Workshop on Science and the Human Exploration of Mars

January 11–12, 2001

NASA Goddard Space Flight Center
Greenbelt, Maryland

LPI Contribution No. 1089

WORKSHOP ON

SCIENCE AND THE HUMAN EXPLORATION OF MARS

January 11–12, 2001
NASA Goddard Space Flight Center
Greenbelt, Maryland

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M. B. Duke, *Lunar and Planetary Institute*

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Preface

The exploration of Mars will be a multi-decadal activity. Currently, a scientific program is underway, sponsored by NASA's Office of Space Science in the United States, in collaboration with international partners France, Italy, and the European Space Agency. Plans exist for the continuation of this robotic program through the first automated return of Martian samples in 2014. Mars is also a prime long-term objective for human exploration, and within NASA, efforts are being made to provide the best integration of the robotic program and future human exploration missions. From the perspective of human exploration missions, it is important to understand the scientific objectives of human missions, in order to design the appropriate systems, tools, and operational capabilities to maximize science on those missions. In addition, data from the robotic missions can provide critical environmental data – surface morphology, materials composition, evaluations of potential toxicity of surface materials, radiation, electrical and other physical properties of the Martian environment, and assessments of the probability that humans would encounter Martian life forms. Understanding of the data needs can lead to the definition of experiments that can be done in the near-term that will make the design of human missions more effective.

This workshop was convened to begin a dialog between the scientific community that is central to the robotic exploration mission program and a set of experts in systems and technologies that are critical to human exploration missions. The charge to the workshop was to develop an understanding of the types of scientific exploration that would be best suited to the human exploration missions and the capabilities and limitations of human explorers in undertaking science on those missions.

This report serves to document the discussions and conclusions of the workshop, as presented there. Little editorial license has been taken by the editor, except to organize the presentations and recommendations in a logical order, based on the agenda that was developed prior to the workshop. The workshop consisted of invited presentations on the topics identified in the agenda and group discussions on several questions. Nearly all of the presentations made at the workshop are included in this report. One of the questions was discussed in plenary session and three were addressed in subgroups that met separately for about two hours on the workshop's second day, following which the subgroup chair made brief presentations to the entire group. Although time was limited, the efforts provided by the subgroups was well focused and useful.

Funding for this workshop was provided by the Office of Space Flight in NASA Headquarters and organized and managed by the Lunar and Planetary Institute, in Houston, Texas. An informal program committee consisted of Gary Martin (Office of Space Flight), Jim Garvin (NASA HQ, Office of Space Science), Ron Greeley (Arizona State University, workshop Co-Chairman), Doug Cooke (NASA Johnson Space Center, workshop Co-Chairman), Lewis Peach (Universities Space Research Association), and Mike Duke (Lunar and Planetary Institute).

Goddard Space Flight Center provided the facilities for the workshop. Special thanks are due to Beverly Switalkski (GSFC) who made arrangements for space and meeting support and Rich Vondrak(GSFC) who participated in the workshop and handled many small logistics problems in real time.

Publications support was provided by the Publications and Program Services Department of the Lunar and Planetary Institute.

Michael B. Duke
Lunar and Planetary Institute

Contents

AGENDA

January 11, 2001

8:30 AM Welcoming remarks: **Gary Martin, Jim Garvin, Scott Hubbard**
8:50 Organization and Objectives of the Workshop: **Ron Greeley, Doug Cooke** (Co-chairs)

Opening session: Chair, **Doug Cooke**

9:10 Scientific Goals of the Mars Exploration Program – **Jim Garvin**
9:40 Roles of Robots and Humans in Mars Exploration– **Matt Golombek**
10:00 Problem Statements – Exploration Requirements – What information is required to address problems as understood now, and how will (should) that change in the next 10-12 years? Presentations and discussion.

- Astrobiology – **Chris McKay**
- Climatology – **Dan McCleese**
- Geology/Geophysics – **Ron Greeley**

11:30 Plenary Discussion: What scientific investigations are most likely to require humans?
(**Jim Garvin**, chair, **Clive Neal**, rapporteur)

What are the characteristics of scientific investigations that make on-site (or at least near at hand) human participation essential? What are the characteristics of human explorers that meet these needs? Need trained observers? instant feedback from observations? complex manipulations? intregrative powers? Etc? What will the important scientific questions be in a post-reconnaissance exploration program? Are they accomplishable without direct human participation? Are scientific investigations posed independently of the context of their implementation modes? How does the implementation mode mold the investigation? Will more complex investigations be posed for human missions than for robotic missions? How might these differ?

12:30 Lunch

Afternoon session Chair: **Ron Greeley**

1:30 PM Two Astronauts' Perspectives on Mars Exploration – **John Grunsfeld** and **Scott Horowitz**
2:15 Cognitive Prostheses – **Ken Ford**
2:50 Environmental constraints to surface operations (radiation, toxicity, etc.) – **John Charles**
3:15 Physical limitations (EVA) – **Richard Fullerton**
3:40 Contamination by human explorers – **Mark Lupisella**
4:05 Telerobotic operation of systems (rovers, other equipment) by astronauts on Mars – **David Akin**
4:30 Analog studies in preparation for human exploration – **Kelly Snook**
4:55 Strategic issues for human exploration linking robotic and human exploration – **Doug Cooke**
5:15 Adjourn

January 12

Morning Session Chair: **Doug Cooke**

8:30 AM Mars Field Geology, Biology and Paleontology Workshop Results – **Pat Dickerson**
9:00 Scientific Tasks for Humans

- Field investigations - **Bill Muehlberger**
- Drilling – **Jim Blacic**
- Geological Sample analysis – **Clive Neal**
- Astrobiology Sample Analysis – **Marc Cohen**
- Plant growth experiments – **Ken Corey**
- Exploration for Resources – **Jeff Taylor**

11:00 AM Plenary Discussion: Can the expected contributions of astronauts to Martian exploration be quantified? (**W. Mendell**, chair, **R. Vondrak**, rapporteur)

What are the criteria that one would use to judge whether a task should be carried out by astronauts, astronaut-supervised robots, or autonomous robots? Can characteristics of task intensity (such as critical observations/hour, number of sites investigated/day, etc.) be utilized? Can characteristics of quality of observation (amount of information/observation, reproducibility of observation, etc.) be used? How can the ability to synthesize information on site be quantified? What is the value of on-site analysis done by astronauts? Can the benefits of ability for astronauts to communicate with scientists on Earth be quantified? How should public interest be incorporated into the criteria?

12:00 Lunch

1:00 Breakout Session Discussions

What understanding of Mars is most likely to influence scientific objectives of human missions? (**Jim Garvin,** chair, **Clive Neal,** rapporteur)

Categories for consideration include: (a) scientific knowledge. (b) knowledge of the environment. Among the current MEPAG objectives, which ones are likely to remain unanswered within a reasonable robotic program? Would they become objectives for human exploration? Which knowledge will most influence site selection?

What science and exploration tasks are best suited to humans? Why? (**Jim Head**, chair, **Kelly Snook**, rapporteur)

Some tasks for consideration: reconnaissance sample collection, in-situ field observations, teleoperated robotic investigations, sample analysis, data evaluation and interpretation, in-situ rock analysis, drilling.

What information/technology should be developed and managed to minimize human limitations and maximize science on human missions (continued)? (**Chuck Weisbin**, chair, **Richard Fullerton**, rapporteur)

What are the principal limitations of humans on a Mars exploration mission? The two principal types of limitations would seem to be the adequacy of time, resulting from the need for humans to conduct activities other than science, and reduction of capability that arises from having to work in the environment at great distances from Earth. Which of these are more important from the point of view of scientific accomplishment and what technology can be developed to optimize the return of science from human exploration missions?

3:00 PM Reports from breakout sessions – Chair: **Ron Greeley**
5:00 PM Adjourn

Workshop Recommendations

1. Take steps to develop a multi-disciplinary community for science-human exploration.
    a. Establish a HEDS-Office of Space Science Working group with science community representation
    b. Establish a "SDT" for a new OSS/HEDS A/O dealing with issues of science and human exploration
2. Continue and develop new mechanisms for open communications
    a. Develop a web site (Frassanito) where the results of this workshop and similar information can be accessed
    b. Organize cooperative HEDS- science session(s) at technical conferences
    c. Create a list server (Neal) that provides a mechanism for interaction between scientific and technical workers in human exploration of Mars
3. Define controlled experiments that quantify the productivity of humans and their robotic tools as scientific explorers, including:
    a. Field exploration
    b. Analytical capabilities
    c. Communication of findings between the planetary surface and scientists and lay people on Earth
4. Explore the capabilities and limitations of robotic tools as aids to human explorers through development of:
    a. Mechanical aids, for complex manipulations, such as sample preparation
    b. Observational tools and techniques.
    c. Data systems
5. Promote better understanding of the ways in which information gained from previous missions can be utilized in the design of field experiments, particularly in:
    a. Site selection and characterization
    b. Training of astronauts in Mars material recognition and field and sample data interpretation.

Some guiding principles in developing this community include:

1. The program integration process between the Office of Space Science, Office of (human) Space Flight, and Office of Biomedical and Physical Sciences should be strengthened
2. Emphasize incorporation of new ideas and technologies into NASA programs and architectures
3. Work on attracting young people to exploration

Additional recommendations:

1. Support analog studies, such as Haughton Crater field experiments
2. Conduct student design competitions with community evaluators.

CONSIDERATION OF QUESTIONS

Four questions were put to the workshop participants:

- Can the contribution of astronauts to martian exploration be quantified?
- What investigations require humans?
- What science and exploration tasks are best suited for humans?
- What information and technologies should be developed for human explorers?

These questions were discussed by subgroups (except for the first, which was discussed in plenary). The summaries of these discussions, as presented in briefing charts compiled at the workshop, are included here.

Can the contribution of astronauts to martian exploration be quantified?

An Ill-posed Question?

W. W. Mendell

Why Quantify?

- Any process whose quality cannot be measured is not worth doing
  - *Well-known NASA Administrator*
- Choices can justified if rankings can be established.
  - Step 1: Convene a panel of experts to derive quantitative measures which, when put into an algorithm, will generate a ranking of quality.
  - Step 2: Apply the measures using a weighting algorithm which will yield desired rankings.

What is the Decision?

- Should a task be performed by
  - An astronaut,
  - An astronaut-supervised robot, or
  - An autonomous robot
- Based on
  - Task intensity
  - Precision of observation
  - Task complexity
  - PR value
  - Etc.

Why do we need measures to determine an agent at the task level?

Cornerstones of the NASA Mission: Science and Exploration

Although the two activities are related, they are qualitatively distinct modes of discovery.

The Space Science Enterprise uses robots for missions.

The Human Enterprise (HEDS) uses the word 'exploration'.

Is there a dichotomy where NASA science implies robots and NASA exploration implies astronauts?

A Contrast of Processes

- The process of scientific research is designed to produce an incremental addition to a body of knowledge.
  - The purpose of peer review is to ensure that a usable result is obtained through proper planning & utilization of accepted procedures.
  - Special expertise and often highly specialized instrumentation is required.
  - Funded research has low risk of unusable data.

A Contrast of Processes

- Exploration is a term used when little information exists prior to an investigation.
  - New information is expected, but its utility is unknown.
  - Sponsors of Exploration expect new 'discoveries' that will lead to unpredictable benefits.
  - Tools of Exploration are general rather than specialized because phenomena to be encountered are known only generally.
  - Peer review of Exploration is limited to assessing the success and safety of the planned activities.
  - *Reconnaissance* is a form of exploration in which the suite of phenomena is thought to be known though not quantified.

A Contrast of Processes

- Scientific observation requires
  - Rigor
  - Specialized training
  - Careful preparation of sample or measurement
  - Controlled conditions
  - Facilities
- Exploration benefits from
  - Experience-based expedition planning
  - Flexibility
  - A set of general skills and broad knowledge
  - Ability to operate without infrastructure

Agents of Science & Exploration

- Robots excel at repeated, precise actions in a predictable environment.
- Humans are better suited to tasks which require adaptability and flexibility.
- As scientific understanding of an environment grows, the discovery process becomes more 'scientific' and less 'exploratory'.
- Ultimately, the thorough 'scientific' characterization of an environment requires instrumentation so sophisticated or massive that it cannot operate in the field. 'Sample return' is required.

How to match task & agent?

- With the scientific community and the exploration planners and the operations experts:
  - Map investigations onto a short list of canonical landing sites.
  - Break investigations into stages of observation and data collection.
  - Define generic activities involved in sorties.
    - Collect samples
    - Take measurements and photos
    - Access unusual features
    - Etc.
  - Evaluate different modes of task completion using multidisciplinary teams
  - Decide what resources for scientific investigation should be part of a surface mission on Mars.

Science and the Human Exploration of Mars Workshop
January 11-12, 2001

Summary of plenary discussion on the question: "Can the expected contribution of astronauts to Martian exploration be quantified?"
(Wendell Mendell, chair; Richard Vondrak, rapporteur)

Dr. Wendell Mendell (JSC) started the discussion by providing his viewpoints in several charts (see attached). He questioned the premise that it is necessary or even desirable to produce a quantitative calculation of the relative benefits of human compared to robotic activities. He contrasted the roles of robotic and human agents, with robots as excellent at repetitive tasks in a predictable environment and humans better suited to tasks that require adaptability. His conclusion is that the agents have to be matched to the specific tasks, which vary with the location and the stages of exploration.

The general audience discussion focused on the theme of identifying those tasks that are best suited for humans and those that are best for robots.

William Muehlberger (U. Texas) asked the question of how canyons on Mars could be explored. He pointed out that astronauts would need to travel in a pressurized vehicle and must be able to remotely measure inaccessible rocks. Site selection could be based on orbital data for context. Robotic reconnaissance could serve as a precursor to human exploration.

It was pointed out that, because of the cost of interplanetary travel, only a few astronauts (perhaps 4 to 8) would be expected on Mars. Therefore, it would be necessary to offload work to robots. An assertion was made that it is possible to measure human performance, as is done for occupations as diverse as airline pilots and typists, so it should be able to establish quantitatively the relative value of automated versus human productivity.

Pascal Lee (SETI Institute) said that EVA time is precious so humans should not be used for dangerous or tedious tasks. He said that researchers at Carnegie Mellon had tested an automated search for meteorites in Antarctica and found it more difficult than expected. Geologists were needed to train the robots to improve their performance.

Jim Head (Brown U.) raised the issue of how the layered terrain could be investigated. In the polar regions there are hundreds of layers, some only a meter thick, with both low slopes and deep valleys. Exploration would require drilling of unexposed layers. John Rummel (NASA HQ) indicated there might be a safety concern if volatilized carbon dioxide were released. Head argued that we should first send robots, and then humans, with a cooperative strategy rather than a competition (he made an analogy with humans using pigs to search for truffles).

Mendell said that any exploration strategy should be tailored to the context of the object of study, with canyons and polar regions requiring very different approaches. A realistic approach could be determined from prior experience in analogous situations.

Mike Duke (LPI) said that a difficulty with learning from analogs is that analog studies yield primarily anecdotal data, with limited quantitative value. He cited the Russian space experience as producing generally stories, rather than documented results. Another difficulty with analogs is designing controlled interfaces.

Mendell concluded the discussion by pointing out that 80% of what we know about the moon (such as its age, composition, and processes) were evident in the rocks returned by Apollo 11. So there is no substitute for collecting hard evidence as the way to solve difficult problems (Mendell recalled the experience of Richard Feynman who was stunned to discover that the Rogers Commission was uninterested in collecting evidence).

Science and the Human Exploration of Mars Workshop Plenary Discussion Report. What Scientific Investigations are the Most Likely to Require Humans

Over 50 investigations have been proposed for Mars - which ones would require or would be enhanced by humans? Need to add "search for distinct life" (second genesis) to the list of investigations.

Need favorable sites and search for evidence of life using robots. Humans would be involved in the search for the "second genesis".

Is the current robotic program good enough for enabling the proposed investigations? Does it need ramping up? Do we need more robotic missions in the plan? Robotic observations are never absolute and require human judgement. Therefore, could the most sophisticated robotic missions be enhanced by human presence? However, we are not going to decide that humans are better than robots so we spend more money. Need to coach the "humans to Mars" concept as an evolutionary process of humans in space - a question of national pride/concern. Our job is to be proactive in this by saying "how can humans be inserted into and expand the currently robotic exploration of Mars?"

Need to distinguish between simple and complex problems. Simple - robots are to determine where local bedrock is, sample it, and bring it back for analysis. Complex - multiple objectives at a given site that require human judgement. In order to maximize exploration potential, both approaches need to be included in mission planning.

Human advantage over robot - experience, judgement, and ability to create hypotheses. Based on this, humans need to be inserted early in the program to maximize the robotic capabilities (e.g., Pathfinder-type mission with humans - could have brushed dust off surface of rock, operated rover from surface without the communication lag time).

Decision to send humans to Mars will be political and, therefore, will be related to risk. Risk can be reduced by knowledge and demonstrated technology. A stepwise approach will demonstrate credibility in exploration, making the insertion of humans a logical part of the program. The logical approach will make it easier for future politicians to approve humans going to Mars.

There have to be clear objectives from which exploration strategies can be developed. What specifically are the human objectives? Human missions will only get governmental support if there is a national interest involved. Science is only one component that is driving Martian exploration. What would make it a "national interest"? [Question posed but not answered].

The discussion should NOT be about humans OR robots. They have different capabilities that operate on different time scales. Humans and robots should be *integrated* into an exploration strategy. The current robot-only program needs to be ramped up to prepare for humans (e.g., nuclear power, sample return - if we can't return samples can we return humans?).

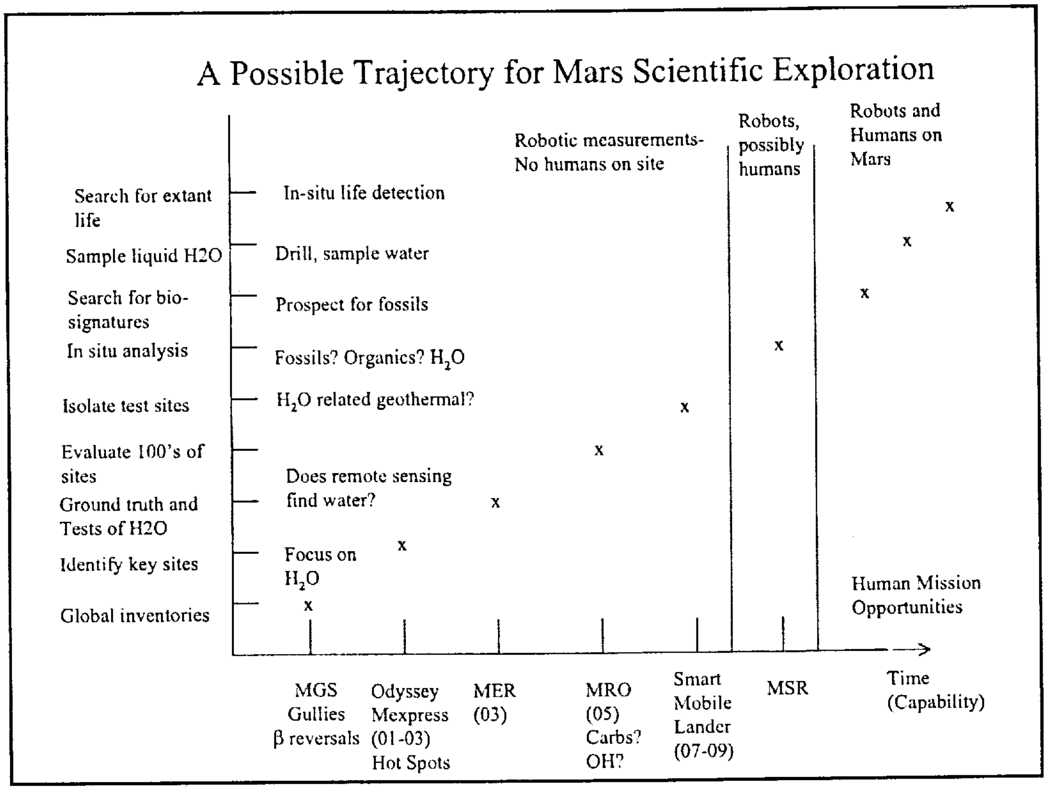
Capability: should go to a site with many specific goals, but also be adaptable to discover the unknown, so we need to be adaptable. This is a multi-parameter problem that can only be resolved by humans going to Mars; they adaptable and have the ability to iterate and synthesize. Humans allow you to deal with the unexpected and they can fix broken robots!

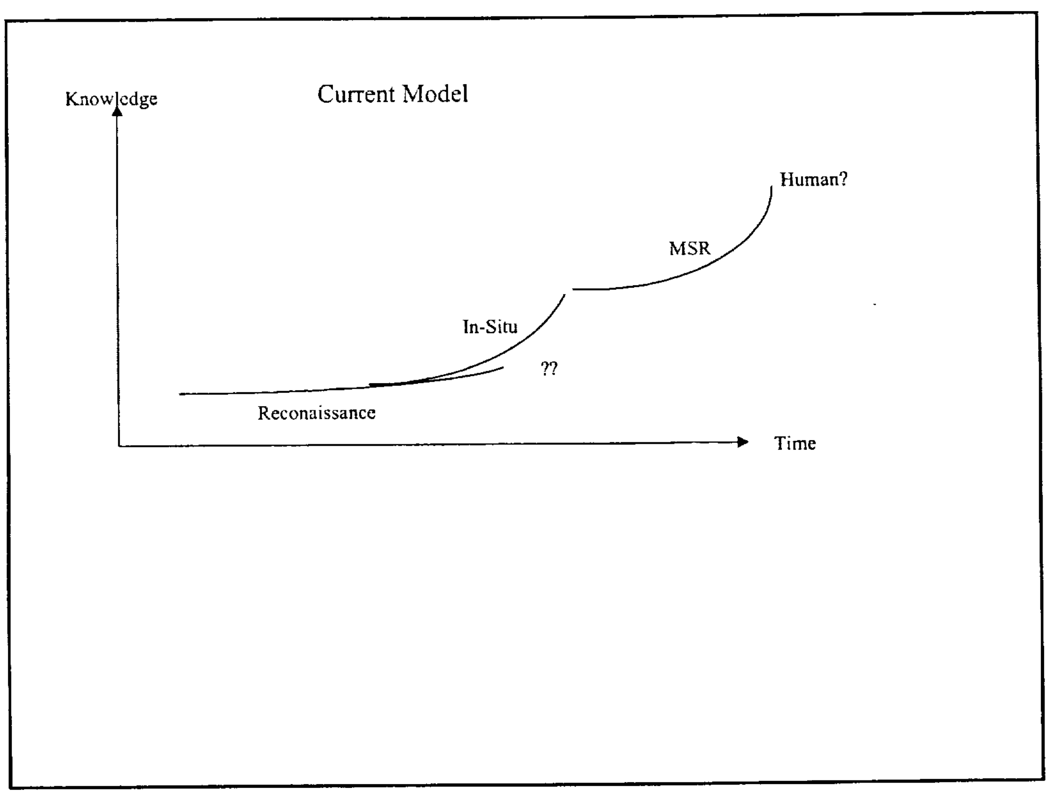
What are the implications of inserting human/robot teams? What are the risks that humans will be allowed to take on Mars? This will determine the role of humans in the mission partnership. Humans should be sent to complex areas, robots to simple areas. However, there is a need to see if there are viable spores in and quantify the oxidation potential of the Martian soil before it is polluted by the presence of humans.

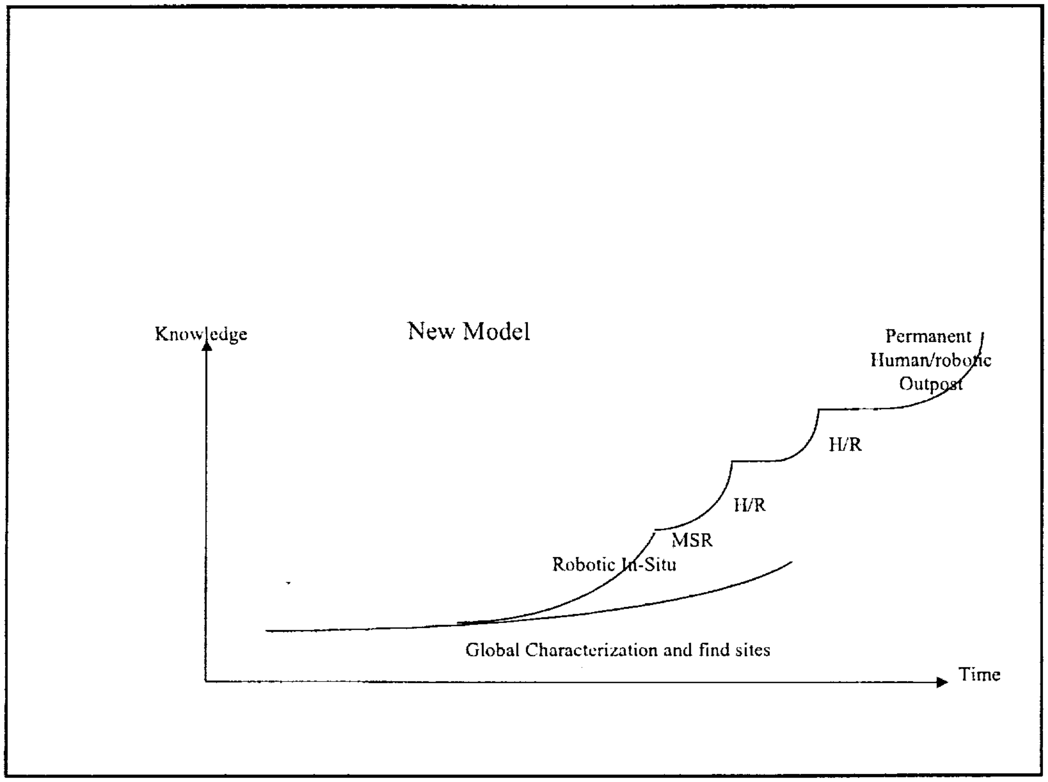
Two fundamental parameters: access to samples and analysis of samples. Can this be done by having robots collect the samples and the humans staying at base camp in the lab to analyze them? Humans would be better at sample preparation and sample selection for analysis - geological context and documentation is critical. Humans need not be physically present, but the human brain does - decisions need to be made in real time. A robot assistant could repeatedly pick up and get basic characteristics of a rock sample that humans could evaluate and tell the robot to go back and sample a selection of rocks. If decisions were made on Earth, efficiency would be impaired because of the time lag in communications. However, this approach could be used if, say, one were looking for a needle in a haystack, such as looking for mantle nodules.

Currently, two classes of mission are envisaged - 30 day and 1.5 years. Don't want to be sitting around in a lab for the 30 day mission as time is precious. With the 1.5 year mission there will be more time. Robots should be doing the reconnaissance and pin-pointing interesting areas that humans would then visit.

What technology development track would need to be taken? Risk factors need to be reduced by investigating how to sustain life (water, growing pants, etc.) on the surface. Information is needed on the availability of water and radiation flux.


A Possible Trajectory for Mars Scientific Exploration
Robotic measurements- No humans on site
Robots, possibly humans
Robots and Humans on Mars
Search for extant life
In-situ life detection
Sample liquid H2O
Drill, sample water
Search for bio-signatures
Prospect for fossils
In situ analysis
Fossils? Organics? H2O
Isolate test sites
H2O related geothermal?
Evaluate 100's of sites
Does remote sensing find water?
Ground truth and Tests of H2O
Identify key sites
Focus on H2O
Global inventories
Human Mission Opportunities
MGS Gullies β reversals
Odyssey Mexpress (01-03) Hot Spots
MER (03)
MRO (05) Carbs? OH?
Smart Mobile Lander (07-09)
MSR
Time (Capability)


Knowledge
Current Model
Human?
MSR
In-Situ
??
Reconaissance
Time


New Model
Knowledge
Time
Permanent
Human/robotic
Outpost
H/R
H/R
MSR
Robotic In-Situ
Global Characterization and find sites

What science and exploration tasks are best suited to humans?

J. Head, Discussion Leader
K. Snook, Rapporteur

What science and exploration tasks are best suited to humans?

Notes from breakout discussion group
January 12, 2001

- Attendance:
  Jim Head, Chair
  Kelly Snook, Rapporteur
  - Brian Wilcox
  - Peter Smith
  - Bill Muehlberger
  - Ralph Harvey
  - Michael Sims
  - Mike Hecht
  - Steve Hoffman
  - John Taylor
  - Ken Corey
  - Tom Sullivan
  - Dave Akin,
  - Marc Cohen
  - Cynthia Null
  - Tom Sullivan

Background discussion: what do humans bring to the picture?

Human Capabilities Relevant to Science and Exploration Tasks

- Synoptic 3-D View, Both near-field and far-field
- Rapid integration time
- In-situ judgment
- Rapid decision-making
- Rapid mobility
- Increased dexterity
- Extended mobility (rover)
- Increased exploration range
- Ability to accept complex input and respond rapidly
- Ability to deploy complex instruments
- Ability to deploy instrument networks (e.g. gravimeters on Apollo 14)
- Ability to deploy instruments/ networks in strategic places (e.g. geophones, seismometers)
- Ability to maximize exploration integration (synergism)
- Temporal integration of input + results (learning, creativity, intuition)
- Serendipity, recognition, experiential leaps, ability to react and respond accordingly
- Ability to redesign experiments and build tools
- Generic strength and versatility
- Maintenance of science equipment
- Off-nominal response, ability to sense danger and say 'no'
- Ability to be debriefed and to debrief
- Goal orientation vs. task orientation

- Iterative experimental capability, spontaneous hypothesis and testing
- Ability to convey excitement and enthusiasm

What is the key element? Human brain is the key. In sensing and manipulation, human brain is not necessarily as key. Realistic goal to have almost human-like manipulation and sensing. Very high performance teleoperator in the next 10-20 years could exceed the capabilities of humans.

Some Tasks for Consideration:

1) Reconnaissance sample collection
2) Insitu field observations
3) Teleoperated robotic investigations
4) Sample analysis
5) Data evaluation and interpretation
6) In situ rock analysis
7) Drilling
8) Instrument deployment
9) Network deployment
10) Experimentation
11) Real time integration and decision making
12) Site region overview and integration

Example of scientifically rich and interesting site:
Mangala valles - Noachian upland cratered terrain
What would we want to do there?

Why assume smart tools vs. dumb tools like on earth. Intelligent decision making is better suited to humans.
If you're going to go to the trouble of sending the humans - marginal cost of having them go EVA isn't that large.

Example of human/robot system good on paper, but not good in practice – human to assist field geologist in finding meteorites. Robot couldn't keep up. Discussion of robots vs humans regarding speed.
Are there things if you add time delay, etc remote operated scenario that the human can do that machines can't do better?

Proposed thought experiment: if you had all the money, budget, etc of a human program and did it all robotically, would you be able to get the same science? Intuitive answer is no.
What studies/technologies are needed?

1) Well integrated, controlled, analog field studies and tests
2) Rover task/field tests and capability development
3) How best humans and robots work together
4) Technology development to increase sensing, mobility, and manipulation of robots, in the context of performing science with humans
5) Develop "in laboratory" capabilities – analysis and handling
6) Extend human capabilities (?? Not sure what this means)
7) Mars reference landing sites and requirement definition
8) Identify crucial problems where technology will make a difference
9) Digging and drilling technology

What information and technologies should be developed for human explorers?

C. Weisbin, Group Leader
R. Fullerton, Rapporteur

*Respective Human & Robot Strengths (ideal)

HUMAN (cognitive)
- Flexibility
- Redundancy
- Communication
- Learning
- Taking risks
- Problem solving
- Decision-making
- Etc.
- Not expendable

ROBOT
- Physical strength and power
- Speed of movement/computation
- Repeatability
- Constancy of performance
- Short term storage capacity
- Complete erase capability
- Reaction time
- Data acquisition, precision
- Expendable

*Compatibility at the human-robot interface is required to optimize the performance and effectiveness of the overall human-robot system. Compatibility is required to get the best of both worlds (human and robot) and not the worst.

Robot & Human Surface Operations

Humans and Robots Complement Each Other

- **Humans are supremely capable of working in unstructured situations**
- **Robots can do heavy duty work and provide force amplification**
- **Human/robot cooperation enhances endurance, precision, reliability, speed, situation awareness, etc.**
- **Robots can enhance human safety - it is safer to send robots to high-risk areas**
- **Accessibility** - Machines can be built to function in a micro-world or a macro-world not reachable by humans.
- **Division of Labor - Let Each Do What It Does Best**
  - Humans concentrate on supervising and ensuring the performance of the machine's functions, and perhaps perception beyond signal processing.
  - Machines can also be "wired" through tele-presence to emulate the dexterity of humans; this assumes that an astronaut is proximate to the robotic system so that there are no appreciable time delays.
  - Human dexterity, versatility, adaptability, and intelligence are in many situations still unmatched by any machine.
  - Structurability and predictability of the work environment are real considerations. The greater the communication delay (light time) the more autonomous the remote systems must be.

Robot & Human Surface Operations

Need More In-Depth Quantitative Analysis

•Relative strengths of humans and robots in performing a wide variety of tasks is well-established CONCEPTUALLY

•Humans are unequaled in unstructured situations

•Robots are good at high-risk access

•Etc.

•There is a wealth of EXPERIENCE to validate these general notions

•Armstrong's decision-making in lunar terminal descent maneuver could not have been done reliably with robotic spacecraft

•Robots have gone to "worse-than-hell" places (Venus, Jupiter) not currently accessible to humans

•Systematic comparisons that validate these general concepts have not been fully investigated for a wide range of envisioned surface operations

•Need standardized METRICS to quantify performance

•Need rigorously defined criteria to EVALUATE relative performance

•Need controlled EXPERIMENTS to arrive at systematic comparisons

Information/Technology Summary

Constraints/Limitations
- Safety
- Time availability
- Time delay
- Contamination

Task allocation (e.g. for one month exploration activity)
- Relative performance
- Human preference
- Serendipity

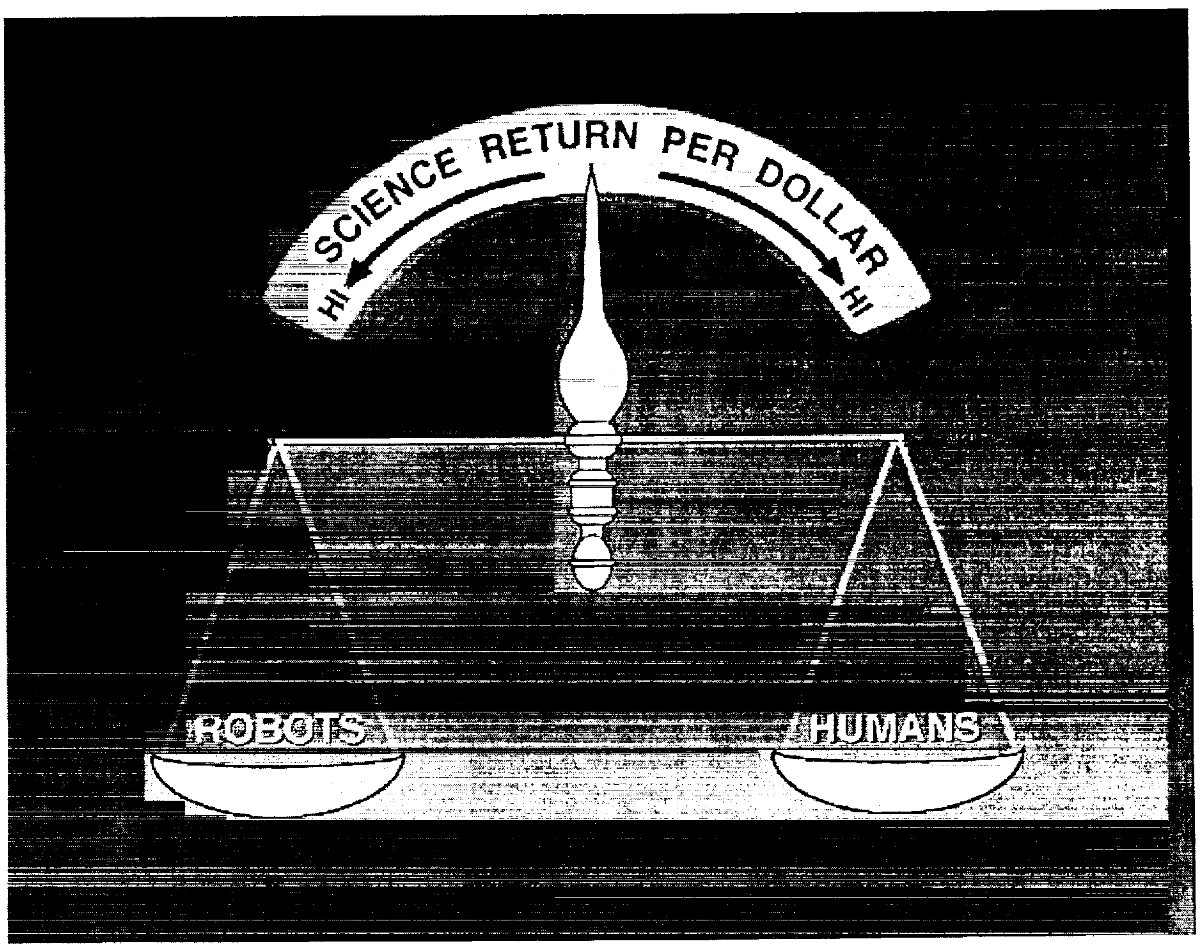
Field and Test (maximize use of existing activity)
- Read devices, real data
- Required technology advances/systems analyses
- Assure operations compatibility

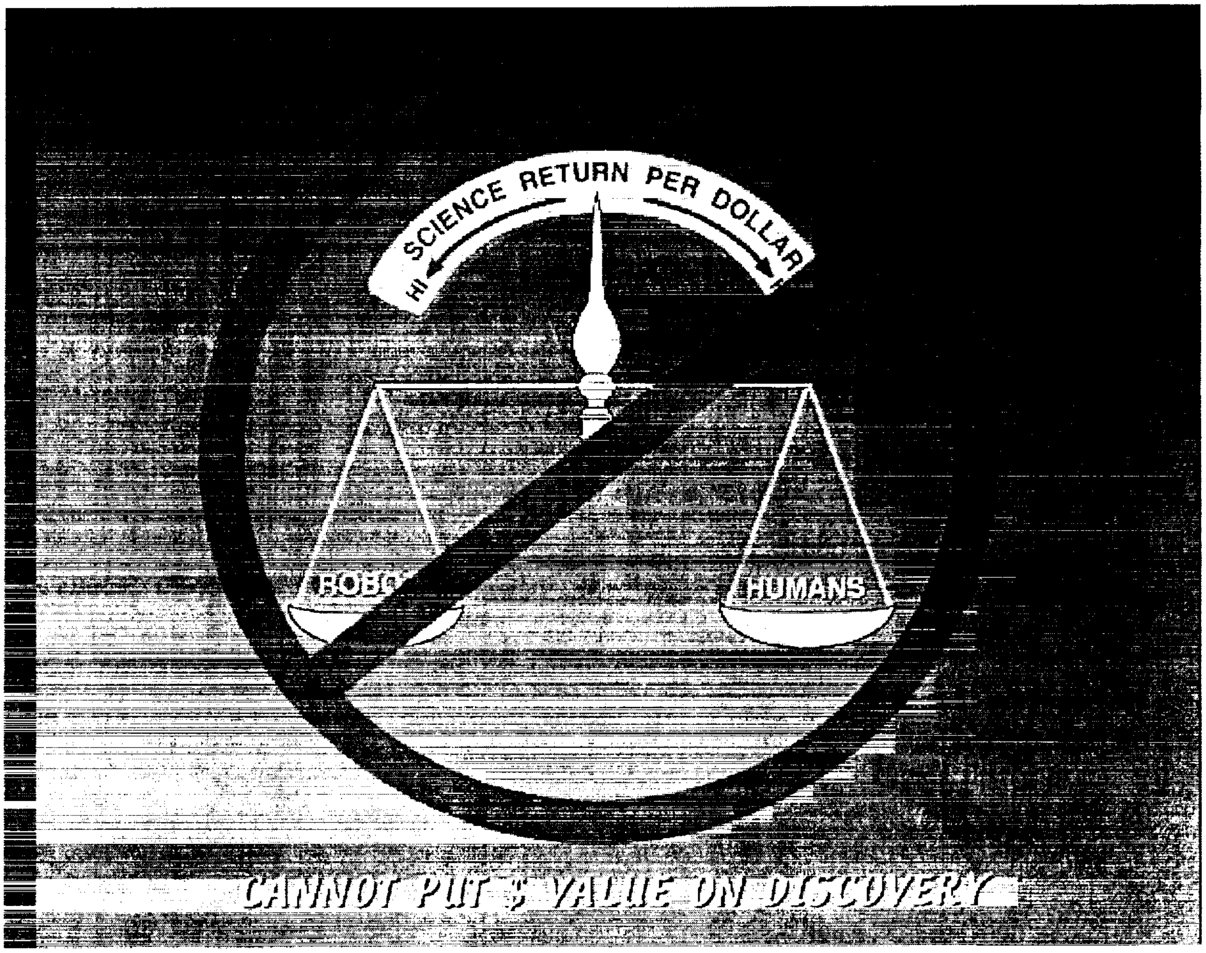
PRESENTATIONS

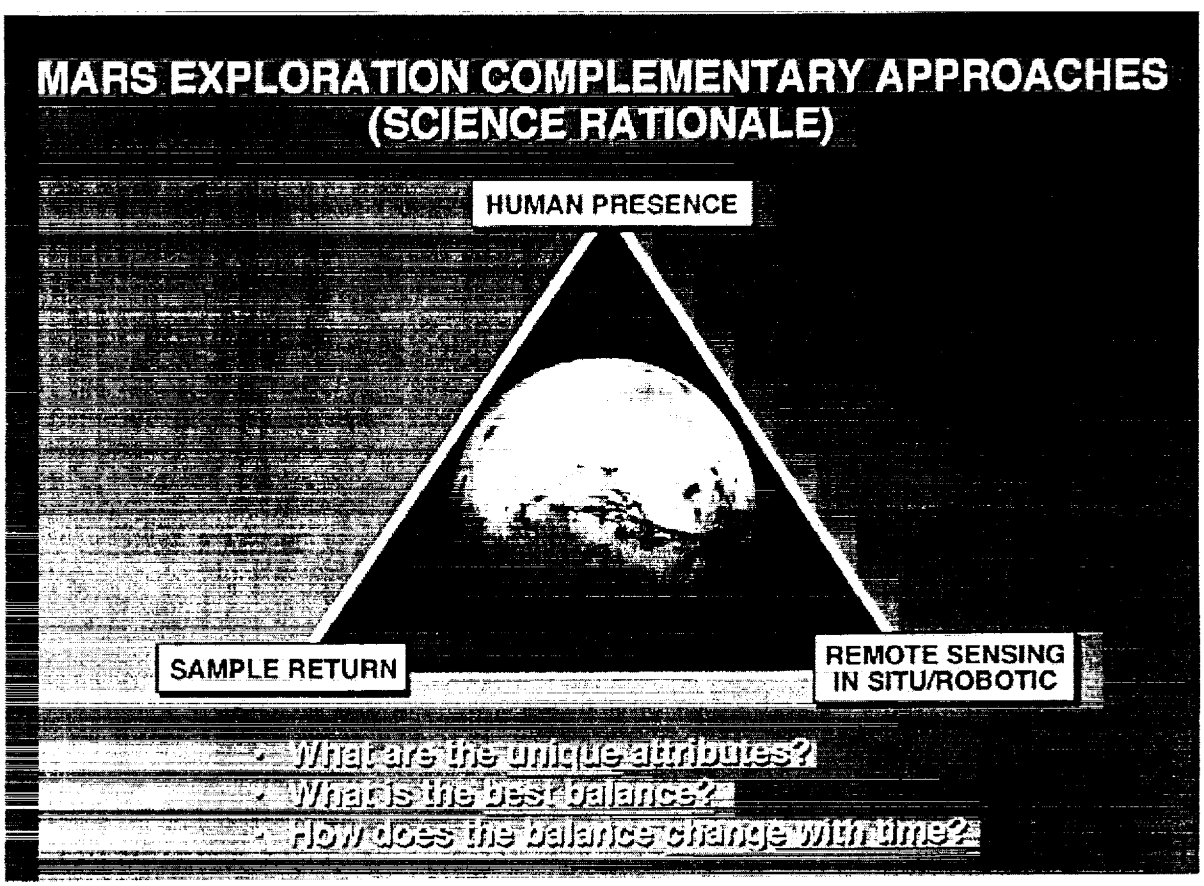
SCIENCE AND THE HUMAN EXPLORATION OF MARS

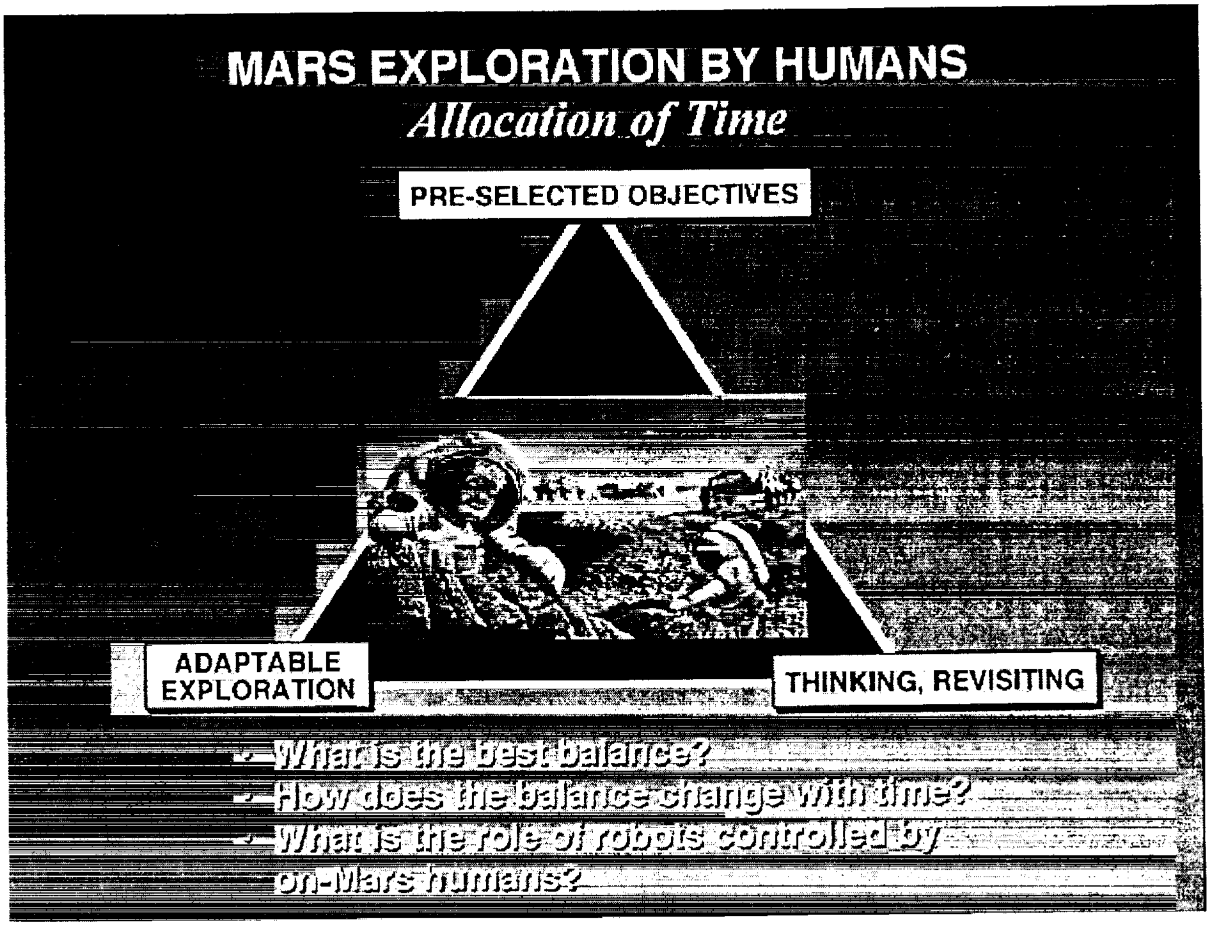
Opening comments

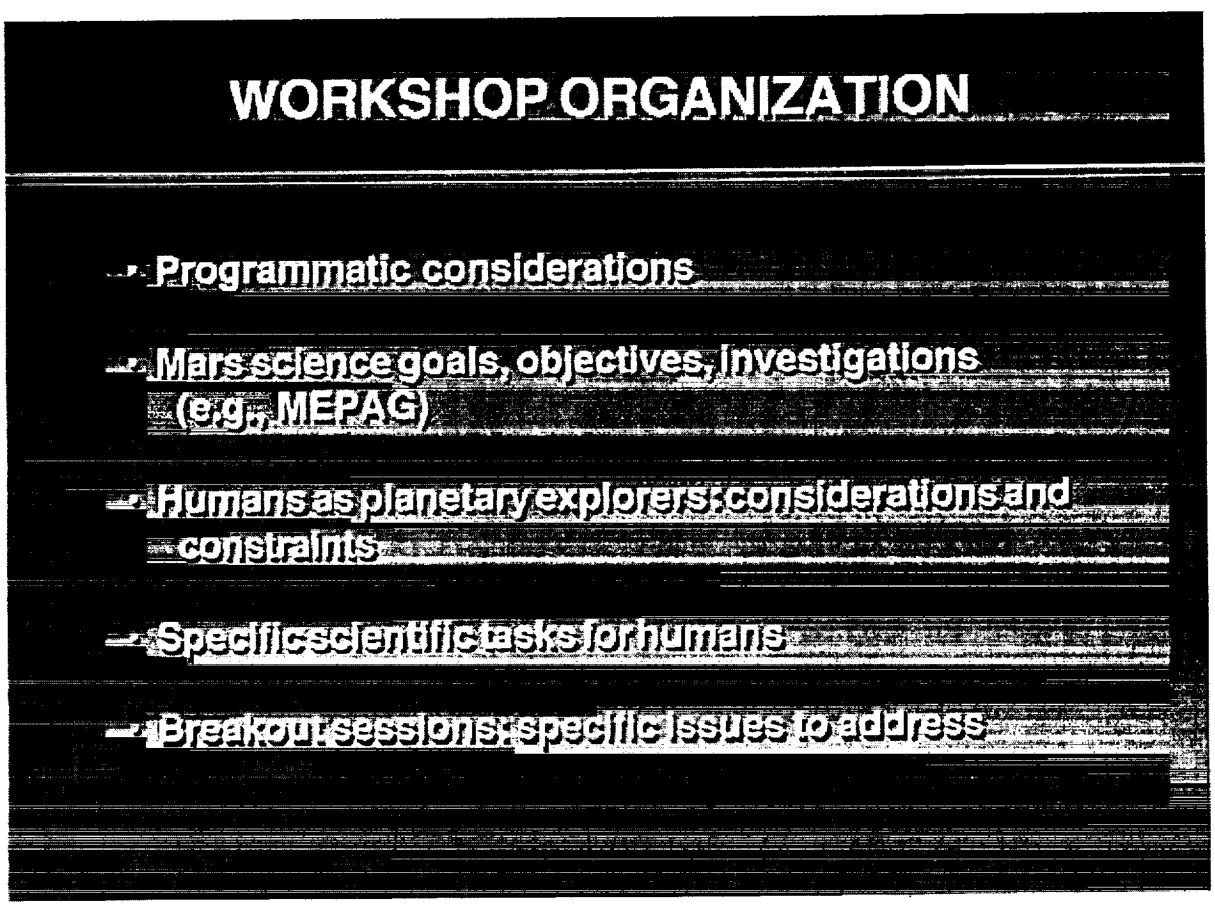
Ronald Greeley
Greeley@asu.edu
Arizona State University
11 January 2001




HI SCIENCE RETURN PER DOLLAR
HUMANS
CANNOT PUT $ VALUE ON DISCOVERY


MARS EXPLORATION COMPLEMENTARY APPROACHES
(SCIENCE RATIONALE)
HUMAN PRESENCE
SAMPLE RETURN
REMOTE SENSING
IN SITU/ROBOTIC
• What are the unique attributes?
• What is the best balance?
• How does the balance change with time?


MARS EXPLORATION BY HUMANS
Allocation of Time
PRE-SELECTED OBJECTIVES
ADAPTABLE EXPLORATION
THINKING, REVISITING
What is the best balance?
How does the balance change with time?
What is the role of robots controlled by on-Mars humans?


WORKSHOP ORGANIZATION
Programmatic considerations
Mars science goals, objectives, investigations (e.g., MEPAG)
Humans as planetary explorers: considerations and constraints
Specific scientific tasks for humans
Breakout sessions: specific issues to address

Science and the Human Exploration of Mars Workshop
Goddard Space Flight Center
Jan 11-12

Doug Cooke
January 11

Workshop Objectives

- Provide Martian exploration goals and objectives for use in determining HEDS program content and focus.
- Develop a better understanding of the potential capabilities of humans working through tools and machines on the surface of Mars.

Workshop Topics

- Martian science requirements for human exploration.
  - What are the principal scientific questions that are most likely to require human explorers on Mars?
  - At what stage in the exploration process would humans on Mars make a difference?
  - What understanding of Mars is most likely to influence human exploration objectives?
- Human exploration capabilities and constraints.
  - What are capabilities of and constraints to humans exploring Mars?
  - What science exploration tasks are best suited for human explorers?
  - What are the most important capabilities/tools that should be provided to astronauts when they are exploring Mars? (This includes supporting tools, semi-autonomous robots, laboratory instruments, etc.).

Approach to Workshop

- Presentations providing various perspectives on the issues
- Plenary sessions to discuss issues
- Breakout sessions to address specific questions
- Reports from Breakout sessions

Workshop Products

- Presentation Materials
- Summaries of the major points developed through Discussions
- Overall Summary and Recommendations

RELATIVE ROLES OF ROBOTS AND HUMANS IN THE EXPLORATION OF MARS

M. GOLOMBEK
JPL

Meeting on Humans and the Exploration of Mars
Goddard Space Flight Center
Jan. 24-25, 2001

DPT EXPERIENCE
MARS - AGGRESSIVELY INTEGRATE ROBOTIC AND HUMAN MISSIONS

NRC Space Studies Board
3 Part Study

1) Scientific Prerequisites for the Human Exploration of Space (1993)
2) Scientific Opportunities in the Human Exploration of Space (1994)
3) Sciene Management in the Human Exploration of Space (1997)

"The ultimate decision to undertake further voyages of human exploration and to begin the process of expanding human activities into the solar system must be based on non-technical factors"
National Academy Report

"Science is the fulcrum of the entire space program."
Augustine Report

CHEX REPORT

Role Robots and Humans

Robotic Probes Provide Enough Information to:

1) Optimize Site Chosen for Human Exploration

2) Define Set Scientifically Important Tasks that can be ***WELL*** Performed by Humans In Situ

SCIENCE BY HUMANS

Planetary Science
Geologic Field Work (although other field work also applies)
- Mapping Distribution of Rocks in the Field
- Measuring Parameters (e.g., bedding attitude, thickness) that can only be made in the field

Two Types of Field Work
- Reconnaissance - broad characterization or
  - answer a specific question
  - can be done by robots or humans
- Field Study - requires human intelligence and experience
  - Geologic materials are complex and subtle
  - Requires extraordinary combination of observation,
    pattern recognition, synthesis of broad experience base

Robotic Missions - Should do most Reconnaissance Field Work
Human Missions - Should concentrate on Field Study
Requires Robust Robotic Program to Identify Places where Humans can Optimize their study

Spudis, P.D., and Taylor, G.J. (1992) The roles of humans and robots as field geologists on the Moon: Lunar Bases and Space Activities of 21st Century, 2nd Symposium Proceedings (W. Mendell, ed.), NASA Conference Publ. 3166, vol. 1, p. 307-313.

Spudis, P.D., 1992, An argument for human exploration of the Moon and Mars: American Scientist, vol. 80, p. 269-277, May-June 1992.

Spudis, P.D., Robots vs. humans, Who should explore space, in The Future of Space Exploration, A Guide to the Voyages Unveiling the Cosmos, Scientific American Presents, v. 10, p. 24-31, Spring 1999. (see also counterpoint by F. Slakey in the same pages.

MARS - AGGRESSIVELY INTEGRATE ROBOTIC AND HUMAN MISSIONS

RATIONALE

CHEX

- Use Robots to Perform Reconnaissance
  - Broad Characterization or Answer a Specific Question
- Use Humans to Perform Detailed Field Work
  - Map Distribution and Parameters of Rocks in the Field
  - Requires Human Intelligence, Knowledge and Experience

PHASING

- Robots
  - Define Scientifically Important Tasks ***WELL*** Performed by Humans
  - Define Environment & Hazards, Identify Resources & Technologies to Extract/Use; Emplace Infrastructure
- Start Broad Characterization to More Detailed Study at Finer Scale
  - Global Remote Sensing
  - In Situ Investigations of 40 Geologic Units on Mars
  - Network-Simultaneous Meteorology & Seismology Measurements
  - Surface Rovers - Characterize Selected Areas km Scale
  - Sample Returns - Definitive Analyses
  - Balloons, Hoppers, Airplanes;
- Send Humans to Robotically Emplaced Outpost

DEVELOP A SCENARIO OPTION THAT AGGRESSIVELY INTEGRATES ROBOTICS AND HUMANS FOR MARS

M. Golombek, P. Curreri, J. Kramer

THE PROBLEM:

Mars Surveyor Yearly Budget has been ~100M/yr
- Missions were FBC (Budget - New Start to Launch + 30 days)
- MPF ~200M
- MPL, MCO ~150M

MS Now Ramped up to ~200M/yr to Accomplish '03 & '05
- Includes Sample Return - Major Engineering Effort

But Reference/Other Human Mission Tens of B!!!

MS Cost Cap Pervades Engineering and Management Decisions
- [Outside of Launch Vehicle Cost]

SO HOW INTEGRATE THESE TWO EFFORTS?

MUST RAMP UP SCALE OF ROBOTIC MISSIONS

- e.g., Current Reference Mission Include Nuclear Reactor
  - Solar Power Insufficient
- Surveyor Program Cannot Use RTG - Political & Cost (Lawyers, EIS)
- Huge Effect of Where Can Go on Mars
  - Solar Power on Surface Marginal
  - Land Near SubSolar Latitude $\pm 25°$ Maximize Power and Data
  - Last Few Months [Viking Landers w/RTGs Lasted Years]
- Human Missions/Outpost Also Driven by Resources
  - Expect Volatiles Stable at Higher Latitudes
  - Trade btw Latitude and Equatorial Launch Assist
- Not Enough Landers to Risk Them at Potentially Hazardous Sites

HOW ATTACK PROBLEM?

- Try to work Backwards - From Reference Mission
  - Subject to Uncertainties/Changes in Reference Mission
  - What Capabilities (Instr., Labs) and Mobility Humans Have?
- Try to Work Forwards - From Surveyor Program
  - Subject to Uncertainties in Timing and Approach
- Try to Work From - What Want to Know Before Send Humans
  - Avoids Problems Above, but Assumes Rationale

RATIONALE

AGGRESSIVELY INTEGRATE ROBOTIC AND HUMAN MISSIONS

- Optimize Sites for Humans
    - Understand Environments and Hazards
- Define Scientifically Important Tasks WELL Performed by Humans
    - Not Reconnaissance but Field Work
- Define Environment and Resources Available for Human Exploration
    - T, P, Wind, Dust (Elect.), Quakes, Water, Soil Reactivity, Materials
- Define Technologies Needed for Human Presence
    - ISRU, Extraction of Water, Oxygen, Power

HOW DO DO THIS? - Need to Know/Learn About Mars

APPROACH START BROAD SCALE - GENERAL CHARACTERIZATION

- To More Detailed Characterization at Finer and Finer Scale
- Global Remote Sensing
- Many Small Surface Landers
    - Surface Reconnaissance at Many Locations
- More Detailed Study by Surface Rovers
- Find Location Where Humans can Perform Important Field Work
- Find Location with Resources

HOW DO WE EXPLORE MARS?

SMALL LANDERS/ROVERS [ORDER 10]

Network Science - Distributed Sites Meteorology/Seismology [>10]

Enough Landers to "Risk" Some at Potentially Hazardous but Scientifically Interesting Sites, Send Beyond Equatorial Latitudes

CAPABLE ROVERS/SAMPLE RETURNS - Thorough Reconnaissance

ADDITIONAL REMOTE SENSING

Orbiting Instruments, Balloons, Planes

AFTER THIS - IN POSITION TO SELECT SITE FOR ROBOTIC OUTPOST

Example: Look for Evidence of Past Life

- What was environment on Mars? Was Liquid water stable?
  - Land in Ancient Cratered Terrain - analyze rocks
- Did life start on Mars?
  - Land at Lake Bed - analyze sediments deposited, organics?
  - Ancient Hydrothermal Systems - ancient volcano w/fluvial activity

Find Resources

- Demonstrate ISRU and Develop Them for use

ROBOTIC OUTPOST

BEGIN PERMANENT PRESENCE
Robotically First

MORE DETAILED AND ADVANCED SCIENCE INVESTIGATIONS
(Including Sample Return?)

EXPLORE AREA TO BE VISITED BY HUMANS FROM SITE
Over Scale that Humans will Investigate

BEGIN EMPLACEMENT OF INFRASTRUCTURE FOR HUMANS

DEMONSTRATE AND DEVELOP ISRU
Robotically First, Then on Scale Needed for Humans

LOCATE RESOURCES
Find Water, Extract Water
Find Other Resources of Importance

DEVELOP MATERIALS FOR HABITAT LOCALLY
Martian Adobe, Soil for Greenhouses, etc.

EVOLUTION OF MARS EXPLORATION STRATEGIES AND MISSIONS

1978 COMPLEX [Strategy for Exploration of the Inner Planets, 1977-1987]
Stressed Local Scale Investigations, Extensive Mobility (Rover) or Multiple Surface Landers, Sample Return

1988 SSEC [Planetary Exploration through Year 2000]
Big Questions; Mars Observer, MRSR, Multiple MRSR

1988 SSB, NRC [Space Science in the 21st Century]
Mars Focus, Global Mapping, Surface Stations
Mars Observer, MRSR, Network

1990 COMPLEX [Update to Strategy for Exploration of the Inner Planets]
Global Processes Stressed over
Local Scale Investigations and Sample Return
[Result of Viking Analysis, Dynamic Planet, Early-Warm Wet]

SSED Strategic Plan, 1991
Mars Observer, Mars Network-Recommended, MRSR Candidate

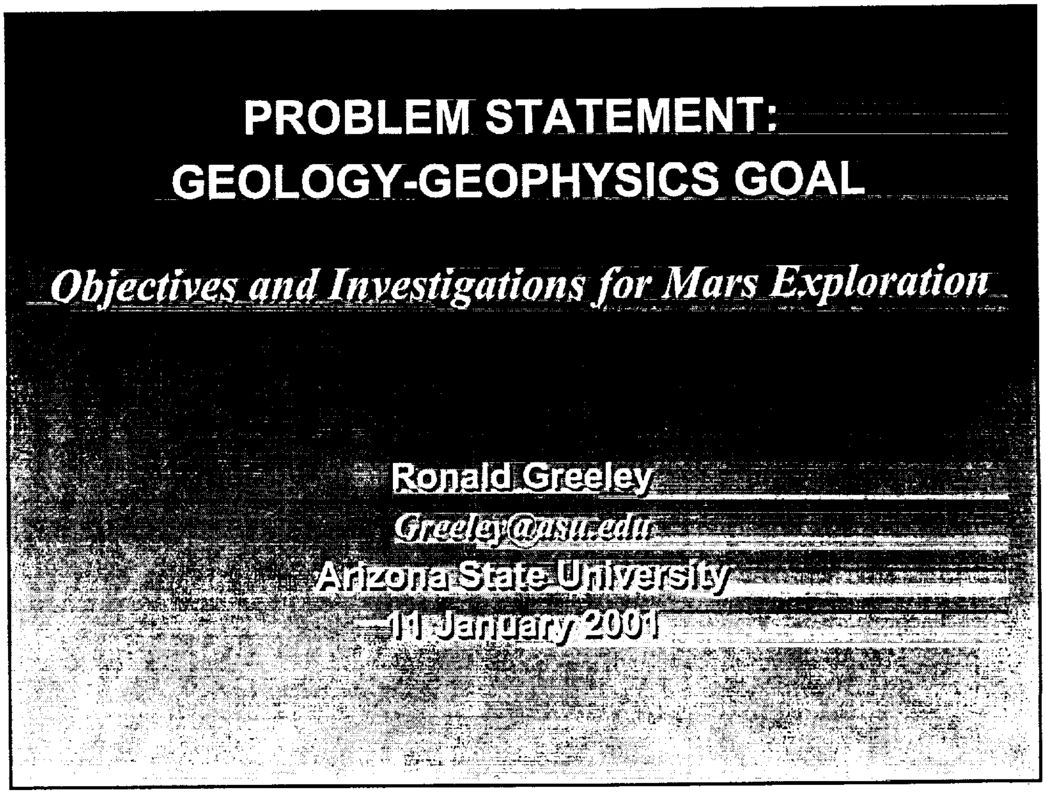
EVOLUTION OF MARS EXPLORATION STRATEGIES AND MISSIONS (cont.)

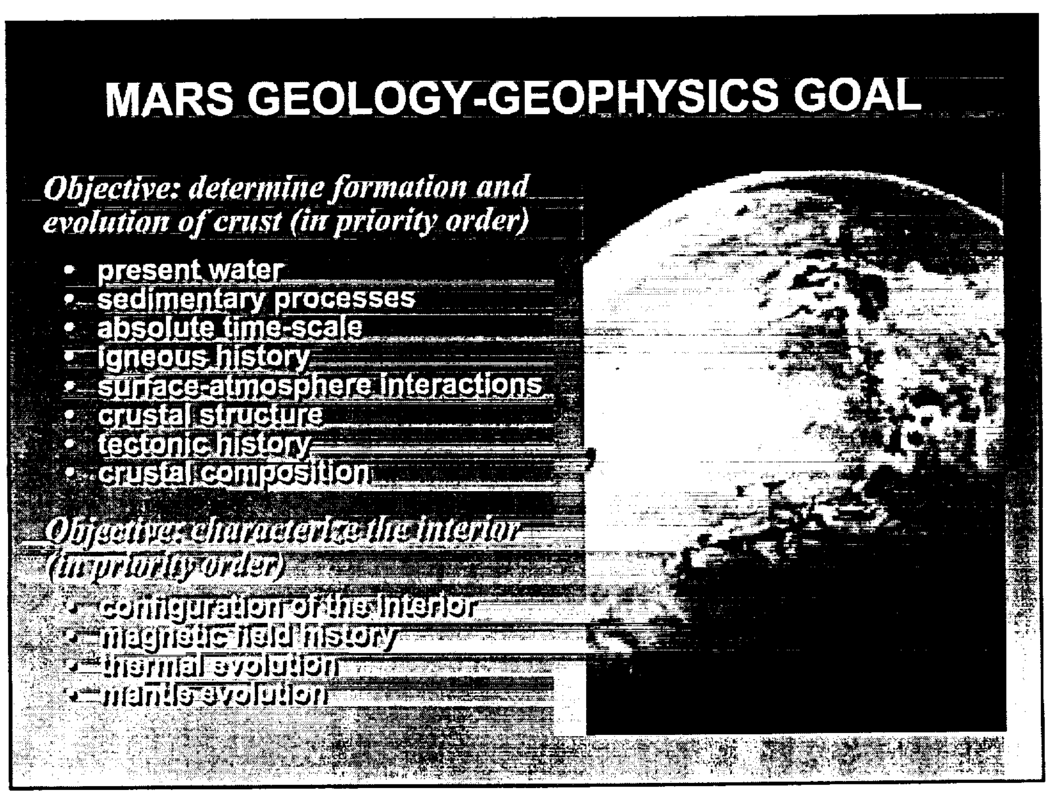
1994 COMPLEX [An Integrated Strategy for the Planetary Sciences: 1995-2010]
- Global Processes, Mars Surveyor, Pathfinder, Network

1994, OSS STRATEGIC PLAN
- Mars Surveyor Program, 2 Landers in '01, 4 in '03
- Either Network or Sample Return

1997, SPACE SCIENCE ENTERPRISE STRATEGIC PLAN
- Mars Surveyor Program, Orbital and Surface Investigations
- 1st of 3 Sample returns in '05
  - [Result of Mars Rock, focus on possible life, aka A Discovery]

OBSERVATIONS
- Evolution of Thought from Local Investigations & SR to
  - Global Processes & Network back to Global Processes & SR
- Basic Science Questions Have Changed Little
- Emphasis and Implementation Linked
  - Depend on Political Environment (cost, relevance) and Engineering Feasibility


PROBLEM STATEMENT:
GEOLOGY-GEOPHYSICS GOAL
Objectives and Investigations for Mars Exploration
Ronald Greeley
Greeley@asu.edu
Arizona State University
11 January 2001


MARS GEOLOGY-GEOPHYSICS GOAL
Objective: determine formation and evolution of crust (in priority order)
• present water
• sedimentary processes
• absolute time-scale
• igneous history
• surface-atmosphere interactions
• crustal structure
• tectonic history
• crustal composition
Objective: characterize the interior (in priority order)
• configuration of the interior
• magnetic field history
• thermal evolution
• mantle evolution

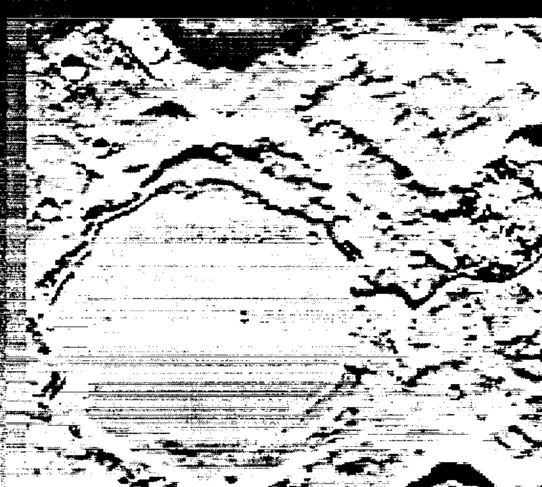
FORMATION AND EVOLUTION OF THE CRUST

Investigation 1: Search for water

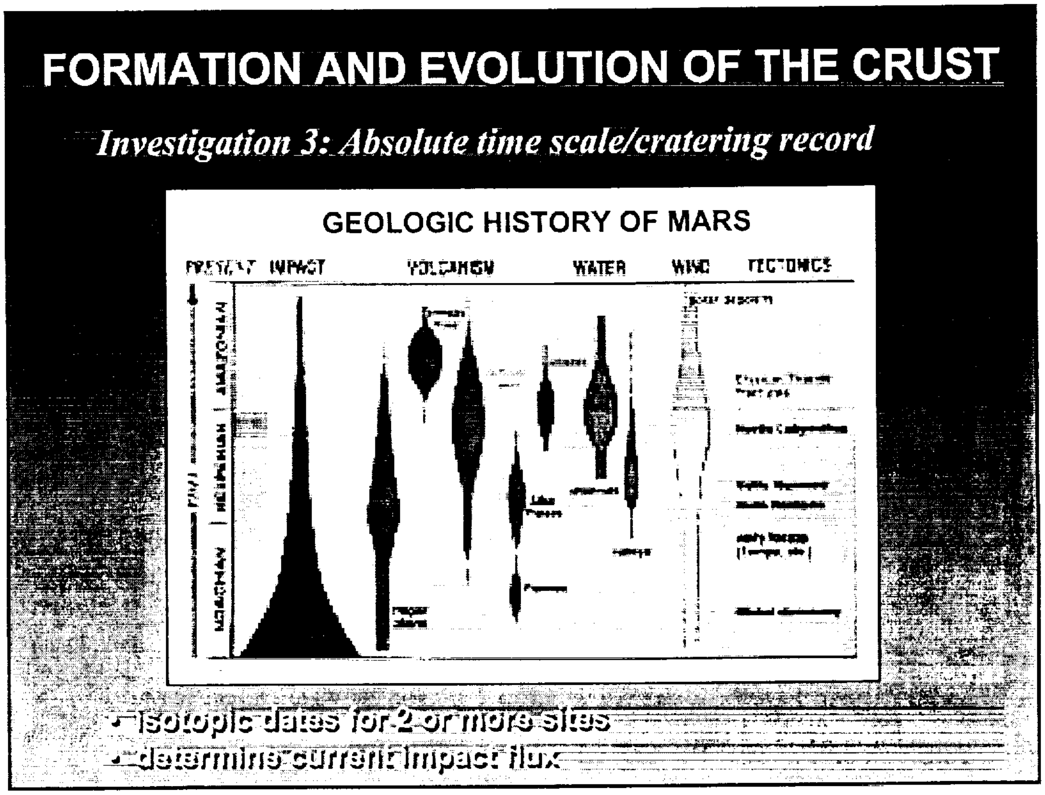
- global mapping
- global search for subsurface water
- search for subsurface water from surface
- drill for water
- in situ measurements, mineralogy, etc.

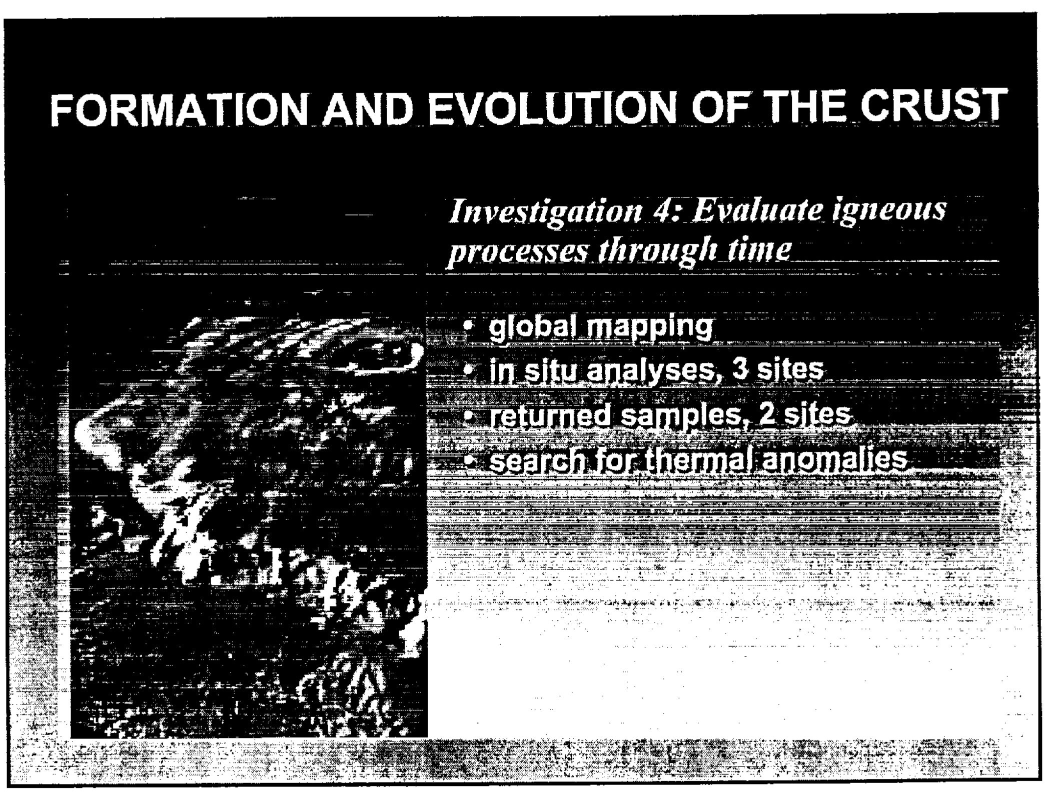
FORMATION AND EVOLUTION OF THE CRUST

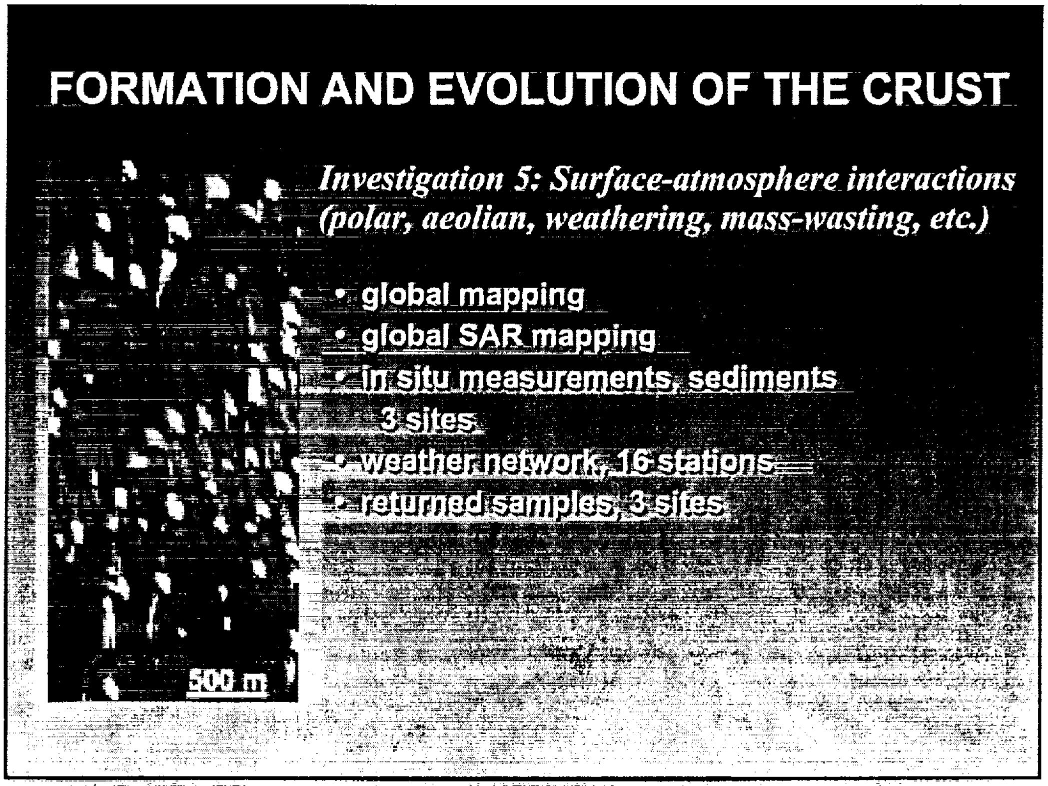
Investigation 2: Evolution of sedimentary processes/materials

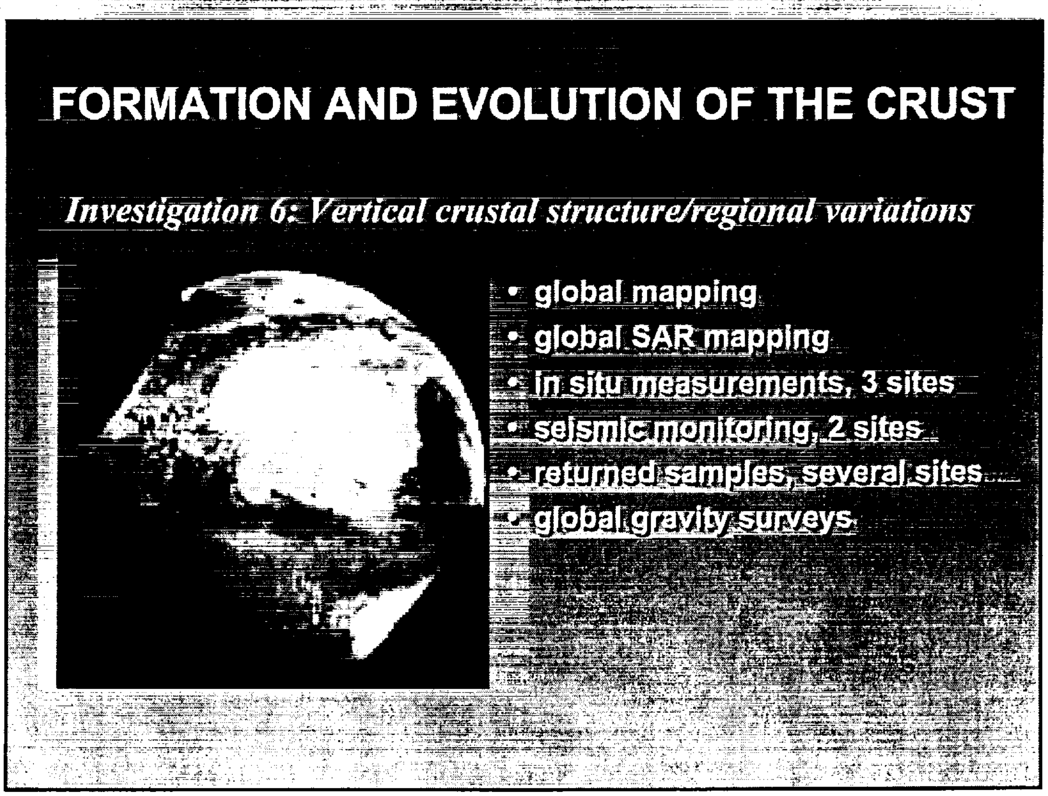


- global mapping
- in situ study
- drilling
  - ? 100m
  - ? 1 km
- returned samples

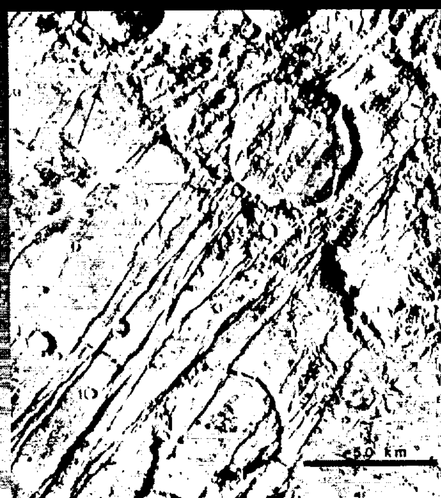

FORMATION AND EVOLUTION OF THE CRUST
Investigation 3: Absolute time scale/cratering record
GEOLOGIC HISTORY OF MARS
IMPACT
WATER
WIND
• Isotopic dates for 2 or more sites
• determine current impact flux


FORMATION AND EVOLUTION OF THE CRUST
Investigation 4: Evaluate igneous processes through time
• global mapping
• in situ analyses, 3 sites
• returned samples, 2 sites
• search for thermal anomalies


FORMATION AND EVOLUTION OF THE CRUST
Investigation 5: Surface-atmosphere interactions (polar, aeolian, weathering, mass-wasting, etc.)
• global mapping
• global SAR mapping
• in situ measurements, sediments 3 sites
• weather network, 16 stations
• returned samples, 3 sites
500 m


FORMATION AND EVOLUTION OF THE CRUST
Investigation 6: Vertical crustal structure/regional variations
• global mapping
• global SAR mapping
• in situ measurements, 3 sites
• seismic monitoring, 2 sites
• returned samples, several sites
• global gravity surveys

FORMATION AND EVOLUTION OF THE CRUST



Investigation 7: Tectonic history and present activity of crust

- global mapping
- global magnetic measurements
- regional magnetic surveys
- seismic monitoring

FORMATION AND EVOLUTION OF THE CRUST

Investigation 8: Bulk composition and evolution of crust

- global mapping
- global SAR mapping
- in situ measurements
- seismic monitoring
- returned samples, 3 sites

CHARACTERIZE THE INTERIOR

Investigation 1: Determine interior configuration

- global gravity survey
- global magnetic measurements
- concurrent rotational dynamics, 2 landers
- global seismic monitoring, 12 stations

Investigation 2: Magnetic field history

- global magnetic measurements
- regional magnetic surveys

Investigation 3: Thermal evolution of the crust

- global gravity survey
- global magnetic survey
- concurrent rotational dynamics, 2 landers
- global seismic monitoring, 12 stations
- in situ heat flow

Investigation 4: Chemical and thermal evolution, mantle

- as above
- returned samples, igneous rocks

GEOLOGY-GEOPHYSICS GOAL

- Will require >decades of work
- Progress will be iterative
- Few investigations will be 100% completed
- For some investigations, humans are more *efficient* and provide *higher quality* results
- Need to determine unique aspects of human exploration *(e.g., real-time adaptability....?)*

Astrobiology & Human Exploration of Mars

Chris McKay
NASA Ames
cmckay@mail.arc.nasa.gov

If the answer is:

- The Mars Program
  - rovers
  - sample return
  - robotic outposts
  - human exploration
  - human settlement
- What is the Question?

Astrobiology motivation

- Mars had early wetter environment:
  - comparing early Mars and early Earth
- Test the idea that life will arise on any suitable planet; cosmic implications
- Searching for evidence of life from early Mars

Robotic Mars Program

- Focus on search for environment and minerals associated with past water
- Eg: paleolake and hydrothermal minerals
- Could result in good evidence for fossil life on Mars

Was there life on Mars?
Is not the main question

The main question is:

Was there a second genesis of life on Mars?

What is the biochemistry?

What was its ecology?

Only one life on Earth:
we seek a second example

(image of tree of life here)

Fossils are not enough:

Possible source of phylogenetic information on Martian Life

- Viable spores in the soil (very unlikely)
- Extant subsurface life
- Organisms preserved in amber or salt
- **Organisms preserved in permafrost**

Really Big Question:

Could Mars have a biosphere once again?

Life to Mars

Implications for robotic & robotic outpost programs

Biology Demonstrator Mission
- grow bacteria in martian soil
- grow plants in martian soil

- Assess biohazard of soil
- Helps defuse planetary protection
  - both forward and backward
- Precusor to human visits

Life to Mars

Robotic Outposts

- Establish & demonstrate agricultural systems
- Experiment with natural ecosystems

Mars Climate:
Science Opportunities and Operational Dependence for Human Explorers

Dan McCleese
JPL

Martian Climate

- Human exploration will contribute understanding in and be influenced by Martian Weather and Climate.
  - Data recently acquired by MGS orbiter confirm earlier findings that Mars is rife with evidence of weather and climate evolution.
    - Surface records such as polar layered terrains appear to capture climate variability estimated to extend fro 10 Myrs. To 1 Byrs.
  - Vehicles entering the Martian environment will experience natural variability of the atmosphere.

Martian Climate

- A program of observations of Mars climate, its history and evolution requires:
  - Orbital observations of global and regional phenomena
    - T(p), Dust(p), H2O(p), Clouds(p)
  - Fixed meteorology stations (order 20 sites, global).
  - Acquisition and return to Earth of samples of atmosphere, rock and soil.
- Global, or near-global, access to the surface by robots and humans is essential.
  - Examples of high priority sites include high latitudes.
    - Polar layered terrain above ± 75 degrees

Matian Climate

- **Layered terrains near both poles are among the most important sites for climatology.**
  - Perhaps the best long-term record of climate change in the solar system
  - Layers are thought to be variable mixtures of dust and ice recording quasi -regular astronomical variability
  - Terrain's slopes are trafficable.
  - Humans are enabling in this field of Mars science.

Mars Climate

- Priority of Mars climatology enabled by humans might be comparable with that of current robotic biology experiments.
  - Unfortunately, the first decade of Mars Surveyor exploration includes no biology experiments.
  - Similarly, prospects for access to the high latitude sites by humans seems remote.
- Achieving needed range of human mobility must begin by extending range of rovers.
- Extending operating environments for humans begins with achieving global access by robotics

Martian Climate

- Global scale atmospheric phenomena represent challenges to human explorers.
  - Upper atmosphere variability could be hazardous to vehiles that aerocapture into orbit.
  - Recently discovered "dust devils" will want to be identified and, perhaps, forecast.
    - Global-scale and regional dust storms, although not hazardous, may limit human activities and possibly communications.

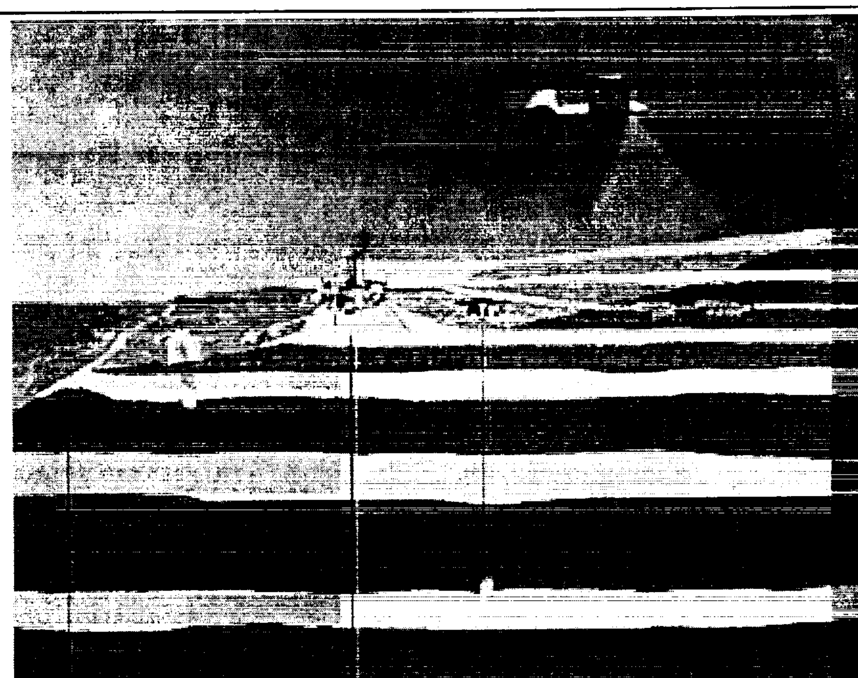
Martian Climatogy

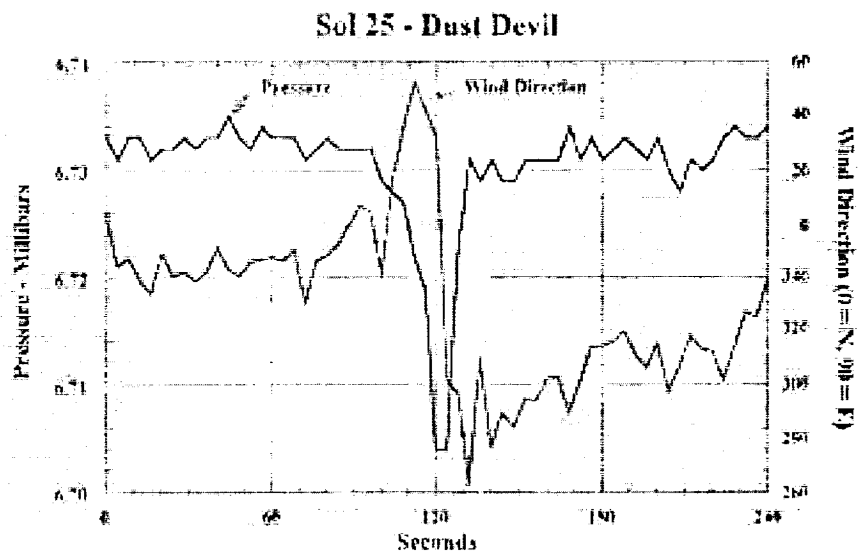
- Density at aerocapture altitudes varies up to a factor 5.
  - In response to regional and global dust storms.
- Airborne dust alters visibility of the atmosphere, such that nearby mountains maybe obscured.
- Atmospheric pressure at surface varies by 20% annually.

Martian Climate

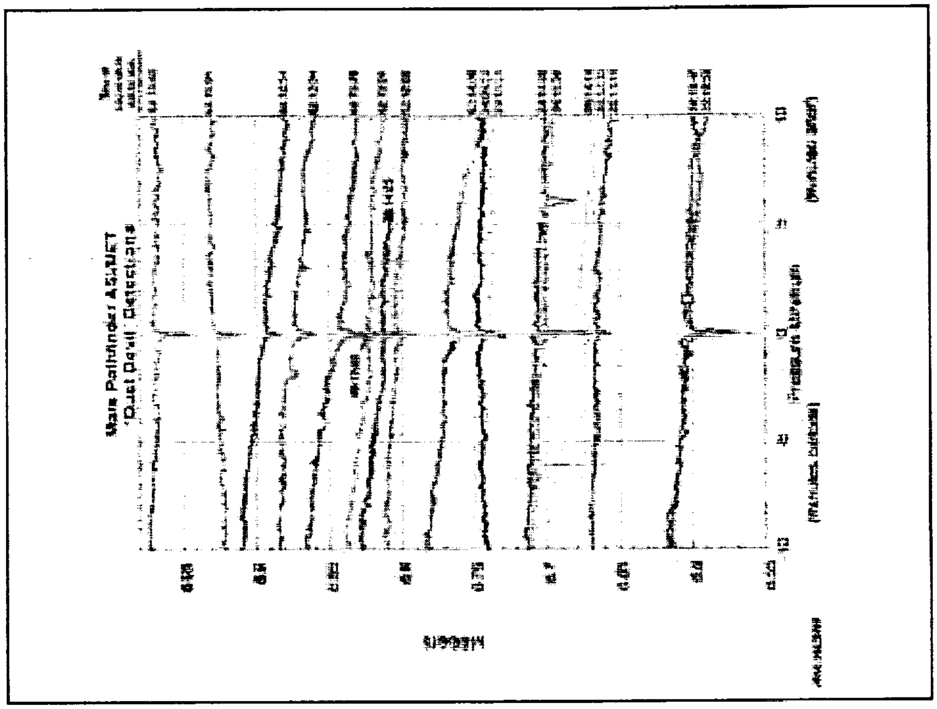
Dan McCleese
Chief Scientist
Mars Program Office

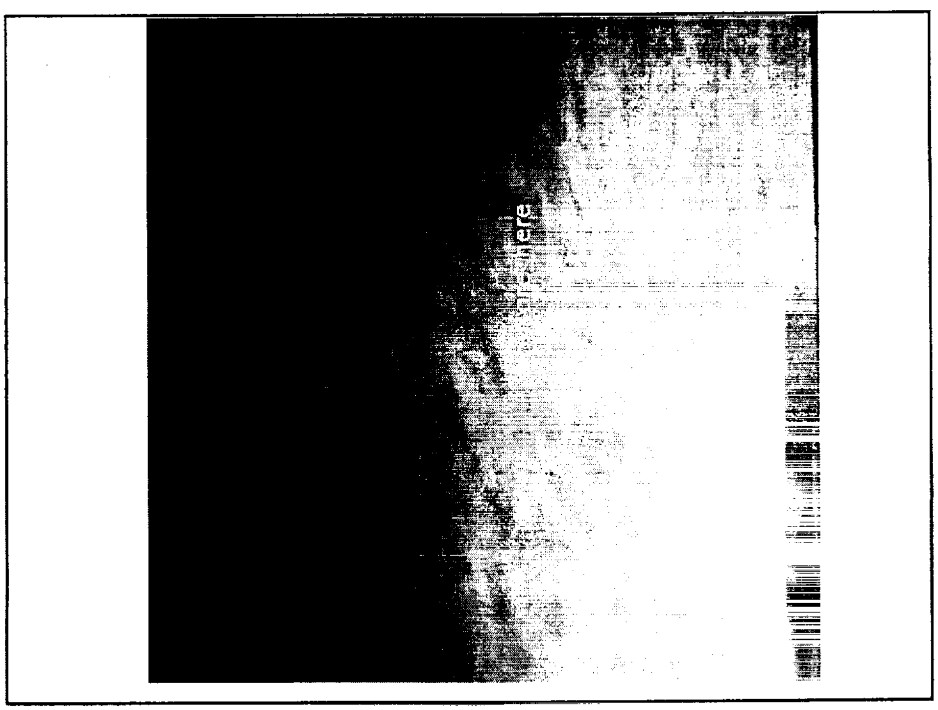
JPL

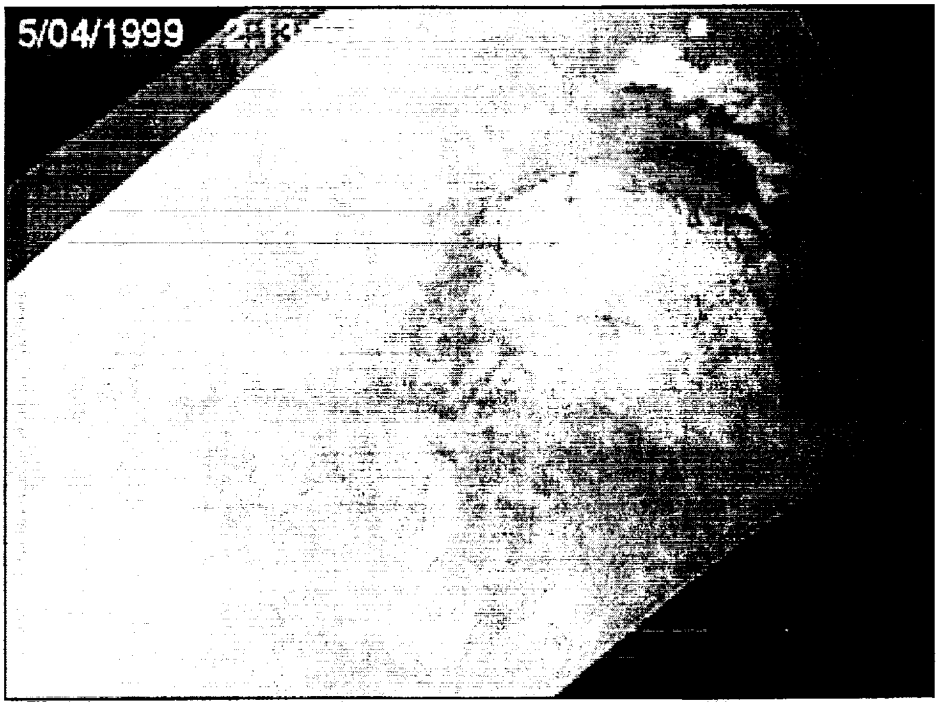




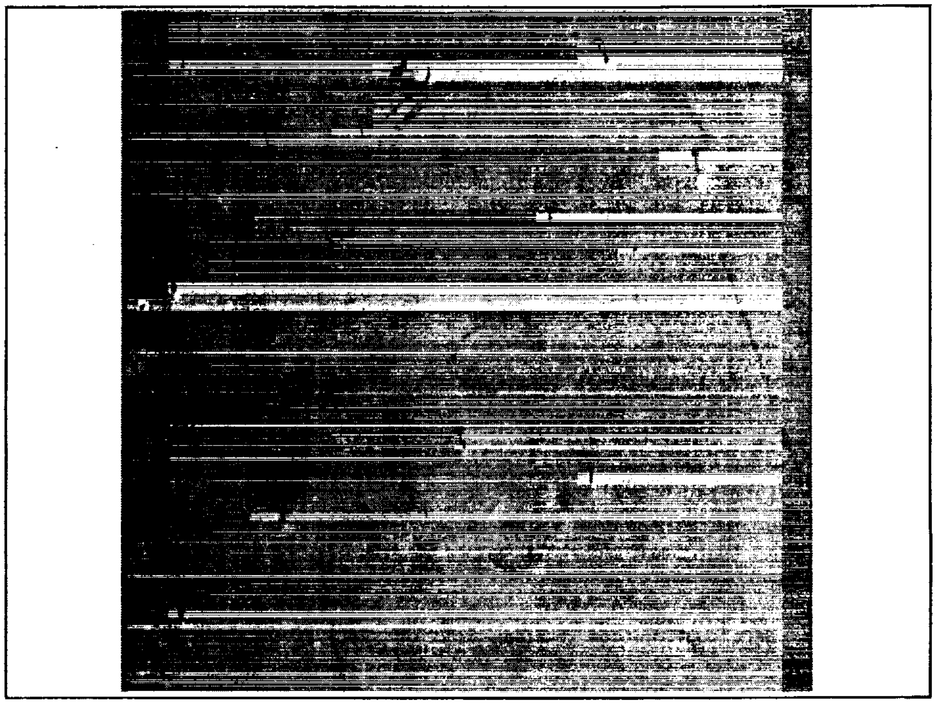
Martian Environment: The surface of Mars is a dynamic environment. This chart shows the passage of a dust devil directly over the Pathfinder lander as recorded by the landed pressure and wind sensors in the meteorology package. These dust devils are common at many locations over the planet's surface. Dust devils may be the primary mechanism by which dust is lifted at at the onset of dust storms.

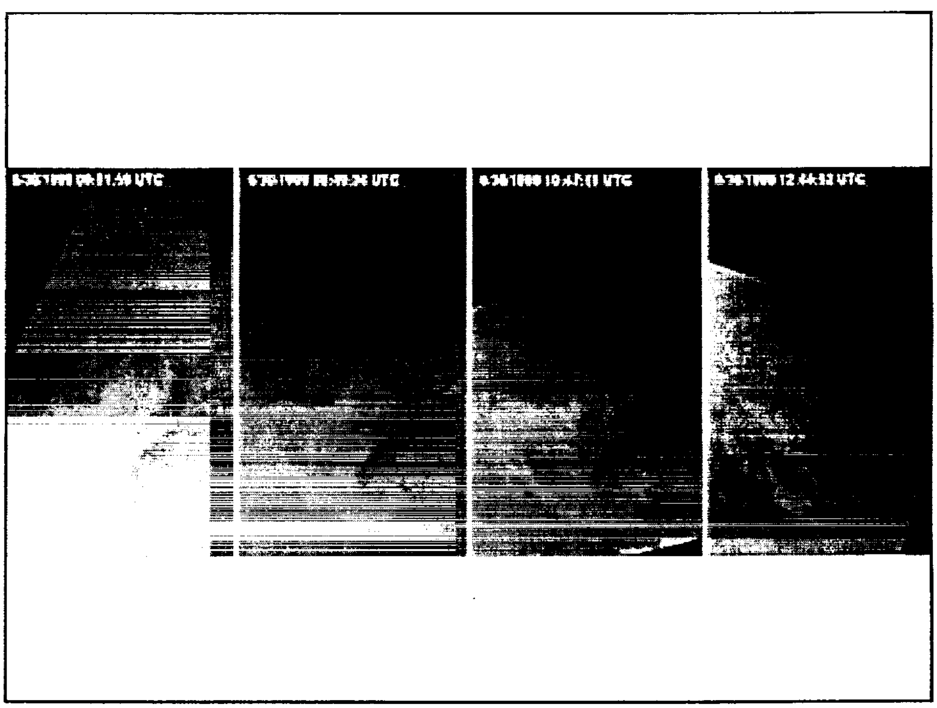

Mars Pathfinder ASI/MET
'Dust Devil' Detections

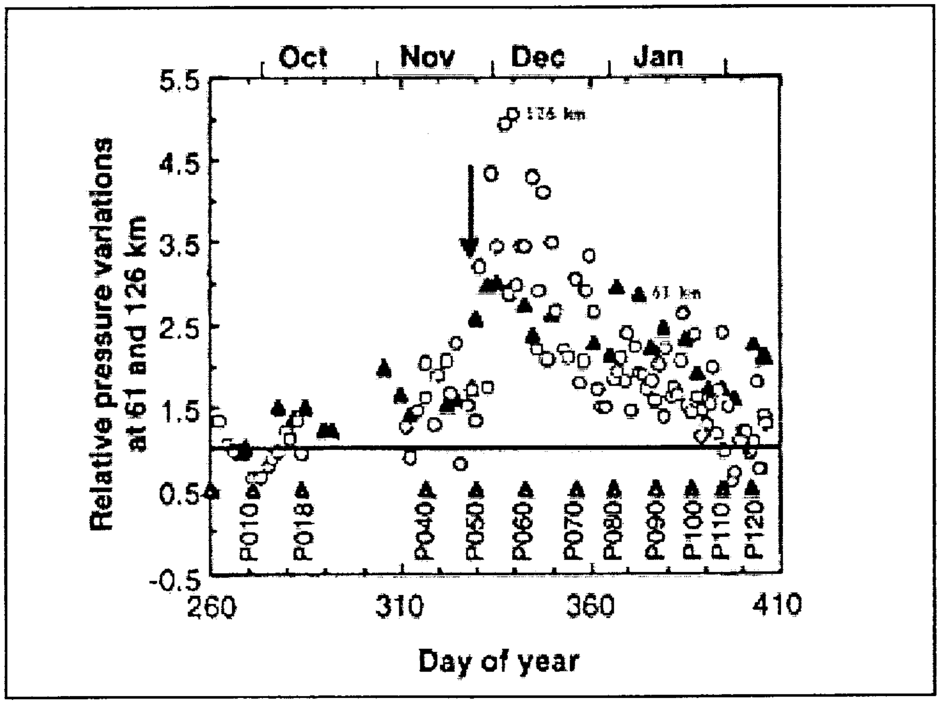



5/04/1999

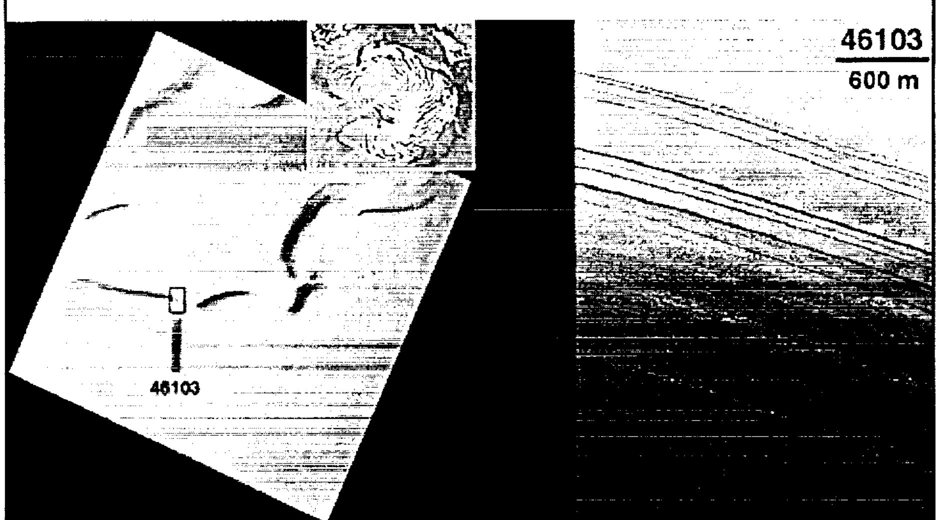

North Polar Layers in Same Trough
500 m
457 yards
86.5°N
281.5°W
86.4°N
278.7°W
85.9°N
257.9°W







Martian Environment: The dynamic environment of Mars may impact mission implementation strategies, for example aerocapture. The chart shows the change in pressure with time (and MGS orbit number) at altitudes of 61 km derived from ground-based Mars disk-averaged microwave data (solid triangles) and 126 km derived from MGS accelerometer (open circles), both normalized to surface pressure. The arrow indicates the onset of the Noachis dust storm.



Human exploration objectives: Today, the investigations of the robotic program, characterized simply as "follow the water" and the "search for evidence of life", are likely to be adopted by human explorers. The image shows the edge of the permanent north polar cap of Mars that has a great many layers. The layers have a thickness ranging from less than 10 m to tens of meters. The layers are thought to be expressions of climate variations, possibly induced by the known variability in the obliquity of the orbit of Mars. Human explorers may have, at location such as this, direct access to the history of Martian climate change.

Human exploration objectives: The north wall of Newton Crater has many narrow gullies eroded into it. These are hypothesized to have been formed by flowing water and debris flow. At these gullies human explorers may have relatively easy access to subsurface water, perhaps from depths of a few hundred meters, possibly from great depth.

Cognitive Prostheses

Kenneth M. Ford
Institute for Human & Machine Cognition
University of West Florida

ABSTRACT

This emerging concept of human-centered computing represents a significant shift in thinking about intelligent machines, and indeed about information technology in general. It embodies a "systems view," in which human thought and action and technological systems are seen as inextricably linked and equally important aspects of analysis, design, and evaluation. This framework focuses less on stand-alone exemplars of mechanical cognitive talent and is concerned more with computational aids designed to amplify human cognitive and perceptual abilities. Essentially these are *cognitive prostheses*, computational systems that leverage and extend human intellectual capacities, just as the steam-shovel was a sort of muscular prosthesis. The prosthesis metaphor implies the importance of designing systems that *fit* the human and machine components together in ways that synergistically exploit their respective strengths. The design and fit of these computational prostheses require a broader interdisciplinary range than has traditionally been associated with AI work, including computer scientists, cognitive scientists, physicians, and social scientists of various stripes. This shift in perspective places human/machine interaction issues at the center of focus. The "system" in question isn't "the computer" but instead includes cognitive and social systems, computational tools, and the physical facilities and environment. Thus, human-centered computing provides a new research outlook, with new research agendas and goals. Building cognitive prostheses is fundamentally different from AI's traditional Turing Test ambitions — it doesn't set out to *imitate* human abilities, but to *extend* them. As humans contemplate journeys to Mars and beyond, research requirements clearly exist for developing a wide range of performance support systems for both astronauts and ground operations personnel.

Cognitive Prosthesis
Notes by Doug Cooke

Cognitive Prothesis information was gleaned from discussions with Ken Ford from the University of West Florida and from an article in Computer Magazine by Scott Hamilton. This was published in the January 2001 edition. The title of the article is "Thinking Outside the Box at the IHMC".

Although Ken was not able to attend this workshop, I thought it was important to relay some of the key points and strategies that he would have discussed. Our discussions tend to revolve around humans versus robots and humans collaborating with robots. The ideas incuded here take this discussion into a different dimension.

Cognitive Prosthesis involves the study of human cognition, studying the human being as a system. Based on this knowledge, the focus of this activity is to augment the capabilities of the human and overcome his limitations. The idea is not to replicate a human being through robotics, but to augment his capabilities.

In looking at human capabilities "humans are wonderful analog computers that process huge quantities of data, often without conscious awareness." The human brain is able to react instantaneously to stimuli, based on all its memory and experience, without any apparent logical search. On the other hand, computers have tremendous logical capabilities and computational skills. If there is a close and carefully designed interchange between them, the combination can be made more powerful.

Examples of prostheses are:

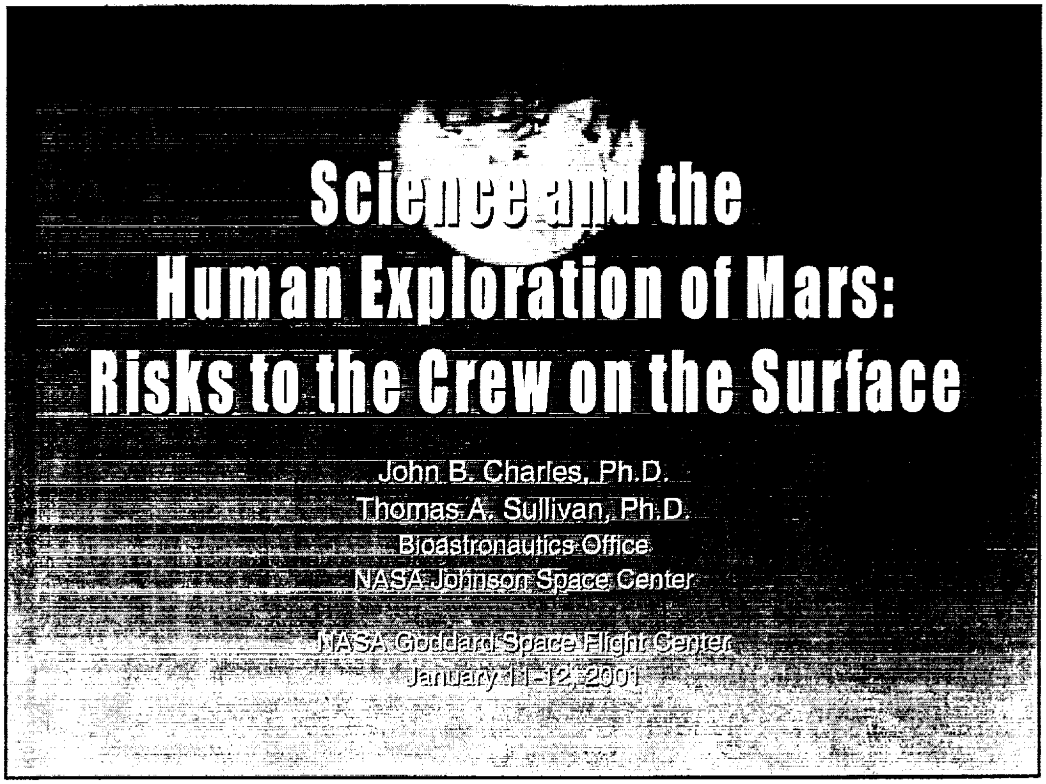
- Eyeglasses, which augment the eye, but don't replace them.
- A steam shovel run by a person greatly enhances his ability to dig.
- The pathfinder rover was an extension of the scientists on earth.

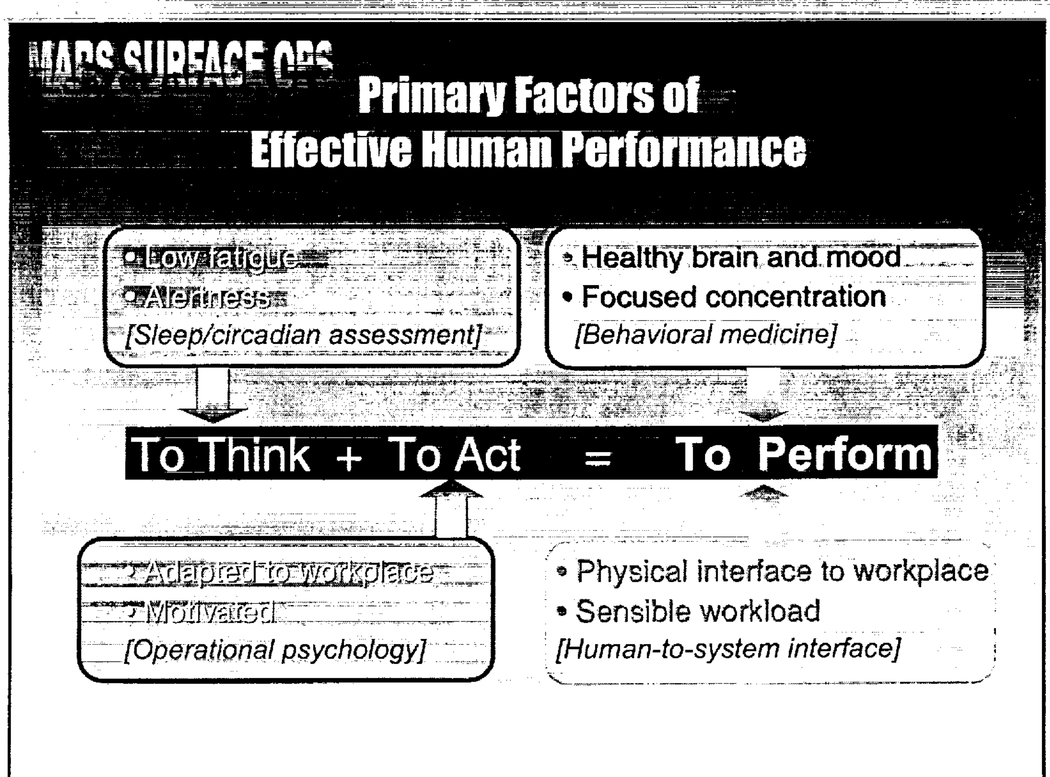
Examples such as these can all be made more effective by designing the human and machine as a system. "Build a total system that includes the user. Fit the human and machine components together in ways that synergistically exploit their respective strengths."

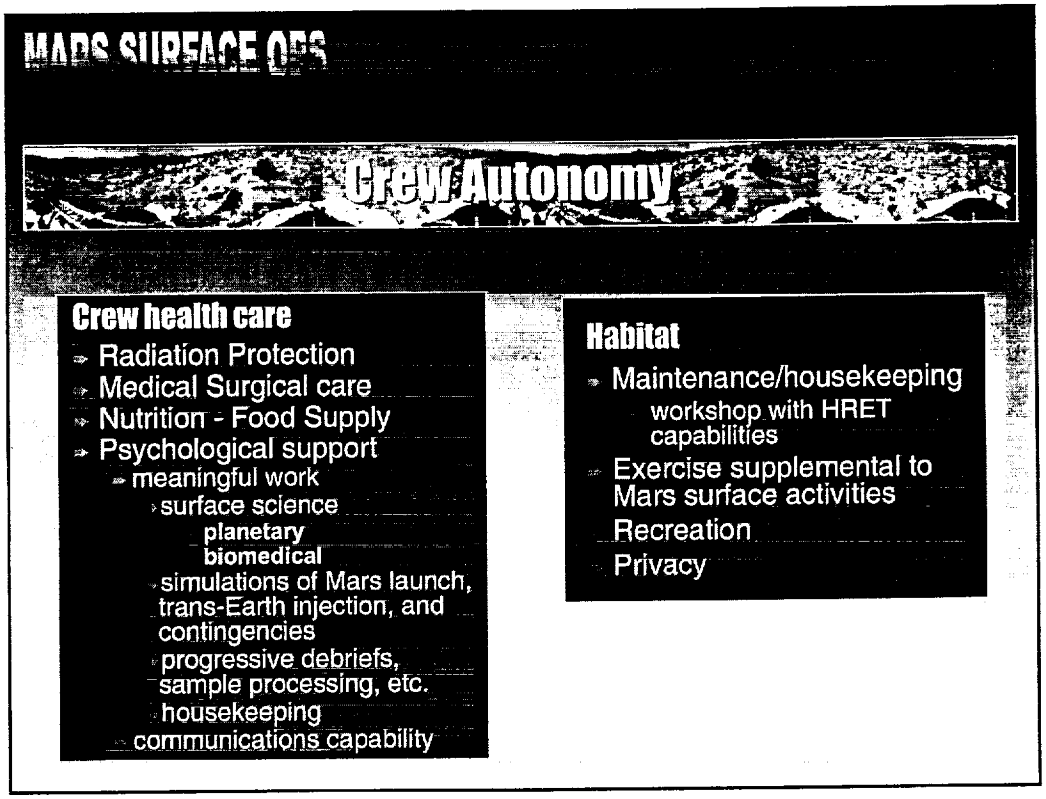
Ken recommends a "shift from making artificial super humans who replace us to making superhumanly intelligent artifacts that can amplify and support our own cognitive abilities."

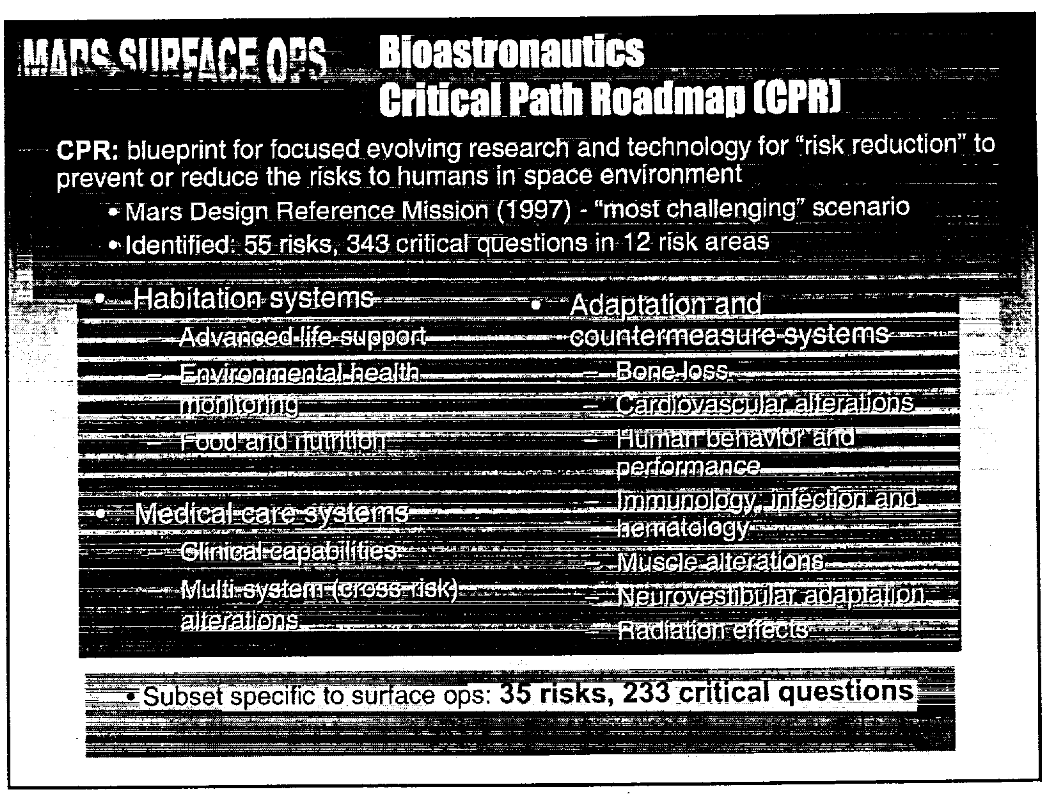
Our current EVA suits are designed to minimize their debilitating effects on the humans who use them, yet they are still debilitating. Imagine an EVA suit that is designed to enhance the astronauts' abilities in terms of information and computational augmentation available; and in terms of enhanced strength, mobility, and sensory inputs. It could have miniaturized sensors built into the gloves that can make the appropriate scientific measurements that aid in sample selection. There could be additional sensors that provide data that address other scientific investigations. This data could all be computationally integrated and provided to the astronaut real time in the suit, as well as being transmitted back to Earth.

In our thinking about what can be achieved on exploration missions, we should begin to look forward and conceptualize how our capabilities to perform with humans could be advanced well beyond today's capabilities and experience. In our thinking of future designs, these concepts should be employed to maximize performance and achievement. The discussion of robotics and human interaction should begin to include the idea of merged humans and machines.


Science and the
Human Exploration of Mars:
Risks to the Crew on the Surface
John B. Charles, Ph.D.
Thomas A. Sullivan, Ph.D.
Bioastronautics Office
NASA Johnson Space Center
NASA Goddard Space Flight Center
January 11-12, 2001


MARS SURFACE OPS
Primary Factors of
Effective Human Performance
• Low fatigue
• Alertness
[Sleep/circadian assessment]
• Healthy brain and mood
• Focused concentration
[Behavioral medicine]
To Think + To Act = To Perform
• Adapted to workplace
• Motivated
[Operational psychology]
• Physical interface to workplace
• Sensible workload
[Human-to-system interface]


MARS SURFACE OPS
Crew Autonomy
Crew health care
Radiation Protection
Medical Surgical care
Nutrition - Food Supply
Psychological support
meaningful work
surface science
planetary
biomedical
simulations of Mars launch, trans-Earth injection, and contingencies
progressive debriefs, sample processing, etc.
housekeeping
communications capability
Habitat
Maintenance/housekeeping
workshop with HRET capabilities
Exercise supplemental to Mars surface activities
Recreation
Privacy


MARS SURFACE OPS
Bioastronautics Critical Path Roadmap (CPR)
CPR: blueprint for focused evolving research and technology for "risk reduction" to prevent or reduce the risks to humans in space environment
Mars Design Reference Mission (1997) - "most challenging" scenario
Identified: 55 risks, 343 critical questions in 12 risk areas
Habitation systems
Advanced life support
Environmental health monitoring
Food and nutrition
Medical care systems
Clinical capabilities
Multi-system (cross-risk) alterations
Adaptation and countermeasure systems
Bone loss
Cardiovascular alterations
Human behavior and performance
Immunology, infection and hematology
Muscle alterations
Neurovestibular adaptation
Radiation effects
Subset specific to surface ops: 35 risks, 233 critical questions

MARS SURFACE OPS — CPR Issues: Radiation

CPR: Radiation effects (possible synergy with hypogravity, other environmental factors)

- Early or Acute Effects from Radiation Exposure (esp. damage to Central Nervous System)
- Carcinogenesis Caused by Radiation

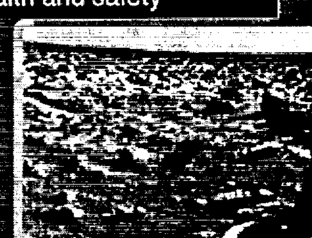
Issue: Surface Radiation Environment

- Large uncertainties about biological effects of GCR, SPE now prevent meaningful risk assessment (-)
- Possible risk from neutron backscatter from surface (-)
- EMU now not effective shielding (mobility $\propto$ protection^{-1}) (-)
- Attenuation of GCR & SPE by atmosphere, bulk of planet (+)
- Habitat, rovers assumed to provide storm shelters (+)
- Countermeasures (+)
  - Shielding: HDPE, H_2O
  - Chemopreventative/chemoprotective pharmaceuticals: possible cocktail of antioxidants, free-radical scavengers, toxic clearance agents

MARS SURFACE OPS — CPR Issues: Environmental

- **Issue: Dust**
  - Operational: fouling of habitat or pressure garment fittings and mechanisms could pose risk to health and safety
  - Medical: possible risk if inhaled
    - Physical irritant
    - Reactive and oxidizing
    - Pulmonary inflammation

    effects likely additive



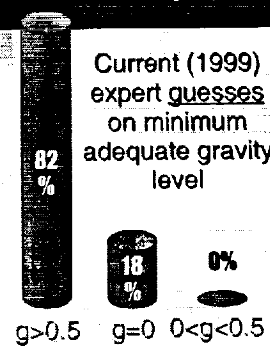
- **Issue: Biohazards**
  - Dependent on extant biological activity
    - Possible health threat to crew (maybe not)
    - Planetary protection issues (Mars as well as Earth)
- **CPR: Immune/Infection/Hematology**
  - Allergies and Hypersensitivity Reactions
  - Immunodeficiency and susceptibility to infections
  - Altered Wound Healing

MARS SURFACE OPS

CPR Issues: Hypogravity

Issue: Efficacy of 0.38 g in countering deconditioning = ???
Therefore, Mars surface gravity <u>assumed</u> to be:
- Too ***LOW*** to be beneficial (for preserving bone integrity, etc.)
- Too ***HIGH*** to be ignored (for avoiding g-transition & vestibular symptoms)

Periodic health monitoring will also serve as applied research:
- probably longest period away from Earth to date
- probably longest exposure to hypogravity (0<g<1) to date

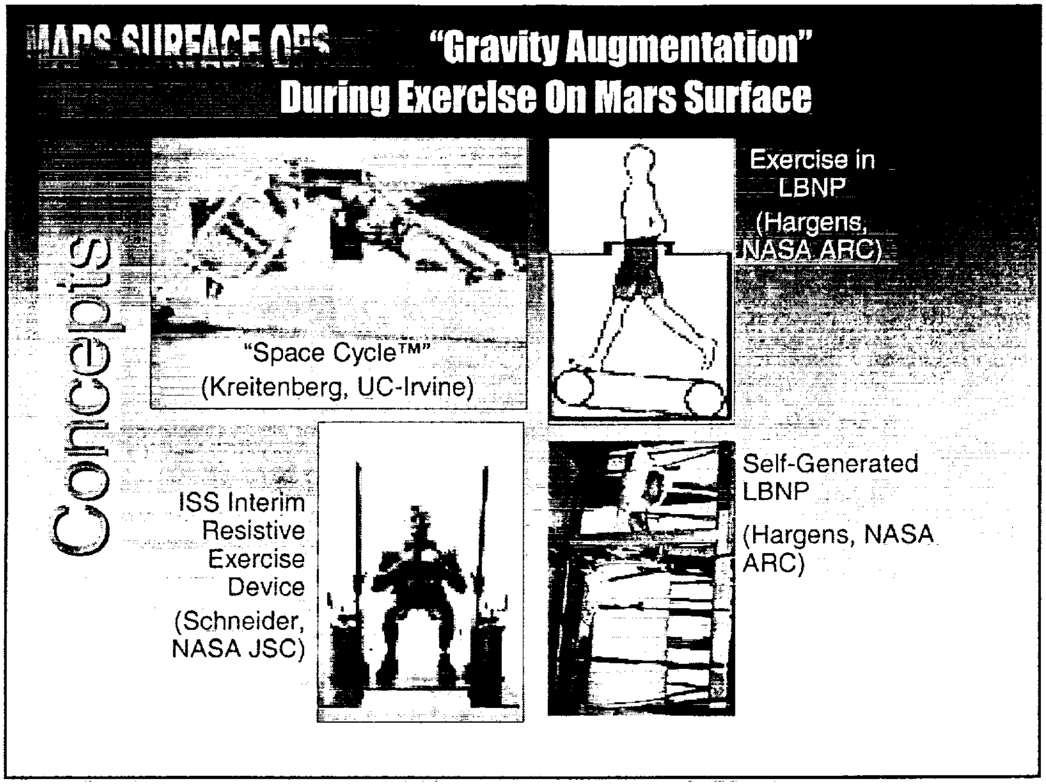


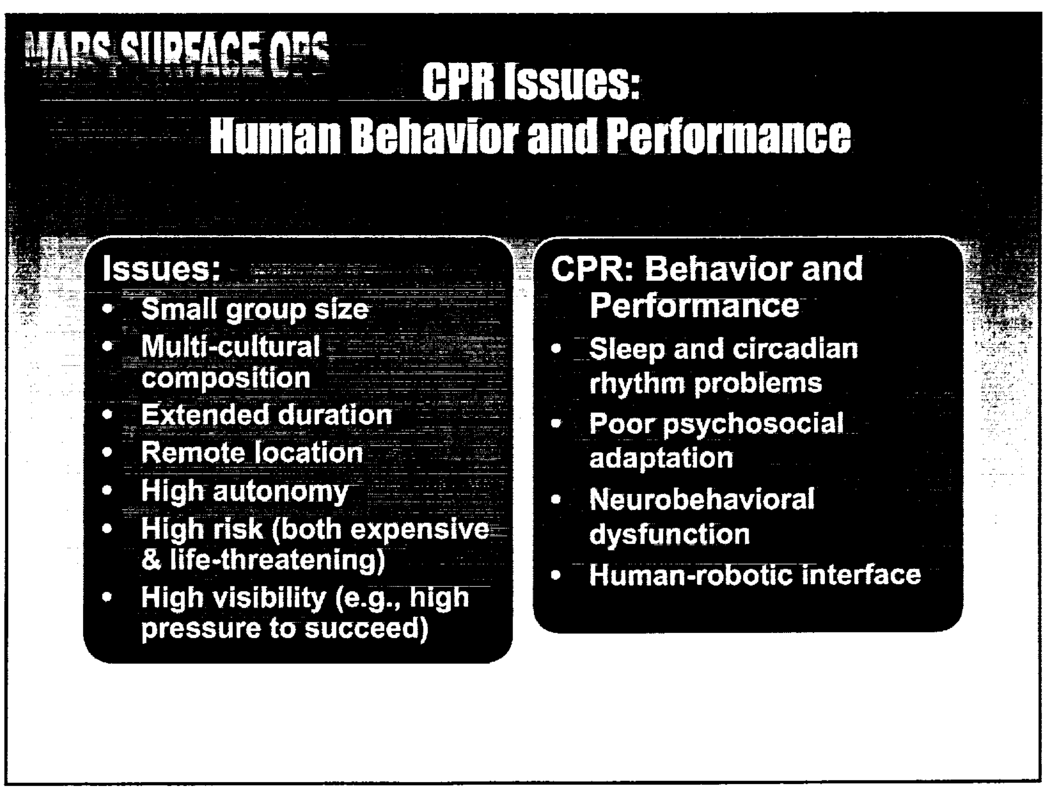
MARS SURFACE OPS

CPR Issues: Hypogravity (continued)

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

- **CPR: Musculo-skeletal atrophy**
  - Inability to perform tasks due to loss of skeletal muscle mass, strength, and/or endurance
  - Injury of muscle, bone, and connective tissue
  - Fracture and impaired fracture healing
  - Renal stone formation
- **CPR: Cardiovascular alterations**
  - Manifestation of serious cardiac dysrhythmias and latent disease
  - Impaired cardiovascular response to orthostatic stress and to exercise stress
- **CPR: Neurovestibular alterations (possible synergy with radiation)**
  - Disorientation
  - Impaired coordination
  - Impaired cognition


MARS SURFACE OPS
"Gravity Augmentation"
During Exercise On Mars Surface
Concepts
"Space Cycle™"
(Kreitenberg, UC-Irvine)
Exercise in LBNP
(Hargens, NASA ARC)
ISS Interim Resistive Exercise Device
(Schneider, NASA JSC)
Self-Generated LBNP
(Hargens, NASA ARC)


MARS SURFACE OPS
CPR Issues:
Human Behavior and Performance
Issues:
• Small group size
• Multi-cultural composition
• Extended duration
• Remote location
• High autonomy
• High risk (both expensive & life-threatening)
• High visibility (e.g., high pressure to succeed)
CPR: Behavior and Performance
• Sleep and circadian rhythm problems
• Poor psychosocial adaptation
• Neurobehavioral dysfunction
• Human-robotic interface

MARS SURFACE OPS CPR Issues: Human Behavior and Performance

Issue: Circadian Rhythm

- Sol = 24.62 hr
  - Human intrinsic rhythm = 24.1 ± 0.15 hr
    - synchronization not assured – may require (chronic) intervention?
- Synchronization successful (best case): Unknown efficacy in maintaining circadian health
  - Daylight EVA ops: safety, efficiency
  - Shorten perceived stay (by 2.5% !)
  - Complicate Earth-based support (ref. Viking, Pathfinder/Sojourner; MER 2003 ping)
- Failure to synchronize (worst case):
  - Crew awake during Mars night every 41 days (40 sols)
    - Well-rested "night-time" ops vs. fatigued daylight ops
    - -200 deg F temperature
      - EMU issues
    - Limited visibility (no IR capability): increased risk of accident, trauma
  - Radiation minimized: reduced SPE influence at night (?)

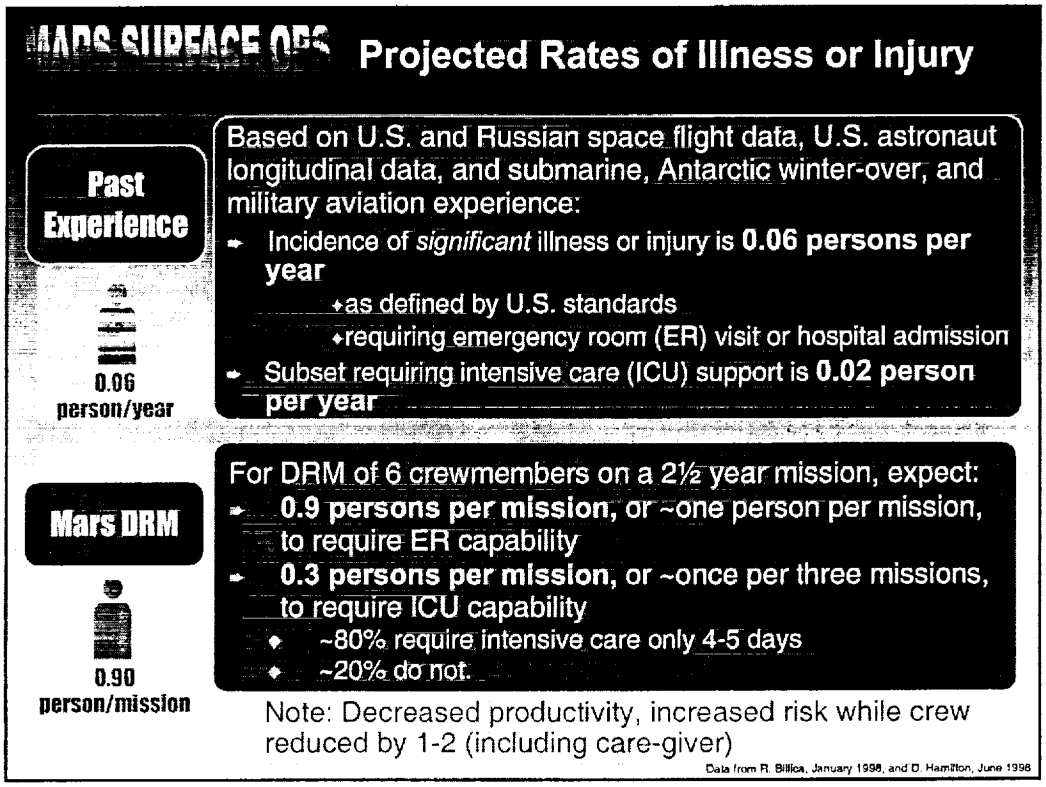
MARS SURFACE OPS Clinical Problems

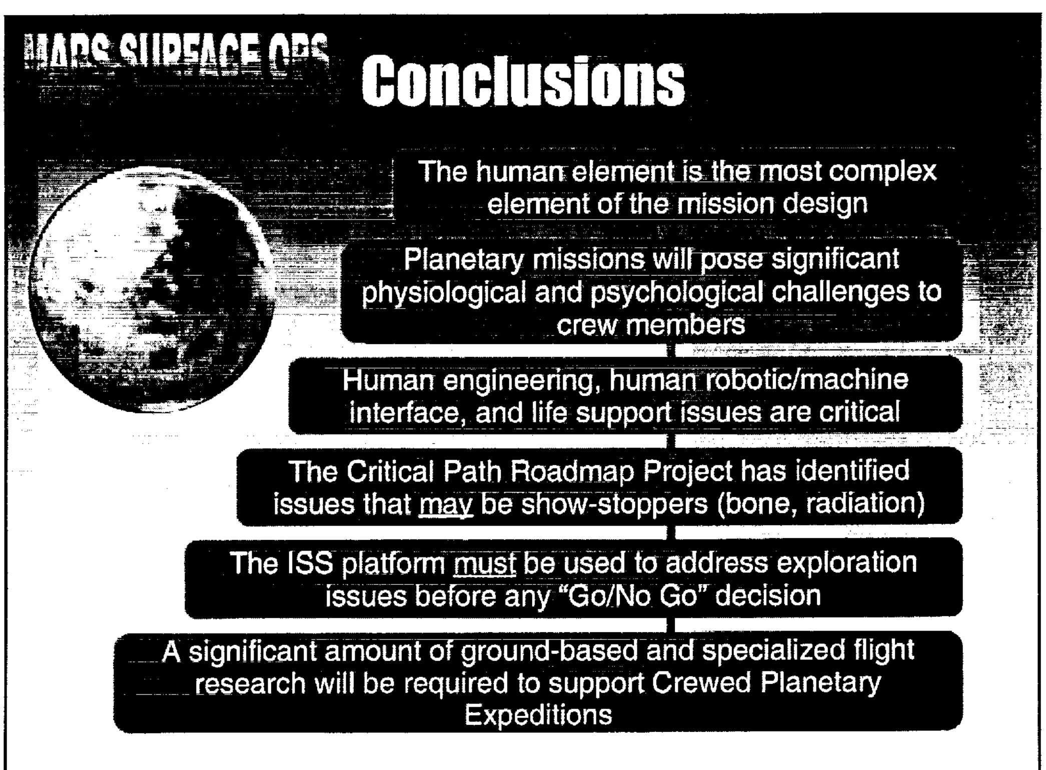
Require appropriate medical capability

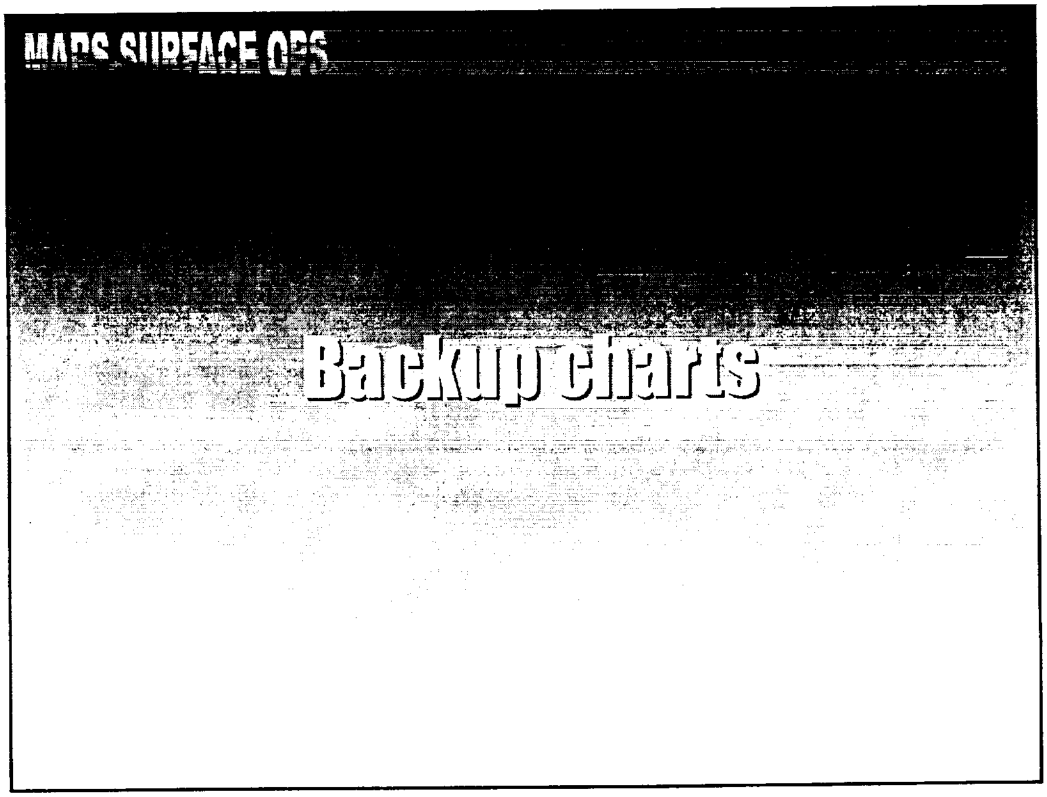
CPR: Medical care systems for prevention, diagnosis or treatment

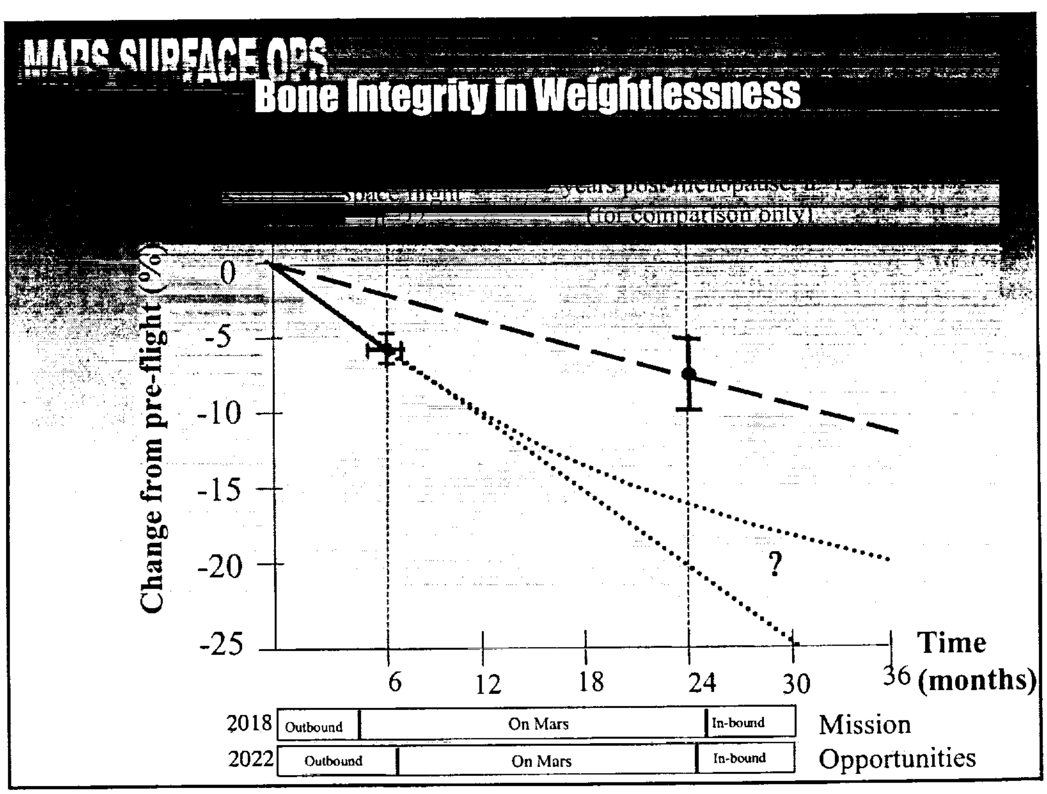
- Difficulty of rehabilitation following landing
- Trauma and acute medical problems
- Illness and ambulatory health problems
- Altered pharmacodynamics and adverse drug reaction

- Expected illnesses and problems
  - Orthopedic and musculoskeletal problems (esp. in hypogravity)
  - Infectious, hematological, and immune-related diseases
  - Dermatological, ophthalmologic, and ENT problems
- Acute medical emergencies
  - Wounds, lacerations, and burns
  - Toxic exposure and acute anaphylaxis
  - Acute radiation illness
  - Development and treatment of decompression sickness
  - Dental, ophthalmologic, and psychiatric
- Chronic diseases
  - Radiation-induced problems
  - Responses to dust exposure
  - Presentation or acute manifestation of nascent illness


MARS SURFACE OPS
Projected Rates of Illness or Injury
Past Experience
0.06 person/year
Based on U.S. and Russian space flight data, U.S. astronaut longitudinal data, and submarine, Antarctic winter-over, and military aviation experience:
Incidence of *significant* illness or injury is **0.06 persons per year**
as defined by U.S. standards
requiring emergency room (ER) visit or hospital admission
Subset requiring intensive care (ICU) support is **0.02 person per year**
Mars DRM
0.90 person/mission
For DRM of 6 crewmembers on a 2½ year mission, expect:
0.9 persons per mission, or ~one person per mission, to require ER capability
0.3 persons per mission, or ~once per three missions, to require ICU capability
~80% require intensive care only 4-5 days
~20% do not.
Note: Decreased productivity, increased risk while crew reduced by 1-2 (including care-giver)
Data from R. Billica, January 1998, and D. Hamilton, June 1998


MARS SURFACE OPS
Conclusions
The human element is the most complex element of the mission design
Planetary missions will pose significant physiological and psychological challenges to crew members
Human engineering, human robotic/machine interface, and life support issues are critical
The Critical Path Roadmap Project has identified issues that may be show-stoppers (bone, radiation)
The ISS platform must be used to address exploration issues before any "Go/No Go" decision
A significant amount of ground-based and specialized flight research will be required to support Crewed Planetary Expeditions


MARS SURFACE OPS
Backup charts


MARS SURFACE OPS
Bone Integrity in Weightlessness
(for comparison only)
Change from pre-flight (%)
0
-5
-10
-15
-20
-25
?
6
12
18
24
30
36
Time (months)
2018
Outbound
On Mars
In-bound
2022
Outbound
On Mars
In-bound
Mission Opportunities

MARS SURFACE OPS

Strategy for Transition from Flight to Mars Surface Operations

Background

Anecdotal evidence suggests ~50% of Russian *Mir* crewmembers were ambulatory *with assistance* immediately after landing, increasing to nearly 100% within hours (with effort), then decreasing for days thereafter, before gradual recovery

Assume

Only 3 out of 6 Mars crewmembers are ambulatory immediately after landing

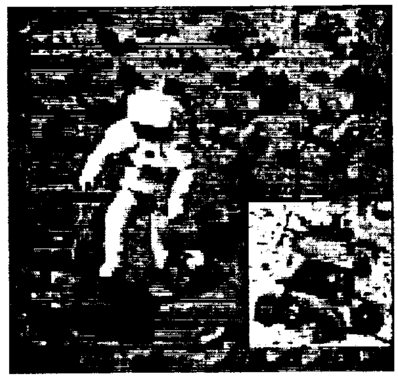
Strategy

Start with passive tasks, progress to strenuous tasks

- **First 1-3 days** activities limited to reconfiguration of lander/habitat and surface reconnaissance
- **Then,** conduct first Mars walk(s) in vicinity of lander (umbilical instead of backpack?)
- **Next,** use unpressurized rover for early, shorter excursions
- **After a week or more,** extended excursions are possible

EVA PROJECT OFFICE

EVA Considerations
Human Exploration of Mars Workshop



JSC/XA/R. Fullerton

December 13, 2000

Outline

- Human Contributions
- Tasks For Humans (History and Future)
- Environmental and Physical Limitations
- Human and Robotic Implementation Options
- Ground Test Experience
- Needed Enabling Information and Technology
- Strategic Issues
- Summary

Human Contributions

While automated means are appropriate for selected applications, the combination of human and robotic capabilities provides leverage to enable otherwise difficult or impossible ventures.

- **Productivity** - Use of the brain's creative cognitive abilities enables rapid on-scene decisions which overcome time delays and data bandwidth limits.
- **Reliability** – Adaptive and proven capability for manual response to unforeseen, unique and non-repetitive activities
- **Cost/Mass** – Less need to expend resources upon complex, redundant and fully automated designs
- **Terrestrial Benefits** – Human space activities engage public interest and advance new opportunities

Metrics = $/data/time, hdw replace risks/costs/time, automation costs, spinoff $

Tasks For Humans

History

- Apollo lunar geology prospecting and instrument deploy
- Skylab (solar array release, thermal shield install, science repairs)
- Mir (solar array assembly, docking system repairs, external science, commerce)
- Shuttle contingencies (Ku antenna stow)
- Satellite servicing (Solar Max, Westar/Palapa, Leasat, GRO, Intelsat, Eureca, Spartan, HST)
- ISS planned and unplanned assembly (mech, elec, fluid)
- ISS maintenance/repair (2A FGB antennas, 2A.2a Node antenna, 2A.2b SM TV target, 4A solar arrays, ...)

Mars Exploration

- Infrastructure setup & repair (power generation/distribution, radiation shielding)
- Science equipment setup and repair (surface sensors, drills, rovers)
- Access and study of challenging terrain (outcrops, ravines, rock fields, subsurface)
- Rescue (crew and hardware)

Environmental and Physical Limitations

Environmental

- Radiation (exposure time constraint and health risk)
- Temperature (extreme hot and cold varies with altitude, seasons and day/night)
- Pressure (1/100 atmosphere, CO2 rich, requires special CO2 and thermal sys)
- Lighting (constrains work time and distance in unfamiliar areas w/o artificial lighting/power)
- Dust (defeats pressure seals, obscures vision and solar arrays)
- Wind (entrained dust erodes, obscures and moves unsecured hardware)
- Gravity (extended 0-G and 1/3-G exposure time weakens bones and muscles)
- Organic Contamination (2 way issue impedes productive time)
- Terrain (slopes/cliffs, obstacles, instability, hardness impede site access)

Physical

- Productive time (limited by assy/maint/ops overhead, exercise, sleep, meals, comm coverage)
- Mobility (only limited by transport aids, suit mass/bearings/consumables, tools)
- Five senses (degradation by enclosures can be compensated by info aids & sensors)

Exploration Implementation Options

Robot Method	Human Role	Site Access	Data Scope	Rel Cost	Hdw Repair	Safety Risk
Remote teleoperation	Earth based control	Lowest	Lowest	Low	None	None
Fully automated	Earth based monitoring	Low	Low	Low-Med	None	None
Local teleoperation	Orbital habitat	Low	Low-Med	Med	None	Low
Local teleoperation	Lander habitat-No EVA	Low	Low-Med	Med-Hi	None	High
Variable autonomy	Lander habitat-No EVA	Low	Med	Med-Hi	None	High
Variable autonomy (pressurized garage)	Lander habitat-No EVA	Low	Med	Med-Hi	Partial	High
Variable autonomy (dockable to habitat)	Canned mobility (No EVA Capability)	Low-Med	Med	High	Partial	Highest
Precursors only	Suited humans on foot	Med-Hi	High	Med-Hi	Full	Med
Variable autonomy (total crew access)	Suited transportable humans (w/Rovers)	Highest	Highest	Highest	Full	Med-Hi

Needed Enabling Information and Technology

Environmental Data

- UV and particle radiation levels at surface
- Season, daily and altitude variations of atmospheric composition, temp, press, dust, natural lighting and wind speed/direction
- Dust and wind impacts to convective/radiation heat transfer and solar flux
- Soil/dust chemical composition, reactivity, electrostatic charge, size, shape, mass
- Soil bearing strength, penetration resistance, cohesion, adhesion, abrasion
- Amount of trapped pressurized fluids/gases, volatile gases and toxic materials
- Terrain characteristics and maps (slopes, cliffs, caves, ravines, craters, obstacle size/distribution, surface instability, subsurface/rock hardness)
- Touch temperatures of surface and subsurface materials
- Short/long term effects from corrosion and abrasion of suit materials and coatings

Technology

- Portable life support, surface transport, airlocks, info/nav aids, robotics, facilities
- Radiation protection, insitu resources, compact power, sample curation

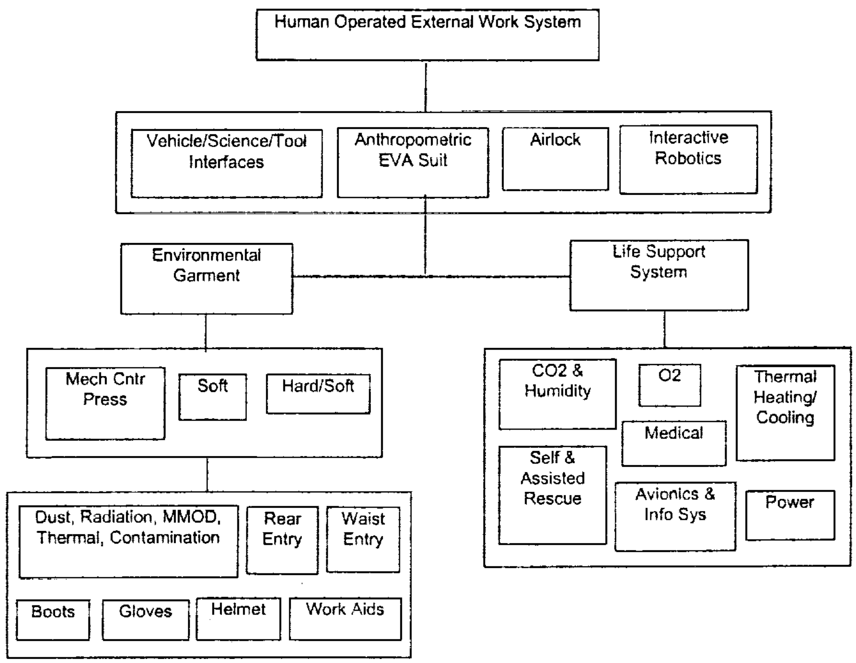
Strategic Issues

- Existing NASA EVA capability is over 23 years old. Only useable in zero gravity and hard vacuum. High costs to purchase, operate and sustain. Only minor upgrades are practical.
- No noteworthy EVA projects sponsored by other U.S. or International governmental agencies, commercial industry or academia.
- Existing programs and flat budgets leave few resources for new ventures.
- No incentives to re-invest potential cost savings or commercial profits.
- Near total adversion to human risks and costs constrains progress.
- EVA is a victim of past successes. Perceived by many to be "rich" & ready for instant callup.
- ISS funding for EVA technology development has been cut by 50% in FY01 and 100% in FY02. All that remains comes from Code U NRA's and SBIR.
- Downward spiral of funding roller coaster makes it impossible to sustain NASA expertise, industrial competition and targeted university research. Existing low TRL solutions languish and limited expertise continues to disappear.
- Existing research solicitation processes will not achieve desired results
  - Single page announcements no substitute for SOW or quantified requirements
  - NASA expertise excluded or discouraged as peer reviewers and PI's
  - No project level dollars for targeted competitive procurements
  - More visions and initiatives than coordinated resources (Code M, R, S, U, Centers)

Summary

- Human beings have robust cross cutting skills which historically enabled terrestrial, undersea and space exploration. Future space exploration and commercial endeavors will be less productive and less successful without human intervention.
- It will take up to 10 years to develop and produce a destination independent set of flight and training quality hardware ready to support existing and long term programs.
- Potential exists to reduce high costs of sustaining current hardware thru less expensive new hardware and scrubbing of current inefficiencies. Government resource commercialization not possible unless legal prohibitions removed and profit retention incentives created.
- Future programs are in jeopardy if advanced EVA and robotic capabilities are not consistently and adequately developed. Existing efforts are not effective or sustainable.

Backup



Limitations of Existing Architecture

- EVA overhead penalties are high in terms of mass, volume and time. Historically, less than 20% of crew time related to EVA is spent on productive external work. 2600 lbs and 90 ft3 were manifested for suits, tools, carriers and consumables on STS-103 for Hubble Space Telescope servicing (1470 lbs and 60 ft3 for 4 suits). The 300 lb mass and 13 ft3 stowage volume of the current U.S. suit is not compatible with the restricted delivery capacity of remote exploration.
- The mass, mobility and visibility of the current suits are not compatible with partial gravity planetary environments. Suited body control in zero gravity is also hampered by these factors. The current U.S. suit is twice as heavy as the Apollo suit and is not designed for kneeling, prolonged walking or inertia free handling. Arm/hand work envelope and foot visibility are severely degraded by chest mounted controls. Physical comfort is not sustainable for high frequency work in partial gravity.
- Suit protection from dust intrusion is inadequate. Even the Apollo suits would have been doubtful for more than 3 days of lunar work due to highly abrasive minerals preventing rotation of mobility bearings.
- Available thermal insulation materials either only work in vacuum conditions or are thick and impede suit mobility and glove dexterity. Even with active heating, touch temperatures are limited to short durations and narrow ranges (-120 to +150F).
- Radiation environment definition, monitoring and protection are inadequate beyond earth's ionosphere.
- Suit consumables are wastefully expended and require frequent replenishment or considerable time/power to recharge. Heavy cooling water is vented. CO_2 scrubbing canisters require wholesale replacement or time/power consuming bakeout between sorties. No insitu resource utilization is possible.
- No real suit maintenance capability exists beyond limited resizing and consumables replacement. Spares change out is only done via large integrated assemblies. Many intricate parts are not crew serviceable.

Limitations of Existing Architecture (cont)

- The effects of planetary unique gases (such as argon) on EVA physiology are undefined.
- Medical monitoring and treatment of EVA crew is minimal. Cannot yet quantitatively track fatigue or decompression sickness symptoms. Non-intrusive and 100% O2 compatible devices are lacking. There is no effective insuit treatment capability for injury or illness.
- Sensitive environments and science devices are contaminated from suit by-products (water, particulates, atmosphere leakage).
- EVA information processing is limited to suit/medical telemetry and is based on old technology that is not inflight reprogrammable. Radio communication is the sole means of information exchange for science interaction, worksite unique data and navigation/tracking status. Visible imagery is marginally captured by simple photographic means. Reference information is paper based because no compatible display yet exists. Hands free interaction is needed to avoid fatiguing manual efforts and obstructed work volumes.
- Robotic EVA aids in use are primarily large arms with limited mobility and dexterous capability. Human capable wheeled rovers are not in development. Highly mobile and dexterous robotics get limited attention. None are yet fully developed for autonomous inspections, cargo handling, worksite setup, crew tracking or self charging/storage/maintenance. Most are too reliant upon unique visual and handling aids.
- Airlock designs have remained static. Depress/repress gas is still vented or pumped with large power penalties. Existing designs are not compatible with dust/biologic isolation or hyperbaric treatment.
- Separate self rescue and emergency life support limits return range and adds to suit mass/volume
- Tools are limited to manual force/torque reaction & zero-G transport/restraint. Limited environmental & mechanical analysis devices. No drills. Few true repair options. Delicate materials not easily handled.

Advanced EVA Technology Topics

Challenges	Priorities
• CO2, humidity, trace gas removal • O2 storage and delivery • Low habitat and suit pressures • Thermal heating/cooling • Suit entry design • Anthropometric sizing • Backpack integration/maintenance • Self rescue integration • Gloves • MCP physiology and comfort • Dust protection • Radiation definition/protection • Contamination provisions • Low temperature tolerance • Low bulk multipressure thermal insulation • Strong, durable, light materials • Small high energy power supply • Wireless sensors/actuators • Airlock entry and exit • Airlock gas loss prevention • DCS studies and monitoring • Hyperbaric treatment • Non intrusive medical sensors • Navigation and communication • Multisensory info displays & controls • Automation • Freeflyer, manipulator & rover aids • Mechanical strength/dexterity aids • Ergonomic interfaces • Design/mobility/fit tools • Environmental test facilities • Vehicle interface standards • Field test experience and verification	– Integrated Concept Definition and Requirements (suit, airlock, robotics) – CO2 system – Mass/Volume reduction and system definition (SSA and LSS) – O2 system – Environmental Protection (thermal, puncture, radiation, dust) – Thermal Control System – Test Personnel and Facilities – Analysis Tools – Power supply system – Instrumentation and info technology (wireless, sensors, automation, controls/displays and crew/vehicle interfaces)

Intelligence Enhancement Concepts

- Miniature and low power environmental sensors (portable or suit mounted for magnification, range finding, x-ray, UV, IR, radar, low light, geochemistry, biochemistry, electromagnetic fields, radiation)
- Small, low power, low light, multiwave length, variable focus/range camera (suit mounted, HUD or laser pointing image feedback)
- Low mass, ultra-low volume, low power and wireless sensors (mobility, suit life support, external environment, contamination)
- Small, low power, high intensity lighting systems (suit mounted and portable)
- Interactive hands free EVA displays and controls for system telemetry/functions and photo/TV images of environment and vehicle interfaces. Capability for crew and ground team updates of software format and content. Multiuse displays to be portable for suit or vehicle mounting. Helmet and arm mounted displays featuring miniature optics, low power, low profile and voice activation.
- Ultraminiature, low power, long range and multiuser radio (voice, video, data, commands)
- Autonomous terrain/spacecraft mapping, navigation and crew tracking integrated with crew and ground team displays. Data supplied by satellite, robotics or cameras attached to suited crew. Target recognition to include artificial landmarks (e.g. colored/patterned flags, targets, radio beacons)
- Non-invasive, low power, wireless, 100% O_2 compatible medical sensors (blood N_2, ECG, temp, fatigue)
- Continuous autonomous system monitoring, trend analysis, diagnostics, malfunction response and feedback for orbital and planetary mission EVA systems (airlock, suits, robotics, tools) in collaboration with crewmembers and ground team members
- Autonomous systems that can support voice communication with and learning from ground support team members and space explorer crew
- Adaptive collaborative system for labeling, recording, cataloguing and retrieval of EVA collected science data (science samples, photos, video, technical notes, etc)
- Autonomous intelligent inventory management system accessible by crewmembers and ground teams

Planetary EVA Ops Questions

1. Comfortable walkable distance and rate (single day)
2. Forced march walking distance and rate (single day)
3. Safe return cache spacing and contents
4. Normal duration of EVA sortie (egress-ingress)
5. Mandatory duration of consumable margin (nominal and backup systems)
6. Normal duration of EVA prep and post activities
7. Number of elapsed days before initial EVA (post arrival)
8. Duration of initial EVAs (post arrival)
9. Minimum distance of safe visibility (dust storm severity)
10. Terrain constraints (stable footing, slope angle, caves, cliff edges, overhangs,
11. Rescue capabilities (climbing harness, winch,
12. Injury treatment (suited in the field or suitless in a safe haven)
13. Training materials access (in-suit or at safe haven or both, full or partial access)
14. Minimum number and location of EVA crew outside (nominal, emergency)
15. Maximum number and location of EVA crew outside (nominal, emergency)
16. Minimum comm and sensor/data definition (voice, email, suit, weather, navigation)
17. Permission for recreational or PAO oriented EVA (in transit or after arrival)
18. Cable routing and crossover techniques (bury, elevate, ramp)
19. Lighting and temperatures constraints on EVA duration, location, distance, etc
20. Robotic aid preferrences (pressurized, unpressurized, range, cargo/crew capacity)
21. Suit rechargability constraints (avoid for nominal EVA, OK or not while outside)

Ground Test Experience

- Apollo/USGS experience, 1970's
- Comparative suit mobility tests (EMU, Mark III, AX-5), JSC, 1980's
- Comparative suit mobility tests (A7LB, EMU, Mark III), JSC, 1996
- Shirt sleeved geology exercises, Death Valley, 1997
- Lower torso mobility tests (Mark III), KC-135, 1997
- Mobility and geology exercises (Mark III), Flagstaff, 1998
- Remote site experience, Antarctica, 1998
- Mobility and robot aid tests (I-suit, Marsokod rover), Mojave Desert, 1999
- Mobility tests (D, I and H suits), JSC, 1999
- Reconnoiter of Devon Island as future test site, Canada, 1999
- Rover seating tests, KC-135, 2000
- Mobility, geology, drilling, power deploy demos (ATRV rover, H/I suits), JSC, 2000
- Mobility, geology, drilling, power deploy demos (ATRV rover, H/I suits), Flagstaff, 2000
- Remote site experience, Antarctica, 2000/1

Robot & Human Surface Operations on Solar System Bodies

--Abstract of a Projected Comparative Performance Evaluation Study--

C. R. Weisbin, R. Easter, G. Rodriguez

January 2001

Robot & Human Surface Operations

Long Range Vision of Surface Scenarios

Technology	Now	5 Yrs	10 Yrs	>15 Yrs
High-Risk Access Systems Mobility & Navigation	Wheeled Rovers 100's Meters; Supervised Autonomy; Conventional Terrain	Multi-Mode Mobility (hop,fly,,etc); >100 km Regional Autonomy; All Terrain Capability; Cliff Ascent/Descent	> 1000 km Multi-Mode Mobility Surface Coverage; Coordinated Communications; Unattended Autonomy	High-Resolution Global Surface Coverage; Precision Access & In-Situ Probe **EXPLORATION & LIFE SEARCH**
Human & Robot Outposts & Colonies	< 10 Sojourner-Class Rover Surveys Local Area in Coordination with Landers; Daily Earth Communications	Low-Cost Robot Teams; Wide Area Measurement & Communication Nets; Weekly Hands-Off Operations	> 10 Yrs Self-Sustaining Systems; Robotic Repair & Maintain; Monthly Hands-Off Operations; Team Work	Permanent /Perpetual Presence in Deep Space Robotic Infrastructures; Long Duration Autonomy **PERMANENT STATIONS**
Deep Sub-Surface Systems	10's of Samples in Low-Depth Coring Devices (Athena 03,05)	< 10 meter in Mars regolith by percussive robot systems; Icy Media Robotic Penetrator Proof-of-Principle Experiments	> 100 m Access to Samples in Regolith	Active Thermal Probe for Icy Planetary Environments **LIFE SEARCH & EXTREME ENVIRONMENT**
Hybrid Human & Robot Systems	Rovers Do Full Sample-Acquire Cycle with 1 Ground Command	Collective Autonomy of < 10 Robots Commanded from Earth	Remote Robotic Assistance to Earth-Based Science Analysis	Robot Crews Help Humans in Surface Science Operations **PERMANENT STATION**
Sample Acquisition, Handling & Curation Systems	Small robot arms for surface sampling (e.g. Mars 03, 05)	Automated Extraction of Volatiles (H,C,N,H20) from Mars Regolith; Returned Sample Handling	Multi-Site Land, Ascent, & Sampling Robotic Systems (10's of sites)	Anchor, Sample & Retrieve Robotic Systems for Irregular & Poorly Known Media (Asteroids & Commets) **MINING**
In-Situ Resource Utilization Systems	Mars propellant production breadboards & precursor experiment	Base technology for Mars ISPP flight demos; Mars & lunar consumable production breadboards (fuel cell reagent, science instruments, etc.)	ISPP-fueled ascent vehicles, hoppers & rovers; micro-g soil processing and collection; Subsurface resource collection & processing	ISPP based robotic & human outposts; ISPP based comet, moon, & asteroid exploration & sample return; asteroid/moon processing for science & human structures **PERMANENT STATIONS**

Robot & Human Surface Operations

Humans and Robots Complement Each Other

- **Humans are supremely capable of working in unstructured situations**
- **Robots can do heavy duty work and provide force amplification**
- **Human/robot cooperation enhances endurance, precision, reliability, speed, situation awareness, etc.**
- **Robots can enhance human safety - it is safer to send robots to high-risk areas**
- **Accessibility** - Machines can be built to function in a micro-world or a macro-world not reachable by humans.
- **Division of Labor - Let Each Do What It Does Best**
  - Humans concentrate on supervising and ensuring the performance of the machine's functions, and perhaps perception beyond signal processing.
  - Machines can also be "wired" through tele-presence to emulate the dexterity of humans; this assumes that an astronaut is proximate to the robotic system so that there are no appreciable time delays.
  - Human dexterity, versatility, adaptability, and intelligence are in many situations still unmatched by any machine.
  - Structurability and predictability of the work environment are real considerations. The greater the communication delay (light time) the more autonomous the remote systems must be.

Robot & Human Surface Operations

*Respective Human & Robot Strengths

HUMAN	ROBOT
• Flexibility	•Physical strength and power
• Redundancy	•Speed of movement/computation
• Communication	•Repeatability
• Learning	•Constancy of performance
• Taking risks	•Short term storage capacity
• Problem solving	•Complete erase capability
• Decision-making	•Reaction time

*Compatibility at the human-robot interface is required to optimize the performance and effectiveness of the overall human-robot system. Compatibility is required to get the best of both worlds (human and robot) and not the worst.

Robot & Human Surface Operations

Need More In-Depth Quantitative Analysis

- Relative strengths of humans and robots in performing a wide variety of tasks is well-established CONCEPTUALLY
  - Humans are unequaled in unstructured situations
  - Robots are good at high-risk access
  - Etc.
- There is a wealth of EXPERIENCE to validate these general notions
  - Armstrong's decision-making in lunar terminal descent maneuver could not have been done reliably with robotic spacecraft
  - Robots have gone to "worse-than-hell" places (Venus, Jupiter) not currently accessible to humans
- Systematic comparisons that validate these general concepts have not been fully investigated for a wide range of envisioned surface operations
  - Need standardized METRICS to quantify performance
  - Need rigorously defined criteria to EVALUATE relative performance
  - Need controlled EXPERIMENTS to arrive at systematic comparisons

Robot & Human Surface Operations

Projected Study Objectives

- Objectives: Develop ways to quantify and compare the performance of robots and humans in the range of surface operations that may be done in the solar system.
  - Robot-assisted & non-assisted humans
  - Tele-operated & autonomous robots
- Projected Results & Products
  - Summary of existing methods for characterizing robotic and human performance and examples of application.
  - Possible approaches for factoring in cost and risk
  - Proposed modeling and analysis process for comparing robotic and human alternatives and combinations for given tasks/missions.

Robot & Human Surface Operations

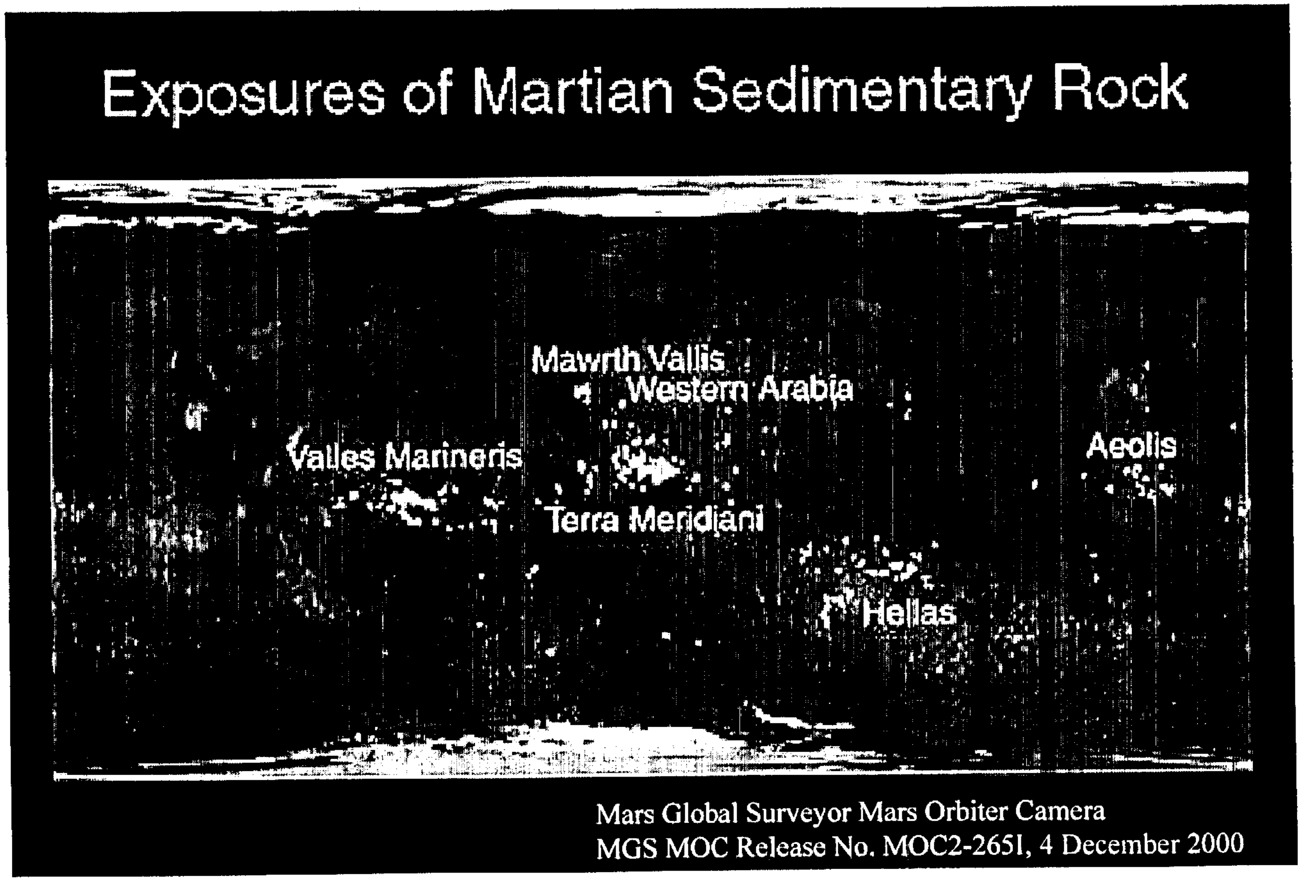
Analysis Process Summary

- Select set of SCENARIOS likely to be of highest interest to NASA (exploration, resource & life search, mining, etc.)
- Decompose each scenario into set of somewhat independent PRIMITIVE TASKS that must be performed (traverse, detect, drill, manipulate, assemble, repair, etc.)
- Define and compute TASK COMPLEXITY METRIC for each primitive task, or several metrics if needed - each metric depends only on the characteristics of the task itself, not on the solution options; complexity is measured relative to baseline task characteristics
- Define and compute a TASK VALUE METRIC for each primitive task - this metric reflects the relative importance (scientific for example) of doing the task.
- Conduct APTITUDE TEST for each primitive task and assign scores to human & robot subjects (thought experiments, simple models, inexpensive lab & field tests)
- Compute COMPOSITE task complexity metrics for 2 OR MORE primitive tasks that must be done jointly to execute COMPLEX mission sequences (e.g. deploy or assemble photo-voltaic solar array); compute joint composite test scores.

Robot & Human Surface Operations

Mission Scenarios Decompose into Primitive Tasks

Example #1: Exploration Mission



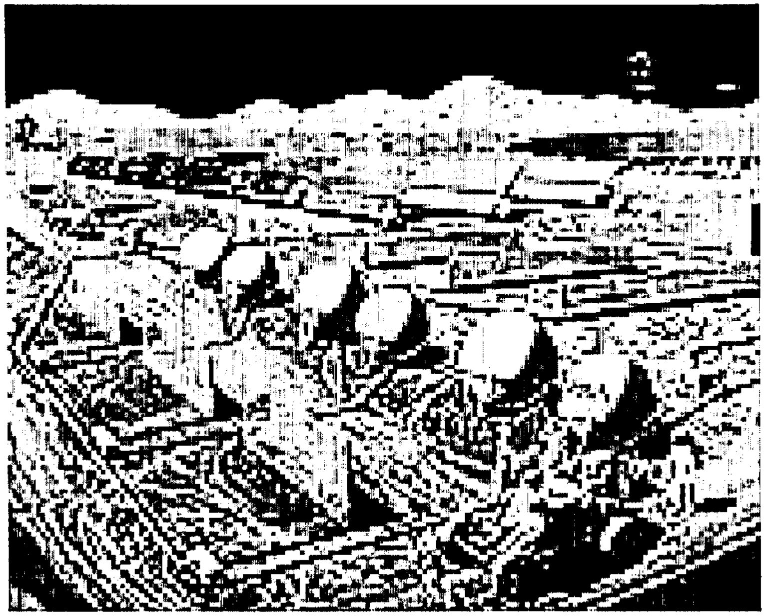
Primitive Tasks

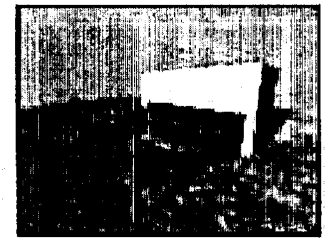
- Traverse - move over varying terrain
- Navigate - where am I; where to go
- Detect & select sample
- Grasp & handle sample
- Analyze sample
- Survive

Robot & Human Surface Operations

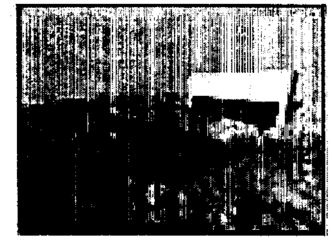
Mission Scenarios Decompose into Primitive Tasks

Example #2: Infrastructure Deployment Mission

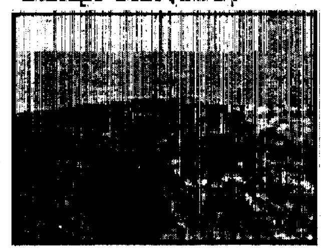




1. Unload container from Container Storage Unit (CSU)



2. Traverse to deployment site



3. Position and open container

4. Deploy PV tent

Primitive Tasks

- •Lift - packaged array module
- •Unload
- •Transport - move object
- •Recognize - object
- •Manipulate & mate parts
- •Localize -determine object x,y,z
- •Maintain & repair

Robot & Human Surface Operations

Features of the Projected Analysis Approach

- Simple to understand and interpret, because complex multi-dimensional problem is decomposed into several 1-dimensional problems

- It is relatively easy to define and compute "1-dimensional" complexity metrics and test scores

- Complexity metrics and aptitude test scores for complex tasks (done by robot-assisted & non-assisted humans, as well as tele-operated & autonomous robots) are estimated analytically to obtain integrated performance results.

- Expensive integrated and test for large complex experiments (e.g. terrestrial analog of structural assembly task) are avoided

- Proposed analysis approach avoids un-needed hardware expense by emphasizing analysis, thought experiments, and simple models.

Robot & Human Surface Operations

The "Getting There" Effect is a Major Consideration

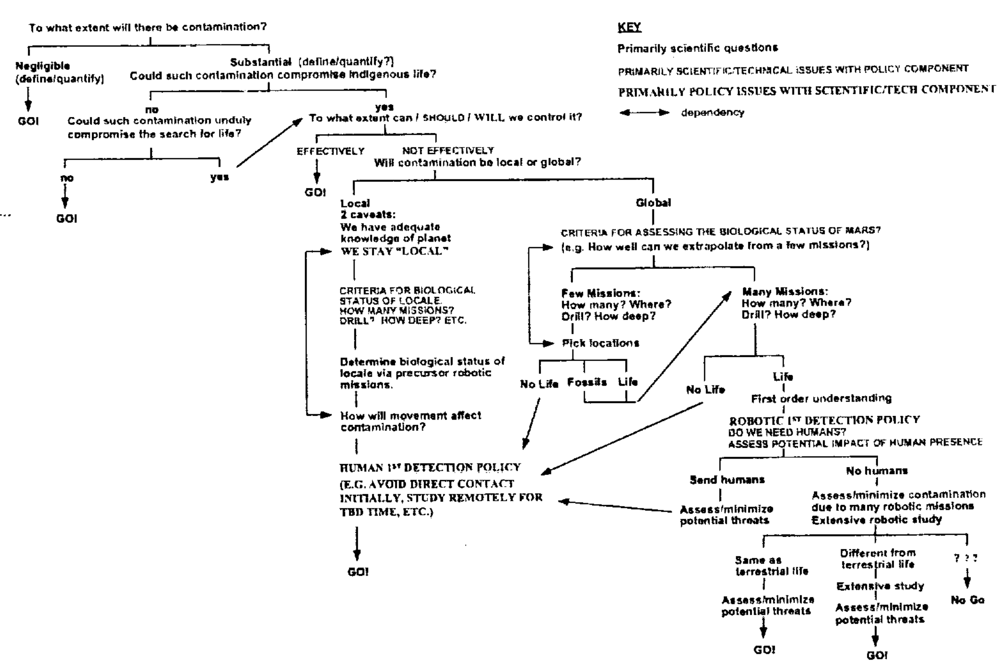
- Need to assess the likelihood that a given human (or robot) mission involving extensive surface operations can be made to happen in the foreseeable future.
  - More affordability
  - Benefits vs cost
  - Risk vs value
  - Public interest
  - Etc.

Human Mars Mission Contamination Issues

M. L. Lupisella

- A potential challenge for a human Mars mission is that while humans are by most measures the obvious best way to search for life on Mars, we may also be the most problematic in that we could unduly compromise the search for life by contaminating relevant environments and/or possibly adversely and irreversibly affecting indigenous life.
- Perhaps more problematic is the fundamental epistemic challenge of the "one data point" limitation which could decrease confidence in applying terrestrially based research to extraterrestrial life issues in general.
- An informal decision tree is presented as one way to begin thinking about contamination issues. There are many sub-questions and distinctions not shown such as biological vs. non-biological (but biologically relevant) contamination, viable vs. dead organisms, masking indigenous organisms vs. merely making the search more difficult, and independent origin vs. panspermia distinctions.
- While it may be unlikely that terrestrial microbes could survive on Mars, let alone reproduce and unduly compromise the search for life, the unpredictable potential for microbial life to survive, grow exponentially, evolve and modify (and sometimes destroy) environments, warrants focusing carefully on biologically relevant contamination as we prepare to send humans to the first planet that may have indigenous life-forms.

A Decision Tree for Addressing Human Mars Mission Contamination Issues



Summarizing thoughts:

- First questions first to avoid unnecessary resource consumption and unduly delaying a human mission. Obviously need more research/data to make informed decisions. Decision tree can help roadmap a research program.
- By addressing the issue now, we may find that the relevant precursor planning and execution should begin now.

  E.g. If contamination could go global, and if it is deemed necessary to assess the biological status of the entire planet (or just surface) with TBD confidence level, then many more life detection missions than otherwise thought may be required, likely effecting the overall program planning (especially schedule) for a human mission.
- Anticipates and addresses public concern.
- Contribute to astronaut safety - much of the research could inform procedural guidelines - e.g. how astronauts might be affected by indigenous organisms.
- Could help establish a planetary protection policy category to help guide program development for human exploration of the rest of the solar system and beyond.

Additional thoughts

- **"Traditional" national interests may not be the ultimate driver.** Alternatives might be:

  Search for a "second genesis" - not yet fully appreciated. E.g. practical implications such as medical, as well as more theoretical/general scientific rewards such as significance to understanding the nature of life. And the potential cosmological relevance: e.g. does the universe naturally produce life? "Is life a cosmic imperative?" Potential "world-view" relevance also. If the search for a second genesis is a primary driver, the contamination issue could be critical.

  Other motivations such as cultural significance (e.g. "Into the Unknown", inspiration for practical and emotional reasons, culture for its own sake), or perhaps international cooperation, may singularly, or together, be enough to justify a human mission. If we think these are important reasons, we should continue to cultivate them vigorously, both internally and with the public, and be a part of the motivation for a human mission, instead of of waiting for the political tide to raise our boats to Mars.
- **May need direct life-detection missions sooner than later** depending on criteria for assessing the biological status of locale, region, planet (surface or sub-surface?) - and depending on when we'd like to send humans. May be more feasible than we're imagining (technically, and cost) given a commitment and present work being done.

Additional thoughts con't

- **Co-evolutionary dependence is not required for organisms/species to adversely effect each other.** E.g. consumption of, and competition for, resources is likely fundamental to anything biological, giving rise to indirect effects such as competition for resources. Predation, toxicity, and general ecological disturbance (environmental modifications) are also possibilities that appear to transcend even a very broad notion of co-evolutionary dependence. So, the significance of, and unknowns of, a second genesis will likely call for much caution.
- **Worrying about this now may help boost confidence when the times comes for a decision.**
- **A near-human/"in-situ" tele-robotic mission could mitigate many contamination concerns, and others as well.** Here is a potential answer to what specific scientific pursuits require what kind of human/robot relationship. As we are doing with the broader program now, the near-human tele-operated mission could be done in a "seek, in-situ, sample" approach at the next level of exploration, that is, more detailed exploration with humans present on the planet, perhaps localized initially to a human base. If orbital data is insufficient, we can "seek" via tele-operated vehicles on the ground and in air (e.g. balloons/aerobots). In-situ searches for life and other science objectives can be pursued via tele-operating sophisticated robots at a specific locations from a home base. Samples can be brought back to the home base/lab on the surface or low Mars orbit, moon, etc., or perhaps an astronaut can go directly to a location to sample after sufficient tele-remote analysis. This keeps the human brain in the loop, allows for "real-time" responses and flexibility, and mitigates risk. Humans driving robots could also have surprising PR value - a different kind of "BattleBots" on Mars? Robots (and humans) challenged by the Martian environment instead...

Cooperative EVA/Telerobotic Surface Operations in Support of Exploration Science

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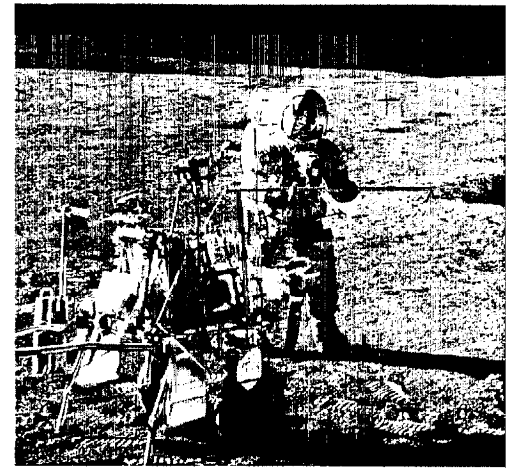
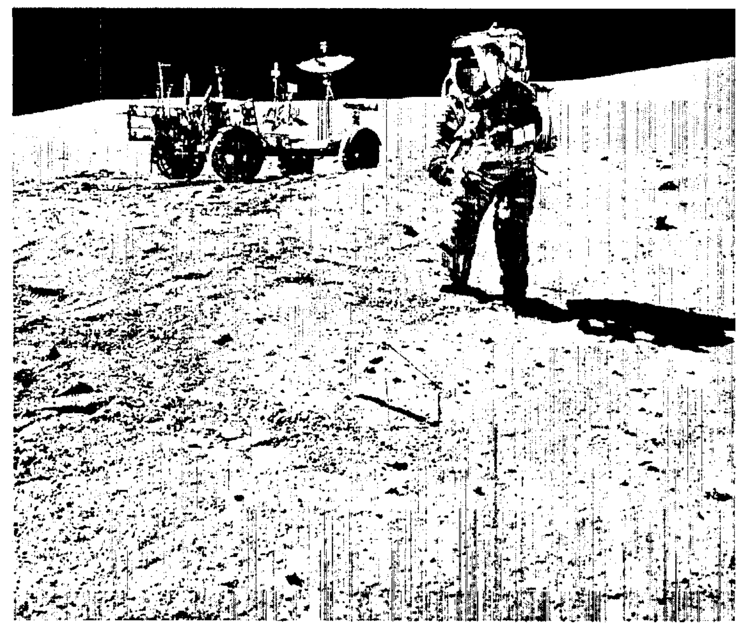
Planetary Surface Robotics

- EVA support and autonomous operations at all physical scales
  - Athena-class scout vehicles
  - Individual EVA support systems
  - 1-2 person transports
  - Extended access devices (e.g., cliff face sampling)
  - Base assembly and maintenance systems (cranes/dozers)
- No single system will be capable of fulfilling all requirements
- All systems should be capable of autonomy, high-level supervisory control, and teleoperation

EVA Difficulties from Apollo

- Extended traverses
- Transport of tools, samples, and instruments
- Navigation
- Situational awareness
- Drilling
- Sampling
- Sample documentation
- Communications
- Safety/Rescue





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Robotic Capabilities for EVA Support

- Surface mobility system
  - Extended traverses
  - Transport of tools, samples, and instruments
  - Safety/Rescue
- High-precision navigation system
  - Navigation
  - Safety/Rescue
- Multiple camera systems
  - Situational awareness
  - Sample documentation
- Robotic Manipulation Capabilities
  - Drilling
  - Sampling
- Communications
  - Relay to base and Earth
  - Public involvement

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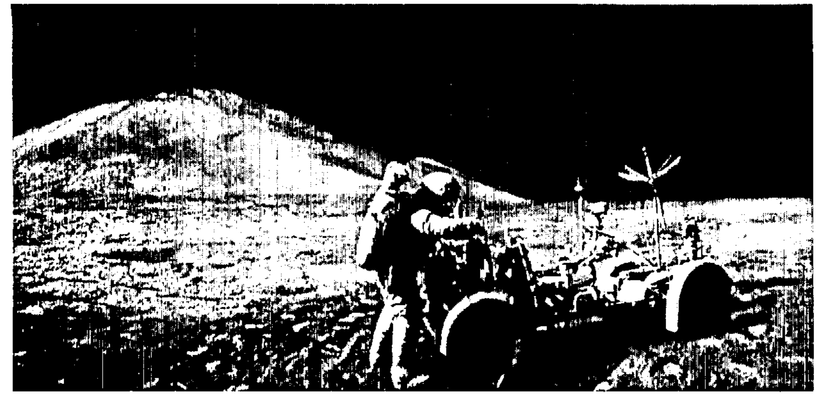
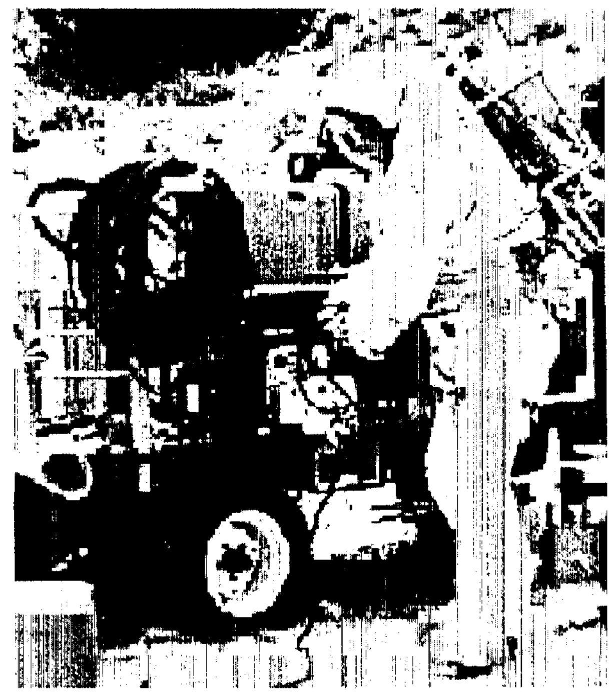
Astronaut Support Vehicle





Motivation

- *Lunar exploration*
- *Recent field tests*
- *On-orbit operations*
- *Interplanetary exploration - Mars*

Rationale

- *Improve extravehicular activity (EVA) productivity*
- *Increase EVA safety*
- *Alleviate load carried by astronauts*
- *Reduce astronaut fatigue*
- *Provide emergency life support*

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Three ASV Preliminary Designs

- Graduate robotics design class in Fall, 1998
  - Trade study between arm configurations
  - Precursor to integrated team design effort
- Displayed at EVA Forum in October 1998
- Formation of final mission assumptions, design scenarios, and design requirements
- Mission requirements
  - Support two astronauts on 4 hour EVA
  - 400-day useful life
  - Capable of astronaut-traversable terrain (0.3m obstacle, maximum astronaut speed = 4.8 kph)
  - Carry EVA tools and contingency life support

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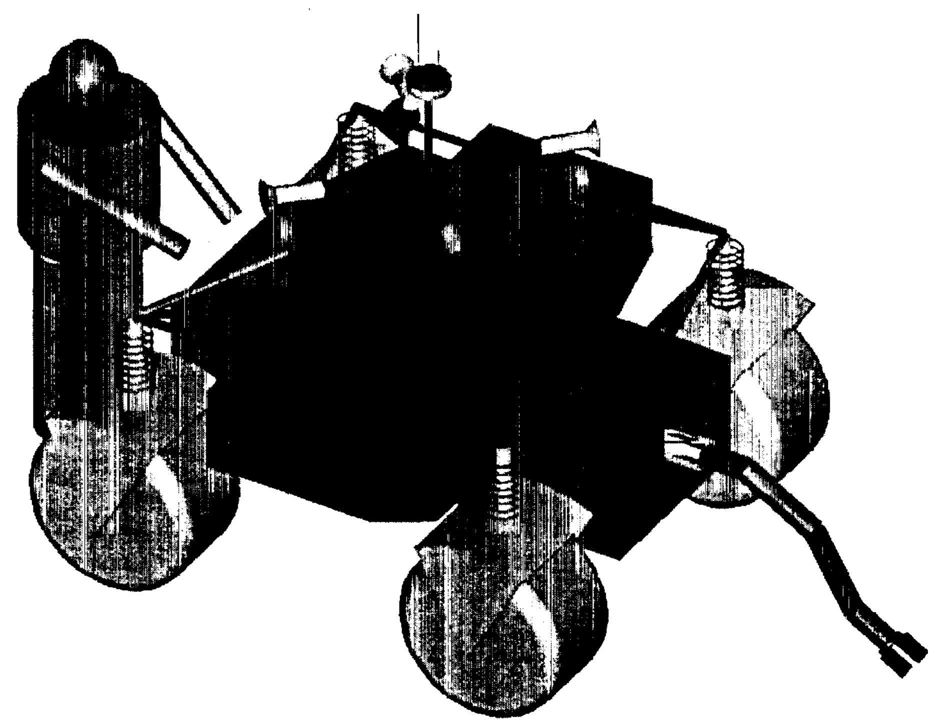
Small Single-arm Assistant

- Single dexterous arm
- Total mass = 760 kg
- Power = 960 W
- 75 kg of samples
- Unable to carry astronauts



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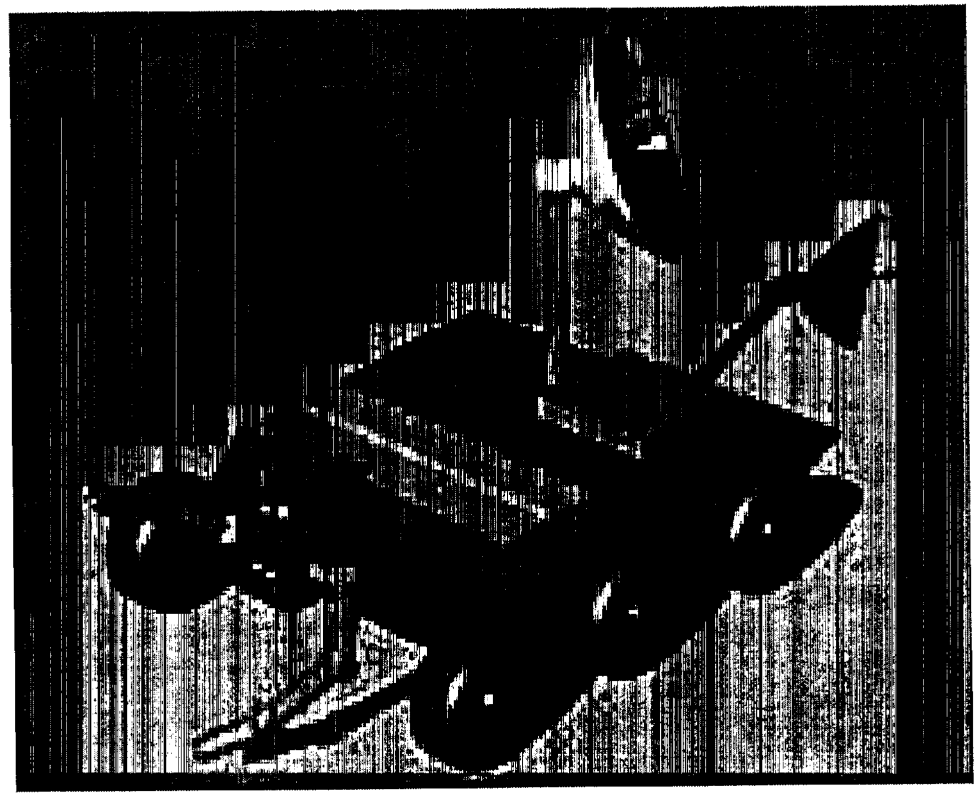
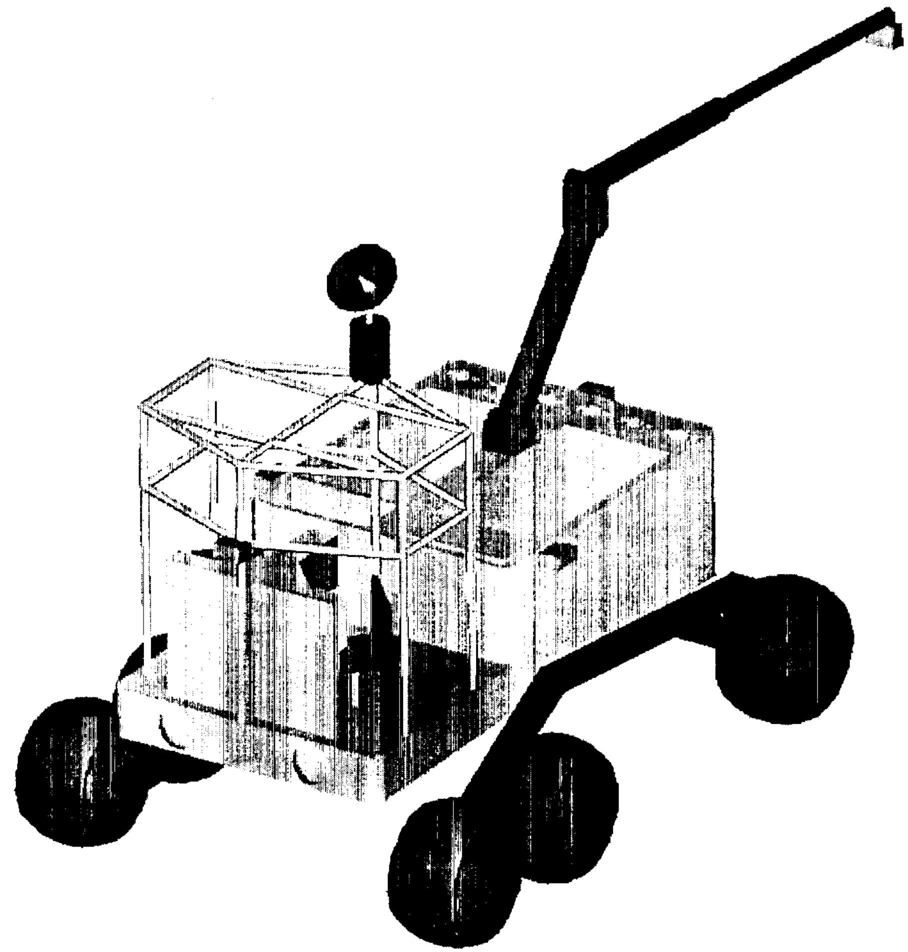
Dual-arm Assistant

- Pair of dexterous arms
- Total mass = 700 kg
- Power = 1000 W
- 370 kg of samples
- Modular 2-hr battery packs and 75 kg sample storage containers
- Ability to carry one astronaut



Large EVA Assistant

- Large positioning manipulator and pair of dexterous arms
- Total mass = 1700 kg
- Power = 4000 W
- 500 kg of samples
- Able to transport two astronauts to and from site



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Lessons Learned - Preliminary Designs

- Decrease mass, power, and volume
- Parameters driving rover size:
  - Manipulators
  - Astronaut transport ability
- One arm sufficient for most geological tasks
- Sample storage a function of quality of science that can be done on site
- Define feasible amount of samples to return to base
- More precise mission scenarios

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Rover Design Assumptions

- Two astronauts per EVA
- Rover assisted EVAs conducted only during daylight hours
- Astronaut maximum speed = 4.8 kph
- 4 hour EVA duration, 6 km from base
- Rover not required to navigate terrain unsuitable for suited astronaut
  - Largest surmountable obstacle = 45 cm
  - Maximum traversable slope = 20°
- Martian satellite terrain images available
- Deployable Instrument Packages (DIPs)
  - Mass = 20 kg
- Pre-integrated 7 DOF dexterous manipulator payload
- Target mass = 300 kg

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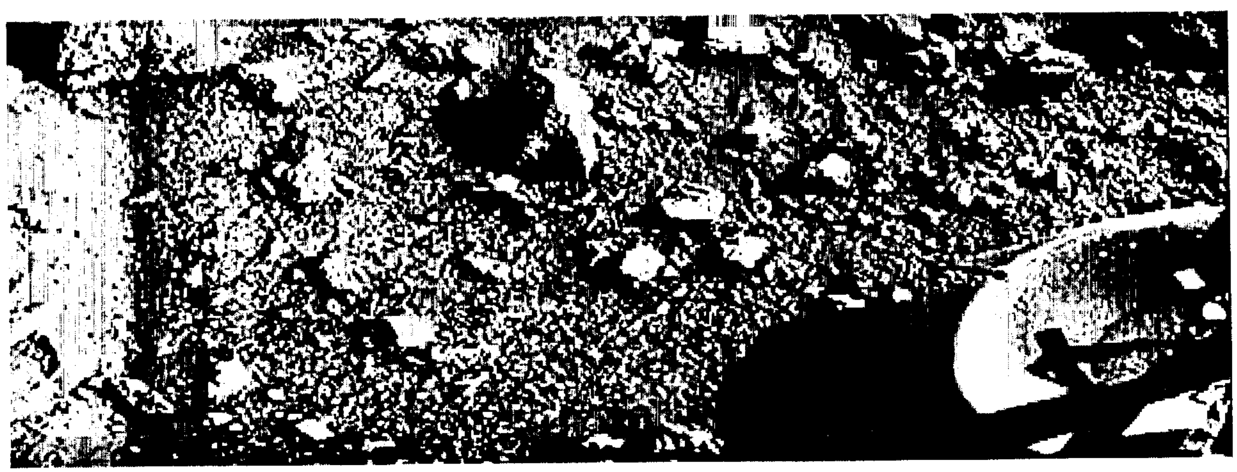
Design Requirements - Terrain

- Maximum rover speed = 8 kph
- Forward and lateral operations on 20° maximum slope
- Obstacle clearance of 45 cm
- 4-hour EVA/day, 6 days/week, for 400 days
- 8 hour maximum battery contingency



Design Requirements - Payload

- Retrieve, label, catalogue, and carry samples
- Carry and support one 7 DOF dexterous arm
- Carry astronaut hand tools
- Provide 2 hours contingency life support for two astronauts
- Support minimal in-field scientific testing

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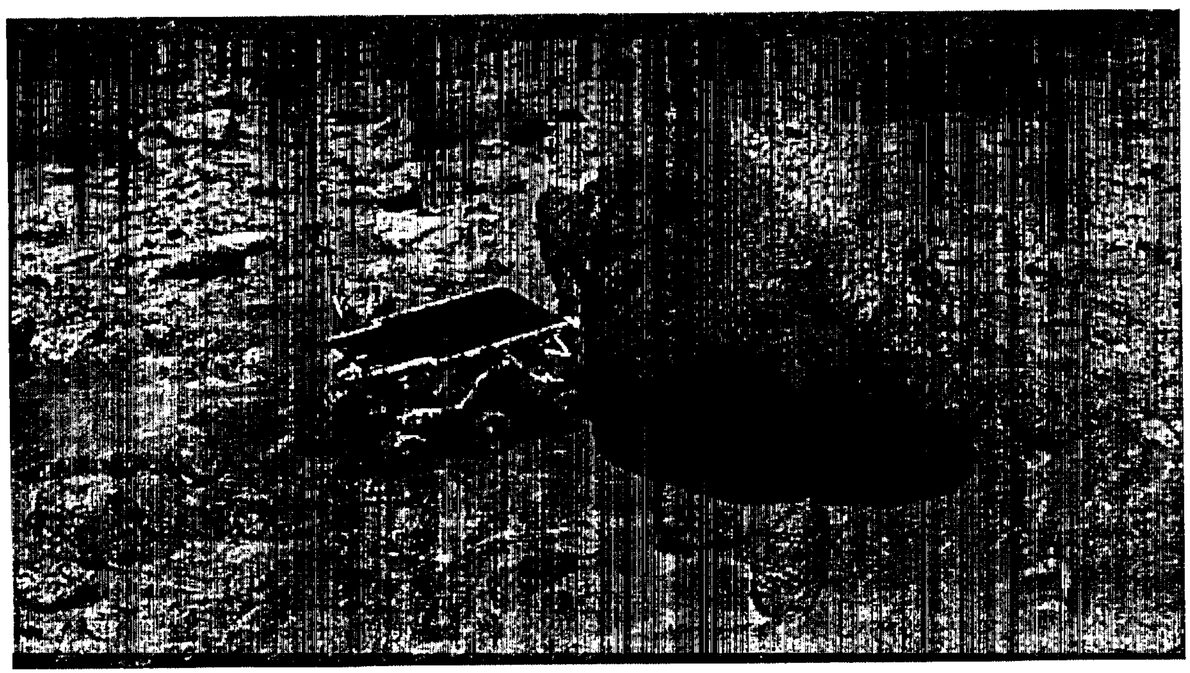
Design Requirements - Autonomy

- Basic obstacle avoidance
- Track two astronauts at all times and relay video to base
- Astronaut awareness and safety parameters
- Maintain current position estimate



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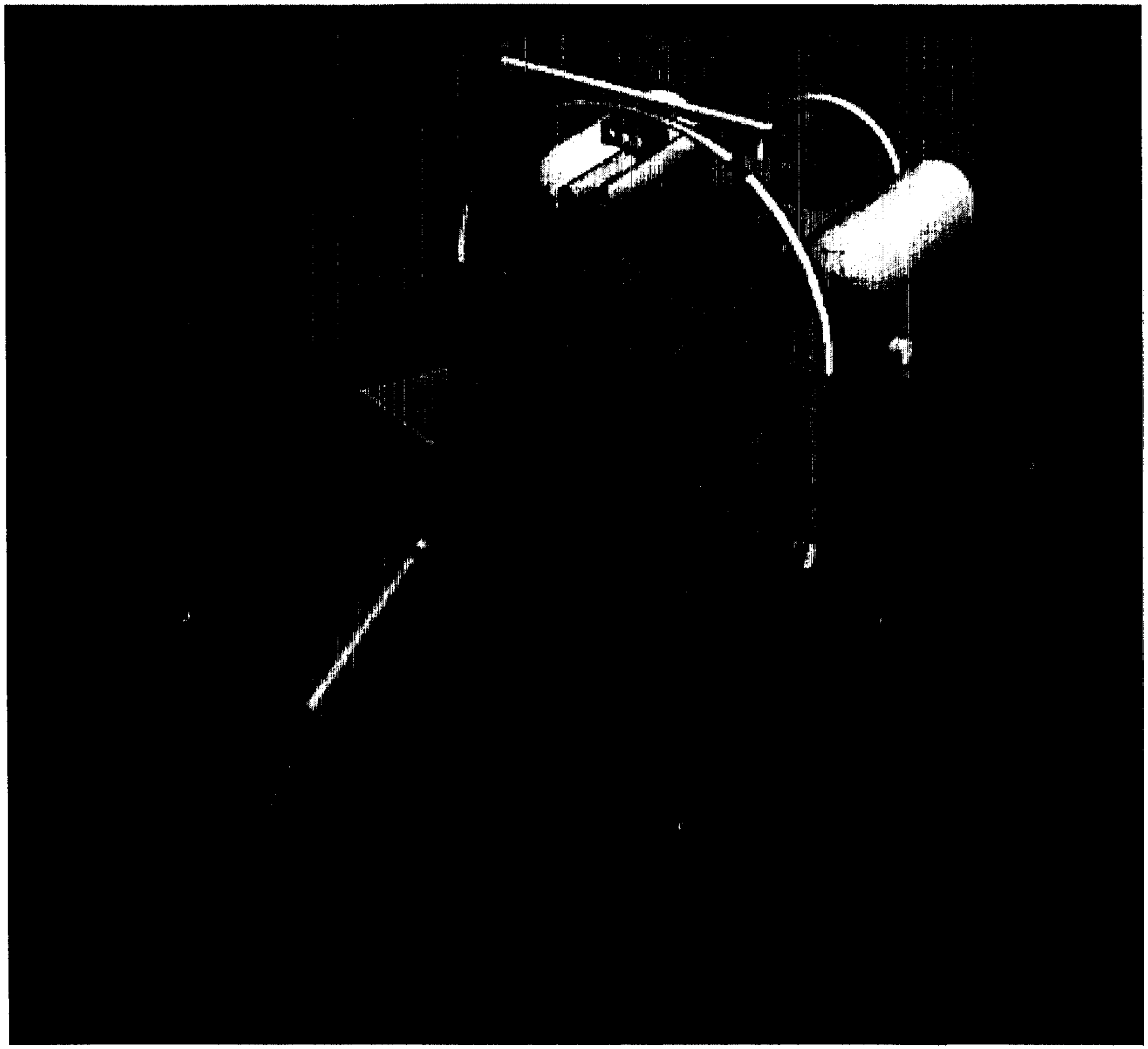
Second Design Iteration



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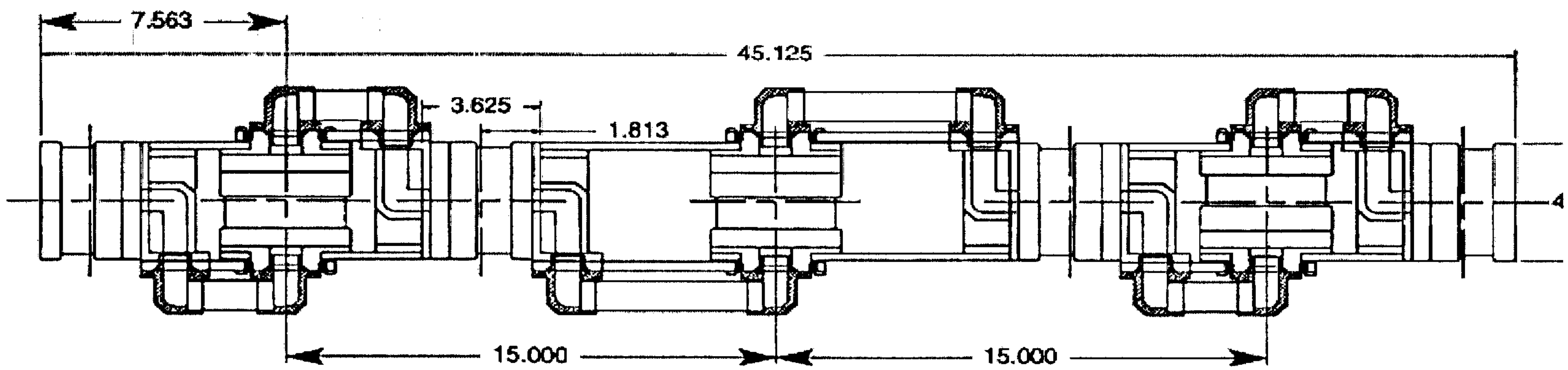
Science Payload

Support geological surveys, sample collection, environmental data collection and minimal in-field testing

- *Cameras*
  - *Panospheric, stereo, infrared, manipulator arm*
- *Telescope, microscope*
- *Images stored digitally on the rover and at base camp*
- *Sample bin and packager*
- *Dexterous manipulator arm*
- *Total mass = 79 kg*
- *Maximum power = 750 W*

Manipulator Arm

- 7 DOF pre-integrated package
  - Requires power and intelligence from rover
- Length = 114 cm
- Tip force = 111 N
- Mass = 18 kg
- Peak power: 590 W
- End effectors
  - Scooper/grasper, jackhammer



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EVA-Robotic Interface Modes

- Geological site survey at all scales
  - Variable zoom telescope for close site inspections
  - Microscope for rapid categorization of samples
  - Images fed to HUD in EVA suit
- EVA-directed site operations
  - Target designation by marker, laser spot, or gesture
  - High-level voice command
  - Autonomous EVA tracking via vision system or laser scanners
  - Ability to control dexterous manipulators through nonintrusive master-slave arrangements
- Contingency command interfaces
  - Ability to manually drive onboard/offboard
  - Access to graphical display for system status, contingency resolution
  - Redundant safety systems

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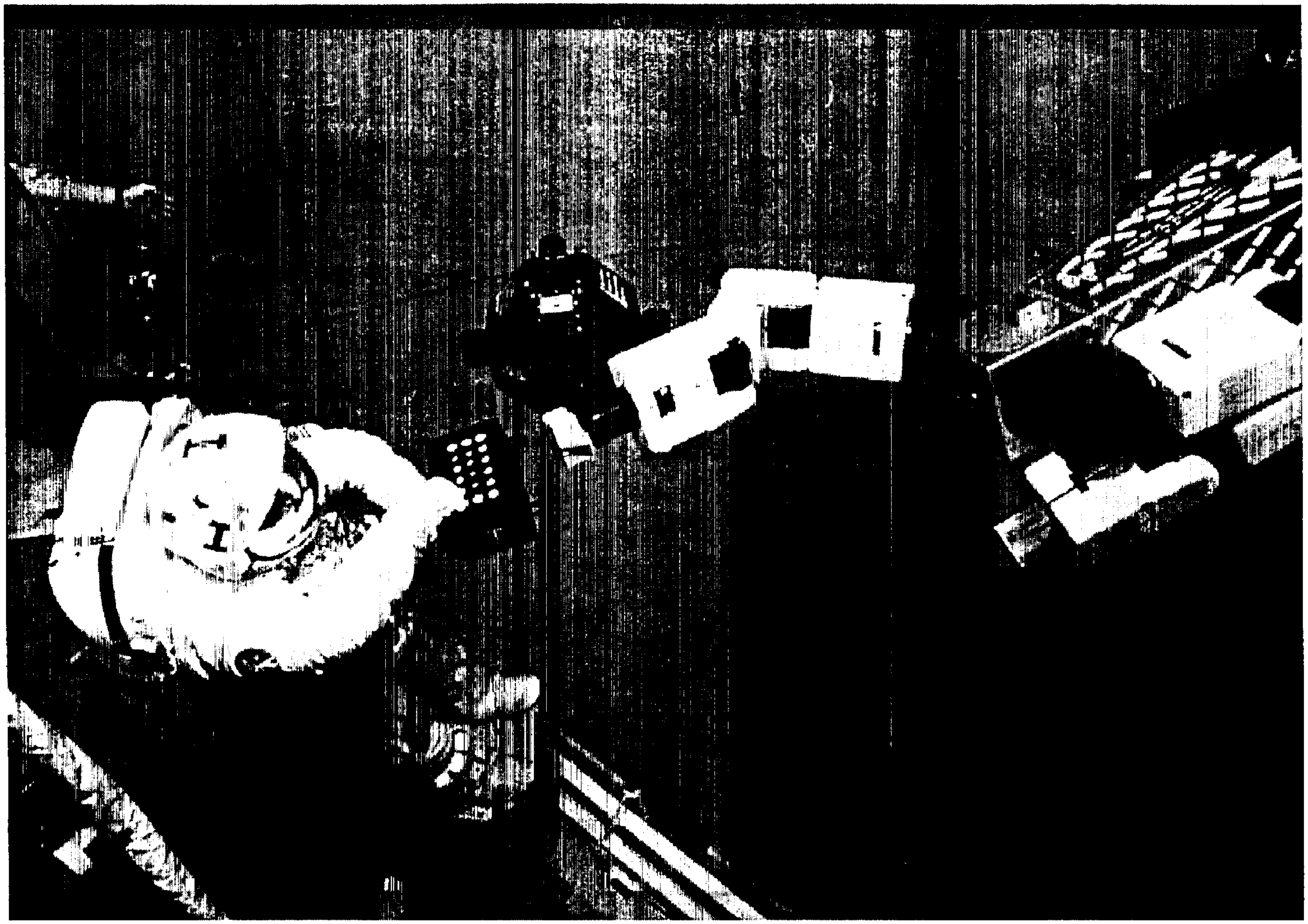
EVA/Multiple Robot Cooperation



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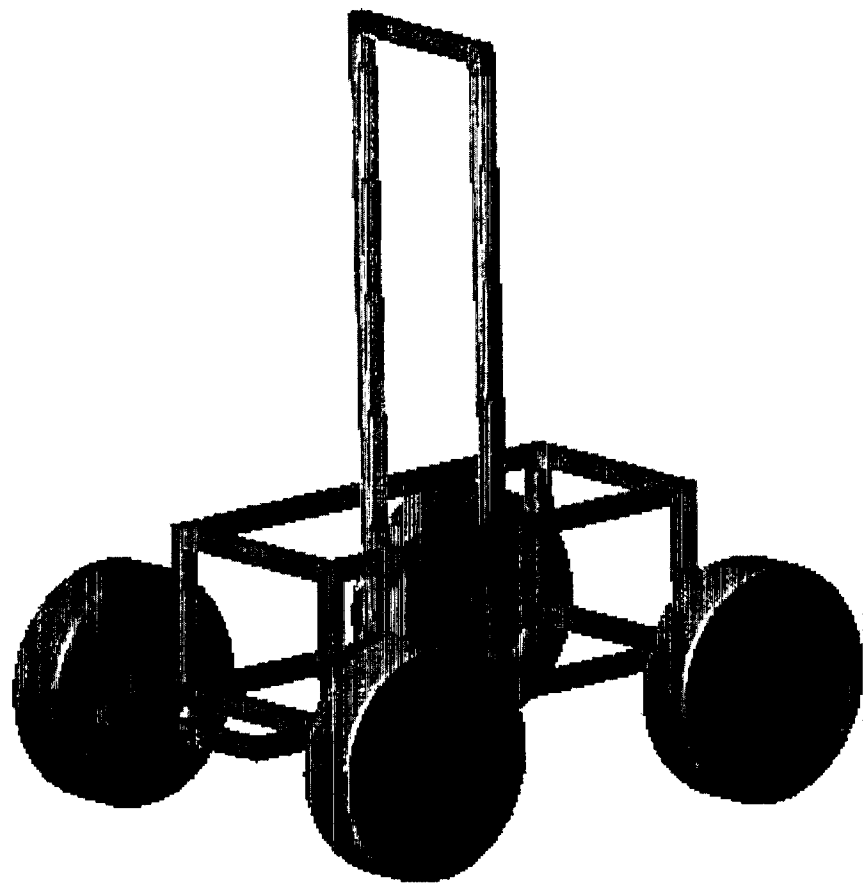
Continuing Research

- *Reconsideration of requirements for EVA support rover*
  - *Single astronaut ride-on capability in nominal operations*
  - *Simplification of basic unit (four-wheel independent suspension instead of six-wheel rocker bogey)*
  - *Incorporation of mission-specific trailers along with basic unit*
  - *Dual dexterous manipulators*
- *Detailed design of experimental unit*
  - *Modular structure for subsequent reconfiguration*
  - *Standard wheel assembly (all-wheel steer, all-wheel drive)*
- *Initiated research into critical technologies*
  - *Autonomous following incorporating obstacle avoidance*
  - *EVA interfaces for direct vehicle control*

SSL Rover Body Concept



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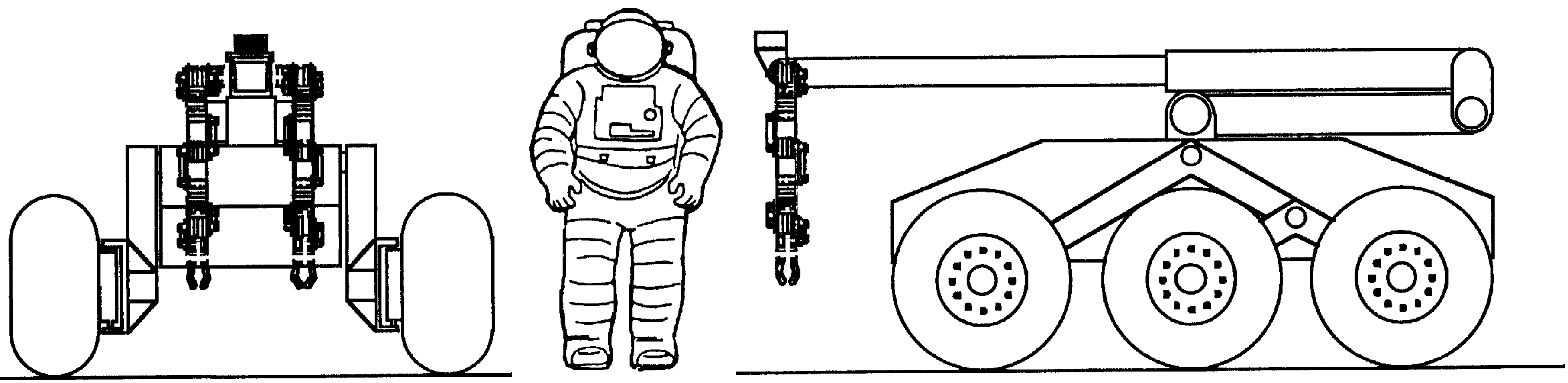
Advanced EVA Support Rover Concept



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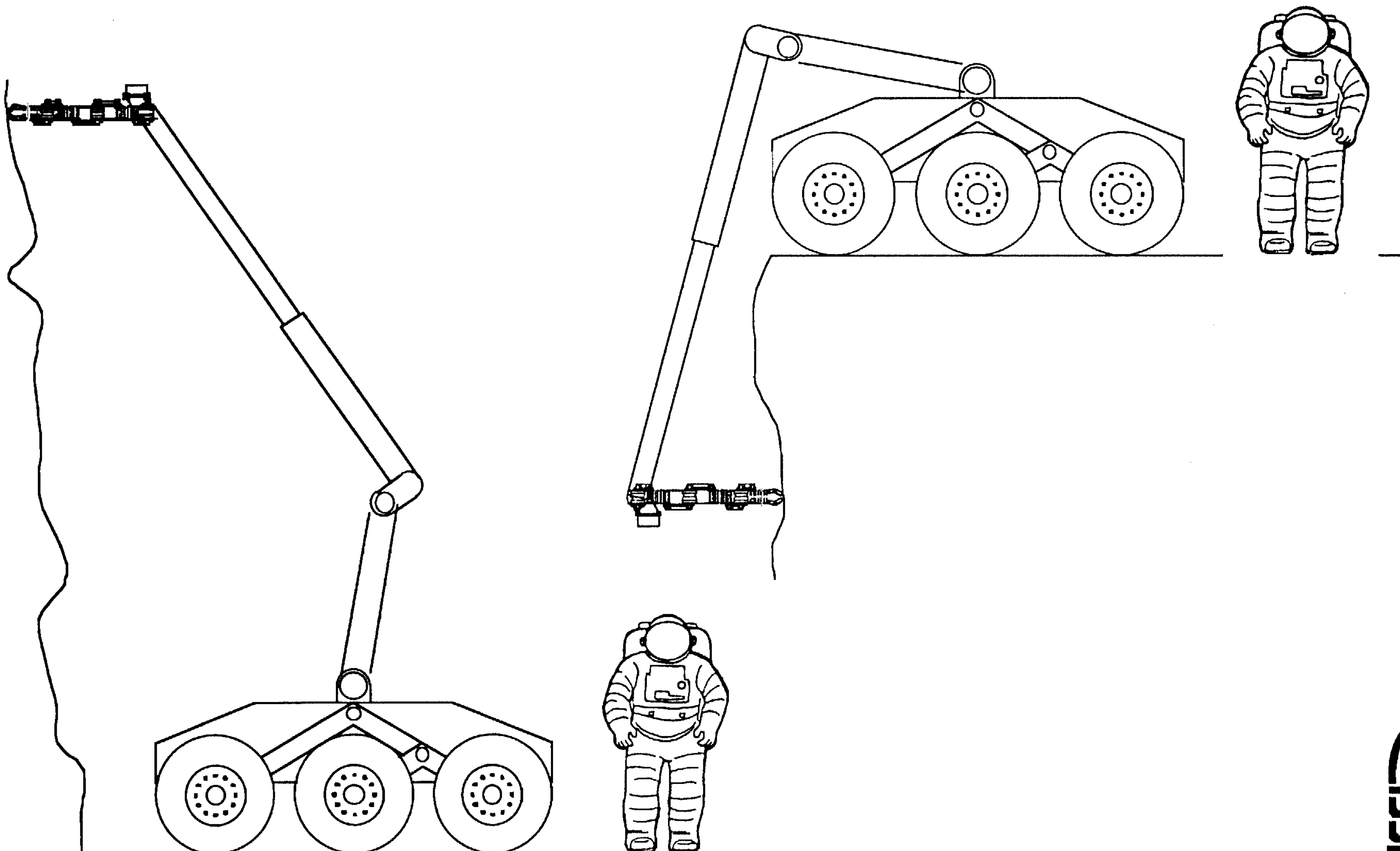
Robotic Access to Restricted Sites



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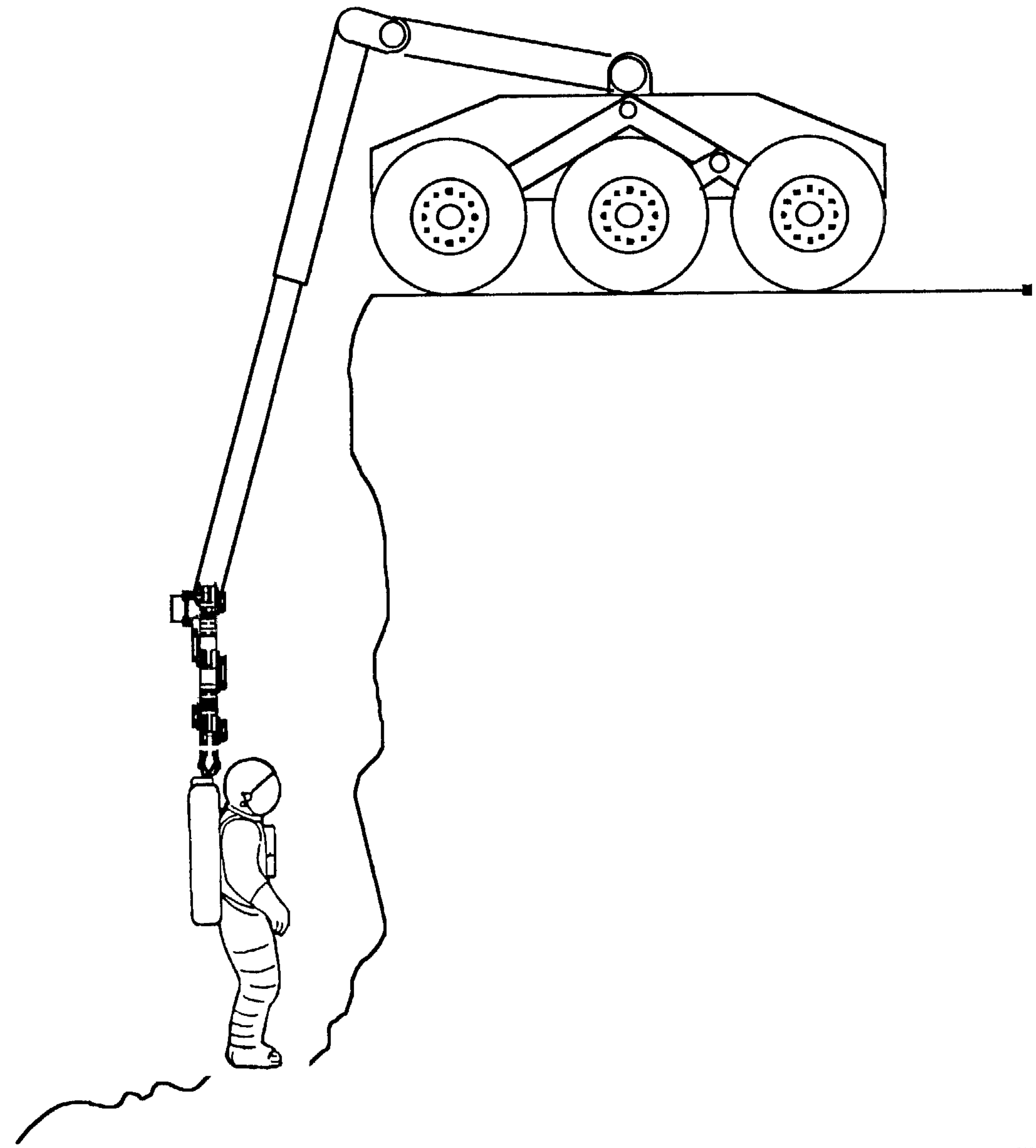
Robotic Rescue of EVA Crew



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Why Do We Need Humans?

- Rapid high-resolution visual discrimination
- Experience and judgement
- Dexterity
- Generically-applicable physical strength
- Resiliancy
- Maintenance and repair
- Improvisation
- Public Involvement
- Fun

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Conclusions

- Robotics are critical for human support and performance enhancement
- Robots in all sizes will be required for human planetary exploration
- Think of EVA suit systems and robotic support elements as a single integrated system
  - Command and data interfaces
  - Commonality of components (e.g., batteries)
  - Interoperability
- Critical near-term capabilities are mobility, safety, and specialized sampling
- Human/robotic cooperative systems will evolve to true symbiotic relationship between humans and robots

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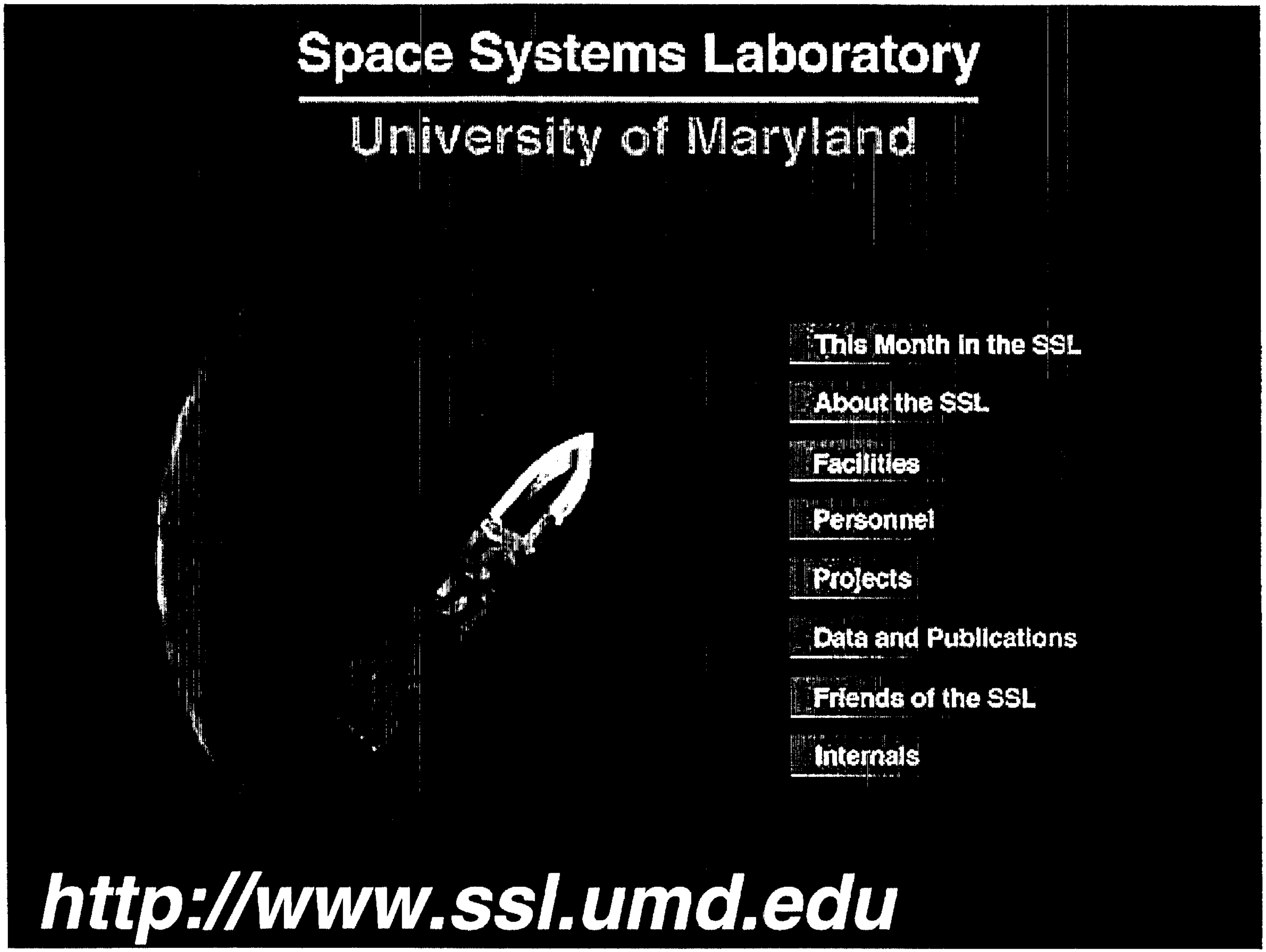
For More Information



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Analog studies in preparation for human exploration of Mars

Kelly Snook
Space Projects Division
NASA Ames

January 11, 2001
Science and the Human Exploration of Mars Workshop

1/11/01

What are the Questions?

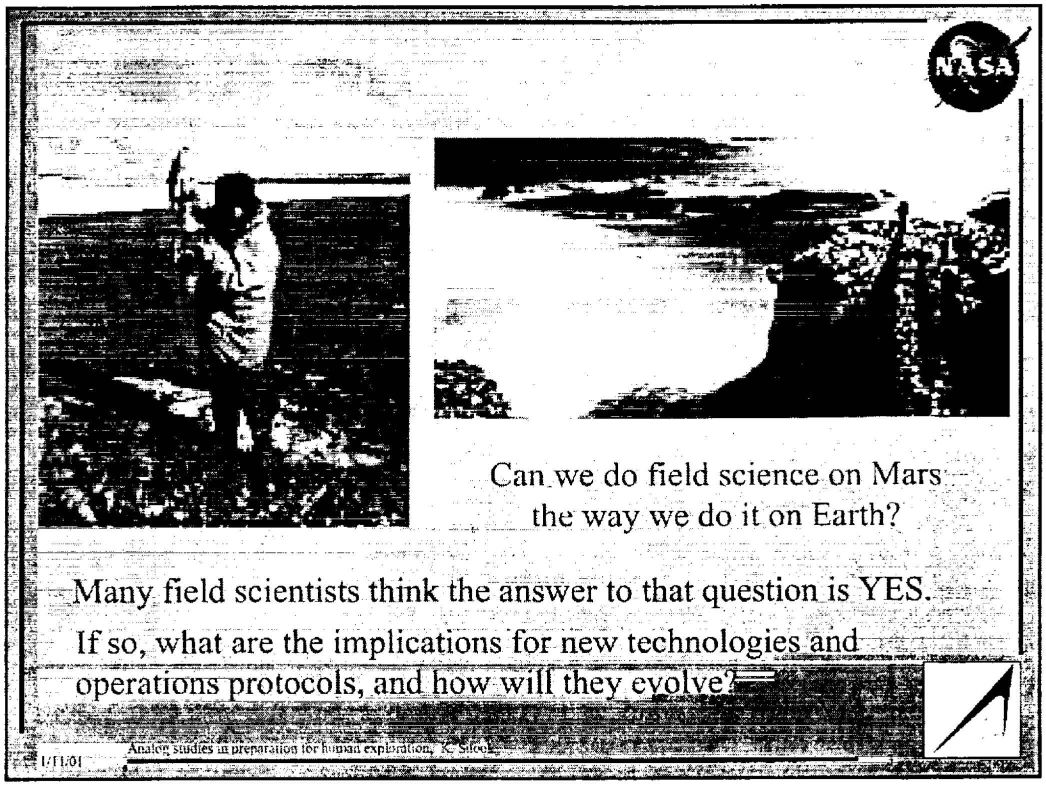
Key question

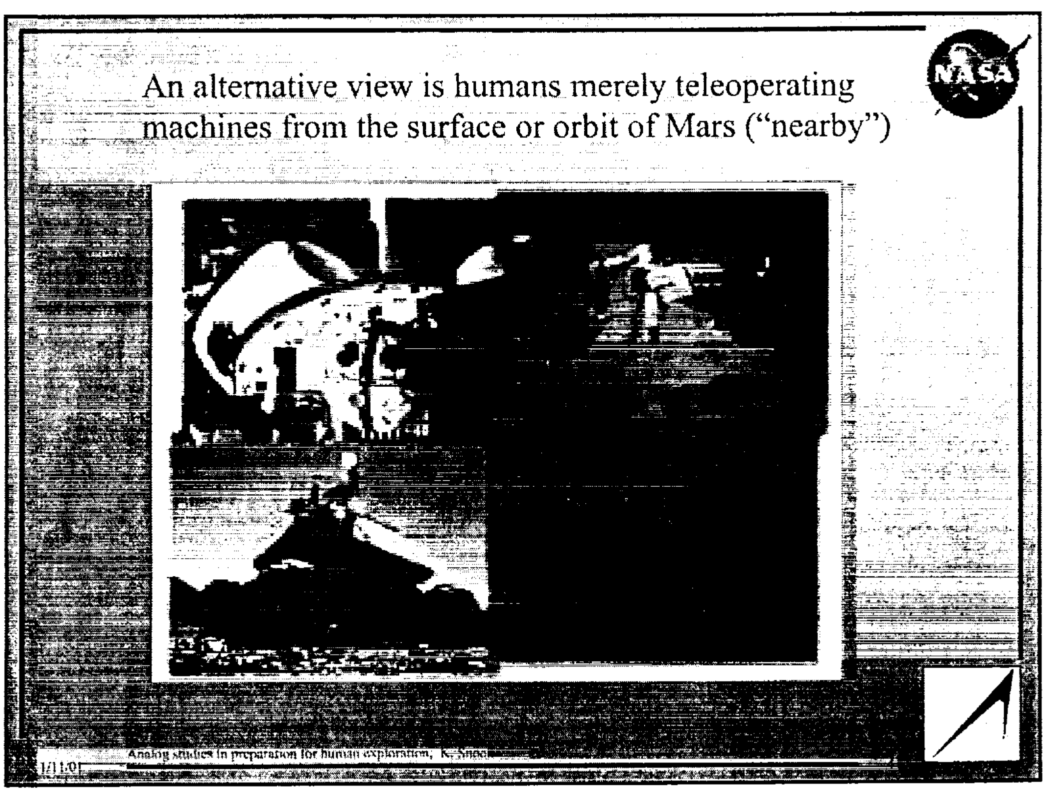
- How will humans and machines work together doing field science and exploration on Mars?

Other questions

- How is the intrinsic scientific merit of analog biology and geology best applied to human space exploration?
- How are the human factors issues associated with long-term human exploration of space best studied?
- What role can analog studies on Earth play in outreach and education towards building public support for humans in space?
- How can analog studies pioneer collaborative human exploration activities between established research organizations and NGO or commercial funding sources?

1/11/01 Analog studies in preparation for human exploration, K. Snook


Can we do field science on Mars
the way we do it on Earth?
Many field scientists think the answer to that question is YES.
If so, what are the implications for new technologies and operations protocols, and how will they evolve?
Analog studies in preparation for human exploration, K. Snook
1/11/01


An alternative view is humans merely teleoperating machines from the surface or orbit of Mars ("nearby")
Analog studies in preparation for human exploration, K. Snook
1/11/01

Solution

- Evolution to solution requires a balanced, strategic, empirical approach
- It takes trial and error, time, and lots of experience to learn how to use new technology in field exploration
- Examples:
  - Airplanes and helicopters revolutionized field work on Earth
    - Transportation
    - Perspective (aerial photography, surveying)
  - GPS technology is in the process of fundamentally altering the way field science is done

1/11/01 Analog studies in preparation for human exploration, K. Snook 5

New Technologies

- Spacesuits - Can we go from spaceship to parka? To what extent do we need to for doing Mars field science?

1/11/01 Analog studies in preparation for human exploration, K. Snook 6


New Technologies
NASA
• Spacesuits - Can we go from spaceship to parka? To what extent do we need to for doing Mars field science?
• Information Technology - What are the high-leverage areas for IT? How will the interaction really work? Will field scientists let machines make autonomous science decisions?
1/11/01
Analog studies in preparation for human exploration


New Technologies
NASA
• Spacesuits - Can we go from spaceship to parka? To what extent do we need to for doing Mars field science?
• Information Technology - What are the high-leverage areas for IT? How will the interaction really work? Will field scientists let machines make autonomous science decisions?
• Rovers - FIDO? Lunar rover? Pressurized 'Winnebago', or combination of all?
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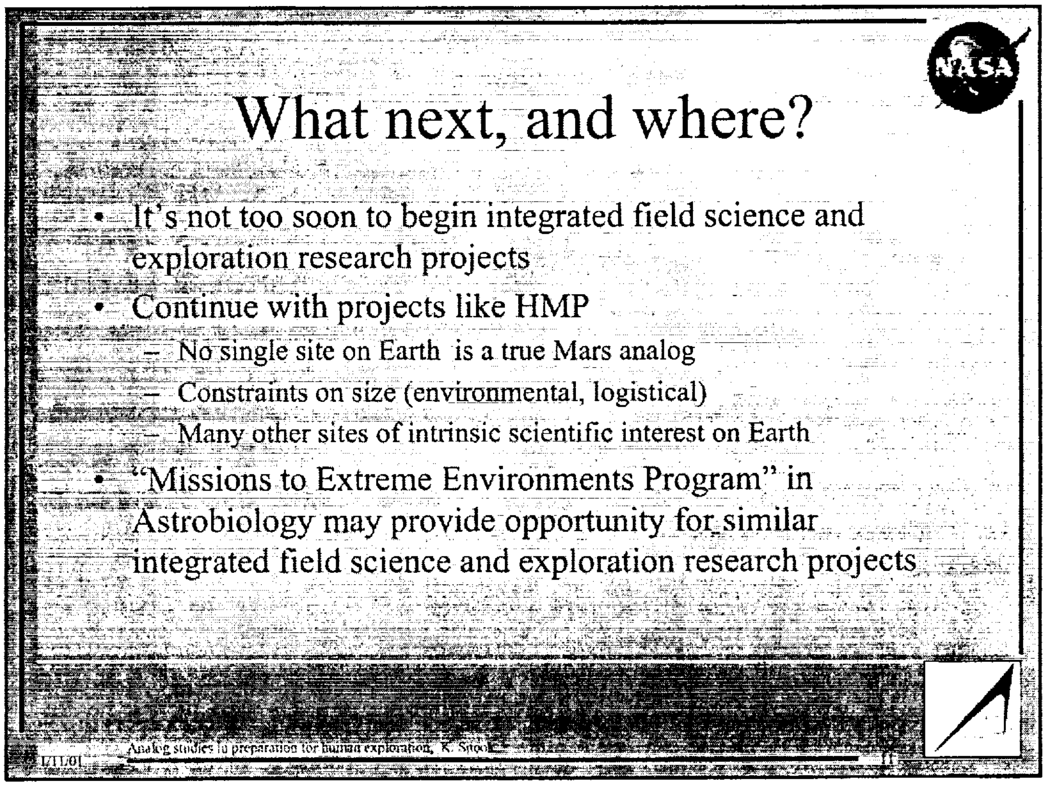
Analog studies in preparation for human exploration

Existing Analog Studies

- Numerous analog studies in Arctic, Antarctic, desert, undersea, underwater, etc., most either pure science or focused on specific technology demonstration (e.g. Nomad, TROV, Marsokhod, Dante, FIDO)
- New technologies have been tested primarily in the lab or in the 'back lot'
- NASA Haughton-Mars Project is the first attempt at a comprehensive integrated field science and exploration research program in the context of advancing overall understanding of human scientific exploration beyond low earth orbit

NASA Haughton-Mars Project

- Field science at the Haughton Impact Crater and surroundings on Devon Island, Canada (High Arctic), since summer 1997
- International, interdisciplinary team (up to 30 separate investigations per field season, typically 20-30 field participants at a time)
- Research program: Field science, and opportunistic exploration research experiments in support of field science (www.arctic-mars.org):
- SCIENCE PROGRAM
  - To characterize those aspects of the local geology and biology that might be relevant to Mars's geologic (in particular hydrologic) and possibly biologic evolution
  - To further our understanding of the effects of impacts on Earth through studies of the formation and evolution of Haughton Crater over time
  - To further our understanding of the possibilities of life in extreme environments
- EXPLORATION RESEARCH PROGRAM
  - Operations: Simulated Mission Control operations (JSC)
  - IT: Intelligent systems and mobile exploration communications tools
  - Tools: EVA, Balloons, rovers, airplanes, helicopters, hoppers, weather stations
  - Other: Human factors, human centered computing, food science


What next, and where?
• It's not too soon to begin integrated field science and exploration research projects
• Continue with projects like HMP
– No single site on Earth is a true Mars analog
– Constraints on size (environmental, logistical)
– Many other sites of intrinsic scientific interest on Earth
• "Missions to Extreme Environments Program" in Astrobiology may provide opportunity for similar integrated field science and exploration research projects
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Analog studies in preparation for human exploration, K. Snook
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Linking Human and Robotic Missions
- Early Leveraging of the Code S Missions

Doug Cooke
Johnson Space Center
January 11, 2001

Introduction

- A major long term NASA objective is to enable human exploration beyond low Earth orbit
- This will take a strategic approach, with a concentration on new, enabling technologies and capabilities
- Mars robotic missions are logical and necessary steps in the progression toward eventual human missions
  - To reduce risk and cost
  - Assure the maximum science and discovery return from human missions

Robotic Missions Add to Knowledge Base

- Provide scientific basis for human exploration
- Understand the environment to:
  - Identify and mitigate hazards to assure safety
  - Reduce environmental uncertainties and identify constraints to assure safe and efficient spacecraft and systems

  Analogies- Ranger, Lunar Orbiter, and Surveyor for Apollo
- Demonstrate technologies that can only be verified in the Martian environment

  Analogies- Surveyor, Mercury, and Gemini for Apollo
- Emplace infrastructure for human use
- Identify high yield landing sites for future missions
- Provide operational experience from analogous missions
- Use Mars resources to enable human missions (Living off the Land, or ISRU)

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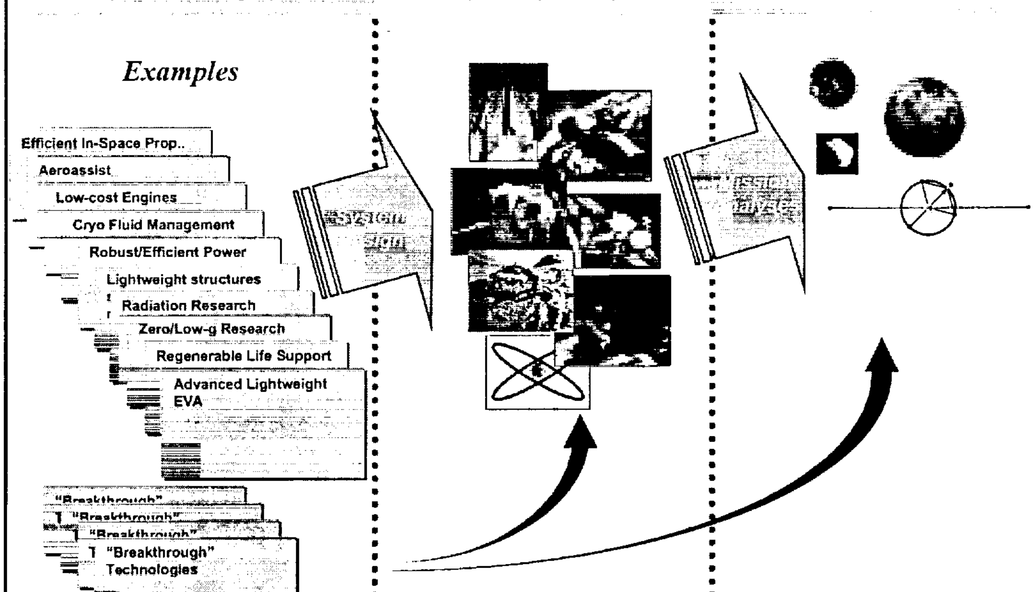
Core Capabilities & Technologies

Common Technology Building Blocks (Core Technologies) | *Common System Building Blocks (Core Capabilities)* | *Potential Destinations*



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Enabling Capabilities- The Importance of Mass Savings

It takes 40 Kg of mass in Low Earth Orbit to propel a Kg of mass all the way to Mars and then return it to Earth, *in terms of engines, tanks, fuels, propellants, and supporting systems*

- A number of technologies/capabilities have been shown to significantly reduce mission masses and therefore costs
  - Aerocapture- using the atmosphere of a planet and the drag of the vehicle to slow vehicles into orbit instead of using propulsive techniques- saving propellant and supporting systems
  - Advanced In-space propulsion technologies can improve fuel efficiencies by 4 to 5 times over the most efficient chemical propulsion. Example- electric propulsion
  - In situ propellant production- If fuel is produced at Mars to get a vehicle into Mars orbit, then that fuel does not have to be brought all the way from Earth
- Savings from these technologies can benefit both human and robotic missions

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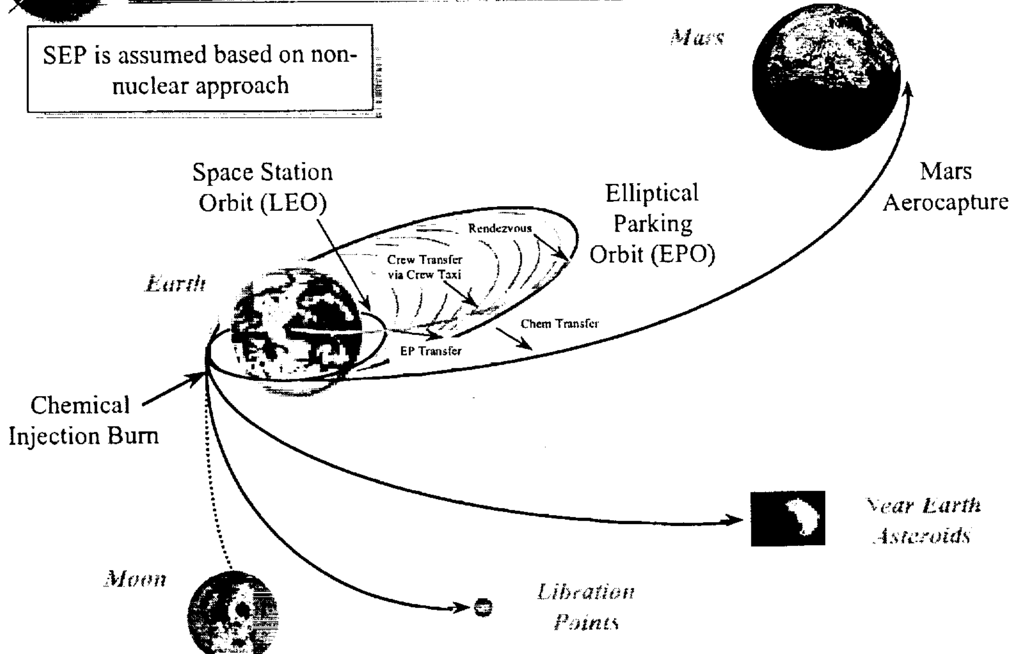
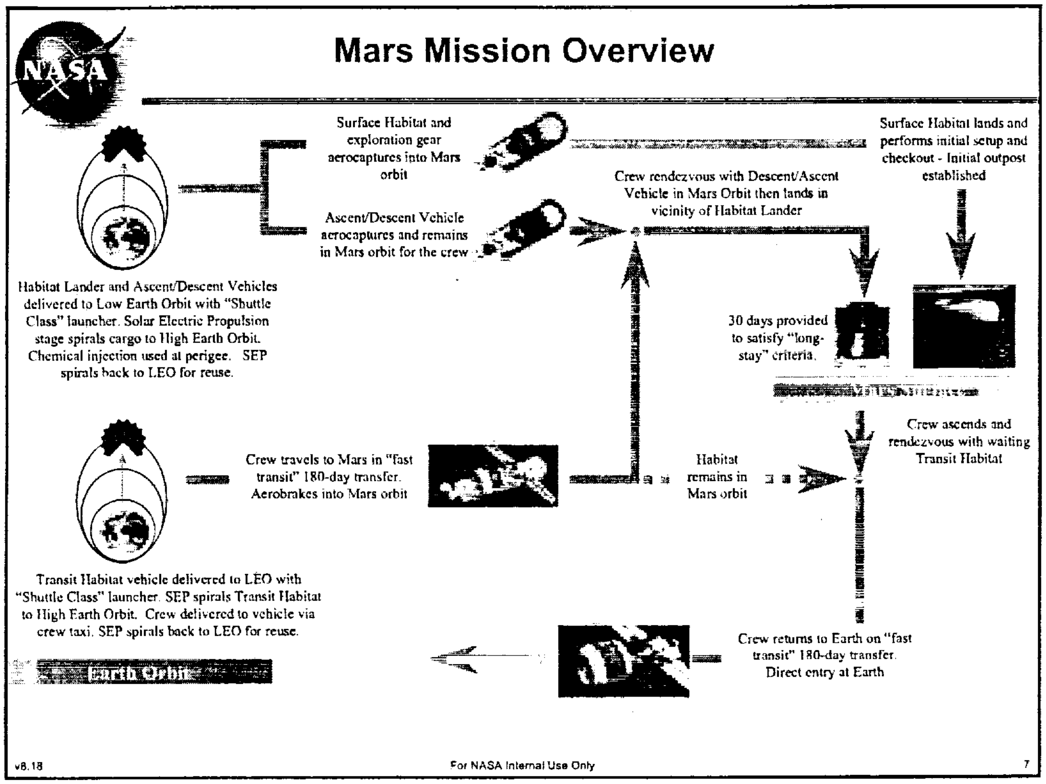
Mission Staging Scenarios

SEP is assumed based on non-nuclear approach




Mars Mission Overview
Surface Habitat and exploration gear aerocaptures into Mars orbit
Surface Habitat lands and performs initial setup and checkout - Initial outpost established
Crew rendezvous with Descent/Ascent Vehicle in Mars Orbit then lands in vicinity of Habitat Lander
Ascent/Descent Vehicle aerocaptures and remains in Mars orbit for the crew
Habitat Lander and Ascent/Descent Vehicles delivered to Low Earth Orbit with "Shuttle Class" launcher. Solar Electric Propulsion stage spirals cargo to High Earth Orbit. Chemical injection used at perigee. SEP spirals back to LEO for reuse.
30 days provided to satisfy "long-stay" criteria.
Crew ascends and rendezvous with waiting Transit Habitat
Crew travels to Mars in "fast transit" 180-day transfer. Aerobrakes into Mars orbit
Habitat remains in Mars orbit
Transit Habitat vehicle delivered to LEO with "Shuttle Class" launcher. SEP spirals Transit Habitat to High Earth Orbit. Crew delivered to vehicle via crew taxi. SEP spirals back to LEO for reuse.
Crew returns to Earth on "fast transit" 180-day transfer. Direct entry at Earth
Earth Orbit
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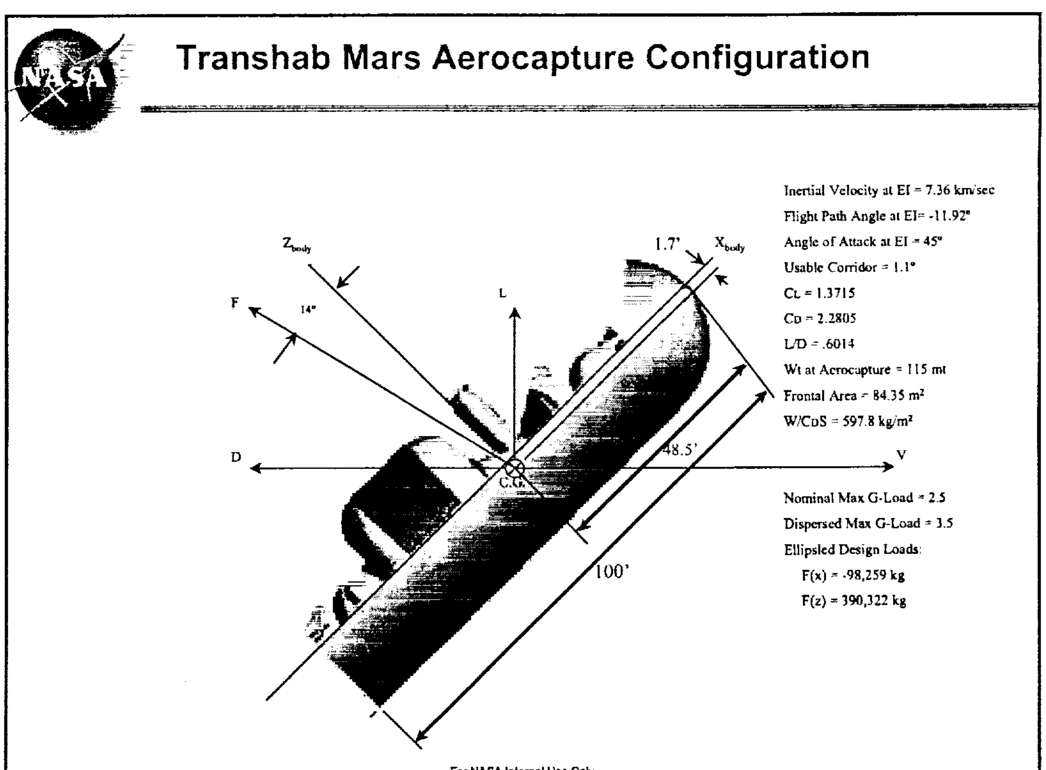
Transhab Mars Aerocapture Configuration
Inertial Velocity at EI = 7.36 km/sec
Flight Path Angle at EI= -11.92°
Angle of Attack at EI = 45°
Usable Corridor = 1.1°
CL = 1.3715
CD = 2.2805
L/D = .6014
Wt at Aerocapture = 115 mt
Frontal Area = 84.35 m²
W/CDS = 597.8 kg/m²
Nominal Max G-Load = 2.5
Dispersed Max G-Load = 3.5
Ellipsled Design Loads:
F(x) = -98,259 kg
F(z) = 390,322 kg
Zbody
Xbody
1.7'
F
14°
L
D
V
C.G.
48.5'
100'
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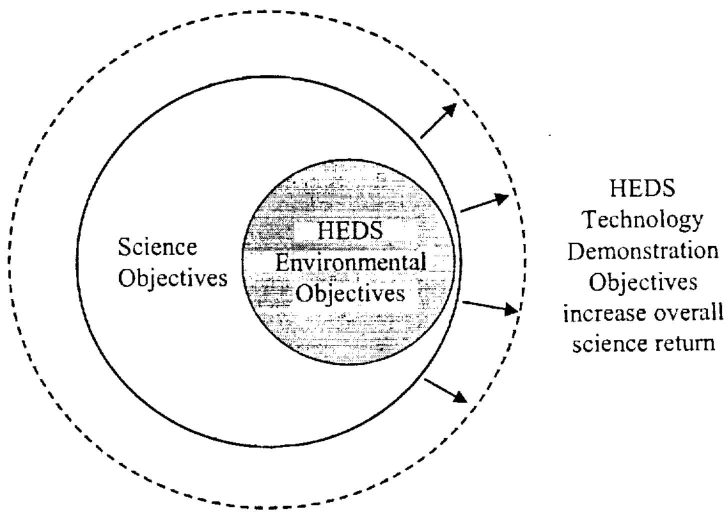
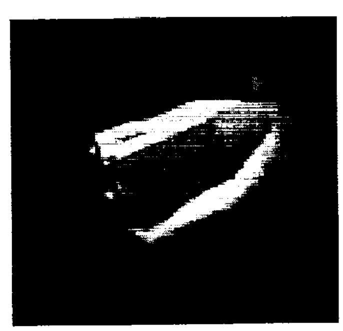
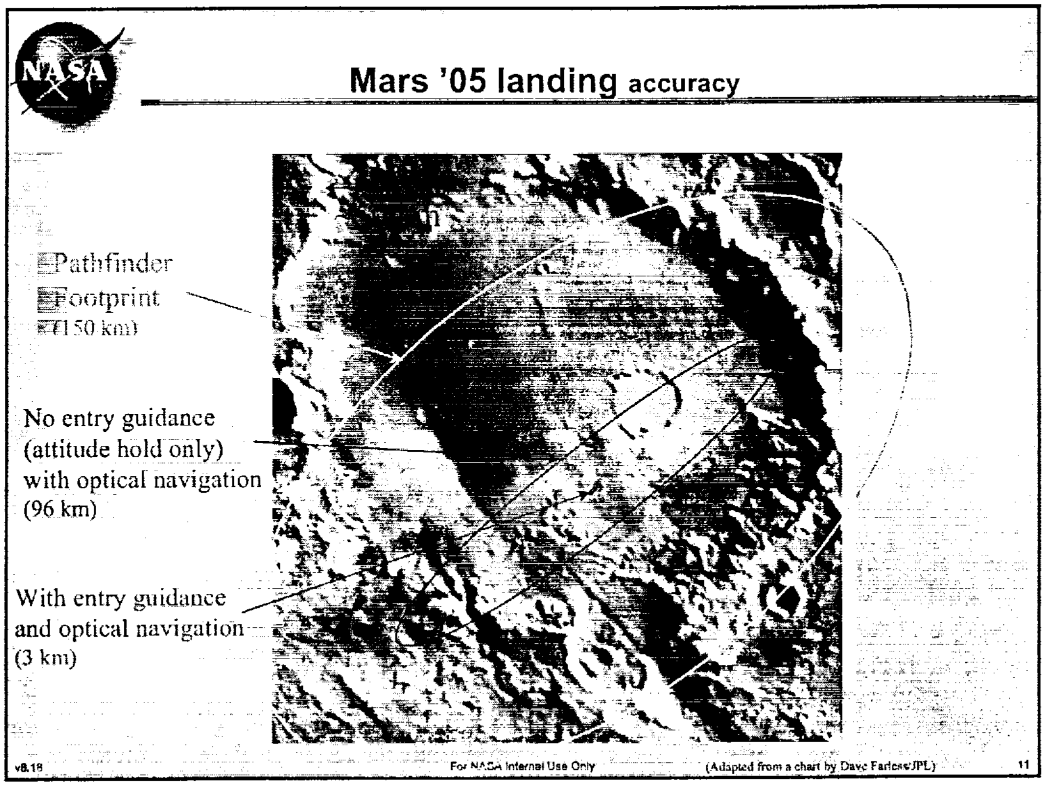
Complementary Objectives



Aerocapture and Entry, Descent, and Landing Capabilities

- Aeroassist is more efficient than propulsion for the deceleration required to enter Mars orbit- reduces IMLEO for HEDS missions by 30% to 35% compared to propulsive capture even for efficient propulsion systems
- Provides for less complexity in systems for aerocapture
- Aero entry is required for descending through the Mars atmosphere to the Mars surface. Mid L/D shapes (.4-.8)with aeromaneuvering provide significant improvements in landing accuracy
- Precision landing required for landing near previously deployed assets
- Aero shell can be synergistic with Earth to orbit launch shroud, significantly reducing mass
- Can control g's on crew and payloads to levels that reduce risk and mass of systems
- Automated hazard detection and avoidance required to minimize landing risks




Mars '05 landing accuracy
Pathfinder
Footprint
(150 km)
No entry guidance
(attitude hold only)
with optical navigation
(96 km)
With entry guidance
and optical navigation
(3 km)
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(Adapted from a chart by Dave Farless/JPL)
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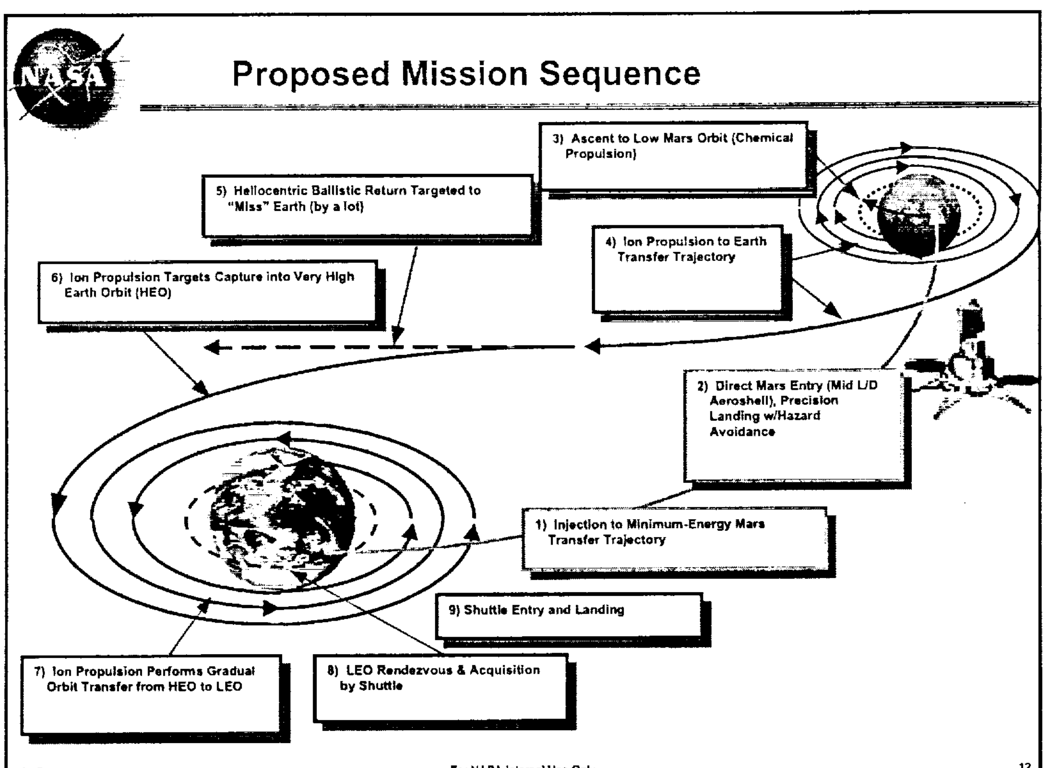
Proposed Mission Sequence
3) Ascent to Low Mars Orbit (Chemical Propulsion)
5) Heliocentric Ballistic Return Targeted to "Miss" Earth (by a lot)
4) Ion Propulsion to Earth Transfer Trajectory
6) Ion Propulsion Targets Capture into Very High Earth Orbit (HEO)
2) Direct Mars Entry (Mid L/D Aeroshell), Precision Landing w/Hazard Avoidance
1) Injection to Minimum-Energy Mars Transfer Trajectory
9) Shuttle Entry and Landing
7) Ion Propulsion Performs Gradual Orbit Transfer from HEO to LEO
8) LEO Rendezvous & Acquisition by Shuttle
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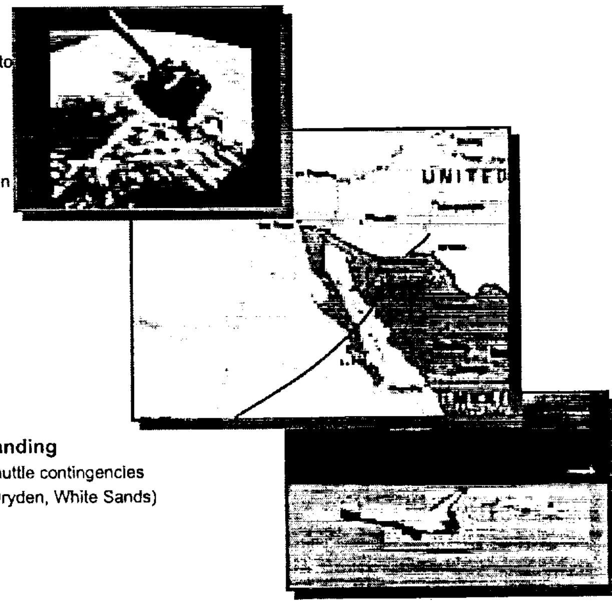
End-Of-Mission Scenario

- **Sample delivered to Low Earth Orbit**
  - Earth Return Vehicle (ERV) spirals down to Shuttle-compatible orbit via electric propulsion
- **Shuttle crew performs rendezvous**
  - RMS grapples ERV
  - RMS transfers ERV to containment cask in payload bay



- **Shuttle conducts nominal entry and landing**
  - Containment cask designed to survive Shuttle contingencies
  - Landing site in remote, controlled area (Dryden, White Sands)

MEPAG GOAL IV:
PREPARE FOR HUMAN EXPLORATION

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

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

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

A. Objective: Acquire Martian environmental data sets

- *1. Investigation: Determine the radiation environment at the Martian surface and the shielding properties of the Martian atmosphere.* **Requires simultaneous monitoring of the radiation in Mars' orbit and at the surface, including the ability to determine the directionality of the neutrons at the surface.**
- *2. Investigation: Characterize the chemical and biological properties of the soil and dust.* Requires in-situ experiments. **If in-situ experiments can not achieve adequate levels of risk characterization, returned samples will be required.**
- *3. Investigation: Understand the distribution of accessible water in soils, regolith, and Martian groundwater systems.* **Requires geophysical investigations and subsurface drilling and in situ sample analysis.**
- *4. Investigation: Measure atmospheric parameters and variations that affect atmospheric flight.* **Requires instrumented aeroentry shells or aerostats.**
- *5. Investigation: Determine electrical effects in the atmosphere.* **Requires experiments on a lander.**
- *6. Investigation: Measure the engineering properties of the Martian surface.* **Requires in-situ measurements at selected sites.**

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A. Objective: Acquire Martian environmental data sets (Continued)

- *7. Investigation: Determine the radiation shielding properties of Martian regolith.* **Requires an understanding of the regolith composition, a lander with the ability to bury sensors at various depths up to a few meters. Some of the in situ measured properties may be verified with a returned sample.**
- *8. Investigation: Measure the ability of Martian soil to support plant life.* **Requires in-situ measurements and process verification.**
- *9. Investigation: Characterize the topography, engineering properties, and other environmental characteristics of candidate outpost sites.* Specific measurements are listed in other investigations.
- *10. Investigation: Determine the fate of typical effluents from human activities (gases, biological materials) in the Martian surface environment.*

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B. Objective: Conduct in-situ engineering science demonstrations

- *1. Investigation: Demonstrate terminal phase hazard avoidance and precision landing.* **Requires flight demonstration during terminal descent phase.**

- *2. Investigation: Demonstrate mid-L/D aeroentry /aerocapture vehicle flight.* Mid-L/D (0.4-0.8) aeroentry shapes will be required as payload masses increase. **Requires wind tunnel testing and flight demonstration during aeroentry phase of the mission.**

- *3. Investigation: Demonstrate high-Mach parachute deployment and performance.* Higher ballistic coefficient entry vehicles will be result from flying more massive landers. **Requires high-altitude Earth-based testing and flight demonstration during Mars entry phase.**

- *4. Investigation: Demonstrate in-situ propellant (methane, oxygen) production (ISPP) and in-situ consumables production (ISCP) (fuel cell reagents, oxygen, water, buffer gasses).* **Requires process verification with in-situ experiments.**

- *5. Investigation: Access and extract water from the atmosphere, soils, regolith, and Martian groundwater systems.* **Requires subsurface drilling.**

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

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C. Objective: Emplace infrastructure for (future) missions

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

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

- *3. Navigation infrastructure* to support precision landings for robotic or human missions.

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How HEDS Investigations Benefit Science

- In General
  - Engineering and life science data gathering will provide data relevant to other science disciplines
- Life Sciences Data
  - Soil/rock compositional data is identical or at least relevant to local geological characterization
- Aeroassist/Precision Landing
  - Reduces risk of entry/descent/landing
  - Provides pinpoint landings at sites of high scientific interest
  - Flying low-g profiles potentially reduces structural mass of rovers, landers and payloads
  - Provides capability to return to previous sites/resources
- ISRU
  - Potential mass savings could be used for additional science, or increase mass of returned samples

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Summary

- Robotic missions are a logical and necessary step in the progression toward eventual human Mars exploration.
  - To reduce risk and cost
  - To provide a basis for maximum science and discovery return from human missions
- HEDS science data sets compliment the understanding of Life, Climate and Resources
- HEDS Technologies can greatly improve reliability, performance and science return
- Science and HEDS objectives can be combined into a successful single integrated program

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BACKUP CHARTS

HEDS/SSE Potential Synergies

Space Science and HEDS exploration goals are synergistic

- Scientific measurements desired by HEDS and Space Science regarding the environment and resources on Mars are similar or identical
- HEDS technology demonstrations, when incorporated in the mission design, can greatly improve reliability, performance and return for Mars robotic missions
- Science and discovery will be the major focus of both robotic and human missions

End-to-end ISPP Production and Propulsion Demonstration

- Human mission studies have shown that utilizing locally produced propellants can reduce the overall mission mass by up to 25%
  - Similar percentage reductions in mission cost
  - Resource utilization is synergistic with othr human exploration elements such as life support and EVA
  - Use of local materials augments crew self-sustainability and autonomy
- Test and Demonstration Characteristics:
  - End-to-end, simultaneous operation of resource collection, chemical processing, and product liquefaction and storage subsystems
  - Autonomous control and failure recovery capability for the ISPP plant for robotic and human mission support
  - ISPP product liquefaction & cryogenic long-term storage in the Mars surface environment
  - ISPP and propulsion system integration
  - Use of in-situ propellants for a Mars ascent vehicle

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End-to-end ISPP Production and Propulsion Demonstration (continued)

- Demonstrate the technologies and provide the operation experience required to support a 2007 ISPP Mars sample return mission
- Subsystems:
  - *Atmosphere Acquisition System*
    - Mars atmospheric carbon dioxide acquisition and compression using sorption pumps
  - *In-Situ Propellant Production System*
    - Advanced Zirconia Carbon dioxide Electrolysis (ZCE) oxygen generation subsystem (similar to MIP), or
    - New technology based on Sabatier/Water Electrolysis (SWE) or Reverse Water Gas Shift (RWGS)/water electrolysis processes
  - *Autonomous Control and Failure Recovery*
    - Incorporate ARC "Livingstone"software developed for the Deep Space 1 (DS-1), and KSC "KATE" reason based control software
  - *Liquefaction & Long-Term Cryogenic Storage*
    - Pulse tube cryocooler can be used to liquify and store >= 0.1 kg per day.
  - *Utilization of ISPP Products*
    - Static engine firing, sounding rocket, or other use of ISPP products

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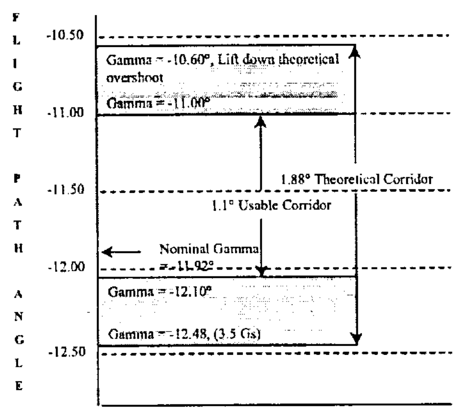
Transhab Mars Aerocapture Corridor



Vehicle Characteristics:

Length = 30.48 m (100 ft)

Weight = 115 metric tons (253,532 lbs)

Frontal Area = 84.35 m^2 (907.92 ft^2)

CL = 1.3715

CD = 2.2805

L/D = 0.6014

W/CDS = 597.84 kg/m^2

Angle of Attack = 45°

Trajectory Characteristics:

Inertial Velocity at EI = 7.36 km/sec

Relative Velocity at EI = 7.12 km/sec

Nominal Max G Level = 2.5

Dispersed Max G Level = 3.5

Corridor Reductions:

Overshoot Side: 0.40°

Undershoot Side: 0.38°

Exit Apoapsis Height = 500 km

Exit Relative Velocity = 3.3 km/sec

Assumed Technologies: Mass Credits Taken

	TODAY		EXAMPLE MISSION SAVINGS				
Technology Area	Current State-of the-Art (SOTA)	SOTA Mass (kg)	Current Assumption	Current Mass (kg)	Mass Saved (kg)	Savings (%)	Agency Technology Investment (1-5)
EVA Suit	None exist	n/a	Advanced planetary high-mobility light-weight suit, dust resistant, high cycle life materials, Mars insulation	182	n/a	Establishes non-existent capability	2
EVA PLSS	None exist	n/a	Lightweight planetary, modular, on-orbit maintainable, rapid/in-field recharge	319	n/a	Establishes non-existent capability	2
Wireless Avionics + MEMS Technologies	ISS MDM 2 lb / channel x 1000 channels. Conventional wiring	1021	High density MCM packaging, MEMS spart sensors, RF MEMS	57	964	94%	2
Maintenance & Spares	TBD ISS Reference: Prepositioned spares through flight 12A	3400	Component level repair, free form manufacturing, printed circuit boards	1000	2400	71%-92%	1
EVA Consumables	Open loop (0% closure oxygen and water)	1601	Oxygen Provided In-Situ (Zirconia Cells), water via ECLSS closure, semi-closed loop atmosphere & thermal (CO2 scrubber & radiator)	165	1436	90%	2
Solar Arrays	Thin cyrstalline Si cells on polymer: 17% LEO efficiency (20+% Mars surface efficiency), 1.75 kg/m2 panel mass	13000	Thin film CuInS2 cell on polymer: 18% LEO efficiency (~14% Mars surface efficiency), 0.2 kg/m2 panel mass	2200	11000	85%	3
PMAD	Space station technology and masses in ball park of 1-3 kg/kW	850	2005 PEBB based technology and masses in the 0.1-0.3 kg/kW range	350	500	59%	3
Thermal Control	Aluminum honey-comb rigid radiators	1900	Advanced, light-weight, body-mounted thermal radiators	920	980	52%	3

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Assumed Technologies: Mass Credits Taken

	TODAY		EXAMPLE MISSION SAVINGS				
Technology Area	**Current State-of the-Art (SOTA)**	**SOTA Mass (kg)**	**Current Assumption**	**Current Mass (kg)**	**Mass Saved (kg)**	**Savings (%)**	**Agency Technology Investment (1-5)**
Mars Orbit Aerocapture*	Propulsive Capture in low-Mars Orbit	196000	Mid-L/D aerocapture into low-Mars Orbit	108000	88000	45%	1
Nuclear Thermal Propulsion*	All chemical injection with aerobraking at Mars	657000	Bi-modal nuclear thermal propulsion provides high thrust and power for payload elements	436000	221000	34%	1
Solar Array Dust Abatement*	No dust abatement technique known (0% efficiency) with complete power loss in 500 days	3300	Electrostatic dust abatement at 95% efficiency (7% power loss in 500 days)	2200	1100	33%	1
Electric Propulsion*	All chemical injection with aerobraking at Mars	657000	High power electric propulsion to and from Mars	467000	190000	29%	2
ISRU Propellants*	Bring all propellants	800000	Produce ascent propellants from local resources	599000	201000	25%	2
Food	Individually packaged, de-hydrated/frozen	8418	Pantry-style, dehydrated/frozen capable of being stored for up to 5 years in deep-space	7320	1098	13%	1

* Mass estimates provided for Mars architecture

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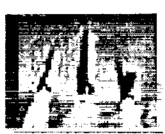
Human Exploration Common Capabilities

Earth to Orbit Transportation



- Moon (follow on)
- Asteroids
- Mars

Interplanetary Habitation

- Moon
- Sun-Earth Libration
- Asteroids
- Mars

Crew Taxi / Return

- Moon
- Sun-Earth Libration
- Asteroids
- Mars

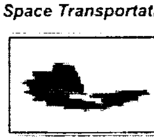
EVA & Surface Mobility

- Moon
- Mars
- Asteroids

Advanced Space Transportation Options

Advanced Chemical
"Small"
- Moon (follow on)
- Sun-Earth Libration

"Large"
- Asteroids
- Mars



Electric Propulsion
≤500 kWe
- Moon
- Sun-Earth Libration
- Mars Outpost

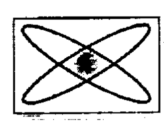
≥1 MWe
- Asteroids
- Mars

Nuclear Thermal
- Asteroids
- Mars
- Moon (follow-on)

In-Situ Resource Utilization

- Moon
- Mars

Com/Nav Infrastructure



- Moon
- Mars

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Supporting Critical Technologies

Human Research & Technologies
- Radiation research and protection
- Zero/low-gravity research and countermeasures
- Regenerable closed-loop life support
- Advanced medical care and diagnostics

Propulsion Technologies
- Efficient in-space propulsion
  - Electric/Plasma
  - Nuclear Thermal
  - Advanced Chemical
- Low-cost, high efficiency engines
- Long-term cryogenic fluid management

Robust/Efficient Power Systems
- Generation, management, and storage
- Stationary and mobile

Flight Technologies
- High-speed aerocapture
- Automated Rendezvous and Docking
- Guided entry and precision landing/hazard avoidance

Information & Automation
- Advanced automation
- Information technologies
- High rate communications and data transfer

Lightweight Structures, Systems, Sensors
- Light-weight materials
- Micro/nano electronics

Sample Curation

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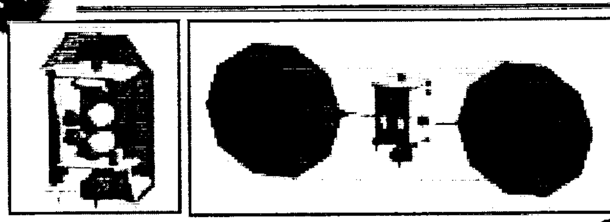
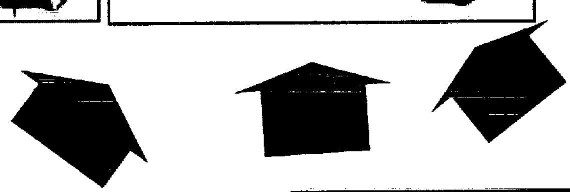
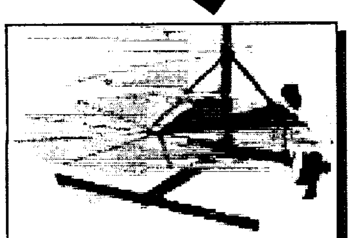
SEP Earth Return Vehicle Concept





- Spacecraft Bus
- Heritage: Stardust



- AEC-Able UltraFlex PV arrays
- Heritage: Mars Surveyor 2001 Lander

- Hughes NSTAR Ion Engine
- Heritage: Deep Space 1

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Mars Field Geology, Biology & Paleontology Workshop (November, 1999)

Scientific Instruments, Robotic Assistant

Communications

Crew Skills & Training

Field Exploration Strategy

Consensus, Recommendations & Progress

Patricia Wood Dickerson

Scientific Instruments, Robotic Assistant

Communications

Crew Skills & Training

Field Exploration Strategy

Field Exploration Strategy

RECOMMENDATIONS

- Robotic reconnaissance of biohazards, terrain, local geology, potential resources
- Safety protocols/contingency plans in place, and drills conducted, prior to any EVA
- Only 2 or 3 astronauts on EVA at any time
- Design traverses for flexibility in time and tasks, with greater complexity as skill and confidence increase
- Initial traverses should be to sites of highest priority

Field Exploration Strategy

RECOMMENDATIONS, continued

- When walking traverses are complete, Earth and Mars science teams should synthesize results, plan extended traverses
- Begin geophysical surveys early, for indications of water and other resources
- Significantly improve EVA suit and glove functionality
- Develop a new reach-and-grasp tool for 10- to 30-cm samples

Field Exploration Strategy

PROGRESS

- Astronaut candidate field training — increased emphasis on sampling techniques, implications of rock types re planetary origins/processes
- Astronaut candidate field training — geophysical data acquisition and planning next survey line based upon results
- Workshop on Apollo exploration strategies and experience, and their relevance for Mars exploration, will soon be convened.

Analytical Capabilities and Instruments

RECOMMENDATIONS

- The need for specific observations/analyses should drive development of compact, integrated instruments.
- Begin miniaturizing existing field/laboratory instruments:
  - Helmet-mounted fiber-optic camera, magnifying camera/hand lens
  - Voice-operated data-recording system with real-time data display within visor
  - In-visor map for locating (x,y,z) samples and outcrops
- Biologists, field geologists, geochemists, engineers should collaborate throughout mission planning.

Analytical Capabilities and Instruments

PROGRESS

- Advances in glovebox design for noncontaminating sample handling (Oceaneering Corp.)
- Probable test of voice-activated data-recording system at Devon Island this season

Crew Skills & Training

RECOMMENDATIONS

- Crew should have twice as many members with surface science skills as with spacecraft and operations systems skills — a possible combination:

Prime Role	Backup Role
Commander/Research & Operations Manager	Geologist
Geologist	Paleobiologist
Systems Engineer	Electronics Engineer/Technician
Physician or Medical Technician	Microbiologist
Geologist	Mechanical Engineer/Technician
Paleobiologist	Systems Engineer

Crew Skills & Training

RECOMMENDATIONS, continued

- Extensive field training — crew, operations and support teams should participate in at least six realistic field exploration sims before launch.
- Field training should begin in 1999 for astronauts, mission operations personnel, and scientific support teams.
- Workshops should be convened on crew selection, on site selection for scientific exercises, and for recording experience/insight of Apollo and Skylab teams.
- An expert workshop should be held to investigate the gender and nationality mix best suited for Mars mission success.

Crew Skills & Training

PROGRESS

- Geophysical exploration training began for astronaut candidates in 1999
  http://geoinfo.nmt.edu/penguins/home.html
- Field mapping exercise for astronaut corps and ISS field science training plans
- Shuttle and ISS crew briefings on Earth/Mars analogues
- Astronaut participant in Antarctic meteorite expedition

Earth-Mars Communications

RECOMMENDATIONS

- Communications network including:
  - Satellites in Mars orbit for navigation, communication
  - Dependable communications with Earth, orbiting outposts
  - Capability for compressing/transmitting large volumes of data, as from geophysical surveys
- More structured communications with Earth during reconnaissance, less as exploration program matures
- Teleoperation of field/laboratory equipment, robotic rovers from Mars base or orbiting outposts

Earth-Mars Communications

RECOMMENDATIONS, continued

- Communications between science teams on the two planets at well-defined levels:
  - Astronaut scientists and "science back room" on Earth in regular contact throughout mission
  - Science team members on Earth would change depending upon the nature of discoveries, exploration progress, data returned
- Briefings/debriefings between departing and arriving crews, as permitted by spacecraft in transit
- Keep the public engaged:
  - Report mission news (crew selection, training, science questions, discoveries) promptly and accurately
  - Translate scientifc discoveries directly into teaching materials

Earth-Mars Communications

PROGRESS

- Communications console in JSC Mission Control dedicated to field exploration and training
- Data compression/transfer capability developing on ISS
- Private-sector plans for communications/navigation satellites orbiting Mars
- Press/public engagement in astronaut field geophysical training

MARS AND MEN

W. Muehlberger, University of Texas
Apollo 16 Lunar Field Geology Team Leader

"Wherever mankind travels in space, people will always be preceded by unmanned probes that will provide the first bit of information. But there comes a time when we've learned all we can by unmanned vehicles. Man comes on the scene and makes the decisions about what is most valuable to us here, and that makes space into a new laboratory. Photography plays a vital role in all that " – John Glenn, in 'The View from Space'.

Why do you take a photograph? We took a lot of documentation pictures because we were supposed to. But a lot of photographs were taken on instinct-things you can't predict you're going to see or that are going to impress you. You say, 'Now I've got to take a picture of that" or "Look at the way that is positioned' or' Look at the way the sun is shining on that." Those 'stand-back' pictures were taken with aesthetics in mind, to capture and document the venture itself." - Eugene Cernan in 'The View from Space'.

The Apollo mode for a Science Support Room in Mission Control will not work for Mars. The time delay makes it nearly useless. Our team was available for instantaneous reaction and assistance to the crew on EVA. Therefore the Science Support Team has to be on Mars! The crew that went out the day before will do the supporting. They will hand off to each other for the next EVA. They will send a daily report back to Earth as to what was accomplished, problems that need resolution, supporting video, data, etc. etc. In Apollo, that was the role of my "Tiger Team," who sat in Gene Krantz' office watching and listening but having no role for directly helping the Back Room. They wrote a summary of the EVA, what was accomplished, what got omitted that was important to insert into the next EVA. It was distributed throughout Mission Control- especially to the Big Brass, Flight Director, and the CapCom.

Apollo Geology Back Room Support Team

Tim Hait - using an overhead projector, kept track of geological comments from the crew- each was preceded by the MET (mission elapsed time) – and projected on the wall. With this we could review recent events as needed, for example, do we need to send a message before they leave that site.

George Ulrich - an overhead TV camera looked down on the landing site map with traverses drew on it. George kept a pointer on the astronauts' locality. He also had a cue sheet that contained the MET of arrival followed by the MET for departure from the Station. Below that were listed the tasks to be done at that station. As the crew accomplished a task he would cross it out. The map and message were transmitted to the leftmost screen in Mission Control for viewing there. On that map were placed the messages we needed to be forwarded to the crew. The CapCom would insert them into the conversation when time permitted.

Bob Sutton- kept 3x5 cards on samples collected (rocks, soils, rakes, core, etc). A card per sample. Station number, time collected, type of material as described by the crew, was it photo documented (thus capable of being reoriented on earth into its lunar position), sample bag number, which large carrying bag did it get put into, etc. He filed these by rock type. This could then be studied quickly for review and for making collecting suggestions to the crew, if needed.

Dale Jackson (sat beside me) and Lee Silver (directly behind me- usually standing and bouncing around!) were my 'science thinkers' who would catch important points in the crews conversation, relay them to me (I was commonly involved in a discussion with Jim Lovell [Head of Science Support Room- and the one who would forward our approved requests to the Flight Director]), and have me forward thru Jim to the crew. Also behind me, would be various people- mostly geologists from NASA (JSC-ex. Bill Phinney) or NASA Headquarters (BellComm- ex. Jim Head). Gordon Swann, my predecessor as PI for Apollo Field Geology, was advisor, gofer, etc. He was invaluable!

Our photogrammetry team (Ray Batson, chief) took Polaroid camera mosaics of the TV camera pan that was performed at the beginning of each stop, annotated it and gave it to me within minutes of taking it. Important rocks or other features were circled, tick marks along the bottom were added so that when time was available when we did not need to watch the crew we could ask the operator of the TV camera in Mission Control (Ed Fendell) to move the camera to the object of our interest and zoom in on it for a better view.

We also had a team of court reporters and typists taking down the entire air-to-ground conversation and furnishing us with a complete transcript within days of the EVA. (Weeks to months before we would get the NASA transcript).

MARS FIELD EXPLORATION

I assume that two astronauts will be the EVA team on a given day. They will trade off with another pair for successive days. I assume that the two teams will not leapfrog each other but will go on separate, but related traverses. They may want to switch pairs during the exploration so that each person sees the relationships between each traverse.

Space suit constraints will prevent writing notes or looking at stereo photos while on traverse. The notes will be the astronauts to Mars Base conversations with the designated CapCom for that EVA- presumably one of the day-before EVA astronauts. The others should (may?) be doing other tasks- meal prep, looking at rocks brought in the day before, maintenance, etc. Helmet-mounted video cameras will help transmit pertinent info back to Base. Video camera on the MRV

(Mars Roving Vehicle) would be operated by Base and will furnish context for sampling, zoom capabilities to investigate features beyond the range of the geology hammer, etc.

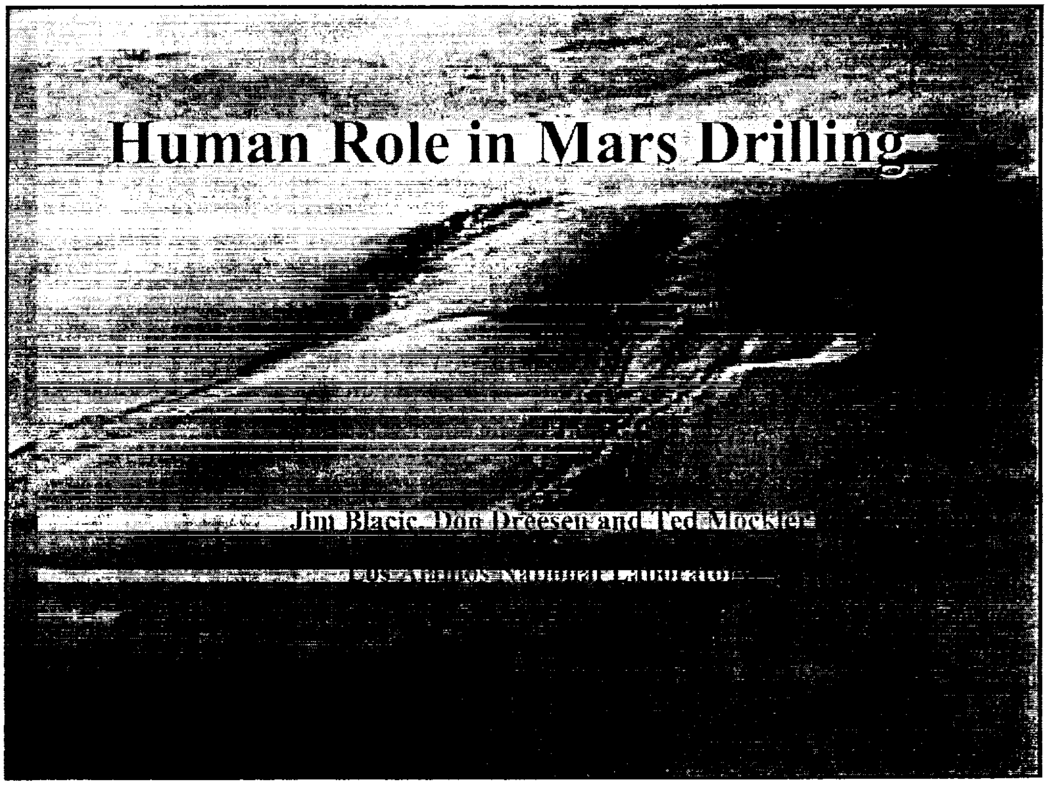
In Apollo, we never (with the possible exception of the margin of Hadley Rille, ever sampled an outcrop in place. It was always trying to sample for context. Sampling on the rim of a crater on the assumption that all the rocks came out of that crater, sampling a boulder that we could see by its tracks where it had rolled down from (Apollo 17), etc.

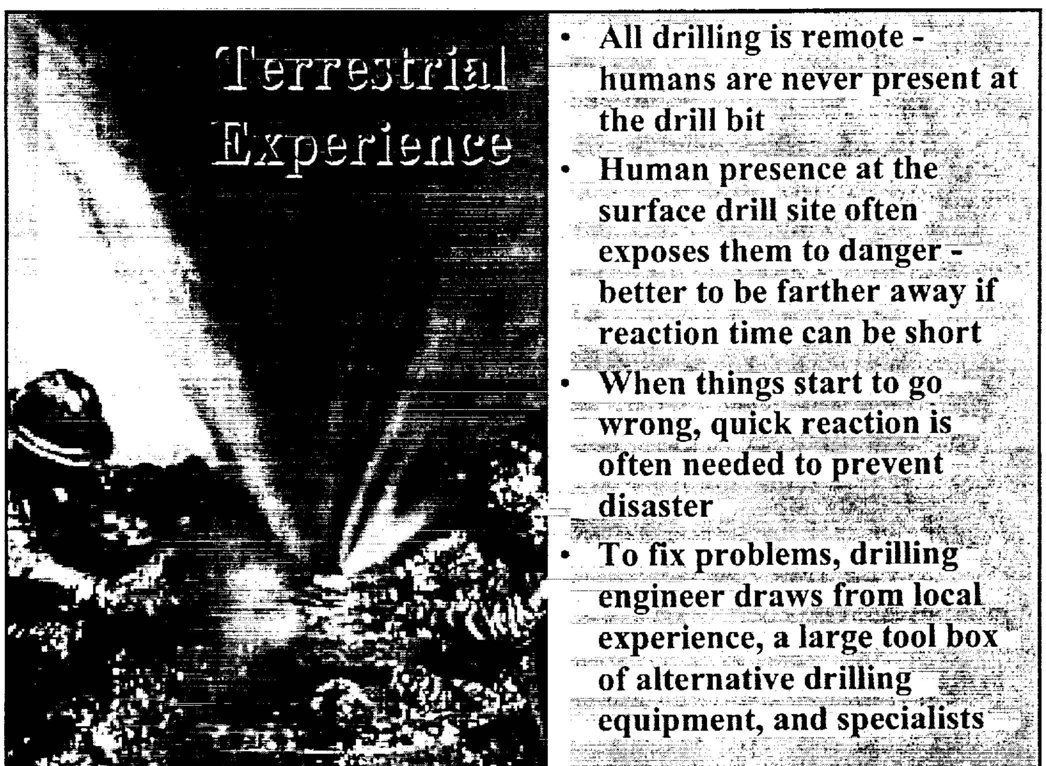
The Moon is nothing but impact debris- Mars has stratigraphy! Another reason a human has to go! No machine could do the thinking and sorting of info to work out the history recorded in those layers.

And- we blew the photo interpretation on both Apollo 16 and 17. Thus, I suspect that there will be interpretation errors in the maps that we will land with and on which we have laid out the first set of traverses.

Only reason to send men to Mars is to do science, geology being most important to me. On Apollo only one man went to the Moon as a scientist. The others were well trained in sample procedures, verbal commentary, and documentary photography so that the geologic context could be interpreted from their results. Harrison H. Schmitt made a significant difference as to the quality and quantity of geologic information that was recovered from the mission. After the mission, he constantly interacted with the sample PI's to give his insights to the complex breccias that were sampled, photographed and returned to earth.

Everyone going to Mars needs to be capable field geologists! In contrast to most sciences, geology is an accumulative one- the more rocks and geologic field problems solved the better is the geologist to be able to interpret the next field area. Thus 10-15 years of geological experience should be required of the astronauts going to Mars before they launch. Now is the time to start the geological field training of the geologist/astronauts, before they launch for Mars!


Human Role in Mars Drilling
Jim Blacic, Don Dreesen and Ted Mockler


Terrestrial Experience
• All drilling is remote - humans are never present at the drill bit
• Human presence at the surface drill site often exposes them to danger - better to be farther away if reaction time can be short
• When things start to go wrong, quick reaction is often needed to prevent disaster
• To fix problems, drilling engineer draws from local experience, a large tool box of alternative drilling equipment, and specialists

What to Expect on Mars

- Environmental conditions will be different than anything encountered on Earth, and subsurface knowledge will be very limited
- Expect trouble! - system must sense it and quickly retreat into a safe mode to await human diagnosis & intervention by teleoperation from base (or Earth)
- Drilling toolbox will be very limited and human experts available only intermittently by remote communication

How to Make it Work

- Dense array of down-hole & surface sensors will monitor drilling/sampling/completion process to a degree never before achieved on Earth; semi-automated control of subsystems will be extensive (but little of the technology and sensors needed presently exists)
- Expert systems and controls will hopefully prevent trouble from getting out of hand & help astronaut (or earth based drillers) diagnosis problems
- Astronauts will draw from a small but carefully designed toolbox to fix problems by teleoperation

How to Make it Work (cont.)

- If fix doesn't work, abandon well and redrill if resources are available (multiple interventions have diminishing potential returns and mass requirement to protect astronauts precludes direct intervention for many types of problems)
- Only reason to go to site is to collect information not available from sensors, perform safe maintenance and repairs beyond the abilities of onboard robotic (teleoperated) systems, retrieve samples, or help move to new site

Best use of Humans

- Diagnose problems, devise fixes, improvise new tools, judge when to quit & move on
- Repair broken system (if it can be safed) & move to new site to try again
- Intelligent processing of samples
- Risk might be reduced by eliminating on site human intervention entirely and using more resources to support multiple attempts

LAUR00-4742

Report on Conceptual Systems Analysis of Drilling Systems for 200-m-Depth Penetration and Sampling of the Martian Subsurface

James D. Blacic, Donald S. Dreesen and Theodore Mockler

GeoEngineering Group
Los Alamos National Laboratory

October 1, 2000

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LANL Mars Drilling Web Site

http://www.ees4.lanl.gov/mars/

GEOLOGICAL INVESTIGATIONS OF MARS: THE HUMAN FACTOR.

Clive R. Neal. Dept. Civil Eng & Geological Sciences, University of Notre Dame, Notre Dame, IN 46556. neal.1@nd.edu.

Humans make better geologists than robots, and putting astronauts on the surface of Mars will greatly enhance scientific exploration and increase the chances for key scientific discoveries. Humans can recognize interesting samples and, importantly, place those samples in the overall geological context of the particular landing site. These attributes were amply demonstrated during the Apollo program, as for example when Jack Schmitt accidentally slipped and discovered the "orange soil" (glass beads) at the Apollo 17 site. These samples remain some of the most important collected during the Apollo program and are still being analyzed by scientists worldwide. Because the Apollo missions were each of limited duration, no instruments were carried along for actual analysis of rock samples prior to returning them to Earth. However, human expeditions to Mars will likely involve extended stays (months). Assuming a limited capacity for returning geological samples, it will be highly advantageous to carry some rudimentary kinds of analytical equipment to the Martian surface in order to ensure that the most significant geological samples are collected and returned to Earth. This paper discusses some of the most useful and practical types of analytical equipment that might be taken along in order to characterize geological samples on the surface of Mars.

Some useful tools actually can be carried by astronauts into "the field" as opposed to remaining on the spacecraft lander. These portable instruments are mainly the simplest yet most important instruments. There is no substitute for a human eye coupled with a well-trained mind, and what the eye can see will be greatly enhanced by having a geological hammer (to expose fresh rock surfaces) and some kind of helmet-compatible magnifier for first-order rock and mineral characterization.

But the electrical power available on the lander, and its controlled atmosphere (permitting removal of spacesuits), permit more sophisticated equipment there than can be carried by a walking astronaut. The most useful analytical tools for the astronaut geologist are a binocular microscope and a petrographic microscope. A simple binocular microscope would be broadly useful for examining both rock and regolith samples to gain an understanding of the components present. But ultimately, for solid rocks, the ability to prepare and examine petrographic thin sections is of paramount importance. A petrographic thin section of all but the finest grained rocks reveals in detail the mineralogy, type, and even the general chemistry of a rock. No other single technique gives so much diverse information so easily about a rock. The conventional technique on Earth requires oil or water cooled rock saws to cut a "billet" of rock, which is then glued to a glass thin section, cut again using a water-cooled rock saw before being ground to the require thickness (30 microns) with water as the lubricant. The liberal use of water in this process means it cannot be used on Mars. An alternative would be the use of lasers to precisely cut a 30 micron wafer from a given rock sample. This would negate the need for water and allow a detailed look at rock textures and, possibly, the identification of microfossils. If coupled with a Raman Spectrometer, mineralogical as well as textural information can be obtained. An estimate of the bulk chemistry of samples is useful for rock classification and obtaining an idea of rock diversity. Use of APXS technology can be made, provided the capabilities are available for reducing the data. This combination of analytical approaches will yield textural, mineralogical, and bulk chemical information on the surface of Mars that can be used to choose a suite of samples to be brought back the Earth for more detailed analyses (trace elements, isotopes, age dating, etc.).

While outside the main scope of the topic, the following three items are not analytical techniques, but are vitally important for gaining a better understanding of Mars. First, astronauts can conduct geological investigations via remote sensing. A network of seismometers around the landing site can be used for short and long term experiments. For the short term, simply striking the surface will allow a look at the immediate subsurface in great detail. This is especially important in the hunt for water. These data can be combined with the sample data to yield a quite detailed look at the local subsurface geology. For the longer term, the network could become one of several to look at the deeper interior of Mars. Second, depending upon mobility, the astronauts can also undertake detailed geological mapping of the region around the landing site. This is crucial for identifying potential aquifers as a water source for more long-term habitation, as well as defining any other potential resources. Third, drilling can gain samples of the subsurface either by cores (as demonstrated by the terrestrial Ocean Drilling Program) or as chips as in oil exploration.

Packaging analytical instrumentation for planetary exploration of the sort described above will require a number of technological advances:

- Hardware development for precise rock cutting with lasers.
- Technique development of precise rock cutting with lasers and mounting the sections for microscope studies.
- Development of a robust, petrographic microscope with a magnification range that will allow petrographic thin sections to be examined.
- APXS and Raman Spectrometer technology are reasonably advanced for use on planetary surfaces, but in order for these to be effective, sufficient computing power is required on the surface to reduce the data obtained by these instruments.
- Miniaturization of seismometers and sufficient computing power to reduce the data.

In summary, a number of important analyses of geological samples can potentially be conducted on the surface of Mars during a manned mission. Perhaps the most important factor involved is having humans to put samples/formations into the geological context using their training and judgement.

Science and Human Exploration

NASA-Goddard Space Flight Center
January 11-12, 2001

ASTROBIOLOGY SAMPLE ANALYSIS AS A DESIGN DRIVER

Marc M. Cohen, Arch.D, Architect
Advanced Projects Branch
NASA Ames Research Center

INTRODUCTION:

This effort supports the Astrobiology Objective 8 the Search for LIFE ON MARS, PAST AND PRESENT -- (Astrobiology Program Office, 1998, p.7).

The essential trade analysis is between returning very small samples to the Earth while protecting them versus in situ analysis on Mars.

Developing these explicit parameters encompasses design, instrumentation, system integration, human factors and surface operations for both alternatives.

This ***allocation of capability*** approach incorporates a "humans and machines in the loop" model that recognizes that every exploration system involves both humans and automated systems.

The question is where in the loop they occur -- whether on Earth, in the Mars Base, in the rover or creeping over the Mars surface.

A FOCUS ON ASTROBIOLOGY SAMPLE ANALYSIS -- LEADS TO THE REQUIREMENT FOR A SURFACE SCIENCE LABORATORY AT A MARS BASE.

MARS SURFACE ASTROBIOLOGY LAB

WORKING ENVIRONMENT FOR SAMPLE PREP AND ANALYSIS

- **There is an unfortunate history of the Human Space Program squeezing Science out of missions.**

PURPOSES FOR THIS DESIGN RESEARCH:

- Substantiate the continuum from
  - Terrestrial samples to
  - Mars Return samples to
  - In-Situ Laboratory Sample Analysis on Mars
- Demonstrate and Ensure a robust Astrobiology science capability from the beginning of Mission Architecture Design and the beginning of Mission Operations

Probably the best statement on Mars Surface Science Lab activities comes from Carol Stoker (Stoker, Strategies for Mars, 1996, p. 558).

Laboratory analysis of samples in the Mars base lab would involve cutting and sectioning samples and using various analytical instruments. For geological samples, standard techniques for determining mineralogy, petrology, grain size, elemental composition, age dating, isotopic composition, and trapped volatile analysis could be used. For samples of biological interest, macro and micro-scale inspection of any prospective fossils would be performed as well as organic analysis, biological culturing, and wet chemistry.

ASTROBIOLOGY: THE SEARCH FOR SAMPLES

These environments correspond in the broadest terms to the three phases of matter:

Solid, Liquid and Gas.

Solid Samples

Scientists conceive living organisms as essentially solid.

The waste products they leave behind and fossils are solid.

Liquid Samples

Levin & Levin speculate that liquid water on may exist today on the surface of Mars, and these pools or reservoirs could serve as cradles of life (Levin & Levin, 1997, 1998).

Kuznetz and Gan produced liquid water in a bell jar under simulated Mars surface atmospheric conditions, at which the conventional wisdom says that liquid water cannot exist (Kuznetz & Gan, 2000).

Gas Samples

Atmospheric Samples are part of any solid or surface water sample.

In picking up a fascinating rock from the Mars surface, the astronauts will want to preserve in its native ambient atmosphere.

TABLE 1. Taxonomy of Astrobiology Sample Characteristics by Phase of Matter

Characteristic	Solid (Rocks and Soil)	Liquid (Aqueous)	Gas (Atmosphere & Vacuum)
Search for **"Pre-Life"**	Organic Molecules	Nutrients	Proto-Amino Acids
Search for Extant Life	Surface rocks, Subsurface deposits, "Bugs under rocks," Deep Drilling cores	Phytoplankton, Zooplankton, Algae, Thermophiles, "Acidophiles"	Airborne Microbes Respiration by products?
Search for Fossils	In Rocks and Sediments	Sedimentary Mats	??
Where to Search	Planetary surface & subsurface	Deep underwater, hot springs, caves, rivers	Atmosphere collection
Preserve Ambient	**Environment**		
• **Maintain Temperature**	Prevent thermal expansion or contraction	Stabilize organisms	Prevent temperature-induced changes
• **Maintain Pressure**	Maintain structural integrity	Prevent deep-water specimens from "exploding"	Essence of the sample
• **Collect with surroundings**	Preserve fossils in bedrock	Collect specimens in liquid medium	??
• **Maintain Chemistry**	??	Collect resupply medium	??
Protect from "Forward" Contamination	Protect from damaging or polluting sample	Protect from interaction with containment vessel	Protect from interaction with pump lubricants, etc.
Protect from "Backward" Contamination	Protect from microbes and toxics	Protect lab and water system from organisms	Protect from potential toxics or microbes

LOCATION & DISCIPLINE ISSUES:

- the scientific objectives such as the types of data the principal investigators seek,

- the types of samples in which they seek it, and

- the locations where they expect to find those samples.

- These locations suggest the environment and terrain in which the science crew will operate, and leads to assumptions about the site and proximity of the Mars base.

- The disciplines for the Project to accommodate include paleontology, geology, atmospheric science, exobiology, exopaleontology, and life science

APPROACH -- Concern that **faulty** assumptions may lead inevitably to an inadequate Mars Surface Science Capability:

Assumption 1 -- Astronauts are essentially just extensions of telescience for principal investigators back on the Earth.

Assumption 2 --Crew sizing to staff the laboratory and planetary rovers is a function of "mission architecture" rather than determined by exploration or Astrobiology goals, objectives and requirements.

Assumption 3 --The Laboratory serves the mission to perform a triage level of analysis, and sends the "interesting rocks" back to Earth for serious analysis.

Assumption 4 --A Mars Surface Laboratory is essentially just a slightly modified Habitat.

Assumption 5 --The use of a crew rover – pressurized or unpressurized is just to pick up rocks and back to the lab for further study.

Assumption 6a: Robot Landers will prove there is No Life on Mars.

. . . but if they don't . . . Assumption 6b --Sterilize everything.

In Situ Analysis

Rapid Sample Return is not possible from Mars or Europa.

Neither is it possible to preserve biotic samples in pristine condition for 3 years in space.

Therefore, it becomes necessary to perform comprehensive, high quality analysis

IN SITU.

Seigel, Clancy, Fujimori and Saghir On-Board (space station) specimen analysis for Life Science research (1989, pp. 77-78).

Four Advantages of On-board/In Situ analysis:

- Allows rapid production of experimental results, enabling iterative research activity.
- Provides a quick-response science capability
- Is critical for characterization of samples which cannot survive return to Earth, or degrade with time.
- Significantly reduces sample storage prior to return to the ground, and reduces specialized return requirements (e.g. thermal conditioning).

Two Disadvantages of On-board/In Situ analysis:,

- Greater costs than performing the analysis on Earth.
- "High skill levels required of crew members" with the associated expenditure of crew time and effort.

ACTIVITY NODES --

Principal investigators and their institutions on earth;

The laboratory in a Mars habitat;

Mobile instrumentation in both a pressurized and unpressurized rover;

And what an EVA astronaut will use in exploring the surface.

The best allocation of capabilities or distribution of responsibilities among the nodes often is **not obvious.** An example of a solution might be that:

- Principal investigators on Earth select the investigation site,
- Mission planners on Earth plan the traversal route,
- The astronauts send a Mars airplane (Hall, Parks and Morris, 1997) ahead of the pressurized rover to survey the route in detail,
- The astronauts drive the pressurized rover to the investigation site, and
- The astronauts select and analyze the samples.

HUMAN ELEMENT 1--

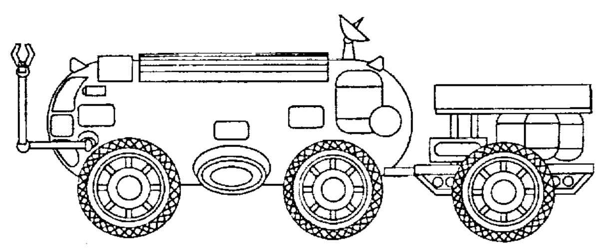
The human element is *the essential component* in the Mars exploration strategy.

What size crew and skill mix is necessary to conduct the Mars surface exploration successfully?

- Who is necessary to perform the science work?

- And who is necessary to keep everyone alive while the explorers do their job?

FIGURE 2. Example of a long-range pressurized rover with robotic arm and power cart.
(Courtesy of Roger Arno, NASA-Ames Research Center)



HUMAN ELEMENT 2--

This study will address primarily science, with a focus upon Mars Base science lab and mobile field operations:

- How many science crew with what skills are necessary to carry out the work from the most physical to the most intellectual exertions?

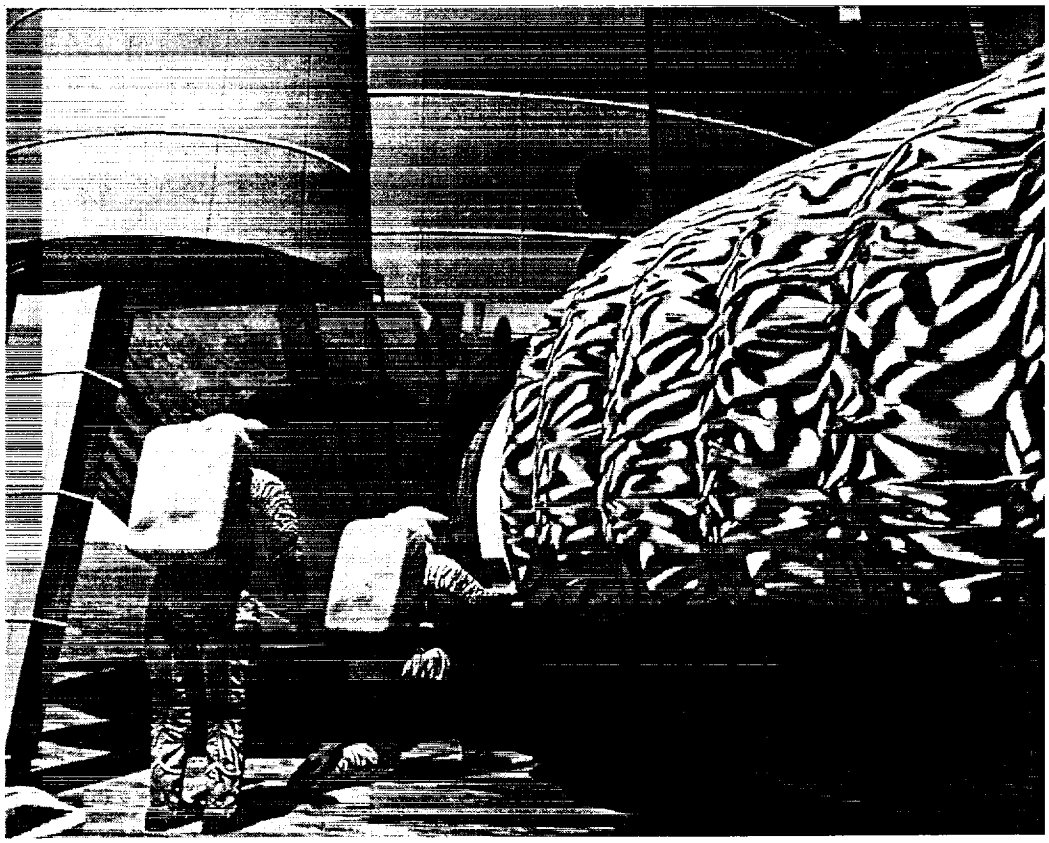
- Who should explore in the rover and who should stay "home" in the laboratory?

- What are the crew requirements for supporting crew members in the pressurized rover and to maintain and operate the Mars base?

The nature of sample collection will affect crew selection and work assignment.

For example, if the deep drilling equipment is installed close to the Mars Base, it may relieve a burden from the rover and its crew.

FIGURE 3. The crew attaches an inflatable laboratory to their lander to increase the internal pressurized volume of their Martian home.



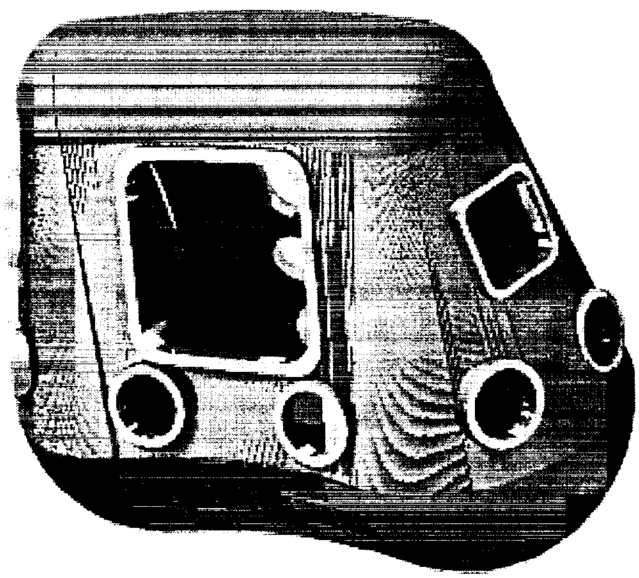
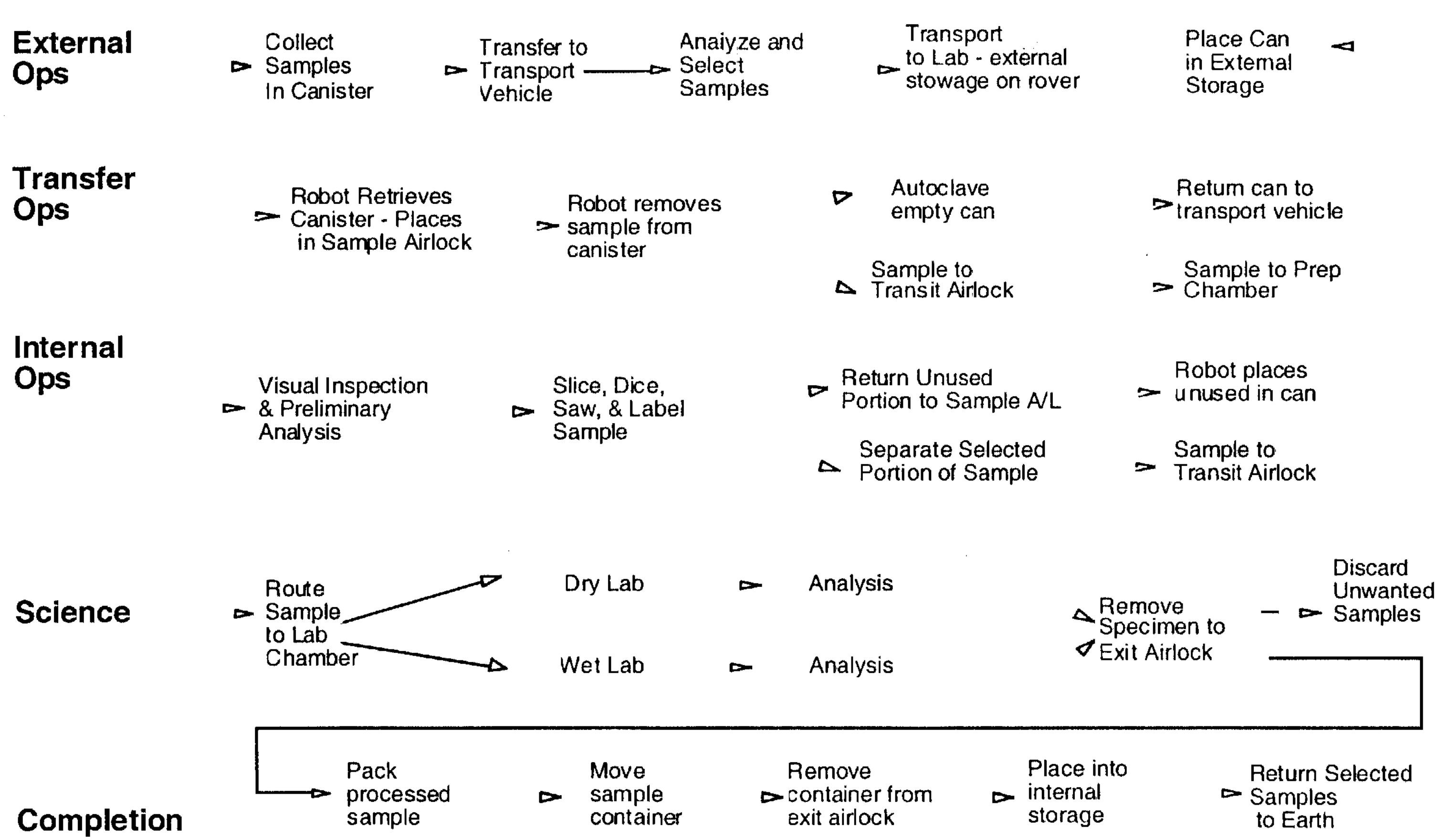


FIGURE 4. Pressurized ΔP Curved Plan "Glovebox" Research Chamber.

Figure 5. Astrobiology Sample Processing Flow Chart



OPERATIONAL SCENARIO: NARRATIVE OF THE SOLID SAMPLE PROCESSING SCENARIO – FIGURE 5

1. **Collect Samples** -- Collect samples at drilling site or other location. Place samples into a protective canister.

2. **Stow Samples for Transport** -- Place canisters on transporter vehicle to carry them to the Astrobiology Sample Lab. The crew may conduct some on-board analysis to make a preliminary evaluation of the samples.

3. **Stow Sample Canisters for Retrieval** -- Place canisters into robotic external storage.

4. **Retrieve Samples** -- Use robotic retrieval system to bring desired sample, place it in the sample airlock.

5. **Bring Sample into Lab** -- In sample airlock, remove sample from its canister. Crew members use remote manipulators or robots to handle and sort the samples.

6. **Move Sample to Working Environment** -- Robots move the sample through a transit airlock to the Preparation Chamber, where crew members examine it then slice, dice and spice it for analysis.

7. **Move Sample to Analysis** -- Robots move the prepared sample to the Dry Lab Chamber or Wet Lab Chamber.

8. **Prepare Lab Chambers** -- Crew prepares lab chambers with tools and equipment, maintenance, repair, and cleaning.

9. **Take Precautions** -- Sterilize and autoclave samples, tools, equipment and chambers at appropriate times and opportunities.

10. **Remove Sample after Analysis** -- Crew removes processed samples from the laboratory system via the exit airlock.

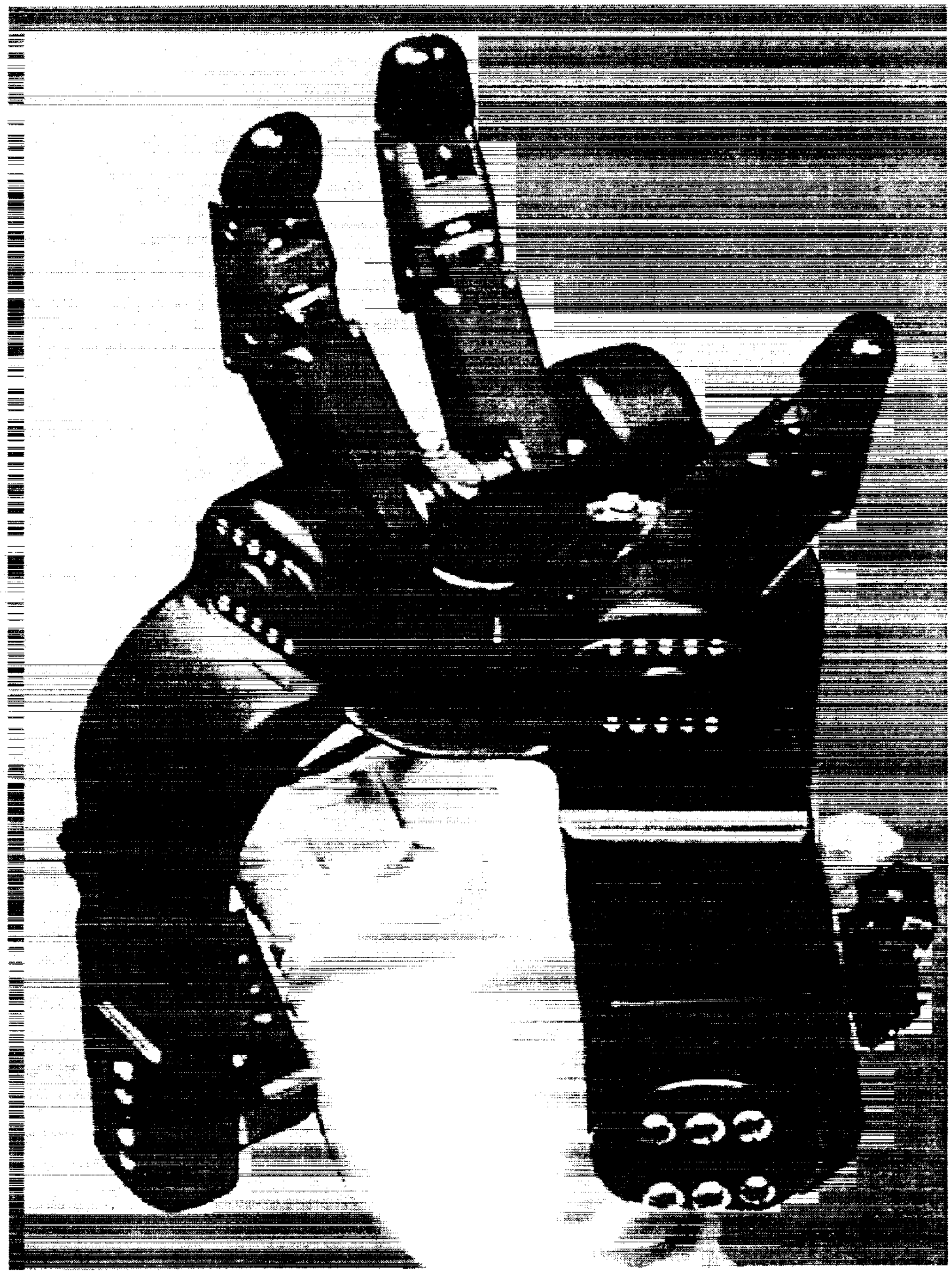


Figure 6. Stanford/Ames Direct Linkage Prehensor, invented by John W. Jameson

FIGURE 7. Astrobiology Laboratory comprised of ΔP "glovebox" research chambers, installed in a circular arrangement.

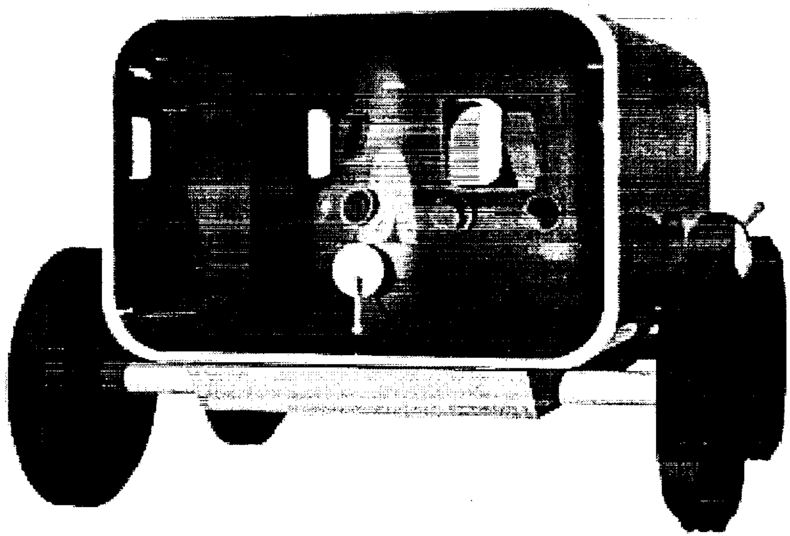


FIGURE 8. Rear view of a simplified planetary rover, with the aft bulkhead removed. The scientific sample airlock appears on the starboard (right) side, between the two wheels, with its handle projecting up at about 45°.

The sample airlock's internal hatch opens into the Astrobiology glovebox, which is essential to handle potentially biotic specimens in a safe manner that will protect both the crew and the sample from contamination.

The sample exit airlock appears in the center of the rover cabin, with its handle pointing straight down.

CREW SIZING – Perhaps the largest unresolved question:

What is the optimal crew size and skill mix to conduct a Mars Astrobiology and Exploration Mission of ten days duration, 500 km away from the Mars Base?

Pressurized rover as microcosm of a Mars mission?

Option A -- two crew members constitute the minimum EVA buddy pair. One is a scientist and the other an engineer who divide the specialized tasks. They stop the rover to conduct an EVA.

Option B -- three crew members afford a buddy pair and a driver who remains in the rover. The skill mix includes both engineer and scientist. The driver can follow the EVA in the rover and use a robotic arm or digger to assist them in digging or turning over rocks.

Option C -- four crew members provide two full EVA buddy teams, involving a multiple mixture of scientists and engineers. While one pair is out EVA, and the driver is observing and following them, the fourth crew member may conduct real-time science investigations of the samples they pass through a sample airlock into a science glovebox in the rover.

Option D -five crew members provide two full EVA buddy teams plus an engineer/driver in the rover.

Option E – Redundant rover for safety and backup. This reliability strategy could require from four to eight crew members.

CONCLUSION

NASA needs to conduct a complete Mars Science Accommodations and Operations Study to understand the In Situ Astrobiology issue.

Developing the Mars surface science laboratory for astrobiology and all the allied sciences represents a great technical and scientific challenge for NASA.

The challenge consists in developing the ability to collect, transport, receive, prepare, process, and analyze exotic samples while preserving them in their ambient environment.

Design research for Mars science exploration requirements:

1. Types of analysis and amounts of data.
2. The expected number type, location, depth, size, mass, etc. of the samples.
3. Mars Science Crew sizing and skill analysis – and overall crew sizing and skill analysis.
4. Mars science accommodation requirements and conceptual design for laboratory facilities.
5. Define the demands on the Mars Base and Habitat to support science laboratory activities and field operations.
6. Laboratory Subsystems modeling and prototyping.
7. The role of Mars surface mobility systems in conducting surface science investigations.

The best way to provide substantive and justifiable requirements to Mars exploration planners is to conduct this design research in cooperation with planetary scientists and astrobiologists.

SCIENTIFIC TASKS FOR HUMANS: PLANT GROWTH EXPERIMENTS

Ken Corey

Biographical Sketch

Ken Corey, former University of Mass/Amherst professor, received his M.S. and Ph.D. at North Carolina State University in plant physiology with minors in statistics and soil science. His research has involved the study of physiological processes and responses of a wide range of agronomic and vegetable crops. As a teacher, he has developed and taught numerous courses in plant, soil, and environmental sciences, including a special topics course in advanced life support systems. For the past 11 years, Corey has been involved with advanced life support systems research for NASA with an emphasis on the use of plants for bioregenerative purposes. Recently, his work has focused on plant responses to rarified atmospheres with applications to the design of atmospheres for extraterrestrial plant growth systems and structures.

Summary

The bioregenerative functions performed by plants are vital to the sustainable management of human life in extreme environments and will require development of new methods and technologies for plant cultivation on Mars. Such methods will likely involve scenarios for cultivating plants in their own atmospheric environments and those directly integrated with human habitats. It will be desirable to use low-pressure atmospheres to reduce structural loads and start-up and maintenance masses for plant growth. Provision of human life support requirements by bioregenerative methods, engineering constraints for construction and deployment of plant growth structures on the surface of Mars, and in-situ resource utilization all suggest the use of hypobaric pressures for plant growth. Past work demonstrated that plants will likely tolerate and grow at pressures at or below one-tenth of sea level pressure on Earth. The use of atmospherically-isolated structures also enables the regulation of plant growth with atmospheric compositions tailored to the plant species. Geometric configurations of those structures will also influence resource requirements, light interception, and function of engineering designs.

There are two broad categories of scenarios for the use of reduced pressures. First, there are scenarios that include direct integration of plants with human habitats or that permit ease of human entry to those habitats. Those habitats would involve the use of moderately low atmospheric pressures (40 to 70 kPa) and relatively high partial pressures of oxygen (14 to 21 kPa). Second, there will be a need for isolated plant growth habitats that will employ very low atmospheric pressures (5 to 40 kPa) potentially with a full range of oxygen partial pressures (1 to 21 kPa) and carbon dioxide partial pressures (0.1 to 10 kPa). The second set of conditions will involve the use of inflatable structures that will employ relatively thin, lightweight materials, capable of transmitting a maximum of ambient photosynthetically active radiation on the surface of Mars. Very few studies have been conducted in either area, but available literature strongly suggests the feasibility of the first (moderately low pressures) and hints at the feasibility of the second, though evidence at this point is scant.

A ***general scientific objective*** driven by a long term presence of humans on Mars is to ***determine the atmospheric limits for normal plant growth and development***. Specifically, limits of interest are low pressure, low partial pressure of oxygen, and partial pressure of carbon dioxide. As a corollary to this objective, it is of interest to answer the following question. ***Can***

plants grow and develop normally at or slightly above the boiling point of water? This question arises from the constraints of materials resupply, material engineering, and the available photon flux available for plant growth on the Martian surface. It also arises from experimental evidence that clearly demonstrates the ability of plants to tolerate low atmospheric pressures. Very low pressures (<5 kPa) are associated with the boiling point of water near temperatures suitable for plant growth. Answers to this question may also be accompanied by the use of tools of genetic engineering to select traits and design plants for adaptation to low pressure and low oxygen extremes. From a long-term perspective, it is of interest to answer the following questions related to the ***technological path*** by which humans choose to explore, settle, and develop the Mars landscape. ***How do we choose to provide people with life support requirements? Do we wish to develop and build a highly sustainable system of Martian agriculture to accompany human exploration and research efforts?***

Plant research efforts on Mars will require further Earth-based testing with a combination of vacuum chambers and Mars analog environments. Analog studies could make use of a Mountain Analog Project (MAP) that would involve controlled plant growth experiments in a High Altitude Plant Production Environment Network (HAPPEN). High altitude balloon flights (stratosphere) would enable short-term plant growth experiments that test and screen genotypes for adaptation to very low atmospheric pressures; those lower than the terrestrial analog limits. During future missions to Mars, it will be helpful to obtain additional information that characterizes the Mars environment. Particularly useful will be a knowledge of the range of photosynthetically active radiation incident on the Martian surface as a function of time, latitude, and atmospheric conditions (e.g. dust storms). Also, plant growth experiments on Mars provide unique opportunities to test plant responses directly to three-eighths gravity and for cultivation in Martian soil. The direct roles of humans in such experiments will be crucial to ensure success and the rapid technological development of sustainable bioregenerative systems. The following is a partial list of important human roles in plant growth experiments. While one can envision many of these roles also being served robotically, most would be better served directly by people.

Roles of Humans

* Site Selector
* Initiator
* Monitor
* Variable Manipulator
* Adjuster/Tweaker
* Diagnostician
* Data Collector
* Sampler
* Interpreter
* Evaluator
* Reporter
* Designer/Planner
* Interactor
* Analyst/Statistician
* Explorer
* Discoverer

Reduced Pressure Rationale

* Structural Considerations
  Minimize Pressure Gradient
  Maximize Transparency of Material
  Decrease Launch Mass or In-situ Processing Mass

* Atmosphere Considerations
  Decrease Start-up Mass for Habitat Atmosphere
  Minimize Leakage and Maintenance Mass

* Crop Performance Considerations
  Photosynthesis
  — Diffusion
  — Photorespiration
  Respiration
  Transpiration
  Gene Expression
  Other?

Key Design Decisions

One Very Large Atmosphere vs. Many Small Atmospheres

A. One Very Large Atmosphere

- Buffering – thermal, atmospheric, chemical
- Minimize atmospheric manipulations or adjustments (control events)
- Large start-up mass, mostly water and carbon dioxide
- Disaster prone — e.g., particle impacts, disease
- Degree of autonomy?

B. Many Small Atmospheres

- Prelude to ecosynthesis
- Modular
- Scaleable
- Adaptable
- Penetrations
- Truncones provide thermal and atmospheric buffering
- Lends itself to extreme environments
- Creates resource caches
- Tailored to plant (crop and noncrop species) requirements
- Degree of autonomy?

C. Combinations of A & B

Concept of multiple barriers
Light transmission/attenuation — Could be used to provide different light environments, e.g., grow lettuce at lower light

Experimental Variables for Plant Growth Experiments on Mars

* ***Atmospheric Pressure***

— With human integration (moderately low pressures)
— Without human integration (very to extremely low pressures)

Possible range for plants isolated from people: 5 to 25 kPa

* ***Partial Pressure of Oxygen***

— Anoxia tolerance
— Intermediate range of tolerance

* ***Partial Pressure of Carbon Dioxide***

— Upper tolerance limit
— Importance of $ppO_2/ppCO_2$

* ***Genotype***

— Food plants (e.g., rice, wheat, lettuce)
— Non-food plants (e.g., *Arabidopsis*, algal species)

* ***Growth Medium***

— Martian regolith
— Solid substrate shipped from Earth
— Hydroponics of some form (several options)

* ***Irradiance***

— Time and site-dependent
— Should the PPF for plant growth experiments be controlled?
— Materials, thermal control, nature of barriers, light attenuation

* ***Gravity***

Three-eighths G has not been the focus of much work.

Reduced Pressure Categories

There are two broad categories of scenarios for the use of reduced pressures. First, there are scenarios that include direct integration of plants with human habitats or that permit ease of human entry to those habitats. Those habitats would involve the use of moderately low atmospheric pressures (40 to 70 kPa) and relatively high partial pressures of oxygen (14 to 21 kPa). Second, there will be a need for isolated plant growth habitats that will employ very low atmospheric pressures (5 to 40 kPa) potentially with a full range of oxygen partial pressures (1 to 21 kPa) and carbon dioxide partial pressures (0.1 to 10 kPa). The second set of conditions may involve the use of inflatable structures that employ relatively thin, lightweight materials, capable of transmitting a maximum of ambient photosynthetically active radiation at an extraterrestrial site. Very few studies have been conducted in either area, but available literature strongly suggests the feasibility of the first (moderately low pressures) and hints at the feasibility of the second, though evidence at this point is scant.

Categorization of atmospheric pressure ranges and generalized adaptations of organisms to those conditions.

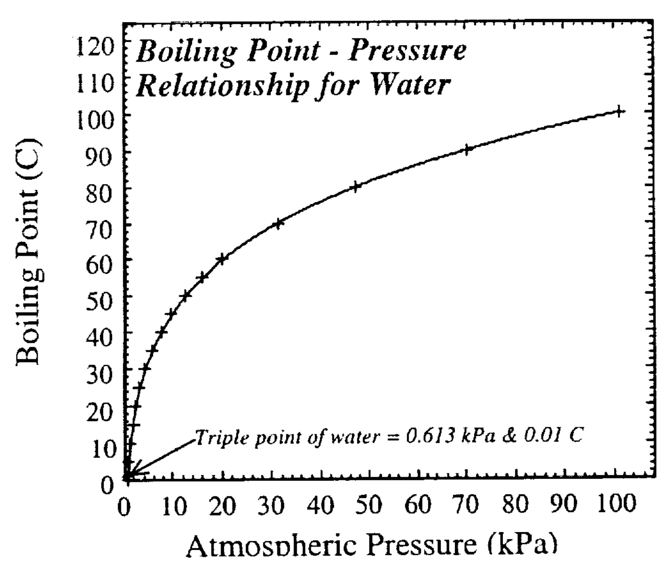
Pressure Range (kPa)	Fuzzy Description	Reference Altitudes (m)	Comments
101 – 75	slight	0 - 2500	* abundant terrestrial analogs * human adaptation easy
74 – 50	moderate	2500 – 5500	* many accessible terrestrial analogs e.g., White Mt. Res. Sta. – 4343 m (59 kPa) * human adaptation difficult, but possible over entire range
49 – 25	very	5500 – 10400	* terrestrial analog limit: Mt. Everest - 8,848 m (~ 31 kPa) * humans require supplemental oxygen
25 – 0.7	extreme	10400 – 27000	* stratosphere, lower Mars atmosphere (0.7 kPa) * plants & microbes can survive and grow, depending upon temperature and atmospheric composition

Can Plants Grow at the Boiling Point?

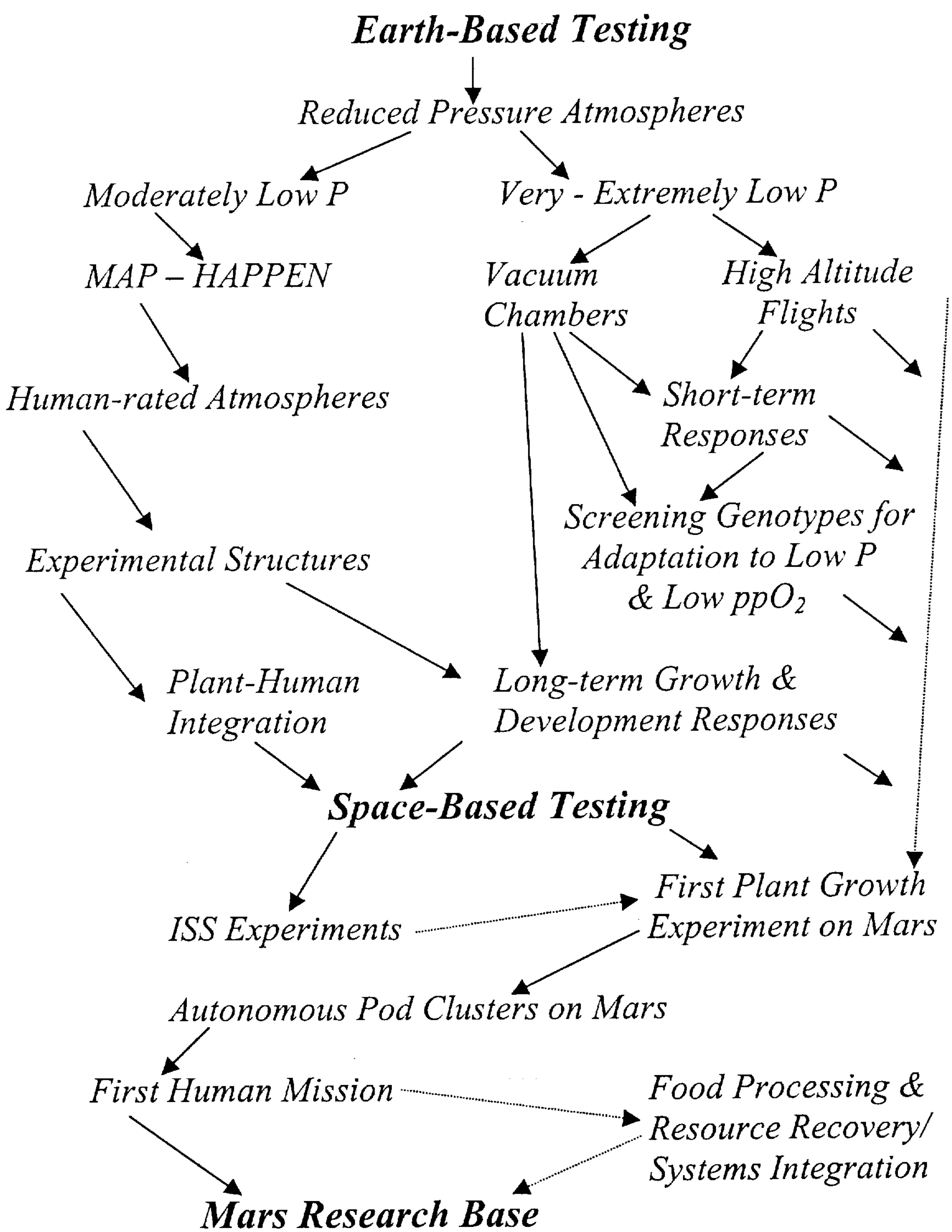
The surface pressure of the Martian atmosphere is about 7 mb or less than one-hundredth the sea level surface pressure of Earth. At this pressure, free water would boil off or sublime rapidly at temperatures where most organisms exist on Earth. However, if one were able to remove the thermal constraint to life on Mars, what would be the atmospheric limits at which plants can survive or even grow?

Recent interest in a human mission to Mars has captivated the public. However, if a long-term human presence is to develop in such a harsh environment, it will be necessary to establish limits for maintenance and growth of other organisms, especially plant life. Plant life will provide other heterotrophs with essential functions of oxygen evolution, carbon dioxide absorption, water recycling, and food. However, until a stage as advanced as terraformation occurs, it will be necessary to grow plants in thermally controlled environments. What then will be the atmospheric design for such a controlled habitat? What are the lower limits of atmospheric pressure for plants? Recent experiments at NASA's Kennedy Space Center strongly suggest that lettuce plants will at least be able to tolerate pressures at or below one-tenth atmosphere pressure for several hours, provided that sufficient water vapor is maintained in the atmosphere. Since plants do not wilt, it is reasonable to presume that they would be capable of long-term growth if provided with carbon dioxide, suitable temperatures, and sufficient photon flux. The limit suggested on the basis of pure water vapor would suggest that pressures of 2 to 5 kPa are likely possibilities, since saturated vapor pressures at normal growth temperatures are in the range of 1 to 4 kPa. Such pressure limits may necessitate the use of plants that would tolerate low partial pressures of oxygen. Such a scenario is well within the realm of possibility. An examination of the boiling point curve for water reveals that at a pressure of 3.2 kPa, water boils at a temperature of ~ 25 C. Thus, it is conceivable that plants will be capable of growth at temperatures at or very near the boiling point. Capability of plant growth at such low pressures would enable the use of lightweight, transparent structures that would minimize launch masses required to establish extraterrestrial plant growth facilities. Given suitably engineered habitats, early Martian travelers and settlers would then have plants as a foundation and life boat for the necessary consumables of oxygen, water, and food.

Figure 1. The relationship of boiling point of water with total atmospheric pressure.



Pathway to Early Martian Agriculture



HUMAN EXPLORATION FOR RESOURCES ON MARS

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I consider two main periods of resource exploration: (1) Near term, defined as the first ten years of operation of a base on Mars, and (2) Long-range resources. I argue that the search for long-range resources must begin during the first ten years.

1. Near-term resources

Searching for water/ice

Undoubtedly a lot of work will have been done to find sources of water or its frozen equivalent before selecting a base on Mars, and surely the base will be near a supply of water if they are identified remotely. Nevertheless, an active base that is expected to grow must have a well-defined supply of water. Hence, the local and regional aquifer must be characterized. This requires:

- Drilling, probable in more than one place
- Examination and study of cores or cuttings to identify lithologies
- Measurement of physical properties of the rocks (permeability etc.)
- Measurement of the ice/rock ratio
- Electromagnetic surveys
- Tracer studies, if liquid water is present
- Sample selection for detailed studies
- Detailed studies of the local and regional geology

Of these tasks, humans may be essential for:

- Core/cuttings examination (macroscopic)
- Determining the ice/rock ratio
- Measurement of the physical properties
- Sample selection for geologic studies, and doing those studies
- Geologic studies

Studies of core samples or cuttings will be valuable for many reasons, not just the exploration for water resources and aquifer characterization. Such studies will help understand local resources in general, such as identifying particularly iron-rich horizons, clay layers, etc.

Resources for Agriculture

It will be crucial for base inhabitants to grow their own food on Mars. This will require using Martian surface materials as soils. However, it is unlikely that we will be able to take any random soil and grow plants in it. We will need:

- The right mix of drainage and water retention, implying both sand and clay components
- Experiments on the value of local regolith as a useful soil for agriculture
- Search for soil additives to increase soil productivity (e.g., sand, clay)
- Search for key fertilizers, such as phosphates and nitrogen.

Nitrogen might be abundant enough in the regolith, though a source of nitrates would be useful. Exploration for rich deposits of phosphates may be difficult. On Earth, these form in marine sedimentary environment and depend on organisms concentrating the phosphorous. This will not have happened on Mars, unless it was teeming with life. Instead, Martians will need to search in other geologic environments. Sediments might still be promising, depending on how they were deposited, the composition of the waters that deposited them, etc. Igneous rocks could be use if highly evolved so that the phosphorous content was increased greatly. The most promising near term source might be the regolith because it contains a few tenths % of P_2O_5. Soil processes, which are not understood at all, might have concentrated P to some extent. This will require detailed studies of the upper meter or so of the regolith.

Aggregates

Aggregate is extremely important when building an infrastructure. It is by far the most mined material in the United States (2.3 billion tons per year). It is used for roads, concrete, bridges, roofing materials, and glass. On earth, the main sources are sand and gravel deposits, and solid rock quarried to produce crushed stone. At first, Mars explorers might simply grade surfaces to make simple roadways, or smooth paths by repeated use. More actively, they will have to seek out naturally occurring aggregates on Mars. These will occur at the bases of gullies and cliffs, and in river beds. The Martian regolith near the site will be the first naturally occurring aggregate that they will use. Depending on the site, there ought to be a range of grain sizes and materials. All these possibilities will need to be characterized by field observations and measurements (e.g., grain size distributions).

Structural materials

The prime resource for structural materials will be the regolith. Humans will have only minor role in exploring the regolith for use as shielding, raw material for bricks, or a source of iron (the regolith has 13-18 wt% FeO). However, humans will play a major role in searching for concentrations of Ca-sulfates and carbonates for cements and clays for ceramics. This will require many soil samples and shallow drill cores. Although in principle some of this exploration could be done by autonomous rovers equipped with instruments that do not exist yet, it is likely that humans will be needed to assess the total resource potential of the regolith in the vicinity of the base.

2. Long-term resources

Essential for future Martian development

Development of all the resource potential on Mars is essential to the continued exploration of the planet. We will need to continuously enhance the Martian infrastructure, and that requires long-range planning. Most important, we will need to eventually export commodities useful elsewhere in the Solar System. For comparison, LEO has its microgravity environment to sell. The Moon has a very hard vacuum, huge solar energy export potential, and possibly ^3He. What will be the commercially viable products from Mars? The answer will come only from extensive exploration for resources, and that exploration must begin during the first few years of Mars base operations.

Need vigorous program of industrial research and development

We do not know what resources will be most important on Mars. One important way of determining that will be to develop manufacturing processes on Mars. Experiments will elucidate the value of the unique Martian environment; for example, could the highly oxidizing properties of the regolith be a useful property that could be exploited? Industrial R&D will help define what resources are needed, hence shape the exploration program. Finally, the development of an industrial infrastructure on Mars will give us opportunities to experiment with unique resources found on Mars. As above, this must be done soon after the base is established.

Potential long-term resources

Some possibilities are pretty clear:

- Find rich iron ores
- Discover other metal deposits (Ni, Ti, Au, Ag, Cr, Al, Cu, Zn, Pb, Pt-group, etc.)
- Organic compounds
- Extensive clay deposits

Finding these resources requires intensive, global geological exploration

We need to explore certain logical geologic settings for potential resources:

- Sedimentary deposits (clays, evaporites, maybe even placers)
- Hydrothermal deposits (Cu, Zn, S, Au, Ag)
- Differentiated igneous provinces (Ti, Cr, Ni, Cu, Pt-group, S, possibly REE, halogens)
- Search in assorted tectonic settings.

Global search requires both humans and robots

Astronauts will not be able to travel all over the globe. But they can beam themselves into teleoperated rovers equipped with high-quality vision systems, multispectral imaging, and chemical analytical sensors. These must be operated by geologists at a base on Mars. The long time delay prohibits thorough geological field work, though some tasks can probably be handled from Earth (e.g., doing the chemical analysis and anything else that takes a long time).

Conclusions

- Resources needed during the first decade of Mars operations need to be kept simple: use the local regolith for as much as possible.
- Water will be essential, so a thorough characterization of the local aquifer must be done. This will require drilling, E-M surveys, and study of drill cores and the properties of subsurface rocks.
- A search will probably need to be done for certain key ingredients, such as fertilizer and other agricultural components. High quality aggregates might also be needed.
- Once the base is operational and local resources are relatively well defined, it will be essential to begin planning for the future. An industrial R&D program must be established. This can include experiment done of Earth before being implemented on Mars. The experiments will help define what resources will be needed.
- A global search for resources must be started early. This is important in attracting capital for Martian investment.
- Humans will need to do most of the exploration. However, they can be helped by appropriate robotic devices, including those teleoperated from Mars, autonomous, and those guided from Earth.

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