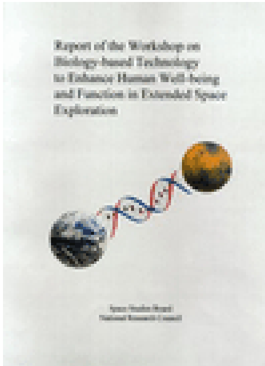

Report of the Workshop on Biology-based Technology to Enhance Human Well-being and Function in Extended Space Exploration

Steering Group for the Workshop on Biology-based Technology for Enhanced Space Exploration, National Research Council

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Steering Group for the Workshop on Biology-based Technology for Enhanced Space Exploration
Space Studies Board
Commission on Physical Sciences, Mathematics, and Applications
National Research Council

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Foreword

It is inevitable that humans will someday venture beyond low Earth orbit to renew our exploration of the solar system. Whether this occurs sooner or later depends largely on our ability to achieve the necessary technical capability at an affordable cost, something quite debatable at present.

The workshop reported on here was effectively a brainstorming session to consider somewhat unconventional technologies based on biology or biological systems. Although most of the technologies required to enable exploration are likely to be extensions of more traditional systems and devices, biology-based technologies have some very attractive features that might be of great benefit for human well-being and enhanced performance during longduration spaceflight.

It is unlikely that all or even most of the possibilities suggested here will actually grow into viable technologies useful to future astronauts. But they do represent a first attempt at defining fruitful avenues for further consideration, research, and evaluation. And one hopes that they will serve to stimulate the creative imaginations of other researchers to conceive additional possibilities.

Claude R. Canizares

Chair, Space Studies Board

Preface

The application of biological concepts and principles to the development of technologies for space exploration is an exciting idea that has sparked the interest of many people, including top-level NASA officials. To help guide its activities in this area, NASA's Office of Life and Microgravity Sciences and Applications (OLMSA) requested that the Space Studies Board organize an informal workshop to identify areas in biology-based technology research that appear to hold special promise for carrying biological science into technology directly applicable to space exploration. The product of this workshop was to be a letter report listing general topics and opportunities deserving further discussion and analysis, which might in turn be the subjects of future workshops.

At a workshop planning meeting held in Washington, D.C., on June 10, 1997, the Steering Group for the Workshop on Biology-based Technology for Enhanced Space Exploration (Appendix A) and OLMSA representatives determined that the workshop should strive not only to identify promising biology-based research areas as topics for follow-on focused workshops, but also to develop more specific findings that would support NASA's research planning more directly. As a result, the scope of the workshop was expanded to include prioritizing the technology requirements—identified by NASA—in three enabling technology areas (habitat systems, human systems, and advanced operations and teleoperations); identifying biology-based principles or concepts that could be applied to meet or enhance the technology requirements; describing the state of understanding of those principles today; and identifying gaps in research and technology work needed to enable a concept design or demonstration. During the workshop, however, it became clear to the participants that fully addressing all of the elements in the expanded scope of work would require a more systematic and detailed understanding of mission requirements than could be obtained in an initial workshop. Accordingly, this report outlines, in Chapter 4, possible steps in a systems engineering approach to defining mission needs as a prelude to exploring how to meet those needs in the future.

The workshop steering group faced two primary challenges: delimiting the task and understanding NASA's technology requirements. NASA representatives had made it clear that the focus should be on missions involving actual human presence at the exploration site. However, systems designed to carry out such missions are enormously complicated. The technologies required, and the mix of disciplines that inform their development, cover a broad range. It is likely that many of the essential major subsystems have components in which biological concepts or principles could be applied. The challenge was thus to contain the extent of inquiry sufficiently to produce usable results, while also ensuring that essential needs and the most promising approaches were addressed. Accordingly, the workshop steering group identified two themes to guide workshop discussions: enhancing human well-being, and enhancing human presence and function.

At the workshop planning meeting, there was considerable discussion regarding the need for workshop participants to have a fairly definitive understanding of NASA's system and system element requirements for envisioned human exploration missions, along with information about how conventional systems fall short of enabling long-duration missions to Mars and other planets. A substantial amount of information was provided by NASA regarding mission needs, but much of it was more general than workshop planners had hoped. Given the limited amount of detail available on NASA needs, the discussions of workshop participants were based on first principles.

The workshop was held on October 21-22, 1997, at the Center for Advanced Space Studies in Houston, Texas (Appendix B includes the agenda and list of the participants). The participants included specialists in a variety of fields, including aquaculture, biomedical engineering, bioprocess engineering, botany, chemical engineering, environmental and industrial microbiology, kinesiology, materials science, mechanical engineering and applied mechanics, molecular biology, neurology, pharmacology and physiology, plant pathology, pomology, public health, robotics, sensor technology, and space medicine. The workshop began with a plenary session at which a number of NASA's mission and technology managers provided general summaries of their current visions of scenarios and technology needs for near-term human exploration missions. The two subsequent discussion sessions focused on identifying areas in biology-based research with a potential for (1) enhancing human well-being in space exploration and (2) enhancing human presence and function in space exploration. These two sessions were organized to emphasize, respectively (1) life support, habitat systems, and human health; and (2) perception, manipulation and locomotion, cognition, and systems and computation.

Following the workshop, participants attempted to ground the discussions in the literature and to assess the ideas presented to the degree possible, based on current understanding of the principles involved and available NASA design criteria and ongoing research. However, several ideas introduced during the workshop were not included in this workshop report because they could not be justified scientifically. The workshop organizers envisioned that NASA would pursue follow-on activities, such as workshops or research, that would involve necessary technical evaluation, including weighing the advantages and disadvantages of the biology-based technologies, comparing their performance with that of conventional systems, and determining where the innovative technologies might best be applied (e.g., on a spacecraft or on the planetary surface). The results of this initial workshop suggest that there is good reason for excitement. This report identifies a number of research topics and opportunities deserving of further attention by NASA.

A number of individuals helped make the workshop a success. In particular, the Space Studies Board wishes to thank Arnauld Nicogossian, associate administrator, Office of Life and Microgravity Sciences and Applications, NASA Headquarters, for requesting the workshop

and for his presentation at the steering group's planning meeting. Special thanks are due to Diana Hoyt, Darrell Jan, and Bette Siegel, NASA Headquarters, for serving as the project's points of contact at NASA, and to Walter Hanby, Johnson Space Center, for helping to organize the NASA plenary speakers for the workshop. The steering group thanks John Anderson, Minoo Dastoor, Steve Davison, Guy Fogleman, Diana Hoyt, Darrell Jan, John Mankins, and Frank Sulzman, NASA Headquarters, and Douglas Cooke, Johnson Space Center, for their presentations at the steering group's planning meeting. The steering group also thanks Douglas Cooke, Bret Drake, Jon Erickson, Donald Henninger, Kriss Kennedy, James Maida, Robert Savely, and Charles Sawin, Johnson Space Center, for their technical presentations during the plenary session at the workshop. Finally, the steering group expresses its appreciation to the staff of Center for Advanced Space Studies, Houston, Texas, in particular, Gail Pachetti and Teri Jones, for their administrative assistance during the workshop. The assistance of Lisa May, Jackson-May Associates, and Guy Orgambide, SciLink Inc., is gratefully acknowledged.

Acknowledgment of Reviewers

This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The content of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

Michael Albin, Perkin-Elmer Corporation,

John Baross, University of Washington,

Aaron Cohen, Texas A&M University,

John E. Estes, University of California, Santa Barbara,

Johann Peter Gogarten, University of Connecticut,

Robert Langer, Massachusetts Institute of Technology,

Gerald E. Loeb, Queen's University, and

John W. Townsend, NASA Goddard Space Flight Center (retired).

Although the individuals listed above provided many constructive comments and suggestions, responsibility for the final content of this report rests solely with the authoring steering group and the NRC.

Contents

Executive Summary

Biological systems are regenerative, energy and size efficient, and adaptable to changing environments. As humans venture further into space and spend longer periods of time there, these attributes may provide the basis for technologies that can sustain life in deep space and on other planets.

This concept was explored at the Workshop on Biology-based Technology to Enhance the Human Presence in Extended Space Exploration, held on October 21-22, 1997, by the Space Studies Board (SSB) of the National Research Council at the Center for Advanced Space Studies in Houston, Texas. The objective was to identify areas in biology-based technology research that appear to hold special promise for carrying biological science into technology directly applicable to space exploration.

Workshop participants sought to identify how biological concepts and principles might contribute to enabling technologies for long-duration missions involving the actual presence of humans (as opposed to robots only) at exploration sites on other planets, such as Mars (see Chapter 1). In the 2010 to 2020 time frame and beyond, NASA proposes to carry out international human missions to planetary bodies such as Mars (a mission of at least 600 days) with no crew rotation or resupply available. Such a mission is beyond today's technical capabilities. Advances are needed in a variety of technical areas to reduce risk, equipment weight, power requirements, and costs as well as to increase reliability.

The workshop's two discussion sessions focused on biology-based research areas with a potential for (1) enhancing human well-being in space exploration and (2) enhancing human presence and function in space exploration. Because the workshop was intended as an initial effort and not a detailed scientific investigation, participants dealt with the discussion topics in a somewhat conceptual manner and did not attempt to assess their merits.

Based on discussions in the two sessions and on their quantitative judgments, participants identified six topics that seem promising enough in the near term to warrant further examination in follow-on workshops: closed-loop aquaculture systems as a model for advanced life support (ALS) water processing and waste management systems; biosensors for detecting pollutants and pathogens in air and water; biomaterials for spacecraft and habitats; space suit design incorporating biological concepts; use of magnetoencephalography to monitor astronauts' cognitive states; and synergistic human-robot systems. Also identified in each session were additional areas in which R&D advances by NASA or others may benefit the space program either in the near-term or over the longer term.

The concepts discussed in sessions 1 and 2 are described in Chapter 2 and Chapter 3, respectively. Chapter 4 touches briefly on workshop participants' observations regarding points for considerations in any follow-on activities—including the importance of defining specific technical requirements for long-duration human exploration of space and the usefulness of tracking developments in fields other than aeronautics and space science that may contribute to the application of biology-based systems and principles in Human Exploration and Development of Space (HEDS) Enterprise missions.

OPPORTUNITIES FOR APPLYING BIOLOGICAL CONCEPTS AND PRINCIPLES

Enhancing Human Well-Being

Session 1 participants sought to identify biological concepts and principles that might be further explored to address needs related to regenerative advanced life (ALS) support systems, spacecraft and habitats, and the health of humans and useful biological organisms. A central theme was the value of reducing, reusing, recycling, and recovering materials so as to reduce size, mass, and power requirements (and thus cost) as well as increase reliability for long-term human exploration of space. Session 1 participants identified three topics that seem promising for exploration in follow-on workshops, as well as two research areas that might offer NASA short-term payoffs and two that might offer longer-term payoffs.

Topics for Follow-on Workshops

Closed-loop Aquaculture Systems as a Model for ALS Water Processing and Waste Management Systems. Provision of clean water is a basic requirement for extended space exploration missions. A workshop on current technologies in the maturing field of closed-loop aquaculture and innovative fermentation processes used in waste treatment might assist in the development of highly efficient closed-loop regenerative ALS systems for extended space missions.

Biosensors for Detecting Pollutants and Pathogens in Air and Water. To maintain human health and comfort as well as functioning plant and microbial populations, rapid and reliable detection and monitoring systems are needed to ensure that air and water in spacecraft and in habitats do not contain disease-causing pathogens or discomfort-causing levels of pollutants. Potential applications of biosensors could be explored in a workshop that would also have to define the research required to identify which microorganisms and pollutants should be detected on spacecraft and habitats and to establish sensitivity requirements relevant to NASA's needs. The use of biosensors in the skin of planetary habitats that could alert the crew to radiation levels and/or level of radiation-induced damage could also be addressed as part of this follow-on workshop.

Biomaterials for Spacecraft and Habitats. Biomaterials and biologically inspired materials might incorporate capabilities ranging from self-diagnosis and self-repair of certain system components to protection of astronauts and other biological organisms from the effects of radiation. Furthermore, such materials could also help make missions to other planets possible by virtue of their being lightweight and renewable, offering opportunities to reduce transportation cost and mass. These and other potential attributes as well as trade-offs in labor, space, and energy should be examined in a focused workshop before specific biomaterials are used in space applications.

Research Areas Offering Short-Term Payoffs

Cultivation of Algae as Food. Algae and cyanobacteria are used as nutritional supplements on Earth and might be cultivated for that purpose on spacecraft, as well as for waste treatment, CO_2 recycling, and O_2 generation. In addition to identifying edible species that could be grown in the space environment, it may also be worth exploring the genetic engineering of algae and/or cyanobacteria to enhance their value and palatability as food, or the development of suitable food processing methods to either remove or degrade undesirable components (such as nucleic acids). Because cyanobacteria are more easily cultured and genetically engineered than eukaryotic algae or higher plants, they may hold greater promise in the short run for use in air recycling, wastewater treatment, and food production. The significant base of information on algae and cyanobacteria needs to be reexamined to identify their potential for use in such applications.

Development of Plants with Enhanced Disease Resistance. The types of diseases likely to occur in space horticulture must be identified so that plants resistant to specific diseases can be developed. Research is also needed to enable identification and management of the relevant disease-causing organisms.

Enzymatic Catalysts for Housekeeping. Humidity control is probably key to preventing overgrowth of microorganisms, which can also become resistant to the biocides used to wipe down bulkheads. When cleaning is necessary, enzymes (e.g., proteases, lipases) can be used as alternatives to chemical cleaning agents, an approach that has emerged for industrial cleaning applications. Enzymes, which are naturally occurring proteins, can be designed to target the compounds that enable microorganisms to adhere to surfaces. Furthermore, enzymes are highly suitable for spaceflight because they are lightweight, biodegradable, and have a long shelf life. However, some enzymes may cause allergies. Research is needed to examine the feasibility of using enzymes for housekeeping in spacecraft and planetary habitats, and to evaluate risks of exposing crew members to these potentially potent allergens.

Research Areas Offering Long-Term Payoffs

Genetic Engineering of Plants. Plants, a fundamental biological system, will be essential to human well-being in long-duration space exploration. Plants can be used not only as food but also as sources of useful materials and chemicals and for the recycling of carbon dioxide and other inorganic and organic wastes. To meet defined requirements for spaceflight, plants might be engineered, for example, to produce miniature roots or leaves, grow under low-light conditions, exhibit increased resistance to disease or radiation, and produce structural materials such as biodegradable plastics or specific nutrients needed by humans.

Radiation Protection and Monitoring. Certain plants and microorganisms have effective DNA-repair mechanisms that confer some measure of radiation resistance or tolerance. Research aimed at understanding such mechanisms might provide a basis for transferring these capabilities to plants and organisms cultivated on spacecraft. It may also be possible to design a biological dosimeter for radiation monitoring through the use of specific microorganisms or designed DNA integrated into biochips for monitoring purposes. The applicability of advanced biological dosimeters for space exploration could be addressed as part of the workshop on biosensors suggested above.

Enhancing Human Presence and Function

Session 2 participants sought to identify biological concepts and principles that might enhance human function in four areas: perception, manipulation and locomotion, cognition, and systems and computation. The group discussions reflected a number of themes, including similarities between deep space and the deep ocean that suggest a potential for transferring diving technologies and concepts to the space program; the merits of biological concepts as models for processes that are inherently simple and evolutionary, as opposed to complex and excessively mechanical; and the need to strike an appropriate balance between the tasks assigned to machines versus those assigned to humans. The group identified three topics that seem promising enough in the short term to be addressed at follow-on workshops.

Topics for Follow-on Workshops

Space Suit Design Incorporating Biological Concepts. As part of the effort to design lightweight space suits suitable for use on Mars, biological concepts and principles could be applied to enhance astronauts' comfort and function. A future workshop could explore, for example, the application of biomechanical concepts such as 40-degree-angle wrist settings to provide maximum dexterity and grip, biomolecular materials modeled on strong yet dexterous sharkskin, technologies such as actuators and microelectrical mechanical systems (MEMS) that could assist with movement or self-repair, external sensors that produce haptic and other sensory feedback to the astronaut, and galvanic stimulation to provide cues about spatial orientation in microgravity.

Use of Magnetoencephalography to Monitor Astronauts' Cognitive States. Physiological monitoring of brain waves could provide confidential biofeedback on astronauts' cognitive states for the purpose of enhancing functional effectiveness and promoting relaxation. Magnetoencephalography, which is based on the use of superconducting quantum interference devices (SQUIDs) to detect very small magnetic fields, offers a number of advantages, including rapid response and ease of use. A SQUID cryogenic cap or helmet for recording brain waves may be particularly appropriate in the space environment, where temperatures are theoretically cold enough to make the SQUIDs superconducting. A future workshop could explore the benefits and feasibility of designing such a system.

Synergistic Human-Robot Systems. A future workshop could explore the design of synergistic human-robot systems that would meet needs for system reliability and configurability, effective human-machine collaboration, improved situational awareness, and optimal decision making. Three biology-based concepts seem particularly promising: (1) collaborative multirobot systems modeled on the task sharing of the insect kingdom. Advantages include rapid adaptation to the loss of individual robots, robust communication among all robotic or biological elements, system reconfigurability, and the capability to deploy specialized individuals. (2) Robotics systems that exhibit emergent system behavior mediated by emotion and anxiety, as well as a learning process augmented by emotion. Such systems would “think” more like humans, whose decision-making and problem-solving abilities are improved by access to their emotions. (3) Interfaces that enable human comprehension of system data without information overload, and the communication of human affect and intentions to robots.

Research Areas Offering Short-Term Payoffs

Artificial Vision Systems. Technologies being actively investigated in many sectors offer the possibility of enhancing human vision and providing new modalities, such as over-the-horizon sight. However, existing devices tend to be bulky, primitive, and, in most cases, far less sensitive, precise, or adaptive than their biological counterparts. The state of the art needs to be improved. Of particular interest is using very large-scale integration (VLSI) and MEMS technology to integrate sensing, processing, and possibly display elements into small, lightweight, low-power units. Biological principles and biology-inspired designs could provide critical guidance in such efforts. For instance, visual computational sensors or artificial retinas that provide spatio-temporal processing at the place of sensing could enable task-oriented, rapidly adaptable processing of visual information.

Exercise Based on Biological Concepts. As an alternative or supplement to the treadmill currently used for exercise during spaceflight, it might be useful to explore an exercise concept that mimics the activities of an embryo during its time in the womb. A “bungee suit” with elastic properties might be designed that would enable gymnastics regimens that could maintain or restore an astronaut's physical state.

Research Areas Offering Long-Term Payoffs

Adaptation to Different Gravitational States. Astronauts' adaptation to microgravity and subsequent readaptation to Earth's gravity might be accelerated by understanding and manipulating the fragile transition between the two states. Evidence from everyday life and biomedical research—including a rapid increase in understanding of the central nervous system and its plasticity—points to an inherent biological capability for dual adaptation. A combination of pharmacological intervention and appropriate training and exercise might effectively prepare astronauts for adaptation to alternating gravitational states.

Software for Emotion-Mediated Learning. In humans, emotional states mediate decision making and learning. Software for robotics systems could be designed to exhibit emergent system behavior mediated by emotion and anxiety, and a learning process augmented by emotion. Such systems might meet needs for software reliability and configurability, effective human-machine collaboration, improved situational awareness, and optimal decision making.

"Principal Investigator (PI) in a Box." Given the complexity and new challenges associated with long-term human exploration of space, astronauts might benefit from having instant access to a database of the accumulated experience of previous astronauts. The database could support dynamic mission planning and execution strategies and improved problem solving and could be self-organizing to respond to immediate needs. Biology-based concepts could also be applied to the presentation of data. For example, algorithms based on the survival instinct might present data on the most-life-threatening situation first.

1

Introduction

In the 2010 to 2020 time frame and beyond, NASA proposes to carry out international human missions to planetary bodies such as Mars (a mission of at least 600 days) with no crew rotation or resupply efforts. Such a mission is well beyond today's technical capabilities. Advances are needed in a variety of technical areas to improve reliability and reduce risk, equipment weight, power requirements, and costs.

As a partner in the Human Exploration and Development of Space (HEDS) Enterprise, NASA's Office of Life and Microgravity Sciences and Applications (OLMSA) seeks to increase space system and mission capabilities by accelerating the incorporation of biology-based advanced technology into both crewed and uncrewed exploration missions. Such technologies could help make current space systems more like biological systems—e.g., “smarter,” smaller, self-repairing—and might include, for example, electronic “noses” capable of emulating or enhancing human sensory capabilities, bio-based sensors for detecting radiation damage, insect-like robots for inspecting crevices, and self-repairing systems and materials.

CHARGE AND APPROACH

To help guide its activities OLMSA requested that the Space Studies Board organize an initial workshop to identify areas in biology-based technology research that appear to hold special promise for carrying biological science into technology directly applicable to space exploration. The workshop, held on October 21-22, 1997, at the Center for Advanced Space Studies in Houston, Texas, opened with a plenary session at which a number of NASA's mission and technology managers described their current visions of scenarios and technology needs for near-term HEDS missions. The remaining two sessions focused on identifying areas in biology-based research with a potential for (1) enhancing human well-being in space exploration and (2) enhancing human presence and function in space exploration. These two sessions were organized to emphasize, respectively, (1) life support, habitat systems, and human health; and (2) perception, manipulation and locomotion, cognition, and systems and computation.

In the absence of immediate access to information about past NASA research in these areas, session 1 and 2 discussions were based on first principles. In addition, because NASA's presentations outlined overall needs and the current thinking about system design for a future Mars mission and other generalized missions, few details were available to session participants concerning requirements at the system level, design criteria for important subsystems, or functional requirements for astronauts. Participants thus sought to identify basic areas of need and discussed creative ways in which biological concepts such as those listed in Box 1.1 might be applied to improve long-duration human exploration of space.

BOX 1.1 BIOLOGICAL CONCEPTS WITH POTENTIAL APPLICATIONS FOR SPACE EXPLORATION

Examples from biomimetics, the science of developing synthetic systems based on information obtained from biological systems, include manipulators that improve dexterity or grip, insect-like robots, neural networks, and recyclable adhesives such as barnacle-based glues.

Examples of the application of biometaphorics principles of function and architecture inspired by life-unique properties include self-replicating systems, self-repairing structures and materials, ecological principles (e.g., critical trace materials seeded in spaceborne structural materials as future resources), and artificial life (e.g., self-organizing principles, self-assembling systems).

Biomolecular materials incorporate biological molecules or concepts in nonbiological devices or systems or are structured in a way that is characteristic of biological materials. Examples include living cells used as sensors and clothing patterned after sharkskin.

Hybrid organisms consist of genetically engineered biological components linked to nonbiological systems. Examples might include biological cells and computer chips (biochips) used in combination to detect radiation, genetically engineered beetles for carrying sensors, root-like plants that can creep into cracks and pores and grow as depositors of sealant, or surface penetration instruments (e.g., tentacle-like micro- or nano-sized probes).

The following section summarizes the presentations by NASA personnel in the workshop's plenary session. Chapter 2 and Chapter 3 summarize the results of discussions by the participants in sessions 1 and 2, respectively. Chapter 4 offers some brief observations by workshop participants on points for consideration in any follow-on activities to further explore areas of biology-based research with the potential to enhance human exploration of space. Biographical sketches of the workshop's steering group are given in Appendix A, and information on the agenda and a list of participants are provided in Appendix B.

In considering optimal use of technology to enable human exploration of space, it is worth noting that there are valid reasons to use physicochemical systems rather than less proven ones with biological elements. One reason is the increase in reliability that comes from using a proven technology rather than a new one for which failure modes have yet to be fully identified. The issue of reliability is important for “biology-based” systems, many of which interact in an as yet poorly defined chemical domain. By contrast, the interactions among mechanical systems are more amenable to complete systems identification and analysis. Methods will have to be developed to evaluate the reliability of biology-based systems, a subject that is outside the scope of this report.

NASA PRESENTATIONS

NASA managers presented their current thinking about system design for a future Mars mission and other generalized missions. These presentations addressed Mars mission planning, exploration technology requirements, risks associated with Mars missions, advanced habitat concepts, advanced life support, human-machine interfaces, robotics and automation, and information processing.

Mars Mission Planning

An overview of Mars mission planning was provided by Douglas R. Cooke, deputy manager for exploration of the Advanced Development Office and manager of the Johnson Space Center (JSC) Exploration Office. The planning effort combines the scientific search for the origin of life and the study of planetary evolution with human exploration of space. Detailed plans have been developed for a set of robot missions to Mars in 2001. In addition, significant planning has taken place for technology investments needed for eventual human missions.

Basic requirements include adequate Earth-to-orbit lift capability (80 metric tons for large payload volumes) and highly efficient space propulsion systems. An autonomous base will have to be established on Mars and fuel will have to be made from in situ resources. Space suits will have to be lightweight enough to enable astronauts to work on the martian surface. High-bandwidth communication and data-storage capabilities will be needed; two-way communications between Earth and Mars currently take 40 minutes.

Payload size and cost to launch must be reduced by the development of closed-loop life support systems, reductions in power requirements, and design of lightweight information systems and instruments using micro- and nano-electronics and system components.

Maintaining the health and safety of crew members will require research on the effects of galactic cosmic radiation on humans, the long-term effects of zero gravity and reduced gravity, and advanced diagnostics and medical care of the crew. In addition, advanced technology is needed for habitat structures and closed-loop life support systems.

Exploration Technology Requirements

Bret G. Drake of the JSC Exploration Office noted that space transportation accounts for 50 to 75 percent of any mission cost. Transportation costs, now $8,000 to $12,000 per pound, need to be reduced to $1,000 per pound. Life-cycle costs need to be minimized by, for example, using the martian atmosphere rather than propulsion to reduce a vehicle's orbit, and obtaining power from in situ Mars resources such as methanol (CH_3OH), methane (CH_4), or oxygen (O_2).

NASA divides the key technologies to support human exploration of space into five thrust areas: human support, advanced space transportation, advanced space power, information and automation, and sensors and instruments. Examples of needs related to human support include the following:

- *Protection against exposure to radiation.* Systems that could predict solar radiation events would contribute substantially to crew health and safety. Such systems might include, for example, x-ray detectors, visible light imagers, sensors attached to habitats, and personal radiation-hazard monitors that, especially if used in conjunction with integrated medical databases, could improve crew safety. Research is needed to understand the effects on biological systems of the deep-space radiation environment. Portable, high-resolution diagnostic systems are needed to detect injury arising from exposure to radiation.
- *Advanced life support systems.* To significantly reduce the consumables that must be taken on long-duration missions, ALS systems are needed for closed-loop air and water processing, solid waste processing, thermal control, and food production. Advanced "intelligent" technologies are needed to monitor and control such ALS systems. In addition, advances in structural concepts and lightweight materials are needed to enable the design of large habitats for transit to Mars and exploration of the planet's surface. Key technology thrusts include habitat concepts and emplacement methods (e.g., emplacement by robots), novel structural concepts (e.g., inflatable rather than traditional hard structures), and integrated protection against the effects of radiation.
- *Systems to support extravehicular activity.* Routine exploration of the surface of Mars will require advanced EVA suits and short- and long-range surface rovers that are dexterous, mobile, and sensitive to sensory and tactile input. Technologies that will contribute to these systems include advanced materials that enhance mobility and dexterity while maximizing protection against radiation and punctures; lightweight batteries that recharge rapidly; efficient, lightweight thermal-control systems; means for storing consumables, including cryogenic backpacks; humidity control; advanced sensors for monitoring O_2, carbon dioxide (CO_2), nitrogen (N_2), temperature, and other environmental parameters; and advanced avionics such as heads-up displays.
- *Environmental and medical monitoring.* Miniature, highly sensitive sensors and instruments are needed to detect fire, toxins, and radiation; to monitor the state of food, air, and water; and to monitor human health. Systems for emergency medicine, telemedicine, and global monitoring and hazard avoidance (e.g., for protection against dust storms) are also needed. Miniaturized biotelemetry sensors and systems are needed for medical monitoring and portable clinical laboratory diagnostics.
- *Robotics.* Advanced robotics systems are needed to enhance mission safety, efficiency, and return by performing routine or complicated tasks prior to, and in conjunction with, the work done directly by astronauts. Systems of interest include those enabling dexterous manipulation

for scientific field work, subsurface sampling, locomotion, and assembly and construction activities on the surface of Mars.

Risks Associated with Mars Missions

An effort to identify the risks associated with a human mission to Mars was described by Charles Sawin, assistant to the director of the Space and Life Sciences Directorate for Science Payloads. A total of 105 risk factors for shuttle, low-Earth-orbit, lunar, and exploration missions are being tallied, and the activities necessary to support such missions are being ranked. Issues under consideration include spacecraft habitability, maintenance of crew health, effects of exposure to radiation, adaptation of humans to microgravity, psychological problems associated with long-term isolation and interpersonal tensions, and working in space and on planetary bodies. The risk factors will be validated by the National Space Biomedical Research Institute. The primary product of this activity—a road map that identifies the research required to mitigate the identified risk (s), the time frame in which the research needs to be accomplished, and the funding levels required—was scheduled to be available in January 1998.

Technology needs in four categories were described: advanced miniaturization, "intelligent" systems, sensors and instruments, and human support. High-priority technologies for human support include those for preserving food and extending its shelf life for up to 5 years, nonintrusive monitoring of performance, data collection for crew training and development, training evaluation for ability to perform critical tasks, and waste recycling.

Advanced Habitat Concepts

Advanced habitat concepts were described by Kriss Kennedy, space architect in the Advanced Development Office of JSC. Three types of habitats of increasing levels of sophistication are envisioned: preintegrated hard-shell modules for deployment prior to the crewed mission; prefabricated (i.e., inflatable) structures for automated assembly on the surface of Mars; and structures made of indigenous martian resources as well as components from Earth, for example, underground habitats constructed with a tunneling or mining mole system to protect against radiation and provide a thermally stable environment.

The planetary habitats will have to be lightweight, reliable, and easy to maintain. They might embody a number of biological concepts, such as artificial intelligence capabilities for self-analysis (i.e., to detect failure) and self-repair, and might feature "living" shells: micro-life-support systems embedded in the habitat skin, for example, to process carbon dioxide into oxygen or grow new matrix material to repair punctures.

Advanced Life Support

Among the technical objectives discussed by Donald Henninger, chief scientist and deputy program manager for the Advanced Life Support program, was development of ALS system technologies that can significantly reduce life-cycle costs, improve operational performance, promote self-sufficiency, and minimize the expenditure of resources for missions of long duration. For example, resource recycling and processing and contaminant control systems need to be designed and integrated into other systems. These systems need to be optimized to provide for air and water revitalization in connection with the growth of crop plants. Efficient, reliable thermal control systems are needed to ensure heat acquisition, transport, and dissipation. Fully regenerative, integrated technologies are needed to recover air, water, food, and resources from waste.

Issues related to performance in hypogravity must be resolved. Predictive models of fluid and fluid-gas behavior and interactions in hypogravity on the planetary surfaces are needed for use in the design of new ALS hardware, particularly for gravity-sensitive ALS components and subsystems (e.g., membranes). The performance of bioregenerative systems needs to be characterized at lunar and martian gravities; ultimately, it must match the performance achieved by such systems on Earth in terms of productivity, control, and predictability.

ALS technology challenges for missions to the moon and Mars include water recovery from wastewater (e.g., by using multifiltration, reverse osmosis, iodine disinfection); control of CO_2 levels (e.g., by using electrochemicals, sorbents, plants, enzymes); real-time air and water quality monitoring (e.g., by using lightweight, durable, low-power sensors); solid-waste processing and resource recovery (e.g., by using bioreactors, supercritical water oxidation); in situ recovery of useful gases from planetary resources; low-power, high-efficiency sources of light for plant growth; and system monitoring, command, and control.

Several tests to integrate biological and physiochemical systems have been conducted by NASA at the Johnson Space Center's integrated life-support systems test facility. One test, done to verify the performance of biological and revitalization life support systems, involved an astronaut spending 15 days in a variable-pressure growth chamber. It has been estimated that at least a 10-square-meter plant-growing area would be needed to provide oxygen and carbon dioxide uptake for one person. In the test, nearly 11 square meters of wheat was successfully grown as a complement and backup to other life support systems; changes in gas concentration were observed with small changes in light intensity. In a second NASA test, four persons spent 30 days in a facility designed to verify the performance of physicochemical life support systems for air and water recycling. A 60-day test with four test subjects evaluated the integrated life support systems baseline for the International Space Station in the spring of 1997, and a three-month test was initiated in September 1997, verifying the performance of both biological subsystems and physicochemical systems for life support. Plants and a CO_2 scrubber and CO_2 reduction units were used for air revitalization along with a catalytic oxidizer for control of trace gas contaminants. A bacterial bioreactor for recovery of water was used in combination with physicochemical components to recycle all the water. An advanced thermal control subsystem was tested along with an automated system monitoring and control subsystem.

Human-Machine Interfaces

Human-machine interfaces were discussed by James Maida, technical director for the Graphics Research and Analysis Facility, Lighting Evaluation and Test Facility, and Anthropometry and Biomechanics Facility in the JSC Flight Crew Support Division. Because of the isolation and long duration of a mission to Mars, human factors need to drive decisions about the use of resources. Three issues are critical: maintenance of the crew's physical and cognitive performance, provision of access to information for meeting contingencies and problem solving, and maintenance of crew performance by ensuring comfortable living conditions.

Human-machine interface devices must be lightweight, small, and durable. Head-mounted displays need to be designed that offer high resolution, ease of use, and multipurpose applications for virtual and augmented vision (i.e., magnification, dynamic overlays, synthetic vision). Such displays could be used for flight control, maintenance, and teleconferencing. Biotelemetry and haptic feedback devices offering a sense of touch could be very useful. Natural language (i.e., voice) processing and comprehension systems would greatly enhance human-computer interactions. Information systems will need to be portable, fully integrated, and operable using voice commands.

Robotics and Automation

Automation technology needs were outlined by Jon D. Erickson, chief scientist for automation, robotics, and simulation at the JSC. As a permanent human presence is established farther and farther from Earth's surface and orbit, additional support systems will be needed that can provide safe, reliable, low-cost, high-performance transportation, construction, use of in situ resources, and closed-loop life support. These systems must be far better than the current state of the art.

Robotics and automation technologies are in the early stages of development for in-orbit as well as extra- and intravehicular activity, and for interplanetary and planetary surface applications. They are being designed for operation and maintenance of spacecraft, surface systems deployment, operation and maintenance of energy generation and distribution systems, fuel generation and storage, regenerative life support (both physicochemical and biological), medical research and operations, surface vehicles, and human-robot teams. They can perform routine tasks while astronauts apply their energy to tasks requiring perception, judgment, creativity, and flexibility.

A genetic architecture designed for monitoring and control in NASA's integrated life-support systems test facility has three layers of intelligence. The top layer consists of simulation-and model-based reasoning for high-level goal setting and planning. The middle layer uses shared and traded control to execute tasks. The third layer is the skill manager, which provides situational awareness with natural-language understanding and generation. In another NASA project, a two-armed, mobile, sensate robot has been designed as a crew and habitat helper. It is similar to the armless robots currently used in some hospitals to deliver pharmaceuticals.

Additional research is needed on sensors (e.g., microelectrical mechanical systems [MEMS]), machine perception, and the transfer between humans and machines of information gained from situational awareness.

Information Processing

Information processing needs were described by Robert T. Savely, chief scientist of the Information Processing Directorate. NASA will need a full-spectrum supercomputing environment consisting of high-speed processors, mass storage, high-performance networks, and visualization hardware and software for extended space exploration by humans. For example, high-performance graphics hardware and software could enable the analysis and display of data in real time, so that multiple users could simultaneously have access to information and quickly identify new patterns and relationships among complex data. DNA computing, cellular engineering, and living neuronal nets could provide the basis for ultracomputers. Hybrid interfaces might be used to combine biological materials with silicon-based computation.

The Defense Advanced Research Projects Agency (DARPA) work on ultrascale computing may suggest biological concepts that would be useful in information processing on NASA missions. For example, swarm computing, parallel computing, and quantum computing may lead to the design of materials that “think.” DARPA's projects on DNA computing involve the development of technologies for performing computations at the molecular level. Those on cellular engineering exploit bioengineering of one-celled organisms for computation and low-cost manufacturing of computational elements. The neural networks projects involve the in vitro growth of neuronal materials to synthesize neural networks that interface directly with electronic circuits.

2

Enhancing Human Well-being in Space Exploration

STUDY APPROACH

Systems that ensure the well-being of astronauts are a prerequisite to launching safe, cost-effective crewed missions to Mars or other planets. To explore biology-based technology's potential to enhance human exploration of space for extended periods, session 1 participants focused on three essential functional needs: regenerative life support systems, spacecraft and habitats, and systems to maintain the health of astronauts as well as biological organisms used to meet needs for food and environmental control. A recurring theme in the discussion was the value of reducing, reusing, recycling, and recovering materials so as to reduce size, mass, and power requirements—and thus cost—and also increase the reliability of systems for supporting long-term human exploration of space.

FUNCTIONAL NEEDS

Regenerative Life Support

Self-sufficient and reliable advanced life support (ALS) systems are needed to ensure the well-being of astronauts and to support productive research and exploration in space and on other planets. NASA anticipates that ALS systems for planetary transit vehicles will be primarily physicochemical and that complex systems with biological elements, such as systems for water recovery and waste management, plant production, and monitoring and control of such systems will be used in the habitats on planetary surfaces. ALS systems will have to work in both a microgravity and a hypogravity environment.

To enable long-term missions without resupply support, subsystems must be developed to fully recycle air and water, recover resources from solid waste, grow plants for food, process raw plant products into nutritious and palatable foods, control the thermal environment, and regulate the overall system. A challenge in the implementation of regenerative ALS is to develop productive, reliable, and integrated systems while also balancing the size and function of the various subsystems (Westgate et al., 1992; Velayundhan et al., 1995). One goal would be to minimize demands on crew time devoted to maintenance of basic life functions.

Spacecraft and Habitats

Transit vehicles and planetary surface habitats used in the human exploration of Mars and for other long-duration missions must protect their occupants from vacuum, low-pressure atmospheres, radiation, extremes of temperature, clinging particles of dust, micrometeorites, and chemically reactive soils. They must also be made of materials that are reliable, easily maintained, and repairable. Of particular interest are lightweight, renewable materials that can tolerate extreme environments and also be converted into needed structures or other basic components such as starch, fuel, or food.

A planetary surface habitat—a closed system consisting of a primary structure to maintain air pressure, ALS systems, internal structures and equipment, and an airlock to limit loss of air and the entry of dust—must be designed to minimize the extravehicular activity (EVA) required for its construction, operation, and maintenance. In addition, a planetary surface habitat's mass is a primary determinant of mission launch requirements and therefore needs to be minimized.

Health of Humans and Useful Biological Organisms

Technologies and principles that promote health offer obvious opportunities to enhance human well-being. Key health-related considerations described by NASA include radiation monitoring and housekeeping. Also needed will be means of keeping air and water free of pollutants and disease-causing organisms. In addition, bioregenerative systems will have to be selected carefully so as to avoid the introduction of pathogenic organisms into the spacecraft or planetary habitat environments. Session 1 participants determined that, in addition to focusing on human health, attention should be given to the health of the other biological systems—plants and microbial systems—that might play a crucial role in environmental control and nutrition for the crew.

POTENTIAL BIOLOGY-BASED RESEARCH OPPORTUNITIES

Ensure a Renewable Supply of Clean Water and Air

Clean water is essential to human survival and well-being, and so recycling of water is one of the highest priorities for extended space missions. Factors in the design and optimization of a closed-loop water system include biological nitrification capacity,[1] control of pH and alkalinity, mechanisms for the removal of solid waste and fines, overall management protocol, and appropriate monitoring and alarm systems to track the status of any microorganisms used to reduce and reuse accumulated wastes such as ammonia, organics, and salts (see the section below titled “Biosensors”). Closed-loop aquaculture systems currently in use and under development for wastewater processing (see, e.g., Mayo, 1991; Metcalf and Eddy, Inc., 1991; Timmons and Losordo, 1994; Libey and Timmons, 1996) may provide insights that could be applied to the development of highly efficient systems for closed-loop regenerative ALS systems for extended space missions.

Aquaculture technology for on-site recovery of useful gases and water in planetary surface habitats could be enhanced by the identification of innovative fermentation technologies used in waste treatment to produce useful products. Fermentation can reduce the size and weight of the waste stream and increase the efficiency and reliability of the waste treatment process. Gases such as CH4 and H2, possible by-products of waste treatment involving anaerobic bacteria, might be converted to fuel. The remaining solid and liquid waste materials could be used as fertilizers for plants. Potential problems include separation of gases and elimination of toxic gases such as hydrogen sulfide (H2S). Technology exists for separating the gases and for monitoring and increasing the efficiency of the process, but issues related to power requirements, size, and weight would have to be resolved.[2]

Because closed-loop aquaculture systems appear to offer insights that might be applied in the near term to enhance wastewater processing in planetary surface habitats, a workshop could be held to explore this topic.

Among organisms that could be used for biodegradation of waste, bacteria might be the most appropriate for use in space, as many species have evolved to survive under unusually severe environmental conditions. Currently, some extremophiles that can tolerate very high or low temperatures, low O2 levels, or high salt concentrations are used in bioprocess engineering (BRS, 1995), although fermentation may be more desirable from an energy standpoint because

[1]Biodisks, which consist of a series of thin disks that act as a substrate for bacterial attachment and increase overall surface area for reactions catalyzed by bacteria in the effluent line, represent an alternative biology-based technology for oxidation of ammonia. The need to create, refurbish, and replace surfaces on which biologically useful reactions could occur would have to be considered in evaluating the usefulness of a technology such as biodisks.

[2]Technologies for separating gases, monitoring, and increasing process efficiency for closed-loop aquaculture systems are not widely discussed in the literature as many are proprietary.

the by-products H_2 and CH_4 have been suggested as a source of fuel for lifting a spacecraft back into orbit from Mars.

The CO_2 produced in biodegradation can also be reduced photosynthetically by higher plants and algae to produce a great variety of foods and other useful products. The quality and intensity of light sources will be factors to evaluate in considering the potential for photosynthetic reduction of CO_2; a related consideration is the need to recycle the lignin from higher plants as it accumulates as a waste by-product (Sarikaya and Ladisch, 1997a,b). Physicochemical methods for waste processing using combustion and electrolysis have been examined (Holtzapple and Little, 1989).

The substantial amount of NH_4^+ produced as a waste by-product can be recovered by alkaline distillation for use in space horticulture in planetary habitats, but the process is energy-intensive. NH_4^+ also can be recovered using ion exchange, but periodic regeneration of the exchanger is required. A space-based ammonia synthesizer that fixes nitrogen for plants or algae could be designed to use recycled NH_4^+ in closed-loop ALS systems (Hotzapple, 1989). Urea also can serve as a source of nitrogen for plant growth, and so it may be feasible to recycle nitrogen without actually recovering NH_4^+ or urea but rather by merely separating solid from liquid human waste. Other biomass can be biodegraded to furnish solids that are suitable for both support and nourishment of plants. This area of active research within NASA is mentioned here to emphasis the importance of reducing, reusing, and recycling waste stream products.

Develop Plants for Use as Food and Other Consumables

Plants will be essential for human well-being in extended space exploration,[3] and their role in closed ecological life support systems has been studied extensively by NASA. Plants can be used not only as food and as a source of useful materials and chemicals, but also for management of CO_2 and other waste materials (NRC, 1988). It appears that space horticulture will be important in establishing self-sustaining systems, and much research has been done on the growth of plants under altered gravitational conditions (see, e.g., Merkys et al., 1985; Cuellar and Mitchell, 1985; Merkys and Laurinavicius, 1991; Takahashi and Suge, 1994; Kordyum, 1997; McKeehen et al., 1996). Wheat, which seems to be the preferred plant, is currently being evaluated, but there is considerable value in cultivating a variety of other higher plants such as rice, white potatoes, sweet potatoes, soy beans, peanuts, lettuce, and sugar beets. These plants are hardy, can be genetically engineered, and provide important nutrients and a good source of valuable raw materials such as starch (Langhans and Dressen, 1988; Olson et al., 1988; Prince and Knott, 1989).

[3] Space horticulture and the role of gravity in plant responses is being examined in an NRC report forthcoming in August 1998. The report notes that it is unlikely that horticulture will be used to provide food aboard a spacecraft in the near future and that a mission must exceed 2.7 years before space horticulture would be of value. Nevertheless, the report points out that space horticulture techniques are worth developing now to prepare for long-term space endeavors in the future.

Algae and Cyanobacteria as a Source of Food and Biomaterials

Algae offer both advantages and disadvantages for use in bioregenerative life support systems (Averner et al., 1984). As do higher plants, algae can remove CO_2 from the air circulated through cultures and release O_2 into the vented air. They are also used as a source of nutritional supplements, such as beta carotene. Algae (and cyanobacteria) provide the advantage of extreme compactness, ease of handling, low waste volume, and high production efficiency for closed-loop life support. Even if they constitute only a small portion of the diet, algae might prove to be a valuable resource for biomaterials. However, the culturing of algae in large quantities may be problematic.

Algae could be grown in a spacecraft environment using light-emitting diodes (LEDs), probably the most efficient units for regenerating radiant energy. The alga *Synechococcus leopoliensis,* for example, can be grown effectively in reflective metal vessels with red LEDs as the sole light source.

Cyanobacteria are more easily cultured and genetically engineered than are eukaryotic algae or higher plants and so in the short run appear more promising for use in air recycling, wastewater treatment, and food production. However, algae and cyanobacteria cannot supply 100 percent of the human diet without a great deal of processing.

If algae and/or cyanobacteria are to be used as a source of food for astronauts, it is important to initiate research to determine desirable growth rates and nutrient requirements, ease of growth and harvesting, palatability, and nutritional value as well as to assess how cyanobacteria compare with higher plants on a practical basis. It might be fruitful to screen edible species to identify those that could be grown in the space environment. It might also be worth exploring ways to enhance the value of algae and/or cyanobacteria as food, new processing methods to either remove or degrade undesirable components, and ways to enhance the palatability of the material. Comparing the effectiveness of algal production versus plant growth for providing complete dietary support or supplementing it would require a detailed analysis of inputs (i.e., energy, materials, space requirements, waste disposal, labor requirements) and outputs (i.e., usable biomass). This represents a short-term research area.

Genetically Engineered Plants

Plants used in extended space missions will likely have to be genetically modified for specific applications. Because of the number of specific traits that may need to be altered in individual plants to adapt them to the space environment, genetic engineering rather than conventional breeding methods will probably be necessary.

Genetic engineering allows the introduction of individual genes into virtually any flowering plant using a particle gun (particle bombardment) or *Agrobacterium*-mediated gene transfer and regeneration techniques in tissue culture (Dandekar, 1995). New methods such as genetic switches and multigene transfer technology are being refined (Hennig et al., 1994; Holtore et al., 1996; Mitsuhara et al., 1996). Virtually any flowing plant can be used in the development of transgenic plants—those with new genetic information that is stably inherited

(Dandekar, 1995).[4]

Plant characteristics would have to be engineered to meet performance goals still to be defined by NASA. Traits that would seem useful in closed environments for extended missions include altered plant forms to conform to space limitations, miniature roots, resistance to radiation and disease, capability for early flowering, altered metabolic pathways, and increased yield and productivity. It might also be possible to engineer multipurpose plants that could provide complete dietary requirements for humans.

However, genetic properties have been examined and expressed only in Earth's atmosphere and not under conditions anticipated for planetary surface habitats. Therefore, techniques need to be developed and applied to determine plant gene expression and functions under the conditions of space exploration. Further research is needed to identify ideal plant species; assess the feasibility of genetic engineering to produce desired traits; evaluate the performance and stability of the trait(s) under spacecraft conditions; and test the products for taste, texture, and safety. This requires long-term research.

Plants That Provide Useful Products. Important chemical products prepared from plants include ricinolec acid from Castor (used in lubricants, plastics, coatings, and sealants), erucic acid from Crambe (used in lubricants, waxes, paints, and nylon), capric and lauric acids from Cuphea (used in soaps, detergents, and lubricants), natural rubber from Guayule (used in rubber products), wax esters from Jojoba (used in lubricants and waxes), and short and long fibers from Kenaf (used in rope and paper products). Plants ranging from *Arabidopsis thaliana* (a model plant) to maize, potato, and cotton can be modified to incorporate genes from bacteria for the synthesis of poly--hydroxybutyrate (PBH) and other biodegradable thermoplastics (Porier et al., 1995a,b; Vanderleij and Witholt, 1995; John and Keller, 1996; Hahn et al., 1997). Studies on cowpeas (*Vigna unguiculata*) and rapeseed (*Brassica nacio*) plant residues have described their nutritional value and potential use in biomaterials (Ohler et al., 1996; Kononowicz et al., 1997; Nielsen et al., 1997).

Plants might be engineered to produce biodegradable plastics or “designer” waste. For example, the waste stream might be used by microorganisms in bioreactors to yield useful products. Biological concepts also might be applied to design materials with functional groups that can be targeted by specific enzymes to promote rapid and effective degradation. Materials could be “depolymerized” into building blocks for reuse in new materials. The lignin content of plant waste biomass could be reduced to speed waste processing. Some efforts to design materials with specific functional groups is under way, especially for medical applications (Nickel et al., 1997), but little attention has been focused on solid waste management.

To apply these concepts in planetary surface habitats will require the development of new

[4]For space applications, transgenic plants might be designed as either delivery systems or biosensors (see the section below “Biosensors”). To serve as efficient delivery systems, plants might be engineered to have altered photoperiods and gravitropic responses as well as regulated synthesis of specific nutrients, biopolymers and biofuels, and products not found in plants such as animal proteins, and for management of pollutants. To serve as biosensors to detect pollutants, plants might be engineered to detect changes in life support parameters.

methods because the processes are complex and it is not known how they would be affected by the space environment. Bioprocess engineering principles and concepts (NRC, 1992) would have to be adapted to enable recovery and processing of materials of interest such as biodegradable plastics. This represents a long-term research effort.

Plants Engineered for Enhanced Productivity under Low Light. Photosynthesis requires radiant energy, especially light, for converting CO_2 into carbohydrates and ultimately food. Light as an energy sources used by plants may be supplied directly by sunlight or, in closed systems, by external arrays of photocells that capture sunlight and convert it to electricity, which then can be reconverted to radiant energy. However, the conversion of energy into light is inherently inefficient.

Much is now understood about how light affects the expression of genes that regulate plant productivity (Ang and Deng, 1994; Millar et al., 1995; Moses and Chua, 1988; Nagy et al., 1986, 1988; Chory et al., 1996; von Arnim and Deng, 1996; Arguello-Astorga and Herrera-Estrella, 1996; Mustilli and Bowler, 1997), and some plants can be engineered to grow well and be productive at low light levels.[5] Because the intensity of sunlight is reduced as distance from the sun increases, plants modified to be efficient at low light intensities will likely prove advantageous. However, direct collection and manipulation of solar radiant energy for space systems will have to be made quite mass efficient per kilowatt.[6] This represents a long-term research area.

Plant Engineering with Enhanced Disease Resistance. Use of disease-resistant plants can help to ensure a continuing capability for stable food production. There can be no absolute guarantee that seeds taken aboard a spacecraft will be pathogen-free. Plants derived from tissue culture and grown under strict greenhouse conditions are more likely to be "clean," but reinfection at low rates may occur. Much is now understood about plant genes involved in resistance to disease (Jones, 1996) and the signaling mechanisms that regulate these genes (Wilson et al., 1997), and genetic engineering for enhancing disease resistance in plants is possible. However, the types of diseases likely to occur in space horticulture must be identified so that plants resistant to specific diseases can be developed. Research is also needed to enable identification and management of the relevant disease-causing organisms (Agrios, 1997). Identifying types of specific disease-causing organisms likely to be encountered in space horticulture and development of resistant plants represents a short-term research area.

[5] Because the amount of photonic energy that must be actually converted to synthesize 1 gram of cell dry mass is fixed by the laws of thermodynamics, lower light intensity will result in lower cell mass production rates per unit volume for any plant physiology.

[6] Optimization of radiation density at a plant growing location is an innovative systems engineering activity and does not necessarily have to result in low growth rates per unit volume.

Plants Engineered for Resistance to Effects of Radiation. A recent report (NRC, 1996) summarizes current knowledge of the types and levels of radiation to which crews would be exposed in space and discusses the range of possible human health effects that need to be protected against. The report points out that, in general, plants are relatively radiation resistant when growing (with overall growth the most susceptible to effects of irradiation) and extremely resistant as dormant seeds. Although the levels of irradiation at which overall plant growth is affected are above those predicted to occur during spaceflight, it would be prudent to use the most radiation-resistant plants possible for extended spaceflight missions and for horticulture on other planets. Plants might be engineered, for example, to produce melanin for protection against ultraviolet radiation on planetary surfaces or to have DNA repair enzymes to counter the effects of other types of radiation damage. Further research is needed to define metabolic products and enzymes that might help to confer radiation resistance under simulated flight conditions, or, alternatively, to identify and transfer genes for radiation resistance from bacteria or insects to plants. This is a long-term research area.

Enhance the Versatility and Function of Habitats

Biomaterials and biologically inspired materials for use in transit vehicles and for construction of habitats on a planetary surface could help to ensure human well-being by providing capabilities ranging from self-diagnosis and self-repair of certain system components to protection of astronauts and other biological organisms from the effects of radiation. Furthermore, such materials could also help make missions to other planets possible by virtue of their being lightweight and renewable, offering opportunities to reduce transportation cost and mass.

Biology-based materials may have unusual properties such as those deriving, for example, from the crystalline structure of biopolymers, that would be useful at the extreme conditions found in space. Such materials might provide the basis for a structure that could repair itself in the event of a puncture: for example, temporary sealing might occur if ice in a cellulose structure melted, perhaps due to a micrometeorite strike, flowed to the hole made at the site of the strike, and then froze again to form a plug. Other pseudoplastic fluids that flow when set in motion could also serve such a function.

Session 1 discussions focused on identifying new biology-based materials and techniques that might enhance or improve performance characteristics for extended exploration of space—i.e., be self-repairing and self-diagnostic, require low maintenance, have dual uses, allow in situ production, and provide robustness and radiation protection—as well as promote recovery, reuse, recycle, and repair. Participants noted that the National Science Foundation has an entire thrust area of basic research in biomolecular materials, identified in 1995 as one of several areas of major opportunity in materials science (see Materials Technology Subcommittee, 1995).

Biological materials are nature's structural composites. Examples of natural composites with strong mechanical properties include sea shells, the exoskeletons of insects, silk, and lignocellulose in wood. Once scientists understand the synthesis and processing of these complex structures, they may be able to provide useful models that can aid in developing complex materials for use on a planetary surface (Askay et al., 1996; Kaplan et al., 1994).[7] Biological materials are also attractive from the standpoint of spacecraft ecology because they are biodegradable and could potentially be synthesized from CO_2, H_2O, N_2, and light on a planet's surface.

New concepts in the design of synthetic materials are offered by biomaterials such as cellulose, starch, silk, collagen, and other types of naturally occurring polymers as well as polymers made from feedstocks of biological origin.

Cellulose has high tensile strength and can be woven into fibers. Cellulose fibers can also be formed directly by green algae. Spider silk is made of proteins and is one of the strongest polymers of biological origin. It is now possible, using modern molecular methods, to develop bioengineered analogs that may perform as well as or better than their natural counterparts.

Starch has several possible applications. It can be used to produce biodegradable plastics for use as building materials, and as a hydrogen-rich compound starch can serve as a source of fuel. Because it can absorb and hold water, starch might provide a means to help control humidity, thereby reducing the cooling load on air conditioning systems. The role of starch adsorbents as possible desiccants[8] was recently reviewed (Ladisch, 1997).

Despite an abundance of knowledge on materials made from cellulose, starch, and other biomaterials as well as significant ongoing research in this area by the U.S. Department of Agriculture and the bio-based industrial products industry, is not known if current materials would be suitable for use in a transit vehicle or planetary surface habitat. Both starch and cellulose, for example, are highly susceptible to microbial degradation, and use of these materials would have to be coupled to technology to prevent such degradation. This applies to all of the “biotechnologies” discussed at the workshop.

New biopolymers are being produced in which “two-sided” materials exhibit different chemical and physical characteristics or specific reactive molecules (e.g., biocides, biosensors). These materials can be formed either as thin films or membranes with selective permeability, or as more structurally rigid compounds. Development of such biopolymers has a potential for near-term results. There is also the potential for producing biopolymers that have unique “self-repairing” attributes. An example cited above, is substances that would become semiliquid at higher temperatures and return to a rigid state upon cooling. Materials might be manufactured

[7]For example, advanced biological composites might be designed by engineering receptors on the surfaces of cells that synthesize biopolymers and monomers. Lattices of cells synthesizing in a composite of silk and cellulose may be a realistic concept.

[8]The maximum amount of water adsorbed by starch (water vapor with respect to solid adsorbent) is likely to be between 10 and 20 percent by weight (Lee et al., 1991). Because microbial growth could be initiated when the moisture level reaches 14 percent by weight (Hoseney, 1986), it might be necessary to reduce the water activity in such gels using, for example, sucrose or fructose (high sugar content reduces the availability of water to microorganisms, thereby serving as a preservative). However, the concentration of the sugars would likely need to be above 20 to 30 percent (wt./vol.) to achieve this effect. The testing of absorbent formulations that include monosaccharides is in the early stages and could be a potential area of short-term research. The issue of microbial growth on biomaterials for space applications needs to be examined.

that would change characteristics (such as color) when punctured or otherwise damaged. This research is probably long term.

Plastic polymers composed of polyhydroxybutyrate and many variants on this structure are potentially important materials for use in recyclable and degradable composites. These polymers are synthesized in high volumes by certain bacteria and can be recycled or degraded with enzymes or other bacteria. The genes for synthesis of the polymer have been cloned and expressed in plants (see the section above “Plants That Provide Useful Products”). Thus, these biopolymers could be a source of versatile, useful materials with important thermoplastic, adhesive, or fiber-forming properties. Such materials might also be recycled directly into new items for use within a planetary surface habitat.

Many adhesives are being manufactured from biological materials that offer less toxic alternatives to petrochemical-based adhesives. These materials are naturally more amenable to biodegradation and might even be engineered to be degradable by specific organisms, although as mentioned above, biodegradability has both positive and negative aspects. However, biomaterials, which succeed over synthetics specifically because they are renewed constantly, often at high rates, either must be biosynthesized in place in the form required or require postprocessing, which is likely to be labor, space, and energy intensive. These trade-offs need to be examined before specific biomaterials are used in space applications.

A focused workshop could examine the attributes of biomaterials and biologically inspired materials applicable to use in spacecraft and planetary habitats—ranging from self-diagnosis and self-repair of certain system components to protection of astronauts and other biological organisms from the effects of radiation—and associated trade-offs in labor, space, and energy.

Facilitate Detection of Pollutants and Pathogens, and Monitor Health Status

Maintaining human health and well-being during extended space exploration will require lightweight and durable monitoring systems to ensure that air and water do not contain disease-causing pathogens or discomfort-causing levels of pollutants. Ways will also be needed to monitor the physiological and genetic state of microorganisms serving useful functions on spacecraft and in planetary habitats, such as microorganisms grown to produce end products such as organic acids and alcohols for use as a potential power source (Wagar, 1996). Biosensors and rapid molecular methods for detection and monitoring represent promising approaches.

Biosensors

Technology exists now to engineer plant leaf surfaces and roots so that they can respond to external stimuli such as pollutants in air or water (see, e.g., Dennison and Turner, 1995; Wang and Rechnitz, 1993; Wijesuriya and Rechnitz, 1993).

Another novel approach to developing sensitive detectors involves genes from jellyfish that encode for a green fluorescent protein (GFP). The protein fluoresces with a green light emission (510 nm) when excited with blue light (480 nm). Plants might be engineered to contain GFP whose fluorescence in response to the presence of pollutants could be detected by blue-light LEDs and a camera. Work would be needed to define the regulatory mechanisms for response to pollutants as well as to determine whether such a response by plants could be quantified.

Many different readout display systems (e.g., fluorescence, electrical, pH) are being developed for biosensors. In principle, each can be used for many different sensing functions. Standardizing one or two such readout systems as a “platform technology” could facilitate the incorporation of biosensors into space missions.

Biosensors must be small and capable of detecting agents of interest. Research is needed to prioritize the targets of detection—particular microorganisms and pollutants that may adversely affect human health, plants, and other microorganisms—in transit vehicles and planetary surface habitats and to establish data-based sensitivity requirements relevant to NASA's needs. Research on biosensors could bear fruit in the short term. A workshop could be held to (1) establish requirements for sensors and (2) examine the application of existing or emerging biosensors to monitor for microorganisms and pollutants in air and water on transit vehicles and planetary surface habitats.

Molecular Detection Methods

Laboratory culture methods currently used to screen air and water for microorganisms are primitive, bulky, and unreliable. Only a relatively small percentage of microorganisms have been cultured from various environments and studied to determine their nutritional requirements, physiologies, and strategies for adapting to stressful conditions. Thus, special methods will be necessary to detect and identify them.

Molecular methods such as rRNA sequencing, DNA probes, and chromosome painting (i.e., hybridization with whole-chromosome DNA probes with fluorescent stains) are available for in situ detection and characterization of individual microbial cells without cultivation (Amann et al., 1995; Matheson et al., 1997; Giovannoni et al., 1996a,b,c; Lanoil and Giovannoni, 1997; Suzuki et al., 1997).[9] The National Institute of Standards and Technology's Advanced Technology Program funds a program to develop automated and miniaturized DNA diagnostic tools[10] Research is needed to simplify molecular methods for use on planetary surfaces or transit vehicles and to adapt such methods for use in detecting organisms in air and water; the latter task includes the development of reference libraries for organisms of concern.

[9]Gene probes, for example, are widely used by microbiologists to profile microbial communities and identify specific microorganisms (Henson and French, 1993; Reeves, 1995; Giovannoni et al., 1996a,b,c; Randles et al., 1996; Schoad et al., 1997). These molecular methods could be used to detect and better characterize the types of organisms in transit vehicles and planetary surface habitats and to identify and monitor those that could threaten human well-being. Molecular methods might also prove useful in analysis of planetary samples to detect extraterrestrial microorganisms.

[10]See, e.g., Advanced Technology Program, 1997, Tools for DNA diagnostics, ATP Focused Program Competition 98-08, National Institute of Standards and Technology, Gaithersburg, Md.

Assays for indicator molecules could also be used in monitoring. Assays for endotoxin are widely used to detect gram-negative bacteria (see, e.g., Milton et al., 1992). Other indicators of the presence of bacteria include peptidoglycan and mycolic acids. Ergosterol and 1,3 diglucans (Saraf et al., 1997) are being used in assays to detect fungal biomass. Research is needed to simplify the methods applied in bioassays, and antibody libraries must be developed for microorganisms of concern in air, on surfaces, and in water aboard transit vehicles and in planetary surface habitats.

Fluorescent antibody techniques are also widely used in microbiology to identify specific organisms in soil, plants, and animals, and enzyme-linked immunosorbent assays (ELISA) are used (see, e.g., Chapman et al., 1987) to quantify antigens and allergens in water, air, and dust. Dipstick methods are under development for specific organisms and antigens. Because crew members could become susceptible to allergies or hypersensitivity diseases such as asthma, research is needed on potential sources of sensitivity, and antibody reference libraries need to be developed for organisms of concern. In addition, some enzymes are well recognized as agents of hypersensitivity (Dolovich and Little, 1972), and their use on transit vehicles and in enclosed planetary habitats must be considered carefully. Outbreaks of hypersensitivity pneumonitis related to *Bacillus subtilis* enzymes used in some laundry detergents have been described (Johnson et al., 1980).

Analytical methods based on gas chromatography, mass spectroscopy, and fatty acid analysis with flow cytometry are currently used to identify and count microorganisms in water samples and to detect and differentiate microorganisms in environmental samples. Their relevance and application for use in transit vehicles and planetary surface habitats need to be assessed.

Rapid methods for tracking the genetic and physiological state of microorganisms could include DNA arrays (see, e.g., Chee et al., 1996) or chips designed to detect mutations and profiling of metabolic products and components using matrix-assisted laser desorption ionization mass spectrometry (MALDI) techniques. MALDI has been used to profile the organic constituents of water samples and to detect biopolymers such as peptides, proteins, oligosaccharides, and oligonucleotides in mixtures and crude samples (Duncan et al., 1993; Kaufmann, 1995; Zhang and Caprioli, 1996). In-line gas chromatography and mass spectrometry or high-pressure liquid chromatography and mass spectrometry based on technology currently available from commercial sources is used to profile metabolites (Larsson and Saraf, 1997).

However, many of these techniques and methods currently require bulky equipment such as fluorescent microscopes, flow cytometers, robotic polymerase chain reaction (PCR), and sequencers that are not easily adapted to the space environment. Further research is needed to develop mini-robotic systems for molecular analyses, and instruments would have to be developed, refined, and miniaturized for the sampling scenarios anticipated in spacecraft or planetary habitats. Additional work will be needed to validate the usefulness of methods and instruments for analyzing the results of air sampling and to develop reference libraries.

The risk of contracting water- and airborne diseases on long-duration space missions also needs to be assessed. If the risk is significant, then biomarkers (indicators of exposure to harmful conditions or substances or evidence of a disease process measured within an individual, e.g., specific antibodies produced in response to exposure to allergens) could be developed to enable early detection of disease and could perhaps be linked to environmental monitoring systems that could in turn be adjusted to control exposure. Potential applications of biosensors for use in protecting and monitoring the health of astronauts and useful biological organisms could be the subject of a follow-on workshop.

Control Growth of Potentially Harmful Organisms

Wiping down bulkheads and surfaces to remove water condensate is a time-consuming but necessary task to minimize the growth of organisms. However, use of wipes containing biocides for cleaning and microbial control needs to be reevaluated. Microorganisms can adapt[11] to the biocides used, and overuse of biocides can result in the replacement of the normal flora on surface with resistant forms, thereby rendering biocides ineffective. Current plans to use wipes containing biocides may result in unhealthy conditions as well as excessive requests for supplies.

Cleaning formulations emerging for industrial use are incorporating enzymatic rather than chemical catalysts (Gross et al., 1998). Enzymatic catalysts[12] are lightweight, specific, and biodegradable, making them highly suitable for spaceflight. To exploit this technology NASA might generate a list of housekeeping requirements and constraints and circulate it to appropriate industries for solutions. This can be accomplished in the short term.

Research on enzymatic removal or reduction of biofilms could be based on technology currently used in industry. An advantage of enzymes is that they can be designed to specifically target compounds that cause microorganisms to adhere to surfaces. They can also be stored in dry form for long periods and are a natural protein that is recyclable as carbon and nitrogen. Research to examine the utility and feasibility of substituting enzyme catalysis for the use of biocides in cleaning bulkheads and surfaces would represent a short-term effort. However, research must also address the potential health hazards of enzymes (see the above section, “Molecular Methods”).

Session 1 participants also emphasized that preventing condensate from forming on bulkheads and maintaining ambient humidity at prudent levels would effectively limit the growth of organisms on bulkheads. Thus, humidity control, not the use of biocides, is the cornerstone of prevention. Another approach might be to use layers of absorbent and hydrogen-rich biomaterials such as cellulose on bulkheads to absorb water and at the same time provide a measure of radiation protection. Research is needed to design and evaluate such an approach and to prevent microbial (fungal) growth on wet cellulosic surfaces. This work can be done in the short term.

[11]A well-known example is bacterial resistance to antibiotics (Tixador et al., 1994; Jorgensen et al., 1997).

[12]Examples include proteases and lipases for cleaning, ureases and cellulase for waste treatment, and possibly advanced enzymatic systems for use in fuel cells.

Enhance Protection Against Exposure to Radiation

Radiation hazards to crews of interplanetary missions have been described (NRC, 1996) and so were not reviewed in session 1. Participants pointed out the need for improved knowledge of the effects of radiation on plants and microorganisms that may be used aboard spacecraft (e.g., in ALS systems) or in habitats on a planet's surface. Although shielding is one method of protecting against exposure to radiation, biology-based approaches might also help to enhance resistance or tolerance.

Plants and microorganisms that demonstrate radiation resistance might be studied and mechanisms of resistance characterized. Little is known about the resistance of microorganisms in environments subject to natural sources of radiation, such as sulfide structures associated with hydrothermal vents. The most radiation resistant microorganisms documented in the literature are mesophilic and thermophilic *Deinococcus* species. Radiation resistance in *Deinococcus* is due to a very efficient repair system for double-strand breaks in the DNA (Minton, 1994) and appears to be incidental to the efficient physiological adaptation to desiccation (Mattimore and Battista, 1996). *Pyrococcus furiosis,* a hyperthermophile that is highly resistant to ionizing radiation, apparently exhibits very active DNA repair (Diruggiero et al., 1997). Similarly, there are few data on the radiation resistance of cells in the dormant stage, although there is evidence for increased radiation resistance in halobacteria during starvation (Whitelam and Good, 1986).

To enhance radiation resistance, bacterial or algal genes for DNA repair enzymes potentially could be transferred to plants (Friedberg et al., 1995). For example, expression of DNA glycosylase-apyrimidine lyase enzyme, encoded by the Chlorolla virus PBCV-1 in transgenic tobacco callus tissue provides significant resistance to ultraviolet radiation (D. Higgins, J. Van Ether, and A. Mitra, January 1998, personal communication).

Because it may be impossible to totally protect all biological systems from radiation damage on transit vehicles or planetary surface habitats, it may be necessary to provide a safe shelter for a “biological archive” (e.g., microorganisms used in ALS systems or seeds for horticulture) that could be used to reconstruct a biological system damaged by radiation and thus reestablish communities of needed biological organisms.

Current techniques in biodosimetry for humans exposed to radiation include analysis of tooth enamel, T-lymphocytes, and interphase chromosomes (Haskell et al., 1997; Bauchinger, 1997; Durante et al., 1997; Yang et al., 1997). When the criteria for acceptable levels of irradiation are established, it may be possible to develop a biological dosimeter through the use of specific microorganisms or designed DNA that could be integrated on biochips. Using biological dosimeters to monitor exposure to radiation, and developing biosensors in the skin of planetary habitats that could alert the crew to both radiation levels and/or level of radiation-induced damage, could be addressed as part of the follow-on workshop on biosensors suggested above in this chapter. The research on mechanisms of DNA repair is long term.

SUMMARY

Session 1 participants identified three topics that may warrant further examination in follow-on workshops. A workshop on current technologies in closed-loop aquaculture and innovative fermentation processes used in waste treatment might assist in the development of highly efficient closed-loop regenerative ALS systems to supply water and manage waste during extended space missions. A second workshop could explore the use of biomaterials, biomolecular materials, and biologically inspired structures for transit vehicles and planetary surface habitats. A third workshop could examine the application of existing or emerging biosensors to monitor for harmful microorganisms and pollutants in air and water on spacecraft, monitor the health status of astronauts and useful biological organisms, and help minimize exposure to radiation.

Research areas offering short-term payoffs include identification and management of disease-causing organisms likely to occur in space horticulture, cultivation of algae as a source of materials and food, and the use of enzymatic catalysts for housekeeping to control the growth of microorganisms on transit vehicles and in planetary surface habitats. Research areas offering long-term payoffs include the genetic engineering of plants to meet defined performance goals for spaceflight and biotechnologies to enhance radiation protection and monitoring.

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3

Enhancing Human Presence and Function in Space Exploration

STUDY APPROACH

To identify areas where the use of biology-based technology might enhance human function in space exploration, session 2 participants developed a generalized framework outlining how biological concepts and principles relate to various types of functions (see Figure 3.1). The framework provides a structured way of analyzing how biological systems and concepts (the left-hand column) can be integrated into advanced technology (the middle column) to provide a range of specific functions (the right-hand column). In examining the list of biological concepts, mechanisms, and methods of analyzing or modeling biological systems, one can envision how they might be applied to perform different functions. Metabolism is a method for storing and using energy, neurophysiology enables human adaptation to different environments and provides mechanisms for modifying that adaptation, modeling of insect behavior reveals different methods for exploring unknown terrain, and so on. The middle column provides examples of technologies that can implement some biological functions. For instance, very large scale integration (VLSI) and micro-electromechanical systems (MEMS) can integrate multiple functions into large-scale computing and actuation platforms. One such platform is an artificial retina, which can limit the resolution of pixels away from the center of the field of view and perform computations using the incoming data to reduce bandwidth requirements. MEMS-based microrobots have been proposed that can float on a breeze and use integrated power, computing, and actuation to explore unknown terrain. The right-hand column indicates some of the applications of biologically inspired technology. For example, an insect antenna could be used as a model for a biosensor system in which living cells are grown on silicon chips for the purpose of sensing radiation, toxins, or other molecules. Or, the ability to access long-term memory could serve as a computational model for a robot assistant that can suggest modifications to experiments based on previous experience.

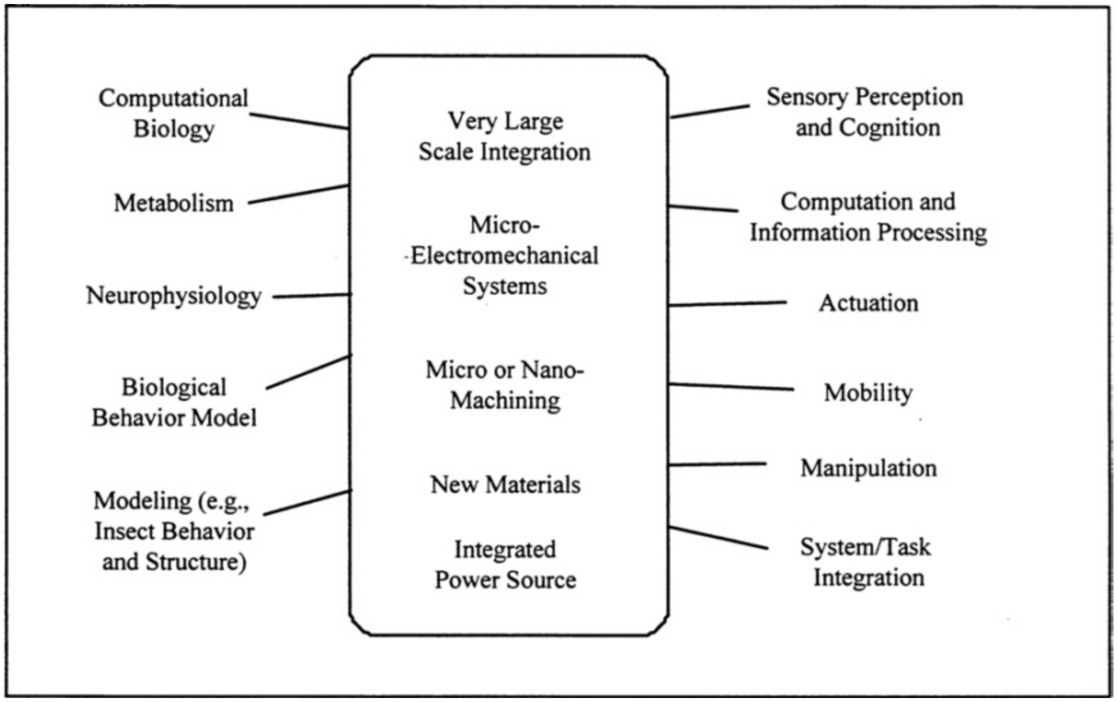

FIGURE 3.1 Generalized framework outlining how biological concepts and principles relate to various types of functions.

Session 2 participants used this framework as the basis for a systems approach to identifying how specific biological activities might be exploited in practical ways to enhance human function in space. Relying on input from NASA, the group identified and inferred some of the functions of astronauts that need to be enhanced. Possible biological approaches to meeting those needs were then explored. The proposed solutions emphasized biological principles and analogies as opposed to living or bioengineered systems.

The analysis is limited in detail because NASA described its requirements only in broad terms. Session participants attempted to elicit additional details from workshop presenters but still had to make some assumptions about practical needs. Thus, the suggestions provided in this chapter need to be examined further by NASA in the context of defined requirements.

A number of general themes were discussed that influenced the analysis of needs and possible solutions. First, functional requirements for space systems differ from those for systems on Earth in a number of ways. Limitations on size and weight are more severe in the space environment, redundancies are needed to prevent system failures on the first error, and higher costs are tolerated in space systems for equivalent benefits. Second, similarities between deep space and the deep ocean—both are extreme environments far removed from home bases—suggest a potential for transferring diving technologies and concepts to the space program. Third, biological principles suggest the merit of processes that are inherently simple and evolutionary, as opposed to complex and excessively mechanical.

Fourth, there is a need to balance the tasks assigned to machines versus those assigned to humans. For example, machines could perform routine functions and notify the astronaut only if problems arise or decisions need to be made. The space shuttle is fully automated for ascent and landing except for lowering the landing gear. However, 15,000 keystrokes are needed on board for a 10-day mission. Some of these operations might be automated, so as to free astronauts to perform critical mission tasks. Yet some astronauts prefer to be more involved in operations. There is also a possibility that automation can go too far. One leading manufacturer, Toyota, has been reducing automation levels in recent years, having found that properly designed factories using simple, robust processes can enable humans to work very fast.

FUNCTIONAL NEEDS

Before humans can visit and live on Mars, the functional capabilities of astronauts need to be radically improved and enhanced, beyond even the technologically enhanced capabilities of humans on Earth. In addition, it would be helpful to compensate for the loss of function normally experienced as a result of the constraints of the space environment and equipment. The enhancements are needed in both human presence (i.e., sensory and information processing capabilities) and human functions (i.e., manipulation and locomotion capabilities).

For discussion purposes, the functions of astronauts that need to be enhanced were organized into the following categories: perception, manipulation and locomotion, cognition, and systems and computation. These problems and needs dictated the types of promising biology-based research identified by session 2 participants.

Perception

Astronauts sometimes experience perceptual difficulties. Spatial orientation in microgravity is a particular problem, especially during extravehicular activity (EVA) when there are no gravitational reference points; familiar cues, such as artificial horizons, are needed. Problems have also been reported with hand-eye coordination during long flights and blurriness of the visual field when exiting and reentering 1 G. Problems with depth perception were reported on the Russian space station MIR. Astronauts also may experience difficulties with proprioception (i.e., knowledge of where limbs are) and motor-sensory coordination.

Manipulation and Locomotion

Posture, locomotion, and balance parameters change when gravity is absent. In microgravity, muscles are loaded and used differently. Muscle mass and cardiovascular capability are lost, and so special exercises are crucial (Desplanches, 1997). Bone can be lost during long missions and may not fully regenerate. Because manipulation is difficult in space, small, lightweight tools that are easy to handle are needed, along with special posture strategies.

Particular problems are reported with constrained motion in spacesuits, which are pressurized at 4 to 5 pounds per square inch. Fatigue is also common during EVA.

Cognition

The word "cognition" is often used in computer science-related fields to denote the level of activities that require "understanding" of what is going on, rather than merely signal-level reaction. The primary orientation problem is adaption to microgravity and then readaptation to 1 G when returning to Earth. Symptoms include motion sickness, loss of coordination, and impaired ability to work. There is some concern that astronauts may not function well upon arrival at Mars. Readaptation to 1 G is the more difficult problem. After a shuttle mission, the readaptation period is 4 to 8 days; this time period is proportional to the period of weightlessness and can last just as long. There is a "fragile" period of adaptation when an astronaut can fluctuate between the microgravity and 1-G states.

Systems and Computation for Mission Planning and Execution

Systems are defined here as encompassing both human and technological elements. System and computation problems are reported with software reliability, control of collective behavior, and human factors, for example. The session participants focused on the mission planning and problem-solving aspects of these problems rather than psychosocial issues and human factors.

POTENTIAL BIOLOGY-BASED RESEARCH OPPORTUNITIES

Improve Space Suit Design

Life support, rather than function and comfort, has been the driver of traditional space suit design. Not surprisingly, difficulties have been reported with fatigue during EVAs and the performance of certain tasks, from mission-related activities to simply scratching an itch. Current-generation space suits need to be redesigned in any case, because they are too heavy for use on Mars and their multilayer insulation would lose most of its effectiveness in the martian atmosphere. As part of the redesign effort, biological concepts could be introduced into space suit design to enhance astronaut function and comfort and provide reliable, mobile, dexterous, comfortable, and easily maintained protection.

Humans are extremely flexible, dexterous, and coordinated, but they have limited manipulation and locomotion capabilities when in a space suit, especially when working at extremely small dimensions. Biomechanical concepts could be integrated into suit design to improve task performance. For example, the human wrist has the greatest finger dexterity and hand grip when positioned at a 40-degree angle (see Box 3.1). Current-generation suits do not maintain the wrist at that angle. A suit might be designed to have two wrist settings, one for resting and one for tasks requiring dexterity or grip.

Current suits are passive, in that they do not assist with movement. With an active compliance control approach, it should be possible to design a suit that could support the astronaut's activities. The suits could be designed to be active through the use of a wide range of actuators combined with MEMS technology for sensing intended motions, a capability that has advanced considerably in recent years (Epstein and Senturia, 1997). Actuators are already used in prosthetic devices to provide guidance. The suit could also be designed to diagnose and repair its own malfunctions.

External sensors could be incorporated into a suit to produce haptic and other sensory feedback to the astronaut. For example, electrical stimulation with stochastic (random) frequency could be used to improve the astronaut's sense of touch. Another possibility is to use low-amplitude muscle vibrators in which the frequency is modulated stochastically. Sensors could be part of a “smart glove” system. An information filter would be needed to ensure that the astronaut is not overloaded with irrelevant sensory data.

BOX 3.1 HUMAN BIOMECHANICS AND SPACE SUIT DESIGN

Human biomechanics is complex and needs to be considered in the development of human-machine interfaces such as in space suit design. A simple example is the production of maximum finger grip. The muscle tendons that cause the fingers to flex run from muscles in the forearm across multiple joints, including the wrist, to end on the bones of the fingers. The ability of the muscle to generate force is very dependent on the length of the muscle. Different positions of the wrist influence the length of the muscle and the amount of force that can be generated. If the wrist is palmar-flexed, then the muscle is shortened and cannot generate as much force. The optimal wrist position for maximal finger grip is approximately 40 degrees of wrist dorsiflexion. If a space suit glove constrains the wrist position to some other degree of flexion, muscle force will not be optimal, resulting in reduced dexterity and increased fatigue. Similar considerations extend to almost every movement because nearly every muscle and tendon extends over multiple joints.

Human joints are complicated, unlike simple hinge mechanical joints. The axis of rotation is not stationary but may move in a complicated pattern. Therefore, space suits and tools need to be developed to allow additional physiological movement of the limbs for maximal efficiency. Again, the wrist is a good example. As the wrist bends, the actual length of the arm and hand lengthens or shortens because the wrist glides forward or backward. This changes the mechanical lever for movements and therefore could influence performance. Although this may not be an issue in the normal Earth environment, the highly demanding environment of space and Mars may exact a severe penalty if human motor performance is constrained to a level that is not physiologically optimal.

It may be possible to exploit the complexities of human biomechanics. The increased complexity of human movement enables the control of greater degrees of freedom, which can be translated into expanded dimensions of information or process control. Thus, tapping into the greater complexities of human movement could increase the amount and complexity of information communicated across the human-machine interface.

A suit might also be designed to provide spatial orientation cues in microgravity. Research aimed at providing these cues through galvanic stimulation (electrical or magnetic) has been under way for many years. Some success has been achieved with vestibular prostheses, such as the “Cuban boot,” in which an expandable bladder applies pressure to the bottom of the foot, and the “Pensacola vest,” in which vibrators are embedded to provide cues as orientation changes. Visual cues can also help with spatial orientation (Kornilova, 1997). (See section below on visual input/output.) Materials are an essential issue in space suit design. Biological materials that could provide useful concepts for space suits include the exoskeletal structures of insects, which are quite dexterous, and sharkskin, which has a cross-hatched fiber orientation that provides both flexibility and structural integrity (Wainright et al., 1978). There are many examples of cross-spiral-wrapped biological structures with well-studied and highly desirable properties such as axial bending (e.g., endomysial connective tissue, worm bodies, giraffe fascia). Cross-hatched material might be used in a lightweight “space leotard” similar to a skin-diving wetsuit. The leotard would counter pressure with elasticity but be transparent to sweat. It could be combined with a helmet and worn under loose coveralls, with bladders in body cavities.

Improved space suit technology could be the topic of a follow-on workshop. This research is short term and could bear fruit within 5 to 10 years.

Maintain and Improve Physical State

A fully effective exercise regimen has yet to be designed for maintaining or restoring the cardiovascular and musculoskeletal function of astronauts (Convertino, 1996; Desplanches, 1997). Biological principles might be applied to exercise concepts to help maintain the astronaut's physical state, including muscle and cardiovascular strength and hand-eye coordination.[1]

The exercise concept mimics a form of resistance training. Gymnastics has been deemphasized by NASA recently in favor of mechanical exercise devices, but some of the best exercise for astronauts involves jumping across the spacecraft and doing flip turns (as is often done in lap swimming) off the walls, because launching off the wall provides some 1 G-like acceleration. The biologically inspired twist on this idea involves having the astronaut exercise in a large sac (emulating an embryonic sac) or “bungee suit” with elastic properties. It might also be useful to design a “microgravity gymnasium” where astronauts could participate in gymnastics. The embryonic sac analog and the microgravity gymnasium might prove to be more effective than, or a valuable supplement to, the current generation of NASA exercise machines (primarily the treadmill). The bungee bag could also be used for sleeping and storage. The exercise regimen could be combined with virtual reality and computer games using joysticks of different sizes and configuration to maintain hand-eye coordination. Appropriate integration of tasks may serve to make exercise more enjoyable.

These projects could be informed by the recent development of rehabilitation strategies for persons with long-standing motor disorders or whose muscles have undergone a prolonged period of disuse. This work demonstrates the importance of the pragmatic (i.e., function-

[1]Basic biological research might also be helpful. Controlled studies of natural and engineered tissues (e.g., using bioreactors under the conditions of simulated and actual microgravity) could help scientists understand the effects of spaceflight on human tissues and develop and test potential countermeasures (e.g., drugs).

oriented) approach, describes attempts at using virtual reality in motor rehabilitation, and details adaptive changes within the central nervous system (Davis and Burton, 1991; Latash and Anson, 1996).

The possibility of the existence of direct human sensing under local conditions for medical diagnosis is being investigated at major medical centers, including the University of Virginia, University of Colorado, Columbia University, Duke University (Meredith, 1997), and Harvard University (Roush, 1997). The Office of Alternative Medicine at the National Institutes of Health has awarded several grants to investigate these abilities in controlled studies. Given the limited medical resources that will be available in long-term spaceflight or colonization, and the remoteness of the astronauts from medical facilities, NASA could monitor research on alternative medicine approaches to see if they can be applied in a space medicine context.

The exercise research projects are short term.

Enhance Adaptation to New Environments

NASA has experimented with various methods (e.g., biofeedback) for accelerating astronaut adaptation to microgravity and 1-G environments but has yet to find an optimal solution. A biologically inspired approach to accelerating the adaptation period might be found in understanding and manipulating the fragile state of transition between microgravity and 1 G. It might be possible to influence adaptation through pharmacological approaches that increase the plasticity of the brain.

There is evidence from both everyday life and biomedical research that points to an inherent biological capability for “dual adaptation” (Welch et al., 1993). These observations suggest that humans can adapt to a dual-mode existence. Examples include the common experience with wearing glasses: It takes a while to see comfortably out of a new pair, but, once the body's systems adapt, the eyes can automatically focus with or without the glasses (the experience with bifocals is similar). Another example is task-specific dystonia, in which a person experiences hand cramps, for example, when performing certain tasks but not others. In other words, the biological response differs from mode to mode (Koller, 1989; Byl et al., 1996).

Researchers have found evidence of a dual-mode capability in the brain (Merzenich and Jenkins, 1996). It may be possible for the brain to operate in multiple modes with the ability to switch from one to the other. This capacity could be explored so as to train the nervous system to operate in two modes: one appropriate to microgravity and the other to 1-G environments. The subject would then be able to switch rapidly from one mode to the other.

There is evidence to suggest multiple representations in the brain; an example is the Necker Cube illusion. The question is whether a particular face of the cube is in front or in back. In fact, the perception of one orientation can alternate with perception of the other. Another example is the illusion of two faces facing each other. Again, the illusion can be perceived as one or the other but not both, and the perception can alternate.

There is another example that is the result of training (Martin et al., 1996). Individuals were trained to throw darts while wearing a pair of eyeglass prisms. These prisms shifted the visual world in one direction. At first, the subject would err in throwing the darts to the side of the target in the direction in which the image was shifted. The subject then learned to compensate and consistently reach the target. When the subject took the glasses off, the subject would err in the opposite direction. However, when the subject used the other hand to throw the dart, the subject was accurate. Thus, training to adapt to the novel environment affected the use of one arm but not the other. Also, the subject could instantly use the untrained arm in the usual environment while the trained arm would err. Thus, there were two states: one capable of functioning in the normal visual environment and the second adapted to the novel environment. These two states also coexisted.

Extensive research is under way on how information is remembered at the cellular and molecular levels. Adaption to the space environment or readaption to the Earth environment may represent a form of learning. Neuroscience has discovered a great deal about the biochemical basis of learning, thus leading to the possibility of using medications to affect learning and, hence, adaption. In the future, medication may help to shorten the time needed for readaption.

Already there are examples indicating that the combination of pharmacological agents and physical training can facilitate motor learning (Walker-Gatson et al., 1995). Although current studies used amphetamine-like compounds, it is highly likely that other safer and more effective compounds can be developed.

A specific group of receptors have been identified as involved in learning. They are known as N-methyl-D-aspartate or NMDA receptors (Blanchet et al., 1997). Research indicates that activation of these receptors combined with electrophysiological activity (as could accompany training) can lead to changes in nerve cell structure and function consistent with learning (McNaughton et al., 1994).

These developments are part of the rapid increase in understanding of the central nervous system and its plasticity. A combination of pharmacological intervention and appropriate training and exercise might effectively prepare astronauts for dual adaptation. It might also be possible to target specific functions and thus counteract some of the more critical adaptability problems.

This is a long-term research project. However, rapid advances in understanding of the biological basis of learning and adaptation may enable relevant results to be achieved in the near term (5 years).

Enhance Visual Input/Output

Visual capabilities play an important role in the human exploration of space, not only in documenting the environment but also in maintaining spatial orientation. Human vision has a number of limitations, including poor three-dimensional measurement capabilities. Technological systems offer opportunities for enhancing human vision and providing remote telepresence (e.g., over-the-horizon sight). However, artificial sensing devices currently tend to be bulky, primitive, and in most cases far less sensitive, precise, or adaptive than their human or biological counterparts. Biological models and concepts might be applied to enhance sensing capabilities or even provide new sensory modalities (e.g., nonvisible or nonaudible domains, or over-the-horizon vision). Biological principles could also be applied to enhance astronauts' ability to maintain spatial orientation in microgravity.

Visual technologies are under active investigation in many sectors, including military research laboratories, the medical community, the entertainment industry, and academia.[2] Considerable hardware exists, but the state of the art needs to be improved. Furthermore, it is not clear which types of visual devices would be most useful to NASA, or what information would have to be displayed.

Current-generation head-mounted displays are bulky and typically offer a restricted (e.g., 90-degree) field of view. Common complaints about heads-up displays in aviation include data overload and too much nongeographical (i.e., text) information. Attempts to increase display resolution result in bandwidth limitations. Another approach to implementing head-mounted displays involves writing directly on the retina with a laser (Tidwell et al., 1995).

Extensive research is under way to design an artificial retina consisting of a sensor and processor on a single chip; the challenge is to reduce data and bandwidth needs and increase dynamic range. The artificial retina is an example of computational sensors, which combine computation and sensing to increase performance and capabilities over those enabled by standard sensing and computing modalities.[3] These sensors integrate VLSI elements, either analog or digital, directly with sensing elements or nearby in a tightly coupled, on-chip manner, or use geometry or material properties to achieve computational gains. Computation is typically performed as a local operation with a distributed model of the sensory data, which, for example, can take advantage of the parallel nature of computing with a two-dimensional image plane (Kanade and Bajcsy, 1993). Efforts are being made to miniaturize head-mounted displays and to design augmented, hybrid reality systems consisting of image overlays (Azuma, 1997). The idea is to replace the goggles with a camera and project the camera's field of view onto the eye. Such a system might help an astronaut see, with the help of exploratory robots or other sensing systems, a projection of what lies over the next hill. Another possible solution is a programmable lens device, a biology-based analog to the flexible cornea, which focuses by changing shape. A programmable lens could, for example, improve vision in poor lighting by picking out and enhancing important features. A similar system currently being worked on involves binary optics, where lenses are built up directly on the chip using standard VLSI and ultra-large-scale-integration techniques (Stern, 1996). Both of these technologies would be very important for decreasing system size and mass and increasing performance for use in space systems.

Many years ago, a device was invented that projects visual images from a helmet-mounted camera onto a person's back or abdomen, using a vibrating-pin matrix similar to a

[2]Some of the current activity in this area is described on the World Wide Web site of Carnegie Mellon University's computer vision home page (http://www.cs.cmu.edu/afs/cs/project/cil/www/vision.html).

[3]One of the most important aspects of biological sensors is their heavy reliance on efferent systems (e.g., oculomotor steering, outer hair cell motility in the cochlea, fusimotor control of muscle spindles) that are much more sophisticated than the usual low-level functions of electronic sensors. Many of these functions could be incorporated into existing electromechanical technology once their principles of operation are understood.

Braille reader. This device was used with blind subjects, who gained the ability to read and, once they had acquired video-to-hand coordination, to manipulate objects (Bach-y-Rita et al., 1969). Such an instrument might be implemented in an elegant fashion using modern technology. An astronaut with normal vision might gain some additional capabilities, especially if the camera could sense, for example, infrared or ultraviolet light. Like other artificial sensing systems, this technology would need to be vastly improved to achieve its theoretical potential.

Another important aspect of vision is its role in maintaining spatial orientation (Matin and Fox, 1989; Matin and Li, 1995). Living things respond to primeval visual stimuli. Pilots can attest to the importance of having a visual horizon; indeed, the need for this cue is so significant that birds have horizon-detector ganglion cells in their retinas (Maturana and Frenk, 1963). A visual horizon might be created on the interior of the transit vehicle, with different colors visible above and below a clearly demarcated line. Astronauts would become accustomed to seeing this visual cue in a spacecraft on the ground and would develop an internal reference system. For further realism, the lighting could mimic the typical human experience, in which light enters the retina from above. “Uplighting,” by contrast, appears unusual, even sinister. Accordingly, the upper horizon within the spacecraft could be illuminated with white light, and the lower horizon with blue light, as it appears to a person diving in the sea.

All these research efforts would achieve results in the short term.

Develop Synergistic Human-Robot Systems

Robots perform many useful functions in space exploration. Their role may be most obvious on unmanned missions, when they serve as human surrogates, but robots can also enhance the presence and function of astronauts by providing various types of assistance.

BOX 3.2 COLLABORATIVE MULTIROBOT SYSTEMS

Collaborative multirobot systems draw on the concept of large numbers of agents performing similar tasks, as often seen in the insect kingdom. Recent advances in MEMS, microactuators, and high-density power sources have made possible the mass production of a large number of small, complex devices that can sense and affect their environment. A system of several small, cooperating robots provides advantages such as graceful degradation in case of the loss of individual robots, robust inter-communication among robots and with their human counterparts, reconfigurability to attain varying objectives, and the ability to deploy individual specialized robots. This type of system could be used to enhance astronauts' capabilities to do large-scale mapping, detailed exploration of regions of interest to build three-dimensional maps that astronauts could explore through virtual reality to determine regions of interest (similar to Sojourner), and automated sampling of rocks and soil.

There may be opportunities to apply biological principles in robot development to help meet NASA's needs for effective human-machine collaboration, improved situational awareness, and optimal decision making. For example, the development of software that senses its own and an astronaut's anxiety could provide robots with the “brains” needed to extend mission capabilities while also enhancing the reliability and configurability of the software. This idea builds on the research community's long-standing use of the biological knowledge base as a source of ideas for the design of algorithms and computational mechanisms for data processing (neural networks and DNA computing are examples). Other biologically inspired robot systems are conceivable (an example is provided in Box 3.2).

Robots are the focus of considerable academic research[4] but their capabilities remain primitive in comparison to those of biological organisms. For example, in the last 5 years, mobile research robots have just begun to succeed in tasks such as navigation of roads and hallways. These successes follow from the increase in robot computer power from 1 million instructions per second (MIPS) to several hundred MIPS, which corresponds to a nervous system less powerful than that of an insect (Moravec, 1998). One way to enhance robot capabilities might be to develop controller software that senses anxiety.

The importance of emotional states is demonstrated by their strong effect on human decision making. There is evidence that individuals whose emotional centers have been damaged by disease make poor decisions (Kandel et al., 1991; Pinel, 1993; Goleman, 1995; Greenspan and Benderly, 1997). The biological principles at work are neuronal. Human behavior and problem solving emerge from resource competition and collaboration, and the environment of the competition is strongly affected by emotion. Furthermore, the learning process is mediated and reinforced by emotion: Humans generally repeat things that feel good and avoid things that do not. Humans also remember events and skills associated with the current emotional state. Based on this biological model, software for robotics systems could be designed to exhibit evolving system behavior mediated by emotion and anxiety. Modules would compete to perform different functions, and the learning process would be augmented by emotion.

A robot of this type would be especially useful as a component of a synergistic human-robot system. The robot would be attuned to both its own and the astronaut's feelings and provide backup (i.e., system robustness) against the introduction of new elements and situations. Communication between the astronaut and robot concerning their respective emotional states could help reinforce the positive or negative results of the associated actions and thereby promote learning. A sophisticated robot could even take over the astronaut's tasks in times of stress. A physiological response (e.g., anxiety) could trigger the software to take on certain functions for the human and delay nonessential activities.

Interfaces could be designed to enable human comprehension of system data without information overload, and to communicate human intentions to the robot. There are interesting human-computer interface possibilities, perhaps using modes of communication involving electrical fields and currents or visual information. Verbal communication is perhaps the most natural medium for humans, and the ability of computer systems to communicate verbally is generally appreciated. However, human verbal communication is highly complex and goes well beyond literal syntax and semantics. There are paralinguistic elements to be considered such as intonation, rate of speech, level of formality, turn-taking, and verbal etiquette (personal

[4]Some of the research activity in this area is described on the World Wide Web site of Carnegie Mellon University's Robotics Institute (http://www.ri.cmu.edu) and Microdynamics Systems Laboratory (www.cs.cmu.edu/~msl/msl_hyperlinks.html).

communication to Ewin Montgomery by Lyn Turkstrata, Department of Communication, Case Western Reserve University).[5]

Apart from their value in mission execution, effective human-computer interactions might also help ease the psychological demands of prolonged spaceflight. For example, a robot attuned to anxiety and the paralinguistic elements of communication might help identify and deal with situations in which an astronaut needs to “psychologically escape” from other crew members. There are already examples (see the section on PI-in-a-box below) of computers programmed to generate appropriate and emphatic responses to human input.

The design of software for telerobotics systems incorporating emotion-mediated behavior and learning is a long-term research project.

Monitor Cognitive States

The influence of emotion on decision making (see previous section) suggests there may be some value in monitoring astronauts' cognitive states. For example, it would be useful to have a process for identifying and dealing with anxiety, which can be correlated with negative performance. It may not be feasible to teach astronauts to be self-aware and express their feelings, because there appears to be a cultural bias against communicating any problems, especially given the public nature of shuttle broadcasts. Anecdotal reports suggest that astronauts' inhibitions against revealing their emotions have compromised abilities to accomplish tasks in the past. Physiological monitoring of cognitive and emotional states could provide confidential biofeedback to promote relaxation. There is already a large literature and clinical practice dealing with these techniques (Basmajian, 1989). The ability to monitor brain states could have additional benefits. The results of monitoring could be displayed solely to the astronauts and ground-support personnel.

Physiological variables can be monitored noninvasively using various techniques. A traditional means of gauging emotions or arousal is the lie detector, which measures blood pressure, respiration, and galvanic skin response. Other standard methods (e.g., electroencephalography [EEG] and electromyography [EMG]) are well established but often awkward, because of the need to attach electrodes to the subject, who must then remain still. Implanted sensors and telemetry can also be used. It is also possible to monitor outward signs of emotion with software. A system is being developed for facial-expression recognition that could be modified to look for signs of emotional state (Cohn et al., 1997).

Magnetoencephalography (MEG) may offer some advantages over EEG because it is less affected by tissue conductivity (Haueisen et al., 1997). Therefore, MEG may be more accurate in

[5]The complexity of paralinguistic elements provides many dimensions for encoding information. Indeed, humans are adept at perceiving and operating on the basis of these paralinguistic elements. For example, factual information could be conveyed in the syntax and semantics while the priority of the information is encoded in the paralinguistic elements. This approach would allow the human to process the factual information and the priority simultaneously and relieve the computer of having to convey the information sequentially, perhaps offering a significant advantage in time-critical operations.

localizing some electrical sources, especially those deep in the brain (Stok, 1987; Hamalainen and Sarvas, 1989; Lewine and Orrison, 1995), potentially accessing relevant neuronal events for the purpose of monitoring or even short-circuiting them. MEG also provides almost instantaneous feedback, making it attractive for cognitive monitoring purposes. As with EEG, MEG responses can be correlated with measures of cognition that are affected by stress and other variables (Rogers, 1994). Compared with EEG, the technology for recording MEG is far more expensive but much simpler to use, because it is not necessary to spend time carefully attaching large arrays of electrodes.

MEG is based on the use of superconducting quantum interference devices (SQUIDS) to detect very small magnetic fields. A SQUID cryogenic cap or helmet for recording brain waves, and perhaps providing immediate feedback to the astronaut using a small display, is an intriguing concept. The technology exists to make very small devices in which the coils are flat and require minimal energy. Indeed, the SQUID cap concept may be particularly appropriate in the space environment, where the temperatures are cold enough, theoretically, to make the SQUIDS superconducting. Even if this theory does not hold up, progress in refrigeration for high-temperature SQUIDS operating at liquid-nitrogen temperatures might make the idea feasible. The Cryogenics Group at NASA Goddard Space Center is developing small Sterling cryo-coolers in conjunction with Lockheed that can probably be miniaturized within 10 years to the size of a 1-kg helmet containing a large array of high-temperature SQUID sensors (Stephen Castles, NASA Goddard Space Center, January 1998, personal communication). Pulse-tube coolers may perform as well in a small helmet (Ray Radebough, National Institute of Standards and Technology, January 1998, personal communication), and reverse-Brayton cryo-coolers may have similar performance capabilities (McCormick et al., 1997; Stacy et al., 1997; Radebough, 1997).

Another rapidly developing technology is magnetic resonance imaging (MRI). Great strides are being made in developing and improving new applications for MRI, particularly as functional information is provided to accompany the anatomical pictures, which continue to improve in quality and spatial resolution. The combined structural and functional imaging capabilities of MRI offer extraordinary opportunities to determine the parts of the brain associated with specific abilities (Orrison et al., 1995). However, the response of functional MRI (on the order of 1 to 2 seconds, because of the inherent physiology of the blood flow response) is far slower than that of EEG and MEG (on the order of milliseconds), meaning that dynamic cognitive states cannot be monitored effectively with MRI. Furthermore, size, power, and extraneous magnetic field considerations currently prevent the use of MRI in space.

EMG is another potentially useful technology, because it can be used to monitor muscle activity for purposes of biofeedback to reduce stress and anxiety (Basmajian, 1989).

Most approaches to monitoring cognitive states would require long-term research. The cryogenic SQUID cap might be practical within 5 years and could be the subject of a follow-on workshop.

Provide PI-in-a-Box

The complexity and new challenges associated with missions to Mars necessarily call for dynamic mission planning and execution strategies and improved problem solving. Astronauts might benefit from having instant access to a database of the accumulated experience of previous astronauts. The database could be self-organizing to respond to immediate needs. Algorithms showing relationships between "faults" and related systems could suggest problem-solving options. This concept is variously described as experience on demand, just-in-time training, or PI-in-a-box (Young et al., 1989; Hazelton et al., 1993; Young, 1994). Research is needed concerning how best to organize and present the data. Biology-based concepts could be applied to data presentation. For example, algorithms based on the survival instinct would present data on the most-life-threatening situations first.

NASA has performed research on the robotic extension of human presence using concepts such as the "third hand." A PI-in-a-box might not be able to make decisions but it could provide information and serve as a "buddy" for the astronaut. A companion robot, similar to a deep-sea diving partner or the sled pulled by Antarctic explorers, could contain support materials such as positioning systems, tents for surviving sand storms, additional oxygen for security, and shovels and other tools for exploration. The robot could also provide mental support when the astronaut is challenged. The robot could contain a computer, database, and logistic backup system that would offer a feeling of security. The U.S. military's tactical information assistants are based on a similar concept.[6]

The research needed to develop PI-in-a-box for space applications is long term.

SUMMARY

The session 2 discussion generated a number of biological concepts and possible applications that may be of use to NASA in extending human presence and function in space exploration. Two topics seem promising enough in the short term to be the subjects of follow-on workshops. One such topic is the design of comfortable, functional spacesuits that incorporate biological concepts, such as 40-degree-angle wrist settings that provide maximum dexterity and grip, and biomolecular materials such as those modeled on strong-yet-dexterous sharkskin. A second workshop could explore the possibility of designing a SQUID cap or helmet that would apply MEG technology to record astronauts' brain waves and provide feedback on cognitive states.

Other R&D areas that might generate practical solutions to NASA's needs in the short term include visual systems and exercises combining gymnastics and virtual reality. Over the long term, biological concepts might be applied to foster the dual adaptation of astronauts to both 1-G and microgravity environments, design synergistic human-robot systems that exhibit

[6]Information about tactical information assistants can be found on various World Wide Web sites (http://www.spectrum.ieee.org/publicaccess/1195inf. html).

emotion-mediated decision making and learning, and develop computational "companion" robots that provide astronauts with rapid access to the combined experience and expertise of their predecessors and enhance both function and a feeling of security.

In pursuing any of this work, NASA would benefit from monitoring cutting-edge developments in biology as well as in various technologies that mimic, implement, or exploit biological concepts and capabilities. Technologies of interest include task-specific robots, visual systems, MEMS, and MEG.

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4

Additional Observations

A SYSTEMATIC APPROACH TO DEFINING MISSION NEEDS

Steering group members agreed on the value of a systems engineering approach to identifying potential biology-based technologies for space exploration but learned that taking such an approach depends on having a sure understanding of specific system requirements. The group observed that the productivity of any future workshops will be increased if participants are provided with systematically defined specific system requirements, especially the capabilities expected of the humans involved in space travel and exploration. The requirements for fulfilling a specific set of Human Exploration and Development of Space (HEDS) Enterprise mission objectives would best be derived using a systems engineering approach in which humans at the exploration site are defined as system elements and incorporated into the total system architecture along with all other elements. Once NASA defines these requirements, future workshop participants can apply their technical expertise and creative energies to considering biology-based technologies for which a systematic analysis has already identified significant issues, risks, or opportunities. This approach would simultaneously channel and stimulate imagination and creativity and maximize the usefulness of the results.

The overall analytical approach could encompass the following steps: (1) Define a desired mission scenario and its candidate total system architectures. (2) Develop a complete set of requirements for each architecture, from the system level down through the major subsystems and subsystem elements. (3) At the element level, define the functional requirements (i.e., inputs, processing, outputs) and engineering requirements (i.e., structural, envelope, environments, margins). (4) Define the design criteria associated with each requirement. Given that information, workshop participants could focus on proposing innovative biology-based technology concepts for enhancing human well-being or human function that would also meet the stated design criteria. As a follow-up activity, the proposed concepts could be compared with conventional systems using a set of figures-of-merit (e.g., risk level, mass, cost).

Once NASA defines the system requirements, a system optimization process could be used to determine the most effective number of humans for a long-term mission and allocate the functions to be performed by them. Several subsystems incorporating biology-based concepts and elements to enhance human well-being or capabilities could be defined for Mars surface exploration missions. These configurations could be included in the systems engineering and optimization process to identify the most promising combinations offering the greatest leverage.

TECHNOLOGY WATCH

Much of the current activity in the research areas outlined in Chapter 2 and Chapter 3 is taking place outside the fields of aeronautics and space science. In biology and some areas of biology-based technology, the state of the art is advancing rapidly and could offer substantial benefits in HEDS missions if transferred and adapted as appropriate. Therefore, it is important that NASA remain abreast of developments in relevant fields.

At present, NASA's technology watch process is largely informal and decentralized. Individual researchers, like any other scientists, are expected to remain current in their own fields. But there is no formal, systematic mechanism to ensure that the myriad relevant areas and developments are monitored. Participants in both sessions of the workshop reported on here noted the importance of following up the identification of requirements with a systematic evaluation of all potential solutions, including innovative biology-based approaches. A number of participants suggested that NASA might benefit from organizing a formal technology watch of research advances in the biological sciences and innovations in biology-based technologies.

A technology watch requires the establishment of monitoring criteria, communication of these criteria within appropriate government agencies and to relevant universities and industries, monitoring for new developments, and assessments of the applicability of these developments for the identified uses. There are many ways to communicate with technology researchers and developers. The U.S. Department of Agriculture (USDA), for example, maintains a technology watch through its extension services, which transmit information to and from end users of USDA products and services. Other possible mechanisms include routine contact with technology transfer offices in academia and industry, Internet searching and monitoring, publication in peer reviewed journals, formation of academic consortia, establishment of technical advisory committees, and regular workshops at scientific meetings.

If a formal technology watch were established, NASA would need to find a way to exchange information about its requirements quickly and effectively with key industries and academic experts and centers, which could then help identify solutions. NASA would have to define its problem areas, issues, and requirements at the appropriate (i.e., subsystem) level. To supplement a central technology-watch network, NASA employees might be encouraged to maintain technology watches and could receive credit for this activity. Increased emphasis on scholarly activities, including publication in peer-reviewed journals and presentations, might increase awareness of the state of the art.

As a means of enhancing its awareness and use of biology-based technologies, NASA might benefit from systematic monitoring of leading-edge science and technology in the following areas:

- *Biosensors.* Cross-disciplinary activity involving biology, chemistry, and electronics has gained momentum in recent years in the development of biosensors. Biosensor technology is advancing rapidly, and technologies with potential applications in spacecraft and planetary habitat advanced life support systems could be monitored.
- *Microbiological methods.* Laboratory culture methods currently used to screen air and water for microorganisms are primitive, bulky, and unreliable. Advancements in modern microbiological methods such as gene probes and fluorescent antibody techniques could be identified, and, where feasible, used to detect and identify microorganisms in the air and water of spacecraft and planetary habitats, as well as to quantify pollutants there.
- *Closed-loop aquaculture.* Current research in closed-loop aquaculture (e.g., fish, brine, shrimp, shellfish) may provide insights that could be applied to the development of highly efficient systems for closed-loop regenerative advanced life support systems for extended space missions.
- *Genetic engineering of plants.* Plants can be used not only as food but also as sources of useful materials and chemicals and for the recycling of carbon dioxide and other inorganic and organic wastes. Advances in the genetic engineering of plants that can meet defined performance goals for spaceflight need to be monitored.
- *Biomaterials for spacecraft and habitats.*Biomaterials, biomolecular materials, and biologically inspired structures could provide enhanced performance characteristics (e.g., self-repair, self-diagnosis, low maintenance, in situ production, radiation protection) and promote recovery, reuse, recycle, and repair. Considerable R&D has been devoted to these types of materials for other applications. Those that have potential applications for space exploration need to be monitored.
- *Ecosystem or biosystem stability and diversity.* Progress in ecosystem engineering and management, especially with respect to the long-term stability of systems used in recycling and food production subsystems, will be pivotal to the success of extended missions to space.
- *Enzymatic detergents and cleaners.* Enzymatic catalysts are replacing chemicals in industrial cleaning applications. The “green chemistry” industry could be monitored. Advances in enzymatic detergents and cleaners could be used in housekeeping aboard spacecraft and in planetary habitats. Enzymes that cause hypersensitivity diseases need to be identified.

- *Technologies for monitoring cognitive states.* Magnetoencephalography (MEG) and other noninvasive monitoring technologies are developing rapidly, and their use is expanding in medicine and other fields.
- *Microelectrical mechanical systems.* The state of the art in microelectrical mechanical systems technology is advancing rapidly and may offer benefits in applications such as active space suits that assist in movement, sensing, and self-repair.
- *Task-specific robots.* Extraordinary advances in computer speed and memory have brought cleaning and delivery robots to the point of commercialization for mass markets. By monitoring the field and adapting commercial robots for its own use, NASA might meet mission needs more cost-effectively than by designing small numbers of robots specifically for space applications.
- *Visual systems.* Heads-up displays, artificial retinas, and other visual systems are under development that offer the possibility of enhanced human vision or new modalities such as over-the-horizon vision. Improvements in these technologies could be monitored as NASA defines its needs in this area.

Appendixes

A BIOGRAPHICAL SKETCHES OF WORKSHOP STEERING GROUP MEMBERS

Gerard W. Elverum, Jr. (chairman) is vice president and general manager (retired) of the Applied Technology Division of TRW Space Defense. Mr. Elverum's expertise is in the areas of research and development of missile, launch vehicle, and spacecraft propulsion systems; high-power directed energy devices; and space-science instruments. His technical interests also include systems engineering and risk assessment and management. He has served on numerous National Research Council (NRC) and NASA committees in space technology and military systems areas. He was a member of NASA's Aerospace Safety Advisory Panel for many years and a former member of the NRC Commission for Engineering and Technical Systems. He is currently a member of the Space Studies Board. In 1995 he served on the Board's Task Group on Gravity Probe B and is currently a member of NASA's Independent External readiness Review Team for GP-B. Mr. Elverum received the Special Achievement Award of the American Society of Mechanical Engineers in 1971, the Outstanding Engineer Merit Award from the Institute for the Advancement of Engineering in 1972, and the James H. Wyld Propulsion Award of the American Institute of Aeronautics and Astronautics in 1973. His professional associations also include Sigma Xi, and he is a fellow of the American Institute for Aeronautics and Astronautics, and a member of the National Academy of Engineering. He received a B.S. degree in physics from the University of Minnesota.

James P. Bagian, a former NASA astronaut, is currently involved in occupational medicine and biomedical research at the U.S. Environmental Protection Agency. Dr. Bagian was a NASA astronaut beginning in 1980 and was active in the planning and provision of emergency medical and rescue support for the first six space shuttle flights. He has written numerous scientific papers in the fields of human factors and environmental and aerospace medicine. He is a veteran of two spaceflights and has logged over 337 hours in space. Dr. Bagian is a member of NRC's

Space Studies Board, the Committee on Advanced Technology for Human Support in Space, and the Steering Committee for the Workshop on Reducing Space Science Research Mission Cost. Dr. Bagian holds numerous honors and awards, including the NASA Space Flight Award, the NASA Exceptional Service Medal, the Society of NASA Flight Surgeons W. Randolf Lovelace Award, and the American Astronautical Society's Melbourne W. Boynton Award. Dr. Bagian is a member of the Aerospace Medicine Association, the American Society of Mechanical Engineers, the Society of NASA Flight Surgeons, Phi Kappa Phi, Phi Eta Sigma, Pi Tau Sigma, Tau Beta Pi, and Alpha Omega Alpha. Dr. Bagian received a B.S. degree in mechanical engineering from Drexel University and an M.D. degree from Thomas Jefferson University.

Rita R. Colwell is president and co-founder of the University of Maryland Biotechnology Institute and a professor of microbiology at the University of Maryland. She is an internationally recognized expert in marine biotechnology, marine and estuarine microbial molecular ecology, microbial systematics, marine microbiology, and temperature and high-pressure effects on marine bacteria. Dr. Colwell serves on numerous government boards and committees and has been appointed to the National Science Board. She has authored or co-authored more than 500 professional publications. Dr. Colwell served on the Polar Research Board and is currently a member of several NRC committees, including the Committee on Opportunities for Advancement of Marine Biotechnology in the United States, the Committee on the Second Forum on Biodiversity, and the Roundtable on Research and Development of Drugs, Biologics, and Medical Devices. She is a former president of the American Association for the Advancement of Science and the American Society of Microbiology. She received a B.S. degree (with distinction) and an M.S. degree from Purdue University and a Ph.D. degree from the University of Washington. Dr. Colwell has an honorary D.Sc. from Heriot-Watt University in Edinburgh, Scotland, and is an honorary professor at the University of Queensland in Queensland, Australia.

Bruce Dunn is a professor in the Department of Material Sciences at the University of California at Los Angeles. Dr. Dunn is a nationally recognized expert in ceramics engineering and thermodynamics and material properties. Previously he was a staff scientist in the Research and Development Center for the General Electric Company. His research interests include electrical and optical properties of inorganic materials, transport and optical properties of solid electrolytes, synthesis of tunable lasers and other materials by sol-gel methods, and infrared transmitting solids. Dr. Dunn is a member of the American Ceramic Society, the Electrochemical Society, the Material Research Society, and the American Association for the Advancement of Science. Dr. Dunn received a B.S. degree from Rutgers University and a Ph.D. degree from the University of California at Los Angeles.

Donald R. Humphrey is a professor of physiology and director of the Neurophysiology Laboratory in the School of Medicine at Emory University. Dr. Humphrey's specialty is neurophysiology and neuroanatomy. His research interests include cerebral cortical mechanisms in the control of movement and posture and neuromuscular control systems. He is a consultant for the National Institutes of Health. Dr. Humphrey is a recipient of the Hans Berger Research

Award of the American EEG and Clinical Neurophysiological Society. He is a member of the American Physiological Society, the Society for Neuroscience, the Biomedical Engineering Society, and the American Association of Anatomy. Dr. Humphrey received a B.A. degree from San Jose State University and a Ph.D. degree from the University of Washington.

Takeo Kanade is director of the Robotics Institute and the U.A. and Helen Whitaker Professor of Computer Science and Robotics at Carnegie Mellon University. Dr. Kanade has made technical contributions in multiple areas of robotics and codeveloped the concept of direct-drive manipulators and the first prototype. Dr. Kanade is a leader and developer of the vision systems for Carnegie Mellon University's NavLab and holds patents for three-dimensional sensors. Previously he was an associate professor in the Department of Information Science, Kyoto University, Japan. Dr. Kanade serves on the NRC's Aeronautics and Space Engineering Board. He has received several awards, including the Joseph Engelberger Award. He is a member of the National Academy of Engineering. Dr. Kanade received a Ph.D. degree from Kyoto University.

Rodolfo R. Llinas is a professor and chairman of the Department of Physiology and Neuroscience at the New York University Medical Center. Dr. Llinas is an expert in electrical transmission in the mammalian brain. His research interests include neuronal function, synaptic transmission, cerebellar function, thalamocortical function, magnetoencephalography, mathematical modeling, and human brain plasticity. He is the chief editor of *Neuroscience* and served on the editorial board for the *Journal of Neurobiology* and the *Journal of Theoretical Neurobiology*. He is a member of the Scientific Advisory Board, the Roche Institute, and the NASA/Neurolab Science Working Group. Previously, he was a member of the NRC Panel on Basic Neuroscience Research, the Scientific Advisory Board, and the Max-Planck Institute for Psychiatry, and chairman, U.S. National Committee for IBRO. He received the John C. Krantz Award in Pharmacology and Experimental Therapeutics, University of Maryland, the F.O. Schmitt Lecture and Award in Neuroscience, Rockefeller University, the UNESCO Albert Einstein Gold Medal Award in Science, and the Augustin Nieto Caballero Medal, Colombia. He is a member of the National Academy of Sciences. Dr. Llinas received a B.S. degree from Gimnasio Moderno (Bogota), an M.D. degree from the Universidad Javeriana (Bogota), and a Ph.D. degree in neurophysiology from the Australian National University (Canberra).

Samuel I. Stupp is the Swanlund Professor of Materials Science and Engineering, Chemistry, and Bioengineering at the University of Illinois at Urbana-Champaign. Dr. Stupp is an internationally recognized expert on self-assembling materials, biomaterials, and nanocomposites. In 1989, Professor Stupp was appointed to the Beckman Institute for Advanced Science and Technology, and he served from 1991 through 1994 as chairman of the Polymer Division in the Department of Materials Science and Engineering. His major research interests include the synthesis of self-organizing supramolecular materials and inorganic-organic nanocomposites that integrate multiple functions. He is also interested in the design and synthesis of novel biomaterials that could induce the regeneration of human tissues. In 1985, he received the Xerox Award for Excellence in Engineering Research and, in 1991, the Department of Energy Prize for Outstanding Achievement in Materials Chemistry. He was named Joliot

Curie Professor for Fall 1997 at the Ecole Superieure de Physique et de Chimie Industrielles by Pierre-Gilles de Gennes, and he received the Humboldt Research Award to spend time at the Max Planck Institute for Polymer Science. Dr. Stupp has served on the editorial boards of the *Journal of Polymer Science*–Polymer Chemistry Edition, *Acta Polymerica,* and *Macromolecular Physics and Chemistry*. He also served on the Air Force Scientific Advisory Board Materials Panel and is currently the chairman of a National Science Foundation workshop considering future opportunities in macromolecular science and engineering for the next decade. Dr. Stupp received a B.S. degree in chemistry from the University of California at Los Angeles and a Ph.D. degree in materials science and engineering from Northwestern University.

B WORKSHOP AGENDA AND PARTICIPANTS

AGENDA

October 21, 1997 Plenary Session

8:00 a.m.	NASA Welcome	Leonard Nicholson, JSC Guy Fogleman, NASA Headquarters
8:15 a.m.	Chair's Welcome	Gerard Elverum, Workshop Chair
	Workshop Goals and Needs Workshop Product and Intended Audience	
8:30 a.m.	Overview of Breakout Sessions	
	Breakout Session 1: Enhancing Human Well-Being in Space Exploration	James Bagian, Chair
	Breakout Session 2: Enhancing Human Presence and Function in Space Exploration	Takeo Kanade, Chair
9:00 a.m.	Presentations	Gerard Elverum, Workshop Chair
9:00 a.m.	Overview of Exploration Planning	Douglas Cooke Johnson Space Center

9:20 a.m.	Overview of Exploration Technology Requirements	Bret Drake Johnson Space Center
9:40 a.m.	Overview of Human Life Sciences Requirements to Support Exploration Plans	Charles Sawin Johnson Space Center
Enhancing Human Well-Being in Space Exploration		
10:00 a.m.	Spacecraft/Habitation Materials and TransHab	Kriss Kennedy Johnson Space Center
10:20 a.m.	Regenerative Life Support Systems	Don Henninger Johnson Space Center
10:40 a.m.	Break	
11:00 a.m.	Continue Presentations	
Enhancing Human Presence and Function in Space Exploration		
11:00 a.m.	Man/Machine Interfaces	James Maida, Tom Duncavage Johnson Space Center
11:20 a.m.	Robotics and Automation	Jon Erickson, Charles Price Johnson Space Center
11:40 a.m.	Information Processing	Bob Savely Johnson Space Center
12:00 noon	Lunch	

Breakout Sessions

1:00 p.m.	Breakout Session 1—Roundtable Discussion	James Bagian, Chair
	Spacecraft Habitat/Materials Regenerative Life Support Systems	
	Breakout Session 2—Roundtable Discussion	Takeo Kanade and Bruce Dunn, Co-chairs
	Sensor Input Information Processing Presentation and Interface Ability to Perform Tasks	

Reconvene in Plenary Session

5:15 p.m.	Breakout Session Progress Reports	Gerard Elverum, Workshop Chair
	Progress Report for Breakout Session 1 Enhancing Human Well-Being in Space Exploration	James Bagian, Chair
	Progress Report for Breakout Session 2 Enhancing Human Presence and Function in Space Exploration	Takeo Kanade, Chair
6:15 p.m.	Adjourn for the Day	

October 22, 1997 Reconvene in Breakout Sessions

8:00 a.m.	Continue Roundtable Discussion	
	Breakout Session 1—Roundtable Discussion	James Bagian, Chair
	Breakout Session 2—Roundtable Discussion	Takeo Kanade and Bruce Dunn, Co-chairs
12:00 noon	Lunch	

Reconvene in Plenary Session

1:30 p.m.	Breakout Session Progress Reports	Gerard Elverum, Workshop Chair
	Summary of Findings for Breakout Session 1	James Bagian, Chair
	Promising Areas Near-term and Far-term Research and Technology Needs	
	Summary of Findings for Breakout Session 2	Takeo Kanade, Chair
	Promising Areas Near-term and Far-term Research and Technology Needs	
2:30 p.m.	Concluding Remarks	Gerard Elverum, Workshop Chair
3:00 p.m.	Adjourn	

PARTICIPANTS

Session 1: Enhancing Human Well-Being in Space Exploration

James P. Bagian, U.S. Environmental Protection Agency, *Session 1 Chair*
Joseph L. Zelibor, National Research Council, *Rapporteur*
Harriet Burge, Harvard School of Public Health
Robert Burris, University of Wisconsin
Abhaya Dandekar, University of California at Davis
Stephen Giovannoni, Oregon State University
Mark Holtzapple, Texas A&M University
David Kaplan, Tufts University
Michael Ladisch, Purdue University
Ferid Murad, University of Texas Medical School at Houston
Stanley Schultz, University of Texas Medical School at Houston
Kevin Sowers, University of Maryland Biotechnology Institute
Bernie Steele, MBI International
Anne Vidaver, University of Nebraska

Session 2: Enhancing Human Function in Space Exploration

Takeo Kanade, Carnegie Mellon University, *Session 2 Co-chair*
Bruce Dunn, University of California at Los Angeles, *Session 2 Co-chair*
Laura Ost, National Research Council (consultant), *Rapporteur*
Stephen B. Baumann, University of Pittsburgh
James J. Collins, Boston University
Gerard W. Elverum, TRW Space and Technology Group (retired), *Workshop Chair*
Mark Latash, Pennsylvania State University
Erwin Montgomery, Cleveland Clinic Foundation
Andrew Mor, Carnegie Mellon University
Hans Moravec, Carnegie Mellon University
Joseph Soukup, SAIC, Inc.
J. Rudi Strickler, University of Wisconsin at Milwaukee
Allen Ward, Ward Synthesis, Inc.
Laurence R. Young, Massachusetts Institute of Technology

NASA Participants

John L. Anderson, NASA Headquarters
Jeri W. Brown, Johnson Space Center
Anthony Bruins, Johnson Space Center
Charles Buntin, Johnson Space Center
John Charles, Johnson Space Center
Douglas Cooke, Johnson Space Center
Minoo Dastoor, NASA Headquarters
Bret Drake, Johnson Space Center
Tom Duncavage, Johnson Space Center
Jon Erickson, Johnson Space Center
Donna Fender, Johnson Space Center
Guy Fogleman, NASA Headquarters
Walter Hanby, Johnson Space Center
Don Henninger, Johnson Space Center
Diana Hoyt, NASA Headquarters
Darrell Jan, NASA Headquarters
Kriss Kennedy, Johnson Space Center
James Maida, Johnson Space Center
Hum Mandell, Johnson Space Center
John C. Mankins, NASA Headquarters
Leonard Nicholson, Johnson Space Center
William Paloski, Johnson Space Center
Trish Petete, Johnson Space Center
Charles Price, Johnson Space Center
R.J. Rector, Johnson Space Center
Robert Savely, Johnson Space Center
Charles Sawin, Johnson Space Center
Scott Simmons, Johnson Space Center
Charles Stegemoeller, Johnson Space Center
Don Stillwell, Johnson Space Center
Robert C. Trevino, Johnson Space Center
Barbara Woolford, Johnson Space Center

Other Participants

Marc Allen, National Research Council
Douglas Hamilton, Krug Life Sciences
Noel Hinners, Lockheed Martin
Patricia Holler, Lockheed Martin