoring & control
- Trash and waste collection/Processing

In Situ Resource Utilization
- Extraction processes and chemistry
- Materials handling

Transportation and Propulsion
- Advanced chemical systems
- Nuclear propulsion
- Aerocapture/aerobraking
- Lightweight/advanced structures

EVA and Surface Mobility
- Durable, lightweight, high mobility suit and gloves
- Lightweight, serviceable PLSS
- Long range surface transportation

Surface Power Generation and Storage
- Regenerative fuel cells
- Surface nuclear power systems
- High-efficiency solar arrays

Health and Human Performance
- Biomedical countermeasures
- Health care
- Radiation health
- Environmental health
- Space human factors

Cryogenic Fluid Systems
- Long-term storage
- Lightweight, high efficiency cryogenic liquefaction
- Zero-g handling and transfer

Teleoperation and Advanced Operations
- Tele-exploration and virtual reality systems
- Automated system control and advanced electronics

Surface Habitation and Construction
- Inflatable structures
- Seal materials and mechanisms

In Situ Resource Utilization

- Multiple processes can be made to work for CH_4 & O_2 propellants
  - Sabatier + electrolysis; Bosch; reverse water gas shift
  - Similar processes can be used for LSS oxygen
- System reliability and endurance still must be demonstrated in reference environment
- Reference mission technology achievable if architecture can solve abort risk issues
- Additional in situ resources should be considered
  - Especially consider use of Lunar resources

Surface Power Generation and Storage

- Initial deployment of > 50 kWe at Mars surface required before in situ resources can be generated
  - Must be deployed years before crew arrives, therefore autonomously
  - Major challenge
- More power will be required when crew arrives
- Solar power will require larger arrays than have ever been flown
- Nuclear power will require compact reactor that can be acceptance tested before leaving Earth vicinity

Cryogenic Fluid Systems

- Multiple technology aspects have yet to be demonstrated
  - Very long term storage of cryogens
  - Microgravity fluid handling
  - Stable heat balance

Surface Habitation and Construction

- Inflatable or rigid?
- Autonomous deployment?
- Must be immediately operable after long hiatus
- Technology must be demonstrated with high reliability before Mars mission
  - Either at ISS or Lunar surface

EVA Surface Mobility

- Both systems absolutely essential for mission success an crew safety
- No human-rated rover has yet been designed to meet reference mission requirements
  - Human rating assures crew safety
  - Human presence allows field repairs
- Trade off between mobility requirements and accuracy of landing location

Teleoperation and Advanced Operations

- Technology still to be developed for lag times of minutes or more
- Many issues remain for advanced operations
  - Rendezvous and docking
  - System checkout and maintenance
  - In-space assembly of Mars vehicles
  - Deployment of habitats, propellant production, and power systems at Martian surface
  - Routine crew operations for long missions with long lag times

Public and Political Support

- Space Program Priority
- Affordability
- Rationale for Humans
- Returns to Society
- International Cooperation
- Society/NASA Goals
- ISS Success
- Commercial Opportunities
- Research Opportunities

Commercial Market Considerations

- ISS-based demonstrations and operations
- Orbital fuel and services
- Space tug
- Lunar and asteroidal resources
- Mars fuel for rovers and ascent vehicles
- Lunar/Mars service provider

Program Challenges

- As a public agency, NASA executes the will of the people.
  - Excitement of human exploration and development
  - Continuation of scientific research for humankind
  - Technology development to improve life on Earth
- A long-term, multi-billion dollar program needs sustained public support.
  - Sell the program
  - Keep it sold

Program Needs

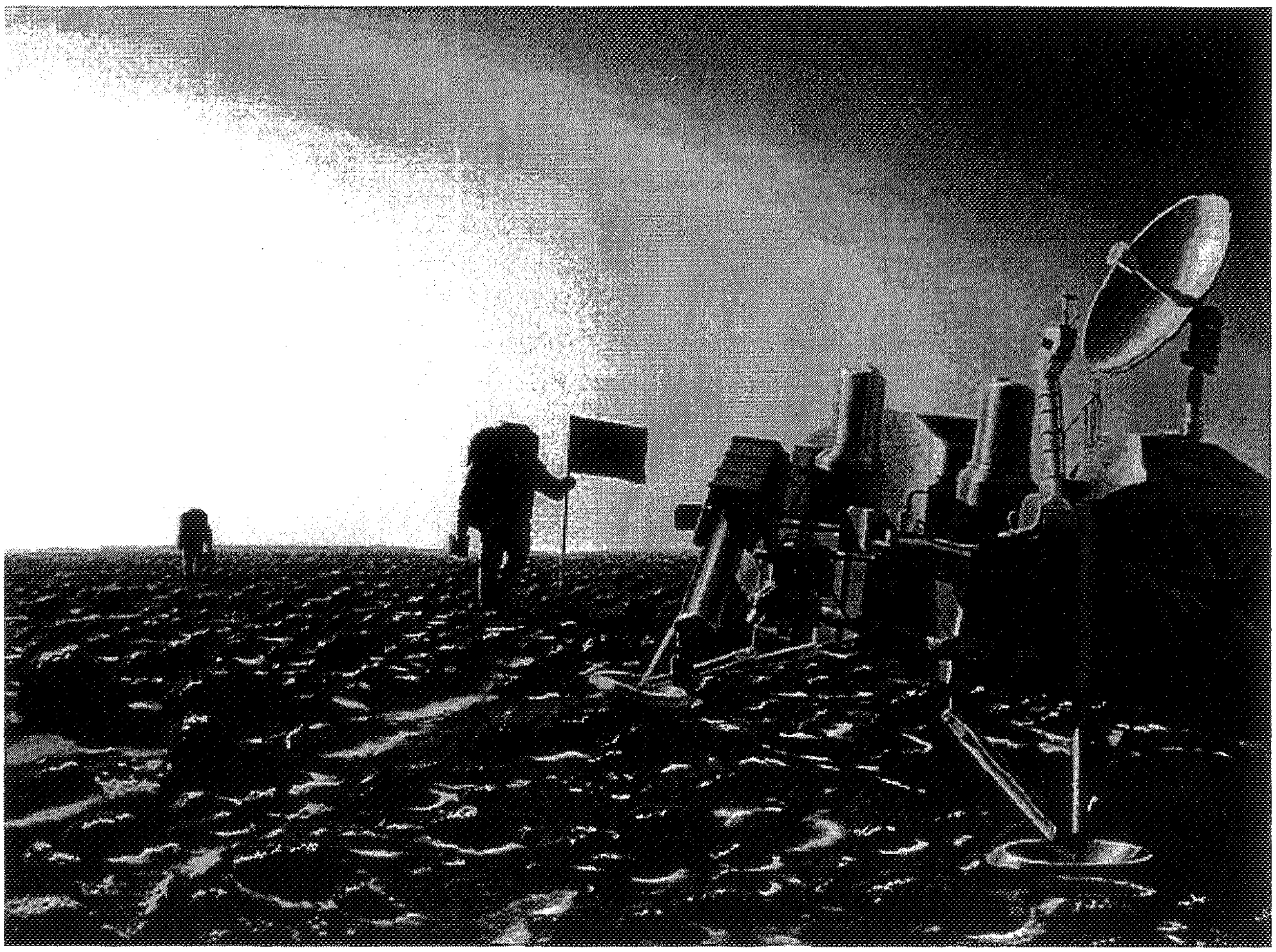
- A vision of human exploration and development that stimulates the public, the funding sources, the program participants, and the users and customers
- A public outreach program that is active, responsive, and an integral part of the planning process
- Understanding of the trade options
  - Costs, timing, technology risk
  - Moon, Mars, asteroids
  - Metrics that include robustness and public excitement
- Technological development
- International participation that involves mutual benefits and reduced individual costs
- An approach that encourages synergies with commercial investment

HEDS
A Contractor's View of the Pivotal Programmatic Questions

- Single mission or sustained campaign
  - i.e. few landings with footprints vs. multiple landings, destinations, and missions
- Sustained, stable requirements and funding
- Sustained public support
- Complementary and enhanced international cooperation
- Opportunities for applying technology, systems, and services to multiple uses
  - Commercial, military, other government uses
  - Consider commercial purchase of data and services
- Integrated product teams with government, academia, and industry

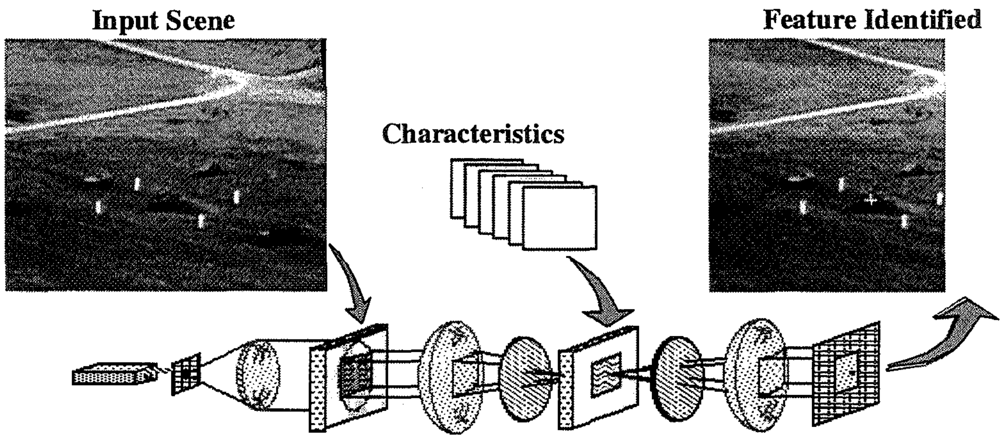
AN INNOVATIVE TECHNOLOGY FOR MARS EXPLORATION

E. Michael Henry
Lockheed Martin Corporation



The human mission to Mars will require innovative technology advances in autonomous control, hazardous avoidance, habitats, environmental protection, and *in situ* resource utilization.

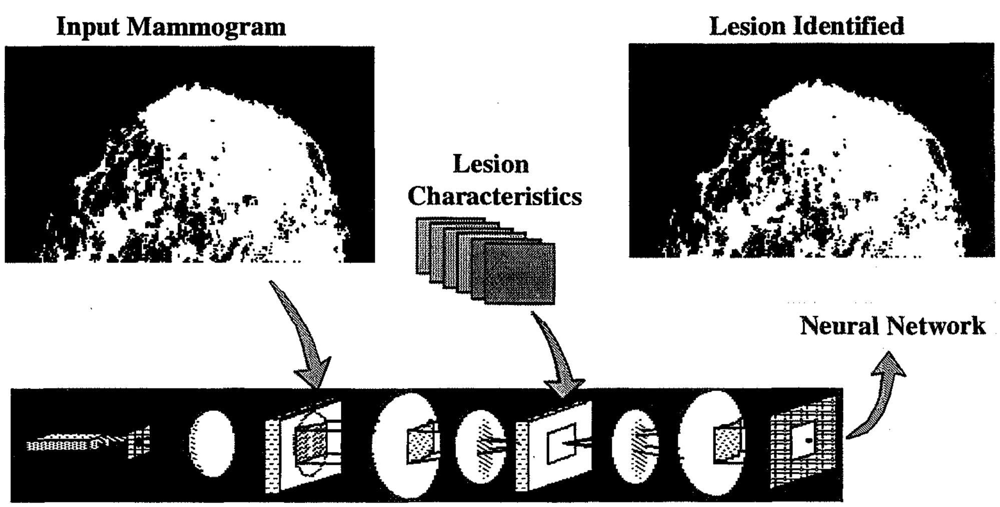
OPTICAL PATTERN RECOGNITION



•Inherently Massively Parallel (Entire Frame Simultaneously)
•Excellent Discrimination, Low False Alarm Rates
•Low Power, Light Weight, Small Volume

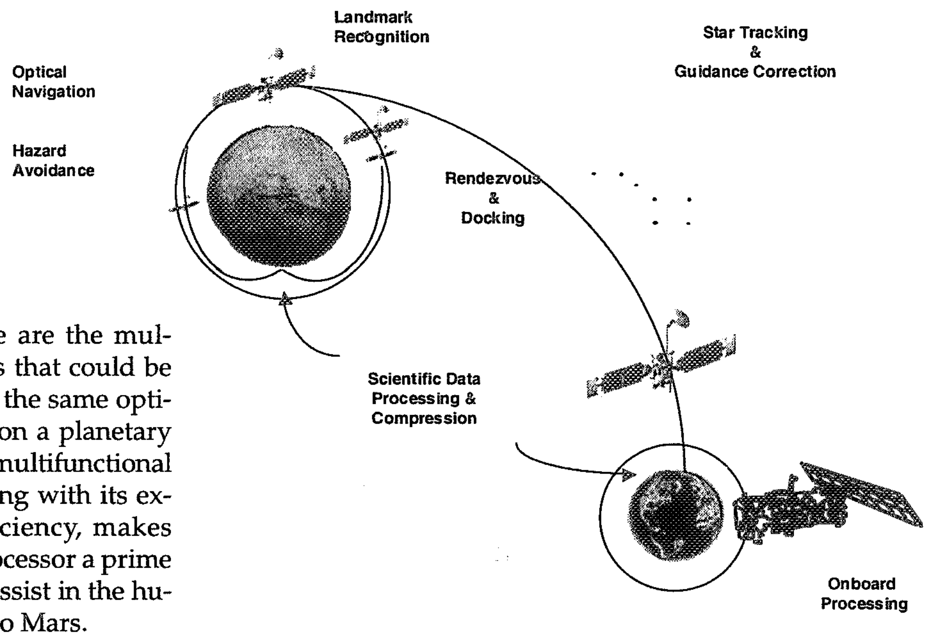
A technology that can perform ultrahigh throughput pattern recognition uses a laser and lenses in a Fourier-transform-based algorithm. It has been shown in DoD applications to have exceptional detection probability and features location accuracy, coupled with the low power/weight/volume essential for a planetary mission.

AUTOMATIC LESION DETECTION

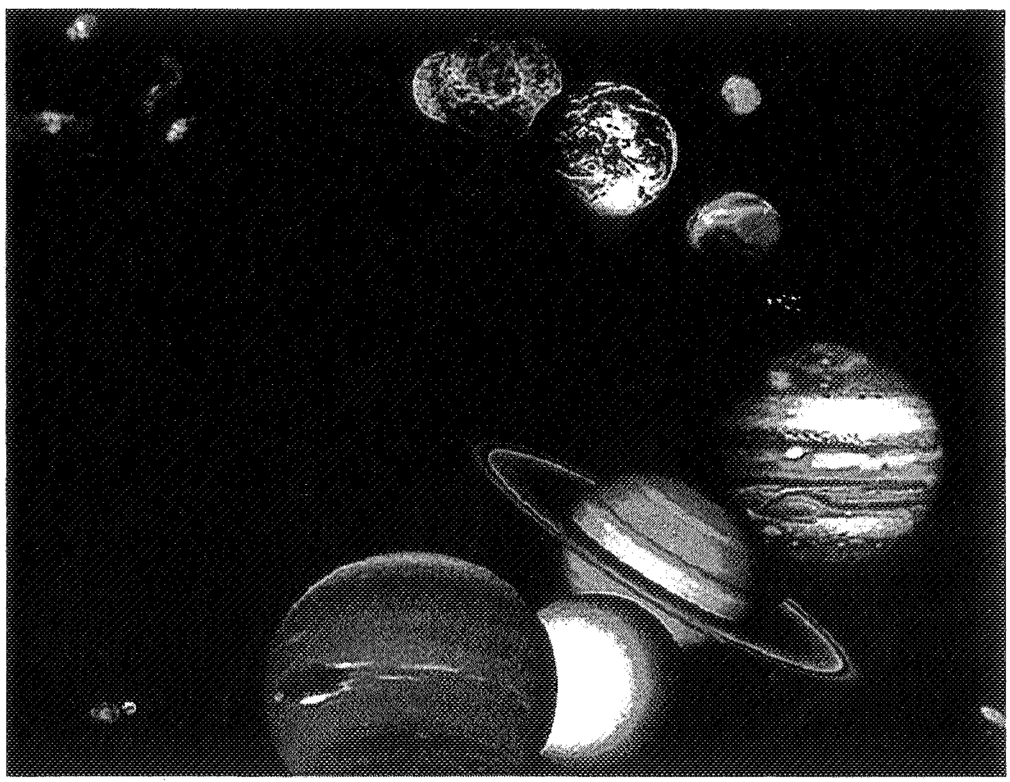


Besides DoD target recognition, the optical processor has been shown to have outstanding capability to detect even tiny cancers in medical imagery.

Application Concepts



Depicted here are the multiple functions that could be performed by the same optical processor on a planetary mission. This multifunctional capability, along with its exceptional efficiency, makes the optical processor a prime candidate to assist in the human mission to Mars.



Out here there are no stop signs . . . . Lockheed Martin believes that no goal in planetary exploration is unachievable.

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Role of ISRU in Mars Exploration and the Importance of Innovative Small Business Contributions

Eric E. Rice
Orbital Technologies Corporation

ORBITEC Mission Statement

To serve government and industry by developing and demonstrating innovative technologies and advanced products that enhance the quality of human life and support mankind's exploration of the Universe.

Discussion Topics
- ❖ AIAA position on ISRU
- ❖ ORBITEC's involvement
- ❖ Other small business involvement
- ❖ Concluding remarks

AIAA Position Paper on ISRU
- ❖ Position paper developed by the AIAA Microgravity and Space Processes Technical Committee in 1997
- ❖ Paper printed and distributed
- ❖ Discusses benefits
- ❖ Provides key recommendations to NASA to develop an active ISRU program

Overview
- ❖ ISRU Program will reduce launch masses and costs by producing return-trip and locally used propellants
- ❖ Mission analyses indicate ISRU could reduce launch mases by up to 63%
- ❖ A small investment in developing ISRU technologies now will return huge savings in future exploration

Lunar-Derived Propellants
- ❖ O_2 can be "mined" from lunar regolith via direct heating and addition of H_2 or C
- ❖ Leading lunar propellants include: H_2O, H_2/O_2, Al/O_2, and CH_4/O_2
- ❖ Mars missions can be enhanced by using lunar-derived propellants
- ❖ Analyses indicated that Al/O_2 propulsion reduces initial mass to LEO by 54% to 63%

Mars-Derived Propellants
- ❖ Mars offers ISRU propellants: H_2/O_2, CH_4/O_2, CO/O_2, C_2H_2/O_2, C_3H_8/O_2, SiH_4/O_2
- ❖ The Mars atmosphere could be dissociated into O_2 and CO and used as a simple propellant
- ❖ Use of lunar SiH_4/O_2 reduce initial launch mass by 36%
- ❖ Use of Mars O_2 and CH_4 reduce initial launch mass by 50% to 60%

AIAA Recommendations
- ❖ Establish and implement a strategic plan and cost-benefit study for ISRU
- ❖ Establish a NASA office to be the focus for the ISRU program
- ❖ Provide a robotic vehicle and lander capability for ISRU missions to the Moon and Mars and support flight experiments
- ❖ Consider ISRU applications in all mission planning for Moon/Mars
- ❖ Encourage other government agencies to support the program
- ❖ Develop an annual conference dedicated to ISRU

ORBITEC's ISRU/Mars Mission Related Activites
- ❖ Propulsion, propellants, and power
- ❖ ISRU materials processing
- ❖ Life support and habitats
- ❖ Automation and robotics

Propulsion, Propellants, and Power

- CO/O_2
- C_2H_2/O_2
- CH_4/O_2
- O_2/H_2
- Liquid metal fuels/O_2
- Solid metal fuels/O_2
- Beamed propulsion
- Nuclear propulsion

ISRU Materials Processing

- Water ice from lunar poles
- Carbon-based reduction for O_2 and Fe and Si
- Hydrogen-based reduction for O_2 and Fe
- Processing of regolith volatiles from He, H_2, etc.
- Processing of Mars Atmosphere for CO/O_2
- Storage technology for ISRU gases
- Lunar concrete development
- Radiation shielding

Life Support and Habitats

- Controlled environments for plants, animals, and humans
- Plant growth systems for Earth orbit research and flight crews
- Plant growth systems for Mars transit and planetary surface
- Inflatable habitats

Automation and Robotics

- Sample retrieval and processing systems
- Micro-g A&R systems for space station and flight vehicles
- IVA robotic servicing vehicles for Mars transit vehicles
- IVA robotic inspection systems for space vehicles
- Robotic applications on the surface

Other Small Business Involvement

- **Physical Sciences Inc.** "Optical Waveguide Solar Energy System for Lunar Materials Processing"
- **Carbotek, Inc.** "Lunar Oxygen Processing"
- **Pioneer Astronautics** "Mars Aromatic Hydrocarbon and Olefin Synthesis System" and "Methanol Mars In Situ Propellant Production"
- **Adroit Systems, Inc.** "Atmospheric Water Vapor Adsorption for Mars In Situ Resource Utilization"
- **EnviroGen, Inc.** "A High Performance, Gravity Insensitive, Enclosed Aeroponic System for Food Production in Space"
- **Nextech Materials, Ltd.** "Oxygen Generation System Using Carbon Dioxide"
- **Vertigo, Inc.** "Inflatable Structure for Mars Trans Hab"
- **Nanomaterials Research Corp.** "Low-Power, In-Situ Oxygen Extraction/Separation Technology"
- **EIC Laboratories, Inc.** "Electrochromic Thermal Control Container for Payloads"
- **Orbital Technologies Corporation (ORBITEC)** "Inflatable Module for Lunar/Mars Surface Facilities" and "Carbon-based Reduction of Lunar Regolith"
- **Physical Sciences, Inc.** "Solar Plant Growth System for Life Support in Space"

Concluding Remarks

- Promising ISRU technology needs to be developed and thoughtfully used for exploration
- Small businesses should provide signigicant innovations to support technology and hardware development for HEDS
- All of us need to improve communication to the public about HEDS

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