NASA/CP—1998-207431

Workshop on Research for Space Exploration: Physical Sciences and Process Technology

Proceedings of a workshop sponsored by
NASA Lewis Research Center, Microgravity Research Division
Cleveland, Ohio
August 5–7, 1997

National Aeronautics and
Space Administration

Lewis Research Center

May 1998

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076
Price Code: A04

National Technical Information Service
5287 Port Royal Road
Springfield, VA 22100
Price Code: A04

Contents

Page

Appendix A

Appendix B

Appendix C

Overview

This report summarizes the results of a workshop sponsored by the Microgravity Research Division of NASA to define contributions the microgravity research community can provide to advance the human exploration of space. The workshop, entitled "Research for Space Exploration: Physical Sciences and Process Technologies," was held in Cleveland, Ohio on August 5 - 7, 1997. The meeting was attended by invited speakers and participants from universities, industry, and various NASA installations. The number of attendees was limited to about 100. Invited speakers and attendees participated in an exchange of ideas to identify issues of interest in physical sciences and process technologies.

This workshop was part of a continuing effort to broaden the contribution of the microgravity research community toward achieving the goals of the space agency in human exploration, as identified in the NASA Human Exploration and Development of Space (HEDS) strategic plan. The microgravity program is one of NASA's major links to academic and industrial basic research in the physical and engineering sciences. At present, it supports close to 400 principal investigators, who represent many of the nation's leading researchers in the physical and engineering sciences and biotechnology. The intent of the workshop was to open a dialogue between NASA and this large, influential research community, to engage this asset in support of human exploration. The workshop provided a forum to facilitate communication between the research community, mission planners, and industry technical experts with the goal of defining enabling research for the Human Exploration and Development of Space Enterprise. The needs and the potential for advances in the relevant technologies for long-duration human presence in space were identified and discussed.

The first day of the meeting was devoted to background briefings on NASA planning for human exploration. Following the briefings, groups of technical experts met with the mission planners and experts for more detailed fact-finding discussions. The groups developed consensus positions on research needs. This was followed by an open discussion as the group findings were reported to the participants. The expert groups prepared written presentations and provided summary recommendations that have been edited and incorporated into this document. This report documents a list and technical description of research areas and problems of importance to NASA's HEDS missions and the space hardware development activities to which the microgravity research community can contribute. Given a decision to define specific exploration initiatives, these research areas would be a core element in developing program content via competitive research solicitations.

Workshop Summary

NASA's Strategic Plan and Roadmap outline a course preparing for the human exploration of space. Within this framework, the Microgravity Research Program can make a critical contribution by conducting basic research in the physical and engineering sciences to resolve fundamental questions and prepare for the development of essential technologies. This effort, already underway to a limited degree, can be effectively undertaken by the engineering and scientific community that is engaged by the Microgravity Research Division.

NASA's Microgravity Research Division is responsible for conducting a program of basic research in the physical sciences and process technologies that uses the space environment as a tool to obtain new knowledge. In the course of exploring the unique behavior of physical processes in Space to obtain new scientific insights, the Microgravity Research program and its participating community have emerged as a primary source of expertise on the effects of the space environment on physical processes.

During the workshop, factors critical for enabling long-duration space exploration were identified by the speakers, factors that covered broad areas of basic research and technology development needs. The presentations describing exploration mission plans suggested numerous areas that require further development. These research investment areas for exploration include advanced life support, health and human performance, *in-situ* resource utilization, advanced power generation, power management, and power storage. The research needs identified by workshop participants were collected into the reports of the topical area expert groups, who developed consensus findings for the workshop. Summaries of the group reports follow.

Fluids and Particulates Management

The oral presentations given at this workshop on the Human Exploration and Development of Space (HEDS) enterprise briefly described many technologies that might be used to sustain a habitat on the surface of Mars. Mars has a thin, windy atmosphere that imposes low pressures, low temperatures, and mobile dust on any structure on the Martian surface. On Mars gravitational acceleration is one-third that of earth. Based on the information delivered and the short time span in which it was delivered, it was not possible to pinpoint those specific scientific problems or issues that underpin the new technologies. This report concentrates on general issues that we believe will arise in trying to optimize designs, or develop more efficient technologies, to facilitate extended space flight, as well as to create a Martian habitat for extended use. Most of the topics identified are ones that are already supported in the microgravity program at NASA, though in the current program there is little or no focus on the 1/3 g environment. In the latter case we would expect most systems to exhibit quantitative, but not qualitative changes in performance or operation relative to terrestrial gravity. Thus although there may be exceptions, studies to corroborate this expectation might be addressed by augmenting existing microgravity investigations in order to encompass the additional parametric ranges associated with the transition from 1 g to 1/3 g.

The topics that seem of most direct interest are listed below in descending order of perceived importance, and they are discussed in more detail in the following pages.

1. Multiphase Transport (Macroscale and Microscale)

Flow regimes in pipes with heat/mass transport, and individual interfaces, contact lines, phase transformations, and instabilities all of which enter the processes for transforming local resources into usable supplies such as fuel, water, and oxygen. In addition there are strategies and processes of transport of liquids and gases which enter the control of fluid configuration such as in fuel tanks and supply vessels.

2. Particulate Dynamics

Dust particles on mars, their capture, deposition, filtration and elimination relevant to the performance, health and safety of any Martian-based facility and the processing and use of the Martian atmosphere for developing (*in situ*) fuels and other materials.

3. Multiphase Processing Technologies

Buoyancy can strongly affect many separations and chemical processes such as fluidized beds, boiling, freezing, or chemical reactions which are proposed as means for producing needed materials *in situ* (on Mars).

4. Structural Aerodynamics

The Martian wind, loaded with dust, can damage or destroy man-made objects on Mars.

Fire Safety

It is assumed that, as the Mars mission program develops, the planners will incorporate a thorough review of hazards, through qualitative and quantitative risk assessments.

The safety working group, composed of those workshop participants who specialize in combustion, focused on both fire-safety and combustion concerns. The report describes fire-safety issues and selected priority research, and it also notes other combustion-related concerns beyond fire safety.

Fire safety research priorities can be summarized as:

1. Research on diagnostics in electrical systems to provide an early, pre-incident warning to breakdowns, possibly resistivity or continuity checks.

2. Determination of flammability and flame spread, flame luminosity, limiting oxygen, and soot sizes under various atmospheres for thick materials and polymers at 1/3 g.

3. Determination of flammability and flame, and soot sizes of thick materials with imposed heat flux at microgravity.

4. Determination of combustion limits, ignitability, and flame luminosity of premixed methane and oxygen at Rover conditions and 1/3 g for propulsion and fire safety.

5. Research on fundamental behavior of various gaseous and liquid extinguishants an solid-surface fires at 1/3 g and microgravity with modeling and experiment verification.

Structures and Surface Operations

The topic of Structures and Surface Operations is very broad and includes both basic Research areas in which are do not appear to be placed elsewhere and the synthesis and application of basic research and knowledge from many other areas.

Of the five areas identified as having the largest mission cost component, and thus the largest potential for reductions in needed resources, the last three of the five involve operations to be carried out at the Martian surface:

1. Transportation from the Earth to Orbit
2. Interplanetary travel and propulsion
3. Life support system
4. In-situ resource utilization/propellant production
5. Surface Power

The last three areas are contained within six major surface systems defined by Dave Kaplan in his workshop presentation:

1. Surface laboratory/habitat module
2. Life support system
3. In-situ resource utilization equipment
4. Surface mobility systems
5. Extra-vehicular activity mobility systems
6. Power systems

These two lists were used to help define the scope and major areas of concerns in the group's consideration.

Focused, but not narrow, research needs in the following seven areas are described. All have high importance to mission success and operations and contain enough components that an overall priority ranking is difficult and probably not very informative. Some areas identify research needs for the first human mission, while others are needs for later human missions or have significant components first needed at both events. The seven areas, moving from reconnaissance to operation issues, and the time of most significant need are:

1. Determination of soil and surface properties of Mars (First and subsequent missions)
2. Handling and movement of soil materials (Subsequent missions, may have little need on first mission)
3. Habitat/lab materials, design and development (First mission)
4. Robotics (First mission)

5. Dust mitigation and control (First mission)
6. Fundamental studies of *in-situ* resource utilization (First mission for propellants subsequent for most others)
7. Life-support research in the areas of plant, algae, and microbe tolerances (First and subsequent missions)

The working group is aware of the general needs for research in the area of life-support, and omission of topics in this area reflects the lack of focused expertise among the working group needed to make specific recommendations, not judgments of low importance. Given the workshop title content of "Physical Sciences and Process Technologies," human factors have not been addressed. Only structures serving the Martian surface are included, and the specialized design of surface facilities including power, liquefaction of gases, and cryogenic storage facilities have been excluded. Research needs will depend on mission features, not all firmly described. For example, if the surface power option selected is a large field of movable solar panels, the magnitude of construction would give rise to a larger research effort specifically on large-scale repetitive and at least nearly autonomous robotics-assisted/performed construction.

Heat Transfer

The group discussed basic research need in four critical areas; surface power, interplanetary travel, in-situ resource utilization, and life-support systems.

Some of the major recommendations are summarized below:

1. Phase change heat and mass transfer, multiphase flow and pressure drop of liquid metals and cryogenics at 3/8 and zero gravity should be studied.
2. Interfacial phenomena under low and zero gravity conditions under transient conditions deserve investigation.
3. Scaling with gravity of thermal phenomena, i.e., identification of boundaries where physics of phenomena changes with g level needs to be understood.
4. Effects of Martian soil and dust on radiative properties of structures should be studied.
5. Trade-off studies for various components in a thermal system should be conducted at an early stage so that their impact on basic research is known well in advance.
6. Computational tools should be developed along with experimental effort so that models can be validated with the data and can be applied with confidence in situations of interest.

Radiation Materials

Scope

Research in the following areas were considered for the Material Science Program: (1) Improvements to physics models, computer codes, and analysis tools for predicting radiation effects, (2) evaluation of the effectiveness of new shielding materials and concepts, and (3) the validation of (1) and (2) by ground tests and flight data.

Not included in the scope here (but needed as Input) are the following: (4) radiobiological response, which is being addressed in the Life sciences Program, (5) improved environment models which is being addressed by other programs (such as NASA's Space Environments and Effects (SEE) Program), and (6) radiation sources from nuclear propulsion, surface reactors, and RTGs, which are assumed here to be adequately shielded by the designs of those devices.

Recommendations

The following recommendations for research related to radiation and shielding materials are made:

1. Improved Calculational Methods for Predicting Radiation Effects

   a) Physics of cross sections: improvements of nuclear cross sections for projectile and target fragmentation by HZE particles.

   b) Cross section measurements: thin-target cross section measurements suitable for mode validation for representative ions, energies and target elements.

   c) Propagation calculations: application of nuclear models and radiation transport codes for representative benchmark thick target shielding configurations and various material compositions

   d) Ground validation: perform ground tests using benchmark cases from (c) to quantify propagation calculation uncertainties based on accelerator beams.

   e) Augment program and compare alternate methods: take advantage of alternate calculational methods developed outside NASA, and perform model comparisons for benchmark cases to select best methods and hasten convergence and validation.

2. Shield Materials, Presently Available and New/Improved.

   a) Evaluate alternative shield configurations with the available materials: for early and evolving mission architectures, shielding calculations and trade studies should be performed to investigate maximum utilization of onboard materials for reducing crew radiation exposure in transit. Study shielding concepts, taking into account candidate habitat structure equipment and regolith material, to reduce surface exposure.

   b) Existing candidate and new composites/laminates: shielding calculations and trade studies should be performed to evaluate the effectiveness, and options, in using new shielding materials to supplement available materials for achieving shielding requirements.

3. Flight Validation

   Flight validation of the result from (1), and (2) above should be performed using either high-inclination shuttle flights or a free-flyer platform in near polar orbit to maximize GCR exposure.

Chemical Processes

The Chemical processes group evaluated the research needs for life support and in-situ resource utilization (ISRU). The use of local resources were limited to the moon, Mars, and near-earth asteroids. The life support applications included transit vehicles and surface scenarios (habitats, rovers, and space suits). Both basic research that needed to be conducted on existing concepts and those pertaining to new and novel concepts were considered.

1. In-situ Resource Utilization

In the category of existing concepts emphasis was placed on research leading to better understanding of zirconia electrolysis and radio frequency glow discharge processes. The zirconia electrolysis process has utility for oxygen production on Mars, the Moon, and in closed loop life support for oxygen recovery. In addition, the fundamental modeling of this process will apply equally well to a solid oxide regenerative fuel cells. Due to its wide applicability it is recommended that the transport processes associated with this device be well studied, the materials issues associated with this device be well characterized and the properties improved, and research be conducted on the high temperature seals and packaging issues. For the glow discharge process that is being considered to obtain high oxygen concentration gas mixtures on Mars, the following fundamental issues were identified. Research leading to better understanding of the effect of dust, trace gas effects, and reduced gravity on the performance of the process would be very beneficial. Also, the ability to remove Mars dust from the RF system without compromising the system performance is important.

In the novel concepts category, the ability to produce parts, both on the surface and in the transit vehicle, on a need basis, thereby reducing the number of Earth carried spare parts and reducing the risk of subsystem failures was considered a high priority. Effect of gravity on the processes associated with rapid prototyping, and welding are important research areas. Equally important is the ability to produce raw materials (chemical building blocks such as paraffins and olefins) from carbon dioxide and water as starter materials. Also identified as an interesting topic is the characterization of the fine Mars soil as a catalyst material for various chemical processes. Such a catalyst would, in addition to lowering launch mass, reduce risks associated with catalyst aging due to poisoning. The ability to separate water, and nitrogen/argon buffer gas from the Mars atmosphere was also noted as a valuable research area.

Many of the chemical processes would require multitudes of sensors, storage tanks and flow controllers. Research that focuses on microscale chemical sensors, light weight storage tanks, and miniaturized flow controllers were identified to be important. Research leading to novel ways of storing light gases (hydrogen and methane for example) at high densities is also of great value.

2. Life Support

Many of the processes associated with both life support and ISRU involve adsorption/ desorption processes. Modeling such processes to understand and optimize them was noted as a high priority. Issues involve design of systems for better heating and cooling, lower pressure drops, better sorbent materials, and faster cycle times. Such processes are currently used/ contemplated for gas separations, compression, trace contaminant control and heat pumps.

Most of the chemical processes used in life support involve liquid-vapor mixtures. A good understanding of two-phase transport phenomena and phase separations in both micro- and hypo-gravity is important. Designs of bioreactors suitable for microgravity environments, transport phenomena in porous nutrient beds for plant growth, and improved oxidation reactions for both organic contaminants and solid waste incineration were identified as topics to be researched.

Appendix A: Group Reports

Fluids and Particulates Management

The oral presentations given at this workshop on the Human Exploration and Development of Space (HEDS) enterprise briefly described many technologies that might be used to sustain a habitat on the surface of Mars. Mars has a thin, windy atmosphere that imposes low pressures, low temperatures, and mobile dust on any structure on the Martian surface. On Mars gravitational acceleration is one-third that of earth. Based on the information delivered and the short time span in which it was delivered, the committee was not able to pinpoint those specific scientific problems or issues that underpin the new technologies. This report concentrates on general issues that we believe will arise in trying to optimize designs, or develop more efficient technologies, to facilitate extended space flight, as well as to create a Martian habitat for extended use. Most of the topics identified are ones that are already supported in the microgravity program at NASA, though in the current program there is little or no focus on the 1/3 g environment. In the latter case we would expect most systems to exhibit quantitative, but not qualitative changes in performance or operation relative to terrestrial gravity. Thus although there may be exceptions, studies to corroborate this expectation might be addressed by augmenting existing microgravity investigations in order to encompass the additional parametric ranges associated with the transition from 1 g to 1/3 g.

The topics that seem of most direct interest are listed below in descending order of perceived importance, and they are discussed in more detail in the following pages.

1. Multiphase Transport (Macroscale and Microscale)

Flow regimes in pipes with heat/mass transport, and individual interfaces, contact lines, phase transformations, and instabilities all of which enter the processes for transforming local resources into usable supplies such as fuel, water, and oxygen. In addition there are strategies and processes of transport of liquids and gases which enter the control of fluid configuration such as in fuel tanks and supply vessels.

2. Particulate Dynamics

Dust particles on mars, their capture, deposition, filtration and elimination relevant to the performance, health and safety of any Martian-based facility and the processing and use of the Martian atmosphere for developing (*in situ*) fuels and other materials.

3. Multiphase Processing Technologies

Buoyancy can strongly affect many separations and chemical processes such as fluidized beds, boiling, freezing, or chemical reactions which are proposed as means for producing needed materials *in situ* (on Mars).

4. Structural Aerodynamics

The Martian wind, loaded with dust, can damage or destroy man-made objects on Mars.

5. Miscellaneous

Brief descriptions are included in two more areas which are of likely importance to HEDS. However, due to the lack of expertise of the committee in these areas, neither amplification of the discussion nor prioritization of the topics is possible at this time.

Multiphase Transport (Macroscale and Microscale)

A. Macroscopic Effects

Multiphase flows is one of the most difficult areas of fluid dynamics to understand, even in the terrestrial environment. At present at 1g, predictions of the performance of such systems, under steady or unsteady conditions, cannot be made with confidence. Hence design of any flow or processing facility that involves a multiphase flow, is done largely based upon experience and "know-how" which does not currently exist either for 1 g or 1/3 g. Three fundamental physical issues are central to the solution of associated technological problems:

1. The phase configuration or flow regime needs to be determined.

2. For a given flow regime, the spatial distribution of the phases needs to be understood.

3. Heat, mass and momentum transfer across interfaces needs to be related to small-scale hydrodynamics near the interface.

The NASA program for the exploration of Mars must face the design of systems with multiple phases, including systems for fluid transport, separation processes, containment of nuclear reactions, heat transfer, boiling, freezing, the handling of cryogenic fluids, and safety relief vents.

In interplanetary flight, the long duration of microgravity produces phenomenological differences from what is experienced on Earth. Work supported by NASA has made, and will hopefully continue to make, contributions to the understanding of these differences. Engineering practice on Earth have revealed that predictions for new situations are often unreliable and, in fact, fail. There is every reason to suppose that the buoyancy changes in going to Mars will have a similarly detrimental effect on the reliability of multiphase flow designs for Martian flows.

Research into multiphase processes will require the active engagement with the multiphase community in the design and development stages in order to advance the reliability of engineering for the range of dimensionless groups characterizing the Mars environment.

B. Microscopic Effects: Interfacial Dynamics and Stability

As gravity is reduced from 1g, surface tension becomes of increasing consequence on large length scales. Thus bulk motion, such as of liquid propellants, as well a small-scale flow in heat pipes, heat exchangers, and fluid-purification systems is driven by the forces on fluid-fluid interfaces and at moving contact lines. Success at predicting boiling, cavitation, interface shapes, wetting and dewetting rates, in evaluating the effects of surface preparation and material selection, and in designing fluids-handling systems, may rely on replacing ad hoc assumptions about the microscopic mechanisms governing moving contact lines with accurate models.

Interfacial instabilities can lead the qualitative changes in interfacial transport. In turn, the conditions for instability can be sensitive to solid/liquid surface energy, surface finish, g-jitter, surface contamination; all these need to be considered. Further, the conveyance of fluids in pipe and tanks can lead to problems of configuration control.

Particulate Dynamics

The removal of contaminant dust from gases is an important element of many potential technologies associated with HEDS. There has been a great deal of fundamental research on appropriate forces/filtering, etc. for such processes. Generally, this existing science base should be applicable to the dust problem on Mars though removal of tiny submicron particles is a difficult problem. In fact, the problem of capturing or collecting submicron size particles has been a major limitation in scientific attempts to monitor the particulate population in air pollution studies.

The following are the major "new elements" here:

1. The likely high particle-loading, especially under "dust-storm" conditions make it necessary to develop a process for continuous filtering over extended times, with extremely high collection efficiencies, and without fouling due to a build-up of fine particles.

2. There is a necessity of removing 100% of the smallest particles, both for the integrity of life support systems, and because of the potential health risks within the habitat of long-term exposure to inhalation of submicron particles.

From a technological point of view, the use of "simple" mechanical filtering is unrealistic. Assuming that there is a range of particle sizes, from 10 µm or less, experience in the development of "particle capture" techniques for reliable sampling of polluted air suggests that several techniques may be required to cover the whole spectrum of particle size.

Many possible technologies, such as electrostatic collection, require knowledge of the physico-chemical properties of the dust particles over the full spectrum of size. Many of the existing high-volume physical processes for particulate removal in an industrial setting will not be applicable. Filtering often involves small particle loadings or relatively short exposures. For long time periods or with heavy particle loadings filter-cake buildup, fouling etc., will degrade such methods of particle removal.

For particulates that might build up on solid surfaces, such as solar arrays, it may make sense to take preventative action using electrostatic forces, or wind shear. The flow of a high-concentration dusty gas is not well understood, especially for charged particles; these are relevant to possible collection; filtering or abrasion effects. The impact of attempts to solve the technological issues of designing systems that are resident in the dusty atmosphere of Mars could have significant spin-off to earth-based applications, and the resolution of these problems will be crucial to "success" on Mars.

Separations and Multiphase Processing Technologies

Many processes for separations or chemical processing, such as fluidized-bed technologies, are either driven by, or strongly influenced by, buoyancy forces in Earth-based applications. These and other processes may involve the production of gases (solids) in a fluid environment, either by boiling (freezing) or chemical reaction. Some of these technologies may be used on Mars where the parameter regimes of operation will change. This may lead to both quantitative and qualitative modifications in the complex dynamics that control the operational characteristics and the performance of such systems. Some of these can be evaluated via ground-based research by compensating for decreased gravitational buoyancy through a reduction of density differences, but this is not always possible. Further, simple scaling concepts are not generally available for the evaluation of performance modifications in the reduced gravity of a Martian environment. It will be necessary to carefully evaluate all separations and multiphase-processing systems that are feasible on Earth to determine whether the Martian environment will significantly alter their operations.

Structural Dynamics

Structures, such as the habitat and inflatables, the return vehicle, and the nuclear reactors will be subjected to the Martian wind. Rough estimates indicate that the viscosity of the Martian atmosphere will be of the same order of magnitude as its terrestrial equivalent. However, the kinematics viscosity of the Martian atmosphere will be one hundred times larger than in the Earth's atmosphere. As a consequence, the Reynolds number of a Martian flow of given speed will be one hundred times smaller than that of the corresponding flow on Earth. A complicating factor is the likely presence of dust in the Martian flows, increasing the effective density of the gas, its spatial homogeneity, and its potential for the damaging of structures.

Studies should be undertaken to determine the aerodynamic forces on structures of the type anticipated to be built and the nature of the flows around them. This can potentially be done either computationally, or via "wind-tunnel" based laboratory testing.

Miscellaneous

There are a number of topics which appear to be important to HEDS but are outside the scope of expertise of the committee members. These are: 1) the mechanics of seals in the presence of dust and/or under conditions of rapid depressurization; 2) physiological flows in the presence of long-term exposure to reduced- or micro-gravity environments. We recommend that all of these be given due consideration.

Fluids and Particulates Management Panel
Stephen Davis (chair), Northwestern University
Thomas Hanratty, University of Illinois
James Jenkins, Cornell University
Gary Leal, University of California, Santa Barbara
Seth Lichter, Northwestern University

Fire Safety

Introduction

It is assumed that, as the Mars mission program develops, the planners will incorporate a thorough review of hazards, through qualitative and quantitative risk assessments.

The safety working group, composed of those workshop participants who specialize in combustion, focused on both fire-safety and combustion concerns. The report describes fire-safety issues and selected priority research, and it also notes other combustion-related concerns beyond fire safety.

Initiating Events

Ignition events are rare in spacecraft because of enclosed electrical systems, grounding, pressure containment, etc. In the long-duration transit and habitation phases, new fire-initiating causes may arise from waste disposal, trash storage, laundry and household activities, etc. The habitation phase introduces new hazard, such as those from the storage of fuel gas and oxygen systems.

Long-term missions need early fault detection; research should investigate methods of electrical-systems diagnostics (perhaps overall resistivity and continuity checks) for warning in both the transit and habitation phases, and flammable gas monitors.

Material Ignition And Propagation

Material flammability is assessed in normal gravity and worst-case atmosphere; few materials are acceptable for service at concentrations of 30% O_2 and above. The existing database can be scaled for prediction of material flammability at reduced gravity to 1/3 and 1/6 g. Experiments are needed to validate models and to predict flammability in microgravity environments which are not covered by models.

No information is available on the performance and fire safety of methane/oxygen propulsion in 1/3 g, as proposed for the Mars rover. The flammability hazards of Martian dust in O_2 are not known. Experiments need to be performed on flammability of thick materials, degrading polymers, and others in 1/3 g, and at various O_2 concentrations and radiant heat fluxes to determine flame spread, luminosity, O_2 limits, soot size, etc. Also experiments need to be performed on flammability of thick materials and others in microgravity at various O_2 concentrations and radiant heat fluxes to determine flame spread, luminosity, O_2 limits, soot sizes, etc. Determinations of combustion performance and fire safety of premixed methane/oxygen systems in 1/3 g would be beneficial.

Atmospheres

As noted, flammability of materials increases with atmospheric oxygen and few materials are acceptable for service at over 30% concentrations. Quantities of agent for extinguishment also increase greatly with percentage O_2.

Atmospheric dilution is necessary for fire protection and the use and nature of the diluent (nitrogen?) has not been decided for the mars mission.

Detection

Data on fire emissions, soot-particle size in microgravity and 1/3 g are needed for optimum detection sensitivity (see material research).

Long-duration missions require new technology for efficient detection systems, in terms of rapid response, discrimination, false-alarm rejection, multiple-sensor logic, etc.

Suppression

New agents or techniques are needed for long-range missions to replace the shuttle halon and space station CO_2 systems. Demonstrations are needed to validate agent application and effectiveness in microgravity and 1/3 g. Others innovations can be developed for habitation and ISRU extinguishment, such as using the Martian atmosphere as the agent.

Modeling of fundamental behavior of extinguishment by dilution should be done with various agents in microgravity and 1/3 g, followed by validating experiments.

Depressurization

Module depressurization may be necessary to control a major fire on the international space station, but it is not an option for the Mars mission.

Post-Fire Cleanup

After a fire, the crew must provide for removal of atmospheric particles, combustion products, and excess extinguishant; all cleanup must be done in place, since resupply missions are impossible.

Survival Modes

Safe haven provided for radiation protection must serve also during a major fire, with life support, supplies, and remote agent controls.

Other Topics

Other topics discussed include safety in ISRU processing: operations at high temperatures, pressures, oxygen handling; rover propulsion performance and safety for internal combustion engine using in-situ generated fuel in 1/3 g; oxygen/diluent atmospheres necessary for transit and habitat phases: composition, total pressure; performance of ascent module engines on in-situ generated fuel; and safety in welding and thermal operations on the Martian surface.

Fire Safety Research Priorities

Fire safety research priorities can be summarized as:

1. Research on diagnostics in electrical systems to provide an early, pre-incident warning to breakdowns, possibly resistivity or continuity checks.

2. Determination of flammability and flame spread, flame luminosity, limiting oxygen, and soot sizes under various atmospheres for thick materials and polymers at 1/3 g.
3. Determination of flammability and flame, and soot sizes of thick materials with imposed heat flux at microgravity.
4. Determination of combustion limits, ignitability, and flame luminosity of premixed methane and oxygen at Rover conditions and 1/3 g for propulsion and fire safety.
5. Research on fundamental behavior of various gaseous and liquid extinguishants an solid-surface fires at 1/3 g and microgravity with modeling and experiment verification.

Fire Safety Group

Robert Friedman (chair), NASA Lewis Research Center
Robert Altenkirch, Washington State University
M. Pedley, NASA Johnson Space Center
Jose Torero, University of Maryland

Structures and Surface Operations

Introduction

The topic of Structures and Surface Operations is very broad and includes both basic Research areas in which are do not appear to be placed elsewhere and the synthesis and application of basic research and knowledge from many other areas.

Of the five areas identified as having the largest mission cost component, and thus the largest potential for reductions in needed resources, the last three of the five involve operations to be carried out at the Martian surface:

1. Transportation from the Earth to Orbit
2. Interplanetary travel and propulsion
3. Life support system
4. In-situ resource utilization/propellant production
5. Surface Power

These three areas are contained within six major surface systems defined by Dave Kaplan in his workshop presentation:

1. Surface laboratory/habitat module
2. Life support system
3. In-situ resource utilization equipment
4. Surface mobility systems
5. Extra-vehicular activity mobility systems
6. Power systems

These two lists were used to help define the scope and major areas of concerns in the group's consideration.

Focused, but not narrow, research needs in the following seven areas are described. All have high importance to mission success and operations and contain enough components that an overall priority ranking is difficult and probably not very informative. Some areas identify research needs for the first human mission, while others are needs for later human missions or have significant components first needed at both events. The seven areas, moving from reconnaissance to operation issues, and the time of most significant need are:

1. Determination of soil and surface properties of Mars (First and subsequent missions)
2. Handling and movement of soil materials (Subsequent - may have little need on first mission)

3. Habitat/lab materials, design and development (First mission)
4. Robotics (First mission)
5. Dust mitigation and control (First mission)
6. Fundamental studies of in-situ resource utilization (First mission for propellants subsequent for most others)
7. Life support research - Plant, algae and microbe tolerances (First and subsequent missions)

The working group is aware of the general needs for research in the area of life support and omission of topics in this important area reflect a lack of focused expertise among the working group as needed to make specific recommendations, not a judgment of low importance.

Given the workshop title content of "Physical Sciences and Process Technologies," human factors have not been addressed. Only structures serving only the Martian surface are included, and the specialized design of surface facilities including power, liquefaction of gases, and cryogenic storage facilities have been excluded. Research needs will depend on mission features, not all now firmly described. For example, if the surface power option selected is a large field of movable solar panels, the magnitude of construction would give rise to a larger research effort specifically on large-scale repetitive and at least nearly autonomous robotics assisted/performed construction.

Determination of Soil Properties for Mars Exploration

The engineering soil properties relevant to the Mars exploration are poorly understood as D. Kaplan pointed out in his presentations on the "Construction and habitat structures" and "surface operations." The working group on "structures and surface operations" believes that the determination of soil properties on Mars is a pressing short-term issue to be addressed in the early planning of the Mars exploration, if possible in the 2001 Mars Surveyor Program. The knowledge of basic soil properties on Mars could promote the use of soils, which are abundant and inexpensive *in-situ* resources; assist mission planners to devise alternate solutions for surface operation and structures; and resolve some engineering issues which may be in the critical path of the Mars mission objectives. The short-term engineering issues are the first step in the long-term scientific investigation of soils on Mars.

Previous Mars probes such as the Vikings and Pathfinder have transmitted photographs of the Mars surface to Earth, giving us some ideas about soils on Mars. These soils are made of various soil particles, the sizes of which range from fine particles (micrometer) to boulders (meter). The mineral composition of these surfacial soils is being gradually measured and deciphered by Pathfinder. Some mechanical properties will also be assessed by launching two penetrators from altitude during the 2001 Mars Surveyor Program. However, these glimpses at soils will yield very little applicable information about the behavior of Mars soils in regard to surface operation, construction, and habitat. We do not have enough information to predict how the soils will behave when they are subjected to the loads of surface habitats and nuclear reactors (weight and thermal load), and those of wheels of heavy vehicles. How many inches or feet will the soil surface settle under the weight of the heavy nuclear reactor (14 metric tons) under planning? How much will the soil creep under the nuclear reactor whose temperature reaches 1500K? On which soils will the rover be able to carry equipment and crew safely? Are there soft dust spots which may stop surface vehicles?

Some of the specific engineering questions to be resolved are:

1. Spatial variability of soil properties at construction sites. The soils on Mars have properties which are not uniformly distributed. Their deposition processes are also poorly understood. The planning of a site investigation for engineering purposes is therefore not a trivial task. It is difficult to select a site based only on the large-scale map produced from orbit, and the data of the two penetrators which will be launched from the 2001 Mars Orbiter. The spatial variability of soil needs to be characterized by some types of *in-situ* testing (e.g., geophysical tests).

2. Variation of temperature versus depth and heat conduction capabilities in soil. On Mars, soils undergo large variations of temperature in natural conditions, but their thermal properties are not well known. We need to investigate them to understand the soil response to extreme temperature variations under the nuclear reactor under planning (up to 1500K inside).

3. Variation of radiation versus depth in soil. Radiation has been determined to be a definite hazard to humans on Mars. The habitats under planning are designed to maximize the radiation protection with the minimum weight. Their protection could be enhanced by covering them with a few feet of soil, provided that we know more about the radiation absorption characteristics of soils.

4. Basic engineering soil properties. Basic soil properties include grain-size distribution, particle shape and mineral composition, shear strength, elastic moduli, and compaction characteristics. These basic properties are required for a rapid classification of soils, and the assessment of their deformation and stability under the loads of surface operation and structures.

5. Dynamic properties. The dynamic properties of soils on Mars, including shear and compression wave velocity and damping characteristics, are not well known. There is no dynamic instrumentation (e.g., seismometer) to measure the microtremors of the Mars surface. Dynamic properties have to be determined to understand the dynamic response of structures on Mars under low-amplitude ambient vibrations, and to larger-amplitude events such as impacts.

Need for research

Geotechnical engineers are familiar with the planning of site investigation on Earth, and to some extent on the Moon. Their expertise could be applied and adapted to the Mars environment, which will be useful to the Mars mission planners for choosing safe and economical sites for habitat and surface operations. Based on their past experience, geotechnical engineers can point out definite gaps in knowledge and the need for appropriate short-term research. This short-term research is the first step of a long-term scientific research on soils on Mars.

Short-term research: Basic *in-situ* tests to assess the engineering properties of soils on Mars. Several types of *in-situ* tests are used on Earth to characterize the soil properties at construction sites. Some of these techniques may be applied/adapted to the Mars environment to obtain a rapid yet relevant site characterization. It is recommended to experiment with such *in-situ* techniques as early as possible.

Long-term research: Simulant and scaling laws for soil studies of structures and surface operation. It is likely that the shuttle payload will constrain the number of Mars soil samples to be brought back for study on the earth. In the engineering projects under planning, it is recommended to identify some soils on Earth that behave similarly (simulant) to those on Mars; it is also recommended that the scaling laws accounting for the difference in gravity between the Earth and Mars be established. These simulants, which behave similarly to the soils on Mars during the same basic *in-situ* tests, could be utilized to test various engineering hypotheses using various techniques including laboratory tests, centrifuge experiments, simplified engineering approaches, and state-of-the-art analytical procedures.

Handling and Movement of Soil Materials

On the Moon and Mars, robots and humans encounter soils with a variety of properties. As planning proceeds for missions in the next several years, there is a requirement that soil property data be gathered that will facilitate our ability to handle and move soils on the Moon and Mars.

We seek the capability to handle and move soil because the missions seek soils as shielding materials, soils as feedstocks for in-situ resource utilization, capabilities to clear and level sites for habitats, roads, landing areas, power installations (nuclear and solar), and to support science activities where trenching and excavation will reveal the nature of subsurface materials.

In the Apollo missions to the surface of the Moon between 1969 and 1972, experience in handling and movement of lunar soils was limited to astronauts digging several trenches into the lunar surface using shovel (e.g., a 20 cm-deep trench during Apollo 12 and a 33 cm-deep trench dug during Apollo 14).

As we go to Mars, soil handling and movement will involve use of more sophisticated site clearance and excavation techniques requiring robotics rovers and teleoperated excavation and handling equipment.

Initial lunar habitats will involve prefabricated shelters and inflatables with "storm shelters" for protections against the radiation, thermal, wind environments, and other aspects of the Martian environments.

On Mars, we must use local resources to produce propellants for rockets, materials for construction, the basis for a crop-growing economy and replenishment supplies of habitat consumables. This wide-ranging supplies needed for ISRU require an understanding not only of Martian soil mechanics, but also knowledge of the interaction of construction equipment with the surface soils in the dry, 0.38g environment. We also need the capability to construct roads, refine sites, and support science activities.

The early rover missions, Sojourner, and follow-on missions are helping to develop the database essential for handling and movement of soil materials on Mars.

We ask that traction information for these rovers be documented and preserved including anomalous behavior not readily explained. Future rovers could be used for soil-moving experiments to enhance the database. It is desirable to record how much power is required (or other applicable effort-related quantities) versus tasks and other parameters such as slope, amount of soil moved, depths achieved, etc.

It is desired to understand wheel slip and other behavior of the rover as a function of terrains. Key behavior should be documented by video coverage so that correlation is feasible.

Habitat/Laboratory Materials, Design and Deployment

The Mars reference mission as presented at the Workshop includes two-component system for the human-occupied surface habitat/laboratory facility. An inflatable laboratory, predelivered in an unpressurized state and using the TransLab inflatable concepts, is one component, while the crew descent vehicle is the other. After the crew landing, the vertically-oriented cylindrical descent unit with the crew is moved several hundred of thousands of meters, as needed, using large integral tractive wheels to a position next to the laboratory module; this module is pressurized and the two components are joined.

Added mass shielding for crew radiation protection may not be needed; this is currently a large design uncertainty. The no-mass shielding scenario avoids the costs of obtaining and placing regolith or other indigenous shielding material, but forgoes the benefits which mass shielding would provide in thermal insulation/stability, micrometeriod shielding, and material radiation protection of the inflatable structure.

Research needs related to the inflatable habitat and its joining with the descent unit are in the followings areas:

1. Design concepts for double or multiple layered wall system perhaps rigidified, that can be reliably provide the needed thermal and structural performance.

2. Define/develop efficient membrane materials and joining techniques which provide long term durability, with the material to be used in the exterior layer most affected by the ambient Martian environment of most concern.

3. Seals, techniques, and operations to reliably join the two habitat/lab components using robust and simple procedures.

The objectives of the research related to the inflatable components are:

1. Define efficient membrane wall systems providing high performance and safety levels.

2. Provide high-efficiency membrane materials, considering strength, durability, cost, and other relevant concerns.

3. Assure reliable and efficient fabrication, joining, and connection techniques for membrane structures.

The overall objective of the operations component is to ensure that the two parts of the habitat/lab can be easily an reliably joined very soon after the crew's arrival onto the surface.

It is assumed that information on the exposure condition on Mars is provided by other research and that the design of the descent habitat is controlled primarily by the requirements of the descent and landing. Many operational issues, including dust control and associated air lock design and operation, may also need research attention.

The successful deployment and reliable operation of the surface habitat/laboratory is absolutely essential for the first and subsequent human Mars missions.

Advances in materials and in fabrication/joining techniques are especially expected to significantly improve the design and use of air supported and other tensile material structures on Earth; these are increasingly being considered for long space coverings and building structures.

Robotics

The use of robotics assistance (especially those outside of the habitat/laboratory) whenever possible to perform strenuous or repetitive tasks will emphasize and facilitate the efficient human role of planning and directing. To develop this capability, it is necessary to define the operations that are to be encountered where robots are needed and then to use this information to design the robots. If robots are to be used for ground penetration, for example, then the nature and composition (size) of the soil particles must be ascertained. These characteristics are planned to be determined in early Mars missions.

The basic design of robots to operate in reduced gravity could be different than the design of those on Earth, since traction will be reduced and all bearings in the moving parts will not be loaded in the same way as in full gravity. Robots could also be programmed to provide life support to the suited astronaut with a fail safe mode in an emergency where the astronaut could be assisted in his return to the habitat.

Robots must also be utilized to perform tasks beyond the astronauts' ability, such as heavy lifting, operations in a hazardous or vacuum environment, or performing routine tasks at predetermined time intervals. The planned division of labor between human and robotics systems should be heavily weighted to the latter, given the limited human resources and the difficulty of working in a suited condition. For the robots to best serve and assist the astronauts, and thus the overall mission, the programming liaison between them should be very user friendly.

Fundamental Studies of In-situ Resource Utilization (ISRU)

Description of Problem:

In-situ resource utilization has been identified as one of five areas with the highest cost leverage for a manned mission to Mars. (David Kaplan, NASA JSC, Workshop for Space Exploration, August 5, 1997; five areas: 1. Space Transportation Earth to Orbit, 2. Interplanetary Travel, 3. Life Support, 4. ISRU, 5. Surface Power). It was estimated that ISRU applied to return propellant reduces the Earth to orbit mass by 20-45% or 300 mt/yr. reduction in Earth logistics. Without this savings, it was stated, the cost of the mission would be too high to be undertaken and to maintain a flat NASA budget.

Current Deficiency:

It is anticipated that ISRU will be even more important to the HEDS planning goals to "Sustain Human presence on Mars," however, only now with the Mars Pathfinder, Sojourner Alpha Proton x-ray Spectrometer composition data are the first Mars composition data available. This can enable preliminary assessment of the potential for ISRU to argument the Mars base and enable permanent presence and growth. ISRU applied to the Mars base may prove to be an affordable Mars base plan.

Objectives:

The objective of the needed research is to understand the extraction and materials processing of important *in-situ* resources in the gravity regimes anticipated for exploration. The starting materials for extraction should be those known to be abundant on the planet surfaces or in near space to the objective bases. These include the Moon, Mars, and Martian moons. The gravity regimes for materials processes should include lunar (1/6 g), Mars (0.36 g), and Mars orbit (microgravity). The Lunar compositions are well known, but novel applications of these resources to the Exploration program needs investigation. Mars materials from the Pathfinder, Sojourner mission have been found to be of volcanic rock compositions somewhat close to terrestrial Basaltic andesite.

Value for Space:

The key value of ISRU is minimizing the launch weight from the Earth surface. The potential products include but should not be limited to propellants. An example of a valuable resource that should be studied is (as Mars Alpha Proton x-ray data shows pathfinder samples have shown) near commercially rich ores in Iron (about 14 wt. Percent). One by-product of propellant production is carbon, raising the possibility of steel production for utilization on a permanent Mars base. Significant quantities of silicon, Aluminum, Magnesium, sulfur, and Calcium are also present in the Pathfinder samples. Mars is also likely to have differentiated ore deposits. Basic studies of extraction, and materials processing in appropriate gravity, could be key to future Moon or Mars plans.

Dust Mitigation

The ubiquitous nature of the dust on the surface of Mars poses many potential problems for surface operations. In many of the processes involved with surface operations, it is impossible to isolate systems from the dust. Therefore, it is necessary to understand the effects of abrasion and adhesion of the airborne dust on external surfaces such as solar cells, habitat materials and EVA suits to be able to predict to what extent performance is degraded. The reliability of joints and other types of moving parts requiring lubrication will be affected by the presence of dust. An example of research that can provide a predictive result is modeling of the tribology in joints with the presence of particulate matter. That research will yield understanding that will provide designers with criteria for how much dust is acceptable and guide the design of seals. Research on the physics of electrostatic attraction of the dust and generic classes of surfaces, once the properties of the dust are known, will provide a way to predict what materials or coatings applied to external surfaces can best be used to minimize the introduction of dust into the habitable environment.

Filtration of the dust is a very important objective for both ISRU applications and habitat cleanliness. Research involved with removing dust from surfaces with techniques such as using electrostatics and returning the dust effectively to external environment is critical to the success of these applications. Transport mechanisms in particle laden flows, for example, will yield understanding of how to handle “dusty air”.

Life Support Research - Tolerance Limits of Plants, Algae, and Microbe

Research needs to be done to establish the tolerance of plants, algae, and microbes to the Mars environment. These studies would focus on the effects of low pressure, carbon dioxide atmosphere, radiation, reduced gravity, and low temperatures. Included in this research are investigations on applications of extremophiles, selection pressures on microbial generations, use of Martian soil to sustain microbial populations, and microbial production of useful products from *in situ* resources. This biotechnological research could be useful for establishing a robust and efficient life support system for long duration Martian habitation.

Structures and Surface Operations Group

Jean- Pierre Bardet, University of Southern California
Marvin Criswell, Colorado State University
Stewart Johnson, Johnson and Associates

Heat Transfer

The group discussed basic research need in four critical areas; surface power, interplanetary travel, in-situ resource utilization, and life-support systems.

Surface Power

Based on the input provided by NASA staff through their presentations and the personal expertise of the members of the committee, it was unanimously concluded that nuclear power is the only viable option for production of abundant and reliable power on Mars. With nuclear power as the heat source, both Brayton and Rankine cycle-based power system concepts are possible. The efficiency of the Brayton cycle-based power concept can be significantly enhanced, and thereby the weight of the system can be reduced if the highest operating temperature can be increased from 1044 to 1500 K. Thus, it was concluded that a need for development of high-temperature materials which can withstand high stresses exists. Since almost 80% of the total thermal energy produced in the reactor is dissipated in the heat rejection system, the weight of the heat rejection system can be significantly reduced with the availability of light weight materials that can be used at relatively high temperatures. Also, an optimization of the heat rejection system in the light of various advanced radiator concepts that have been developed should be undertaken. The choice of the radiator may influence some basic research issues.

In the Rankine cycle concept for power production, it was concluded that liquid metal is the coolant of choice. For the liquid metals, it is important to have a good understanding of such processes as freezing, thawing, boiling and condensation, two-phase heat transfer, two-phase pressure drop, flow stability, and phase separation. Distinction should be made between pool, low velocity and high flow velocity conditions. Also, the effect of noncondensibles on transport processes at 3/8 g should be investigated. Before embarking on the research program it will be helpful to do a world wide literature search on phase change/natural convection/forced convection heat transfer data for liquid metal of choice. Because of the abnormal conditions that may develop (e.g., due to pump trip or leak in the piping system) flow transient and decay heat removal systems should be investigated. Due to dust storms on Mars, the effect of dust on radiative properties (emissivity, absorptivity) of heat exchange surfaces should be studied.

Interplanetary Travel

For electric power and propulsion during interplanetary travel, power systems based on Brayton and Rankine cycle can also be used. In this case, the heat transfer basic research issues are the same as those for surface power except that now one has to deal with a zero gravity situation. The one exception to the research areas identified for surface power is the radiate properties of the heat transfer surfaces in the presence of dust from Mars. It should be added that in studying phase change and two-phase flow heat and mass transfer, proper emphasis should be placed on interfacial transport processes with or without noncondensibles.

In-Situ Resource Utilization (ISRU)

One of the key areas identified for research related to ISRU was the understanding of heat transfer processes associated with storage and transfer of cryogenic liquids both at 3/8 g and 0 g. The thermal issues identified in connection with propellant production are coupled chemical reaction, heat and mass transfer and fluid flow including stability in porous media; identification of ignition temperature for the chemical reaction; and high temperature compact heat exchangers. An other generic issue identified was thermal management of electronic devices. This may involve study of boiling and condensation in narrow passages and at zero and 3/8 gravity.

Life Support Systems

Although no details of the bio-reactors were known to the committee, it was noted that heat transfer issues related to bio-reactors should not be overlooked. With respect to habitat, three key issues were identified. These include innovative insulation concepts using Martian materials; radiative properties and thermophysical properties including thermal conductivity of structural materials; and innovative thermal control systems (e.g., acoustic, absorption and desorption heat pumps, heat pipes, etc.). Because of the large temperature transients to which humans may be subjected, it is imperative that bio-transport processes in reduced gravity be studied.

Some of the major recommendations are summarized below:

1. Phase change heat and mass transfer, multiphase flow and pressure drop of liquid metals and cryogenics at 3/8 and zero gravity should be studied.

2. Interfacial phenomena under low and zero gravity conditions under transient conditions deserve investigation.

3. Scaling with gravity of thermal phenomena, i.e., identification of boundaries where physics of phenomena changes with g level needs to be understood.

4. Effects of Martian soil and dust on radiative properties of structures should be studied.

5. Trade-off studies for various components in a thermal system should be conducted at an early stage so that their impact on basic research is known well in advance.

Computational tools should be developed along with experimental effort so that models can be validated with the data and can be applied with confidence in situations of interest.

Heat Transfer Group

Vijay Dhir (chair) University of California, Los Angeles
George Bankoff, Northwestern University
Christopher Crowley, Creare Inc.
Amir Faghri, University of Connecticutt
Cila Herman, Johns Hopkins University
George Peterson, Texas A&M University

Radiation Materials

Introduction

Radiation safety is a key consideration in determining a HEDS "go" decision in 2004. In 1989, the National Council on Radiation Protection (NCRP) recommended[1] a career limit on radiation exposure to flight crews of 2 Sieverts (200 rem), for males at age 30, based upon risk considerations for the low earth orbit environment (principally electrons below a few MeV and protons below a few hundred Mev). An increase of 3% for death by cancer was the risk criterion.

A 1996 study[2] by the Space Studies Board of the National Academy of Sciences considered flights beyond the shielding effect of the Earth's magnetic field where cosmic ray particles (protons and heavy nuclei above a few hundred MeV with average energy - 7,000 MeV), and rare but intense solar energetic particle events (protons and heavy nuclei up to several hundred MeV) produce interplanetary mission doses[3,4] approaching or exceeding the recommended annual limit of 50 rem[1]. That report considered the significant differences between the ambient and induced environments in low earth orbit and those dominated by cosmic rays (and occasional solar energetic particles) which contain a significant flux of heavy nuclei, and a wider-range of secondary constituents produced by high energy interactions in shielding. The uncertainties in both the cosmic ray flux and the secondary particles from interactions were discussed. Also stressed was the greater biological risk from highly ionizing heavy nuclei and the larger uncertainties in the present knowledge of this risk. The 1996 report[2] "Radiation Hazards to Crews of Interplanetary Missions" concluded that the uncertainty in estimates of carcinogenic risk for that environment range from a factor of 4 to 15. In the worst case of that estimate the excess carcinogenic risk would increase to 45% for a "career dose".

For the HEDS Interplanetary mission the present estimates for radiation shielding necessary for crew protection cover a wide range dependent upon solar cycle, risk level, and the full range of uncertainties cited above. For a shield of aluminum the estimates range from a few centimeters to tens of centimeters. It is well known that for hadronic particles (e.g., protons and nuclei) materials of the lowest atomic number are the most effective radiation shields per unit weight. Thus the development of more effective radiation shielding materials of low atomic number has been considered[5].

The task for the present panel has been to recommend appropriate research for the Materials Science discipline that will be of greatest benefit in achieving a "go" decision for HEDS in 2004. For the purpose of the panel discussion, the overall uncertainty was divided into the following categories: "environment", uncertainties associated with defining the ambient environment that would be encountered in a Mars mission, mainly from galactic cosmic rays (GCR) and solar particle events (SPE), "physics", uncertainties related to predicting the induced radiation environment after propagation through materials, and "biology", uncertainties in the biological response, particularly for high charge and energy (HZE) ions. Addressed here are research needs related to reducing the "physics" uncertainties and in producing validated predictive methods for evaluating shielding and radiation effects. Many of these considerations were covered in a workshop on radiation shielding held at JSC in 1995.

Scope

Research in the following areas were considered for the Material Science Program: (1) Improvements to physics models, computer codes, and analysis tools for predicting radiation effects, (2) evaluation of the effectiveness of new shielding materials and concepts, and (3) the validation of (1) and (2) by ground tests and flight data.

Not included in the scope here (but needed as Input) are the following: (4) radiobiological response, which is being addressed in the Life sciences Program, (5) improved environment models which is being addressed by other programs (such as NASA's Space Environments and Effects (SEE) Program), and (6) radiation sources from nuclear propulsion, surface reactors, and RTGs, which are assumed here to be adequately shielded by the designs of those devices.

Recommendations

The following recommendations for research related to radiation and shielding materials are made:

1. Improved Calculational Methods for Predicting Radiation Effects

   a) Physics of cross sections: improvements of nuclear cross sections for projectile and target fragmentation by HZE particles.

   b) Cross section measurements: thin-target cross section measurements suitable for mode validation for representative ions, energies and target elements.

   c) Propagation calculations: application of nuclear models and radiation transport codes for representative benchmark thick target shielding configurations and various material compositions

   d) Ground validation: perform ground tests using benchmark cases from (c) to quantify propagation calculation uncertainties based on accelerator beams.

   e) Augment program and compare alternate methods: take advantage of alternate calculational methods developed outside NASA, and perform model comparisons for benchmark cases to select best methods and hasten convergence and validation.

2. Shield Materials, Presently Available and New/Improved.

   a) Evaluate alternative shield configurations with the available materials: for early and evolving mission architectures, shielding calculations and trade studies should be performed to investigate maximum utilization of onboard materials for reducing crew radiation exposure in transit. Study shielding concepts, taking into account candidate habitat structure equipment and regolith material, to reduce surface exposure.

   b) Existing candidate and new composites/laminates: shielding calculations and trade studies should be performed to evaluate the effectiveness, and options, in using new shielding materials to supplement available materials for achieving shielding requirements.

3. Flight Validation

   Flight validation of the result from (1), and (2) above should be performed using either high-inclination shuttle flights or a free-flyer platform in near polar orbit to maximize GCR exposure.

Multi-use of Radiation Prediction Methods

Many of the computational tools developed and validated under this recommended research program will be valuable in assessing radiation issues related to design and shielding of radiation sensitive components, as well as in determining crew safety. This is particularly important since emphasis will be placed on efficient designs, advanced instrumentation and sensors etc. This will require advanced technology components, which, in many cases, have higher susceptibility to radiation damage. Examples of radiation susceptibly components and systems include: microelectronics, electro-optics and photonics, sensors, components based on evolving micro/nano technologies, navigation/guidance components, life support controls, and data and communications systems

Also, the methods developed can provide guidance in radiation detectors/sensor development particularly for some of the newer semiconductor radiation detector materials (CdZnTe, Hgl2, etc.)

The radiation analysis models and codes resulting from the recommended research have applicability in addressing numerous radiation issues and trade studies related to design and mission feasibility, including:

- Spacecraft design (configuration for shielding safe haven for solar events)
- Surface habitat design
- Surface operations (EVA restrictions)
- Mission planning (transit times, orbit, staytime, etc.)
- Precursor missions (radiation data needs)
- Materials research/development (shielding, detectors for in-orbit evaluation)
- Mission radiation monitoring requirements
- In-situ resources (regolith shielding)
- Advanced sensors (radiation damage susceptibility)
- Avionics (radiation damage)
- ECLSS Control System
- ECLSS flora (growth degradation due to radiation)

Other Considerations

The panel considered the following aspects of the problems posed by other observer/participants.

1. In view of the problems to be solved, decisions to be made and the impact of the "go" decision, an augmented program that includes comparisons with other transport codes and methods is advisable to enhance convergence of "physics" related problems.

2. Consideration of "concurrent" approaches, such as uncertainty analyses to establish needs for additional cross-section physics modeling and measurements and to establish supplementary shielding requirements, are advisable.

3. Early feedback of flight measurements (part (5) below) will likely also speed convergence.

4. Early interaction with mission designers is encouraged to ensure best utilization of available transit/surface materials for shielding.

5. Early flight validation of candidate "thick" shields on high inclination or polar orbit missions using available instrumentation is encouraged. Considering the time that an earth orbit mission samples the interplanetary cosmic ray spectrum (above -50° geomagnetic), a mission of about 2 weeks is needed.

6. It was noted that in-orbit radiobiology response measurements were not recommended in the NRC/Space Studies Board report of 1996 for solution of the addressed interplanetary problems. This is, in part, because in low-earth-orbit specimens do not receive the requisite cosmic ray environment, and that equivalent doses are generally quite low compared to interplanetary doses, and those available from particle accelerators. This places limitations on the statistical significance of orbital radiobiological experiments. These are not limitations for the in-orbit radiation shielding measurements recommended here.

7. The best available prediction methods are needed for the 2004 "go" decision. Earliest validation of the methods will be of most benefit to the design.

References

1. National Council on Radiation Protection (NCRP) Report #98 (1989), National Council on Radiation Protection and Measurement, 7910 Woodmont Ave. Bethesda, MD 20814.

2. Space Studies Board, National Research Council Report, "Radiation Hazards to Crews of Interplanetary Missions", National Academy Press, Washington, DC, 1996

3. Adams, J.H., "Cosmic Radiation: Constraints on Space Exploration", Nuclear Tracks Radiation Measurements, V20 No. 3, pp. 397-401 (1992)

4. Wilson, J.W., et al, "Issues in Space Radiation Protection: Galactic Cosmic Rays", Health Physics, V68, No. 1, pp. 50-58 (1995).

5. "Shielding Strategies for Human Space Exploration: A Workshop", Johnson Space Center, Houston, TX., Dec. 6-8, 1995, J.W. Wilson, et al. Editors (1997)

Radiation Materials Group

Thomas Parnell (chair), Marshall Space Flight Center
Anthony Armstrong, Science Applications International Corporation
Robert Bayuzick, Vanderbilt University
Nolan Hertel, Georgia Institute of Technology
Rose Scripa, University of Alabama, Birmingham

Chemical Processes

The Chemical processes group evaluated the research needs for life support and in-situ resource utilization (ISRU). The use of local resources were limited to the moon, Mars, and near-earth asteroids. The life support applications included transit vehicles and surface scenarios (habitats, rovers, and space suits). Both basic research that needed to be conducted on existing concepts and those pertaining to new and novel concepts were considered.

In-situ Resource Utilization

In the category of existing concepts emphasis was placed on research leading to better understanding of zirconia electrolysis and radio frequency glow discharge processes. The zirconia electrolysis process has utility for oxygen production on Mars, the Moon, and in closed loop life support for oxygen recovery. In addition, the fundamental modeling of this process will apply equally well to a solid oxide regenerative fuel cells. Due to its wide applicability it is recommended that the transport processes associated with this device be well studied, the materials issues associated with this device be well characterized and the properties improved, and research be conducted on the high temperature seals and packaging issues. For the glow discharge process that is being considered to obtain high oxygen concentration gas mixtures on Mars, the following fundamental issues were identified. Research leading to better understanding of the effect of dust, trace gas effects, and reduced gravity on the performance of the process would be very beneficial. Also, the ability to remove Mars dust from the RF system without compromising the system performance is important.

In the novel concepts category, the ability to produce parts, both on the surface and in the transit vehicle, on a need basis, thereby reducing the number of Earth carried spare parts and reducing the risk of subsystem failures was considered a high priority. Effect of gravity on the processes associated with rapid prototyping, and welding are important research areas. Equally important is the ability to produce raw materials (chemical building blocks such as paraffins and olefins) from carbon dioxide and water as starter materials. Also identified as an interesting topic is the characterization of the fine Mars soil as a catalyst material for various chemical processes. Such a catalyst would, in addition to lowering launch mass, reduce risks associated with catalyst aging due to poisoning. The ability to separate water, and nitrogen/argon buffer gas from the Mars atmosphere was also noted as a valuable research area.

Many of the chemical processes would require multitudes of sensors, storage tanks and flow controllers. Research that focuses on microscale chemical sensors, light weight storage tanks, and miniaturized flow controllers were identified to be important. Research leading to novel ways of storing light gases (hydrogen and methane for example) at high densities is also of great value.

Life Support

Many of the processes associated with both life support and ISRU involve adsorption/ desorption processes. Modeling such processes to understand and optimize them was noted as a high priority. Issues involve design of systems for better heating and cooling, lower pressure drops, better sorbent materials, and faster cycle times. Such processes are currently used/ contemplated for gas separations, compression, trace contaminant control and heat pumps.

Most of the chemical processes used in life support involve liquid-vapor mixtures. A good understanding of two-phase transport phenomena and phase separations in both micro- and hypo-gravity is important. Designs of bioreactors suitable for microgravity environments, transport phenomena in porous nutrient beds for plant growth, and improved oxidation reactions for both organic contaminants and solid waste incineration were identified as topics to be researched.

Recommended Topics for Research

Zirconia Electrolysis

This process generates oxygen from the predominantly carbon dioxide atmosphere of Mars by a solid oxide electrolysis process. A yttria-stabilized zirconia (YSZ) electrolyte is sandwiched between porous electrodes (platinum) to form the electrolysis cell. Basic research needs to be conducted in the following areas:

Bulk diffusion, mixed convection, and radiation in reacting, participating media need to be modeled. Gas and charge transfer in porous electrodes can be improved by further analysis of transport processes. Also charge transfer mechanisms at the electrode/electrolyte interfaces need to be studied in greater detail.

Material issues include development of lower temperature electrolytes that lead to lower energy consumption and/or reliability. Studies on optimized electrodes for processing in local environments as also on compatibility of electrodes, electrolytes and interconnects will yield efficient designs. Dopants can be used for improving the mechanical strength of such materials for withstanding launch environment. High temperature seals are necessary for safe operation. Packaging issues include better thermal and flow design and improved shock and vibration loads handling and/or isolation.

Radio Frequency Base Glow Discharge Chemical Processing and Particle Manipulation

Gaseous reduction of CO_2 (and H_2O) can be accomplished at low temperatures (<800 K) using RF glow discharge systems which are tailored to the particular molecule, thereby producing very high oxygen yields [O (80%)] at moderate temperatures, directly in Mars atmosphere. These systems can be designed to avoid high temperature thermal dissociation while eliminating the need for compression of Mars atmosphere. In addition, it is possible to incorporate features which are similar to an electrostatic precipitator to concentrate and remove dust particles found in the Martian atmosphere. Hence, these systems can eliminate the requirement for high temperature dissociation operations, filtration, and compression of Mars atmosphere. In addition, the CO_2 rates are sufficient to produce a "dirty" carbon monoxide fuel as a by product.

By designing electrode geometries which optimize the glow discharge volume, RF frequency, current and voltage amplitudes it is possible to produce on the order of 80% conversion of Mars atmospheric CO_2 in CO, O and O_2 in the discharge zone. Using a (silver) permeation membrane, the oxygen thus generated can be removed and collected for storage. Simultaneously, these systems can be designed to remove particulate and the mildly heated waste gas can be collected for use as fuel. Since the permeation membrane can be the electrode on one side of a stabilized zirconia "electrochemical pump", the RF system can be integrated with the zirconia systems or the permeation membrane can be placed between the glow discharge and any other oxygen pumping system.

Specific fundamental questions that need to be answered in this area include:

1. Energy required per unit mass of product (both oxygen and fuel).
2. Ability to collect and store "dirty" carbon monoxide fuel.
3. Ability to concentrate and eject Mars dust without compromising the basic performance of the RF system.
4. Influence of reduced gravity on system performance and design.
5. Influence of dust and other Mars molecules on system performance.

Insitu Production of Parts

The ability to produce parts during transit or while on Mars, the Moon or an asteroid reduces greatly the quantity of spare parts that need to be transported from earth. In addition, this also allows for the possibility of making parts for unforeseen problems.

Given the long duration of the flights, it is likely that components of spacecraft, rovers, or habitats will need to be replaced. It is not possible to bring a sufficient quantity of replacement parts given all the possible failures that can occur. Furthermore, the ability to produce parts will provide an added flexibility to address unforeseen circumstances. Thus, it is desirable to be able to form parts, for example, by the casting of metals, and the forming of polymers. Both of these metals and polymers can be produced insitu. The ability to produce parts requires a better understanding of the effects of reduced gravity on the microstructure and thus the properties of casting. Also, processes for the production of polymeric parts in reduced gravity need to be investigated.

Welding and Joining

These processes will be necessary to repair spacecraft, habitats, rovers and parts thereof if these should become damaged. It is more likely that critical parts or major pieces of equipment will become damaged during a mission. Repairing these objects will likely require two or more materials to be joined. Unfortunately, a fundamental understanding of the manner in which microgravity and hypogravity affects the shape of weld pools, microstructure formation, and the resulting properties of the weld is lacking. Joining processes for nonmetallic materials, such as polymers, also need to be developed.

Higher Hydrocarbons Synthesis

The ability to produce raw materials (chemical building blocks such as paraffins and olefins) from CO_2 and water as starter materials is important. Research on a process to convert CO_2 and Hydrogen (from earth or mars water) into C_2- C_5 paraffins and olefins can lead to production of many chemicals, fuels and polymers on need basis. The current Sabatier reactor can be turned into a Fischer-Tropsch reactor merely by replacing the catalyst. The chemistry is quite similar to the chemistry in Sabatier process and leads to formation of progressively higher molecular weight alkanes and alkenes. For example Ni catalyst (when properly promoted) selectively makes 80% C_2- C_5 paraffins at 100% conversion of $CO + H_2$. Lower conversions yield higher proportions of olefins.

This technology can benefit from research on development of suitable catalysts; on assessment of process conditions (temperature and space velocity and H_2/CO ratios) that yield larger quantities of olefins; and by testing the process in Sabatier process conditions.

Characterization of the Mars Soil for Catalysis

In the event the catalyst in the organic and waste incinerator fails, it would be necessary to prepare replacement materials from Mars resources. It has been postulated that the Martian soil is a montmoullinite clay. Montmoullinite was an early catalyst used as a cracking catalyst in petroleum refining area as a catalyst support. However, before we can assess its potential value as a catalyst or catalyst support, more characterization is needed. Physically, the porosity, pore size distribution, and surface areas need to be determined, along with a detailed compositional analysis. Also studies on the soil (montmoullinite) chemical manipulation to yield pallets which can be used as a catalyst will be beneficial.

This technology will provide a backup catalyst for the fluidized bed incinerator in the event it becomes contaminated and unusable. If the montmoullinite has the desired properties, it could be available as a support for other proposed catalytic systems such as catalyst for Fischer-Tropsch conversion of $CO + H_2$ to higher molecular weight hydrocarbons. The montmoullinite is also an excellent absorber and could be a replacement for molecular sieves although they may not be as efficient as zeolite that can make up for efficiency by volume.

Recovery of Water from Martian Atmosphere

The hydrogen balance will be crucial for establishing an outpost on Mars. A replenishing source of condensed water to provide hydrogen will likely be necessary. Further studies are needed on new processes and materials for the water from the Martian atmosphere where it is present at trace levels (0.03%). Adsorption and other technologies should be considered. For adsorption, adsorbent selection and process design including optimization are critical. Reliability and energy requirements are key concerns.

Microscale Phenomena in Micro and Hypogravity

Microsensors and microdevices are needed for light weight life support systems for EVA and Rovers. Many of the chemical processes would require multitudes of sensors, storage tanks and flow controllers. Research focusing on microscale chemical sensors, leak detectors, light weight storage tanks, and miniaturized flow controllers is important. These devices must be robust enough to withstand large temperature swing, operate in variable gravity and survive space-vehicle launch environment.

Improved Adsorbents for Trace Contaminant Control

Materials with improved desorption kinetics when exposed to vacuum at ambient temperature can provide savings in energy as compared to materials which must be desorbed at high temperature. The use of such materials can have a significant payback for long duration missions and lunar/mars outposts for which resupply will be more expensive than for low-earth orbit mission.

Present spacecraft contamination control systems used onboard U.S. and Russian vehicles rely primarily upon expendable activated charcoal, regenerable activated charcoal, ambient temperature catalytic oxidation, and high temperature catalytic oxidation to remove trace chemical contaminants from the cabin atmosphere. While efficient for short duration and long-duration low earth orbit missions, these technologies as presently deployed have power and logistics constraints when applied to interplanetary missions and lunar/Mars outposts. Improved means for catalytic oxidation are presently being developed to help improve the overall situation; however no additional research is underway to identify new classes of adsorbent materials that may be amenable to regeneration by pressure swing alone. Past research on regenerating activated charcoal determined that heating in addition to applying a vacuum was necessary to achieve acceptable contaminant desorption rates (Robell, NASACR-1582, 1970). Since that time, especially in the last decade, new classes of adsorbents have become commercially available.

Adsorptive Heat Pumps

Improved and efficient adsorptive heat pumps are potentially useful for energy storage. Its possibly to construct these devices economically and power them by abundantly available solar radiation or waste heat. The simplicity of this technology even avoids need for any electrical power except to switch a valve and possibly slide panels to deflect heat or run a small pump.

Process demonstrations are recommended to check for feasible operation. Improved efficiency and design can be achieved by research on modeling processes including heat transfer rates in adsorbent beds and by developing adsorbent materials with improved heat transfer characteristics.

Primary and Regenerative Fuel Cells

Fuel Cells are important for night-time energy storage for lander and for outposts on Mars. They can also provide power supply for Rover and extra-vehicular activity purposes. Primary fuel cell systems need to be modeled and tested with the metrics of power density (Whr/Kg) achievable and the compatibility of fuel and oxidant of the primary fuel cell with the in-situ propellant production plant. Regenerative fuel cells need to be developed to deliver higher full cycle efficiency. Performance issues involving evaluation of effects of gravity must also be addressed.

High Density Storage of Light Gases

Possibilities exist for storage of light gases in adsorption media at densities higher than that of bulk gas for a given pressure and temperature. Total container weight for storage at a given amount of gas may be reduced. Prior technology has been developed to increase safety of gas burning “clean” vehicles.

Research is needed on development of new adsorbents, new materials for complexation for metal hydrides, etc. Modeling and process studies should address issues of performance during tank purging and recharging. Experiments should establish cycle-to-cycle performance, material aging, and reliability.

Oxidation of Organic Contaminants

The accumulation of organic contaminants from various sources, for example from human body, and desorption of volatiles (similar to the continual accumulation of formaldehyde from insulation) must be controlled to provide a reasonably pure breathing atmosphere and prevent contamination within the transit or habitat.

Oxidation of organic contaminants using monolithic/noble metal oxidation catalyst(s) in a fixed bed reactor would successfully convert all likely organics to CO_2 and water. The monolithic system would resemble the current Pt-Pd systems used in automobile exhaust mufflers. Small quantities of potential catalyst poisons, such as sulfur, are not permanent and are reversible. Sulfur levels if present at all are estimated to be tolerable at the 100-200 ppm level. The catalyst system can be altered by adding small (0.1 wt %) amounts of rhodium to the Pt-Pd (concentrations in the monolith in the range of 0.1 - 0.2 wt %) to handle any probability that nitrogen would be a potential contaminant. The end products of the combustion are CO_2 and water (and N_2 in the presence of nitrogen organics). The metals are impregnated on the monolith after precoating the monolith with alumina (Al_2O_3). Operating temperatures are nominally in the 800-1000 K range when using air as the oxidant. Experimentation would be required to simulate the organic mixture and determine the light-off temperature for the oxidation. In hypogravity, air probably would be the oxidant; in microgravity, oxygen would be used and the effect of this would need to be assessed to determine the light-off temperature.

The reactor system would be a small, packed tube similar to the Sabatier reactor and preheated in the same manner.

Alternately, H_2O (as steam) may be used to remove VOC's (both organic and halogenated) using steam reforming reactions:

$$H_2O + zH_2O = mCO + nH_2$$

This reaction occurs from 500 to 1000°C (depending on compound type and condition). Conversions have been demonstrated at 99.999+ %. A large amount of catalyst research has been done, but no commercial process has been developed yet.

This process has the advantage of generation of CO and hydrogen which are potentially useful. Also this process uses water rather than oxygen as a starting material thus saving scarcely available oxygen.

Research needs in this area are to verify performance with the types of hydrocarbons expected in the space environment and to optimize catalyst type and process conditions to maximize CO/H_2.

Improved Oxidation of Habitat Waste Combustion—Solid Waste Incineration

Solid wastes in the Habitat and Transit are to be oxidized in a fixed fluidized bed. Presently an uncatalyzed system using low surface area ceramic particles is used. One disadvantage of this operation is the generation of NO_x at the high operating temperatures, about 1000°C. Ammonia addition is used to reduce the NO_x to N_2. By incorporating a metal oxidizing catalyst in the support, such as platinum (0.2 - 0.5 wt %), vanadium (1 - 10 wt %), or cerium (1 - 10 wt %), the temperature for incineration would be lower than 1000°C, below the temperature for NO_x formation. This would make the oxidizer more efficient, eliminate the need to use ammonia, and either reduce the size of the reactor or increase the throughput of organics. In addition, ilmenite ($FeOTiO_2$) located on the moon could be transported to Mars where it could be used as a combustion catalyst in the fluidized bed incinerator.

Biomedical Redundancy Strategies

The inability to carry redundant hardware and extra biological stores on long duration missions makes it very desirable to identify and plan for contingency which can partially couple biological process steps with mechanical processing and vice-versa in order to reduce that rate at which biological systems and mechanical systems go to complete shut down after a major element failure.

Stability Considerations in Chemical Processes

Chemical reactions used for ISRU and life support must be evaluated in terms of the stability of the reactions in reduced gravity and pressure. Chemical reactions should be utilized which tend toward controllable states rather than reactions which depend upon very precise maintenance of state variables. In that way, reliable, autonomous chemical processing systems can be designed and built.

Corollary I: For all Earth-Mars transit elements, the possibility of a communication lag for more than 20 minutes means that those elements must be completely autonomous.

Corollary II: A design goal for near term microgravity experiments in space, whenever possible is to build and operate systems which have sufficient internal instrumentation and autonomy to begin to evaluate the suitability of these fundamental process steps for manned Mars missions.

Chemical Processes Group

M. Douglas LeVan (chair), Vanderbilt University
Robert Ash, Old Dominion University
Ralph Bertolacini, University of Delaware
James Richardson, University of Houston
K.R. Sridhar, University of Arizona

Appendix B: Participants List

Sirish Agarwal
USRA
300 D Street SW., #801
Washington, DC 22202
F-(202) 479-2609
sagarwal@hq.nasa.gov

Jeff Allen
NASA Lewis Research Center
21000 Brookpark Rd., MS 500-102
Cleveland, OH 44135
P-(216) 433-3087
F-(216) 433-8050
jeff.allen@lerc.nasa.gov

Robert Altenkirch
College of Engineering and Architecture
146 Dawn Hall
Washington State University
Pullman, WA 99164
P-(509)-335-5593
F-(509-335-9608
raa@cea.wsu.edu

Judith Andersson
National Center for Microgravity Research
Case Western Reserve University
10900 Euclid Ave.
Cleveland, OH 44106
P-(216) 368-0748
F-(216) 368-0718
jandersson@ncmr.cwru.edu

Tony Armstrong
SAIC
1706 Prospect Rd.
Prospect, TN 38477
P-(216) 468-2603
F-(216) 468-2676

Robert L. Ash
Aerospace Engineering Dept.
Old Dominion University
Norfolk, VA 23529-0013
P-(757) 683-3460
F-(757) 683-3004
rash@odu.edu

Raymond Askew
Microgravity Research Division
NASA Headquarters
Washington, DC 20546
raymond.askew@hq.nasa.gov

B. Balsubramaniam
National Center for Microgravity Research
21000 Brookpark Rd., MS 500-102
Cleveland, OH 44135
P-(216) 433-2878
bala@lerc.nasa.gov

George Bankhoff
Dept. of Chemical Engineering
Northwestern University
2145 Sheridan Rd.
Evanston, IL 60208
P-(847) 491-5267
F-(847) 491-3728
gbankhoff@casbah.acns.newu.edu

Jean-Pierre Bardet
Dept. of Civil Engineering
University of Southern California
Los Angeles, CA 90089-2531
P-(213) 740-0608
F-(213) 744-1426
bardet@rccgol.usc.edu

Robert J. Bayuzick
Dept. of Chemical Engineering
Box 164, Station B
Vanderbilt University
Nashville, TN 37235
P-(615) 322-7047
F-(615) 343-7951
bayuzick@vuse.vanderbilt.edu

Ralph Bertolacini
572 Millcreek Lane, 6S
Naperville, IL 60540
P-(630) 355-5518
bertolac@che.udel.edu

James E. Cake
NASA Lewis Research Center
21000 Brookpark Rd., MS 500-205
Cleveland, OH 44135
P-(216) 433-3565
j.cake@lerc.nasa.gov

Brad Carpenter
NASA Headquarters
Microgravity Research Division
Washington, DC 20546
P-(202) 358-0826
F-(202) 358-3091
bcarpenter@hq.nasa.gov

Bob Cataldo
NASA Lewis Research Center
21000 Brookpark Rd., MS 500-201
Cleveland, OH 44135
P-(216) 433-7082
bcataldo@lerc.nasa.gov

David F. Chao
NASA Lewis Research Center
21000 Brookpark Rd., MS 500-102
Cleveland, OH 44135
P-(216) 433-8320
F-(216) 433-8050
david.chao@lerc.nasa.gov

Thomas Cochran
National Center for Microgravity Research
21000 Brookpark Rd., MS 110-3
Cleveland, OH 44135
P-(216) 433-2342
F-(216) 433-3793
thomas.cochran@lerc.nasa.gov

Douglas Cooke
NASA Johnson Space Flight Center
EX13/Exploration Office
Houston, TX 77058
P-(281) 483-8422
F-(281) 244-7478
douglas.cooke@jsc.nasa.gov

Robert R. Corban
NASA Lewis Research Center
21000 Brookpark Rd., MS 500-217
Cleveland, OH 44135
P-(216) 433-6642
F-(216) 433-8660
rcorban@lerc.nasa.gov

Marvin E. Criswell
Dept. of Civil Engineering
Colorado State University
Fort Collins, CO 80523
P-(970) 491-5048
F-(970) 491-7727
mcriswel@eng.ColoState.edu

Christopher Crowley
Creare, Inc.
PO Box 71
Hanover, NH 03755
P-(603) 643-3800
F-(603) 643-4657
cjc@creare.com

Peter Curreri
NASA Marshall Space Flight Center
MS ES75 Space Science Lab
Huntsville, AL
P-(205) 544-7763
F-(205) 544-7763
peter.curreri@msfc.nasa.gov

Gretchen Darlington
Pathology Dept., MC 1-2261
Baylor College of Medicine
One Baylor Plaza
Houston, TX 77030
P-(713) 770-1868
F-(713) 770-2205
gretchen@bcm.tmc.edu

Stephen Davis
Dept. of Engineering Science & Applied Math
Northwestern University
2145 Sheridan Rd.
Evanston, IL 60208
P-(847) 491-5397
F-(847) 491-2178
sdavis@nwu.edu

Steve Davison
NASA Headquarters
Washington, DC 20546
P-(202) 358-0647
F-(202) 358-3091
sdavison@hq.nasa.gov

Richard DeLombard
NASA Lewis Research Center
21000 Brookpark Rd., MS 500-216
Cleveland, OH 44135
P-(216) 433-5285
F-(216) 433-8660
delombard@lerc.nasa.gov

Vijay Dhir
Dept. of Mechanical & Aerospace
Engineering
University of California at Los Angeles
Los Angeles, CA 90095
P-(310) 825-8507
F-(310) 206-4830
vdhir@seas.ucla.edu

James Patton Downey
NASA Marshall Space Flight Center
MS ES75
4481 Digney Rd.,
Huntsville, AL 35812
P-(205) 544-6423
F-(205) 544-2102
james.downey@msfc.nasa.gov

J.C. Duh
NASA Lewis Research Center
21000 Brookpark Rd., MS 500-102
Cleveland, OH 44135
P-(216) 433-2850
F-(216) 433-8660
jduh@lerc.nasa.gov

Amir Faghri
Dept. of Mechanical Engineering
University of Connecticut
191 Auditorium Rd., U-139
Storrs, CT 06269
P-(860) 486-2090
F-(860) 486-5088
faghri@eng2.uconn.edu

Robert Friedman
NASA Lewis Research Center
21000 Brookpark Rd., MS 500-115
Cleveland, OH 44135
P-(216) 433-5697
F-(216) 433-8660
robert.friedman@lerc.nasa.gov

Donald C. Gillies
NASA Marshall Space Flight Center
MS ES75
Huntsville, AL 35812
P-(205) 544-9302
F-(205) 544-8762
donald.gillies@msfc.nasa.gov

Thomas Glasgow
NASA Lewis Research Center
21000 Brookpark Rd., MS 105-1
Cleveland, OH 44126
P-(216) 433-5013
F-(216) 433-5033
thomas.glasgow@lerc.nasa.gov

Sandra Graham
Senior Program Officer
Space Studies Board, HA 584
National Research Council
2101 Constitution Ave. NW
Washington, DC 20418
P-(202) 334-3477
F-(202) 334-3701
sgraham@nas.edu

Thomas Hanratty
Dept. of Chemical Engineering
205 RA Lab; Box C3
University of Illinois
600 S. Mathews Ave.
Urbana, IL 61801
P-(217) 333-1318
F-(217) 333-5052

Mohammad M. Hasan
NASA Lewis Research Center
21000 Brookpark Rd., MS 60-4
Cleveland, OH 44135
P-(216) 977-7494
F-(216) 977-7545
mohammd.hasan@lerc.nasa.gov

Donald Henninger
NASA Johnson Space Flight Center
MC EC3
Houston, TX 77058
P-(281) 483-5034
F-(281) 483-5060
d.henninger@jsc.nasa.gov

Cila Herman
Dept. of Mechanical Engineering
Johns Hopkins University
3400 North Charles St.
Baltimore, MD 21218
P-(410) 516-4467
F-(410) 516-4316
herman@titan.me.jhu.edu

Nolan Hertel
School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0405
P-(404) 894-3717
F-(404) 894-3733
nolan.hertel@me.gatech.edu

Jim Jenkins
Dept. of Theoretical & Applied Mechanics
Cornell University
Ithaca, NY 14853
P-(607) 255-7185
F-(607) 255-2011
jtj2@cornell.edu

Milburn J. Jessup
Dept. of Surgery
New England Deaconess Hospital
110 Francis St., Suite 3A
Boston, MA 02215
P-(617) 632-9817
F-(617) 632-7424
jessupj@delphi.com

Stewart W. Johnson
820 Rio Arriba, SE
Albuquerque, NM 87123-5103
P-(505) 298-2124
stWJohnson@aol.com

Lu-Kwang Ju
Dept. of Chemical Engineering
The University of Akron
Akron, OH 44325
P-(330) 972-7252
lukeju@uakron.edu

David Kaplan
NASA Johnson Space Flight Center
Code EX1/Exploration Office
2101 NASA Road 1
Houston, TX 77058
P-(281) 483-7667
F-(281) 483-5800
david.kaplan@jsc.nasa.gov

Mohammad Kassemi
Ohio Aerospace Institute
21000 Brookpark Rd., MS 105-1
Cleveland, OH 44135
P-(216) 433-5031
F-(216) 433-5033
kassemi@sarah.lerc.nasa.gov

Isabella Kierk
Space/Earth Science Programs Directorate
Jet Propulsion Laboratory
4800 Oak Grove Dr.
Pasadena, CA 9109-8099
P-(818) 354-1879
F-(818) 393-4950
isabella.kierk@jpl.nasa.gov

Merrill K. King
Microgravity Research Division
NASA Headquarters
Washington, DC 20546
P-(202) 358-0817
F-(202) 358-3091
merrill.king@hq.nasa.gov

Fred Kohl
NASA Lewis Research Center
21000 Brookpark Rd., MS 500-115
Cleveland, OH 44135
P-(216) 433-2866
F-(216) 433-8660
fred.kohl@lerc.nasa.gov

L. Gary Leal
Dept. of Chemical & Nuclear Engineering
University of California
Santa Barbara, CA 93106
P-(805) 893-8510
F-(805) 893-4731
LGL20@engineering.ucsb.edu

Alex Lehoczky
NASA Marshall Space Flight Center
MS ES71
Huntsville, AL 35812
P-(205) 544-7758
F-(205) 544-8762
sandor.lehoczky@msfc.nasa.gov

Douglas LeVan
Dept. of Chemical Engineering
Vanderbilt University
Nashville, TN 37235
P-(615) 322-2441

Seth Lichter
Dept. of Mechanical Engineering
Northwestern University
2145 Sheridan Rd.
Evanston, IL 60208
P-(847) 467-1885
F-(847) 491-3915
s-lichter@nwu.edu

Jerri S. Ling
NASA Lewis Research Center
21000 Brookpark Rd., MS 500-102
Cleveland, OH 44135
P-(216) 433-2841
F-(216) 433-8050
jerri.ling@lerc.nasa.gov

Ralph Logan
Committee on Microgravity Research
7 Cindy Dr.
Manahawkin, NJ 08050
P-(609) 597-5292
ralphlogan@aol.com

Franklin Moore
Dept. of Mechanical & Aerospace Engineering
Cornell University
Ithaca, NY 14850
P-(607) 255-4100
F-(607) 255-1222
fkm1@cornell.edu

Jennifer Morgan
Microgravity News
1040-D Settlers Landing Rd.
Hampton, VA 23669
P-(757) 723-2197
F-(757) 723-0241
jennifer.morgan@msfc.nasa.gov

Henry Nahra
NASA Lewis Research Center
21000 Brookpark Rd., MS 500-102
Cleveland, OH 44135
P-(216) 433-5385
henry.nahra@lerc.nasa.gov

Robin Neely
NASA Marshall Space Flight Center
Microgravity Research Program Office
Huntsville, AL 35601
P-(205) 544-1738
robin.neely@msfc.nasa.gov

G. Paul Neitzel
Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, GA 30332
P-(404) 894-4342
F-(404) 894-2291
neitzel@me.gatech.edu

Arnauld Nicogossian
NASA Headquarters
Code U
Washington, DC 20546
anicogossian@hq.nasa.gov

Joe Nieberding
NASA Lewis Research Center
21000 Brookpark Rd., MS 500-201
Cleveland, OH 44135
P-(216) 433-7096
joe.nieberding@lerc.nasa.gov

Sandra Olson
NASA Lewis Research Center
21000 Brookpark Rd., MS 500-115
Cleveland, OH 44135
P-(216) 433-2859
F-(216) 433-8660
sandra.olson@lerc.nasa.gov

Thomas A. Parnell
NASA Marshall Space Flight Center
MS ES84
Huntsville, AL 35802
P-(205) 544-7690
F-(205) 544-7254
parnell@ssl.msfc.nasa.gov

William C. Patterson
NASA Marshall Space Flight Center
MS ED62
Huntsville, AL 35812
P-(205) 544-7224
F-(205) 544-0800
william.patterson@msfc.nasa.gov

Michael Pedley
NASA Johnson Space Flight Center
Houston, TX
michael.pedley@jsc.nasa.gov

George Peterson
Engineering Program Office
Texas A&M University
301 Wisenbaker Bldg.
College Station, TX 77843-3126
P-(409) 862-1463
F-(409)-845-8986

David Plachta
NASA Lewis Research Center
21000 Brookpark Rd., MS 60-4
Cleveland, OH 44135
P-(216) 977-7126
F-(216) 977-7545
david.plachta@lerc.nasa.gov

Alex Pline
NASA Headquarters
Microgravity Research Division
Washington, DC 20546
P-(202) 358-0820
F-(202) 358-3091
apline@hq.nasa.gov

Bob Rhome
NASA Headquarters
Microgravity Research Division
Washington, DC 20546
P-(202) 358-1490
F-(202) 358-3091
robert.rhome@hq.nasa.gov

James Richardson
Dept. of Chemical Engineering
University of Houston
4800 Calhoun Ave.
Houston, TX 77204
P-(713) 743-4324
F-(713) 743-4323
jtr@uh.edu

Judith Robey
NASA Headquarters
Microgravity Research Division
Washington, DC 20546
P-(202) 358-0823
F-(202) 358-3091
judith.robey@hq.nasa.gov

Rick Rogers
NASA Lewis Research Center
21000 Brookpark Rd., MS 105-1
Cleveland, OH 44135
P-(216) 433-6512
F-(216) 433-5033
richard.rogers@lerc.nasa.gov

Howard Ross
NASA Lewis Research Center
21000 Brookpark Rd., MS 500-115
Cleveland, OH 44135
P-(216) 433-2562
F-(216) 433-8660
hross@lerc.nasa.gov

Kurt Sacksteder
NASA Lewis Research Center
21000 Brookpark Rd., MS 500-115
Cleveland, OH 44135
P-(216) 433-2857
F-(216) 433-8660
kurt.sacksteder@lerc.nasa.gov

Jack Salzman
NASA Lewis Research Center
21000 Brookpark Rd., MS 500-205
Cleveland, OH 44135
P-(216) 433-2868
F-(216) 433-8660
jack.salzman@lerc.nasa.gov

Rose Scripa
Dept. of Materials Science and Engineering
University of Alabama at Birmingham
1150 10th Ave., S.
Birmingham, AL 35294
P-(205) 934-8453
F-(205) 934-8485
rscripa@eng.uab.edu

Nancy Shaw
NASA Lewis Research Center
21000 Brookpark Rd., MS 500-102
Cleveland, OH 44135
P-(216) 433-3285
F-(216) 433-8050
nancy.shaw@lerc.nasa.gov

Steve Simons
NASA Lewis Research Center
21000 Brookpark Rd., MS 500-217
Cleveland, OH 44135
P-(216) 433-5277
F-(216) 433-8660
stephen.n.simons@lerc.nasa.gov

Colin Sims
NASA Lewis Research Center
21000 Brookpark Rd., MS 110-3
Cleveland, OH 44135
P-(216) 433-9417
colin.sims@lerc.nasa.gov

Bhim Singh
NASA Lewis Research Center
21000 Brookpark Rd., MS 500-102
Cleveland, OH 44135
P-(216) 433-5396
F-(216) 433-8050
bhim.singh@lerc.nasa.gov

Ray Skarda
NASA Lewis Research Center
21000 Brookpark Rd., MS 500-102
Cleveland, OH 44135
P-(216) 433-8728
ray.skarda@lerc.nasa.gov

K.R. Sridhar
14611-A Big Basin Way
Saratoga, CA 95070
P-(408) 867-8262
F-(408) 868-9855
krsridhar@mail.arc.nasa.gov

Peter M. Struk
Case Western Reserve University
21000 Brookpark Rd., MS 110-3
Cleveland, OH 44135
P-(216) 433-5948
F-(216) 433-3793
peter.struk@lerc.nasa.gov

John Taylor
NASA Lewis Research Center
21000 Brookpark Rd., MS 500-102
Cleveland, OH 44135
P-(216) 433-5324
john.taylor@lerc.nasa.gov

James S. T'ien
Mechanical/Aerospace Engineering Dept.
Case Western Reserve University
Cleveland, OH 44106
P-(216) 368-4581
F-(216) 368-6445
jstz@po.cwru.edu

Jose Torero
Fire Protection Engineering Dept.
0151 Engineering Classroom Bldg.
University of Maryland
College Park, MD 20910
P-(301) 405-0043
F-(301) 405-9383
jltorero@eng.umd.edu

David Urban
NASA Lewis Research Center
21000 Brookpark Rd., MS 500-115
Cleveland, OH 44135
P-(216) 433-2835
david.urban@lerc.nasa.gov

Raymond Viskanta
School of Mechanical Engineering
Purdue University
West Lafayette, IN 47907-1288
P-(765) 494-5632
F-(765) 494-0539
viskanta@ecn.purdue.edu

Peter Voorhees
Dept. of Materials Science & Engineering
Northwestern University
2145 Sheridan Rd.
Evanston, IL 60208
P-(847) 491-3108
p-voorhees@nwu.edu

Peter Vrotsos
NASA Lewis Research Center
21000 Brookpark Rd., MS 500-216
Cleveland, OH 44135
P-(216) 433-3560
F-(216) 433-8660
pete.vrotsos@lerc.nasa.gov

Michael Wargo
Microgravity Research Division
NASA Headquarters
Washington, DC 20546
P-(202) 358-0822
michael.wargo@hq.nasa.gov

Dale Watring
NASA Marshall Space Flight Center
MS ES75
Huntsville, AL 35812
P-(205) 544-7032
F-(205) 544-8762
dale.watring@msfc.nasa.gov

Mark Weislogel
NASA Lewis Research Center
21000 Brookpark Rd., MS 500-102
Cleveland, OH 44135
P-(216) 433-2877
F-(216) 433-8050
mark.weislogel@lerc.nasa.gov

Allen Wilkinson
NASA Lewis Research Center
21000 Brookpark Rd., MS 500-102
Cleveland, OH 44135
P-(216) 433-2075
F-(216) 433-8050
aw@lerc.nasa.gov

John Wilson
NASA Langley Research Center
MS 188B
Hampton, VA 23669
john.wilson@larc.nasa.gov

Appendix C: Agenda

Monday, August 4, 1997

6:00 to 8:00 p.m.	Early Registration and Cash Bar

Tuesday, August 5, 1997

7:00 a.m.	Registration and Continental Breakfast* - Outside Grand Ball Room

A.M. Plenary Session - Grand Ball Room

8:00 a.m.	Overview Welcome - Director's Office Representative LeRC Opening Remarks - Arnauld Nicogossian, MD Welcome - Robert Rhome, HQ Workshop Purpose and Objectives - Bradley Carpenter, HQ
9:00	Planning for Human Exploration - Douglas Cooke, JSC
9:45	In-Situ Resource Utilization - David Kaplan, JSC
10:30	Break (Refreshments*)
11:00	Ecological/Environmental Systems - Don Henninger, JSC
11:45	Propulsion, Power, and Cryogenic Fluids Systems - Joe Nieberding, M.M. Hasan, LeRC
12:30 p.m.	Lunch* - October Room

P.M. Plenary Session - Grand Ball Room

1:45	Radiation Protection and Safety - John Wilson, LaRC
2:30	Surface Operations - David Kaplan, JSC
3:15	Break (Refreshments*)
3:45	Construction and Habitat Structures - Kriss Kennedy, JSC
4:30	Charge to Splinter Working Groups - Brad Carpenter, HQ
5:00	Adjourn
5:30	Cash Bar
6:30	Dinner* - October Room
7:30	After-Dinner Speaker - Robert Rhome, HQ

Wednesday, August 6, 1997

7:00 a.m	Continental Breakfast* - Outside Grand Ball Room

A.M. Splinter Sessions with Discipline Expert Groups

8:00 to 12:00	The following groups meet with Day 1 A.M. Presenters:

Fluids and Particulates Engineering Group
Heat Transfer Group
Chemical Processes Group

8:00 to 12:00 The following groups meet with Day 1 P.M. Presenters:
Radiation/Materials Group
Structures and Surface Operations Group
Safety Group
- Informal Break (Refreshments*)

12:00 to 1:00 Lunch* - October Room

P.M. Discipline Expert Group Working Sessions

1:00 to 5:00 Fluids and Particulates Engineering Group
Heat Transfer Group
Chemical Processes Group
Radiation/Materials Group
Structures and Surface Operations Group
Safety Group

Thursday, August 7, 1997

7:00 a.m Continental Breakfast* - Outside Grand Ball Room

A.M. Plenary Session - Grand Ball Room

8:00 Group Reports
Closing Comments
12:00 p.m. Adjourn

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
May 1998

3. REPORT TYPE AND DATES COVERED
Conference Publication

4. TITLE AND SUBTITLE
Workshop on Research for Space Exploration: Physical Sciences and Process Technology

5. FUNDING NUMBERS
WU-962-24-00-00

6. AUTHOR(S)
Bhim S. Singh, responsible person

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-11157

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA CP—1998-207431

11. SUPPLEMENTARY NOTES
Responsible person, Bhim S. Singh, organization code 6712, (216) 433-5396.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category: 91 Distribution: Standard

This publication is available from the NASA Center for AeroSpace Information, (301) 621-0390.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report summarizes the results of a workshop sponsored by the Microgravity Research Division of NASA to define contributions the microgravity research community can provide to advance the human exploration of space. The workshop, entitled "Research for Space Exploration: Physical Sciences and Process Technologies," was held in Cleveland, Ohio on August 5 - 7, 1997. The meeting was attended by invited speakers and participants from universities, industry, and various NASA installations. The number of attendees was limited to about 100. Invited speakers and attendees participated in an exchange of ideas to identify issues of interest in physical sciences and process technologies. This workshop was part of a continuing effort to broaden the contribution of the microgravity research community toward achieving the goals of the space agency in human exploration, as identified in the NASA Human Exploration and Development of Space (HEDS) strategic plan. The microgravity program is one of NASA's major links to academic and industrial basic research in the physical and engineering sciences. At present, it supports close to 400 principal investigators, who represent many of the nation's leading researchers in the physical and engineering sciences and biotechnology. The intent of the workshop was to open a dialogue between NASA and this large, influential research community, to engage this asset in support of human exploration. The workshop provided a forum to facilitate communication between the research community, mission planners, and industry technical experts with the goal of defining enabling research for the Human Exploration and Development of Space Enterprise. The needs and the potential for advances in the relevant technologies for long-duration human presence in space were identified and discussed. This report documents a list and technical description of research areas and problems of importance to NASA's HEDS missions and the space hardware development activities to which the microgravity research community can contribute. Given a decision to define specific exploration initiatives, these research areas would be a core element in developing program content via competitive research solicitations.

14. SUBJECT TERMS
Microgravity; Reduced gravity; Space exploration; Mars; Chemical processes

15. NUMBER OF PAGES
55

16. PRICE CODE
A04

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	