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A RAND NOTE

Human Support Issues and Systems for the Space Exploration Initiative: Results from Project Outreach

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United States Air Force
National Aeronautics and Space Administration

RAND

PREFACE

This Note describes the findings of the Human Support panel, one of eight project panels established by RAND to evaluate submissions to the Space Exploration Initiative (SEI) Outreach Program, also called Project Outreach. Project Outreach is a NASA-sponsored program to elicit innovative ideas, concepts, and technologies for space exploration. The project was sponsored by Project AIR FORCE and RAND's Domestic Research Division, with technical oversight provided by the Assistant Secretary of the Air Force (Space).

The findings of other RAND panels are reported in the publications listed below.

Space and Surface Power for the Space Exploration Initiative: Results from Project Outreach, C. Shipbaugh, K. Solomon, M. Juncosa, with D. Gonzales, T. Bauer, and R. Salter, N-3280-AF/NASA, 1991.

Space Transportation Systems, Launch Systems, and Propulsion for the Space Exploration Initiative: Results from Project Outreach, T. Garber, J. Hiland, D. Orletsky, B. Augenstein, and M. Miller, N-3283-AF/NASA, 1991.

Automation and Robotics for the Space Exploration Initiative: Results from Project Outreach, D. Gonzales, D. Criswell, and E. Heer, N-3284-AF/NASA, 1991.

SUMMARY

The human support panel received over 10 percent of the 1697 Project Outreach submissions. The panel screened the 156 submissions that were amenable to technical review to select those that merited detailed analysis. Screening criteria chosen were intended to maximize the likelihood of selecting programmatically useful and technically promising contributions that demonstrated innovativeness by complementing or differing from approaches being pursued by NASA and its contractors. Successful submissions were subject to a broad issue-oriented analysis performed in the context of the present status of SEI life science/life support issues and plans and strategies to increase the knowledge base.

Ultimately, twenty-four submissions were selected for more detailed consideration, and the top twelve of these were recommended to the Project Outreach Synthesis Group. This Note discusses the analysis and implications of the highly ranked submissions in the larger context of addressing the human support questions confronting the SEI.

OVERALL OBSERVATIONS

Human support issues hold the key to mankind's future in space. Success in resolving these issues and achieving the broader goals of the Space Exploration Initiative (SEI) will evolve only from a view of human space exploration as an ongoing enterprise where investments in research and development resolve operational problems, create infrastructure for future missions, and provide spinoffs that enrich the quality of American life.

Fundamental questions of crew adaptability, tolerance, performance, and survival must be confronted squarely and systematically to assure SEI feasibility, continued support, and eventual success. Further, human support issues should be incorporated by life scientists early in (1) formulating preliminary requirements and guidelines, (2) planning missions, and (3) designing spacecraft. This should be done in ways that reflect the best judgment of both the space and life science communities. Properly posed requirements will facilitate the development of robust system concepts and design solutions that can be adapted to new knowledge, not always favorable, from R&D and test programs conducted on Earth and in space. Only in this manner can we identify (and reject) architectures that rely on potentially unstable, overly optimistic design solutions that exist in a narrow region separating feasibility from failure, and that can accommodate only favorable new findings. Another virtue of a robust approach is that new findings, for example, in radiation

protection, microgravity countermeasures, or life support systems, will be less likely to loom as mission limiters or even "show stoppers."

In the case of radiation protection, the present state of knowledge mandates that planners of multiyear and/or multiple interplanetary voyages consider passive or active systems to protect astronauts from ionizing radiation from **both** high-energy galactic cosmic rays (GCRs) and solar protons. Architectures that lack prudent and flexible radiation protection systems obviously fall in the unstable category, given the large existing uncertainty (a factor of 30 or larger) in the assessment of harmful space related radiobiological effects on humans. A decade or more of Earth (accelerator) and space-based testing and analysis is needed to develop precise radiation protection guidelines that can be translated into engineering design.

The concept of justifying minimal crew protection against GCRs by scheduling missions to avoid peak galactic cosmic radiation also seems unstable. Recent observation⁻, taken during solar cycle 22, imply that high-energy solar proton events are not only unpredictable but far more ubiquitous than previously thought. Thus, the tradeoffs involved in scheduling manned interplanetary voyages to minimize exposure to GCRs or high-energy protons stemming from solar flares are more complex and uncertain than they appeared just a few years ago. And the possible need to perform activities in space, or to communicate during all portions of the solar cycle, must not be overlooked.

Similarly, large uncertainties exist in understanding the effects of prolonged exposure to microgravity, and the efficacy, relative costs, and risks of potential countermeasures. This is not surprising given the limited human experience (in terms of duration and subject) in extended orbital flight (84 days maximum for the United States, 366 days maximum for the Soviets), and the difficulty of systematically acquiring and interpreting human data.

Thus, planning that considers a robust system of microgravity countermeasures appears prudent, combining pharmaceutical interventions, rigorous but tolerable exercise and conditioning, and perhaps even artificial gravity. We view artificial gravity as a contingency option should lower-cost, less complex alternatives appear inadequate after future manned long-duration (multiyear) orbital tests. Although it is not yet possible to predict the exact types of pharmaceutical intervention that may be utilized, it seems possible that new metabolic engineering approaches for regulating cellular and bone growth, control, and function already being pursued by the mainstream biomedical community will yield new compounds to mitigate or even prevent the deleterious effects of microgravity.

NASA, in order to realize the benefits of these advances, should adopt a wide-ranging and diversified approach to life science problem solving that involves aggressive and effective

collaboration with the broader biomedical community. Past history, particularly the remarkably prescient work performed by NASA-supported research teams nearly two decades ago on certain inorganic compounds (including etidronate) to prevent bone resorption under bed-rest conditions that simulated microgravity, suggests that a future NASA life science program could again be successful in integrating its work with mainstream biomedicine.

The NASA Life Sciences program has been reviewed in depth a number of times, and the recent report of the Augustine Committee emphasized the need to enhance NASA's capabilities in this area. Our broad findings are in substantial agreement with those of the Augustine Committee, except for slight differences in organizational emphasis.

Potentially harmful biological effects are likely to increase with time of exposure to microgravity and/or ionizing radiation from GCRs and energetic solar protons. Although nuclear propulsion systems could shorten mission durations, planners should be sensitive to the differing human support requirements for baseline missions, longer baseline contingency missions that entail safe return orbits, and emergencies.

But virtually no data yet exist to inform sensitivity and trade studies relating exposure time, propulsion type and mass, active or passive shielding, microgravity countermeasures, relative costs, technical risk, and, ultimately, human support measures of success. Clearly, a short interplanetary voyage (say, less than a year) is less likely to incur serious risks than a longer journey. However, it is important to emphasize the value of multiple missions that would permit crew members to learn from experience. It is also necessary to recognize the need for systems that can properly protect crew members during longer safe return contingency orbits as well as the possibility of multiple emergency Extra Vehicular Activity (EVAs). The latter is especially significant for rotating artificial gravity systems that may be required to stop and restart a number of times.

The potential advantage of nuclear propulsion over chemical propulsion should be examined in the context of a realistic mission duration. This examination should also incorporate a baseline contingency that entails a mission abort with the associated risks of extended exposure to microgravity and/or space radiation and the premature exhausting of life support systems.

WHY SPACE LIFE SCIENCES ARE DIFFERENT

Space life sciences are multidisciplinary by nature, involving a difficult collaboration among engineers, natural scientists, physicians, astronauts, and policymakers. For optimal progress, they require stable support and creative, motivated research and operating groups

that work in a collegial and open fashion with the biomedical community at large. The phasing of R&D needs careful attention if technology is to be available to support flight operations on a timely basis.

The importance of maintaining continuity and institutional memory must be stressed in a field where manned planetary voyages have been planned but not flown for nearly three decades. Science has methods for preserving institutional memory, but details involving process, technique, and know-how are not easily recoverable from the past. The last extended orbital flights manned by U.S. crews occurred in 1974 during the Skylab era, and consequently the data reliable enough to support SEI decisions are limited. However, the promise of increased cooperation between the United States and the Soviets could mitigate this problem, particularly the possibility of long-term follow-up of Soviet crew members to monitor their postmission health status.

Despite impressive ground simulations, the resolution of critical SEI human support issues still requires data from space, in many cases from humans who will simultaneously perform tasks and undergo monitoring of physiological/psychological effects and responses to countermeasures.

RECOMMENDATIONS: SCIENCE AND TECHNOLOGY

Against this background, we have performed issue-oriented analyses, in which Project Outreach submissions are discussed in the context of addressing a number of critical problems.

Radiation protection for Mars missions requires further research in active shielding techniques, including the feasibility of magnetic shields generated by high-temperature superconductors operated at cryogenic temperatures. GCRs could be far more damaging than Xrays or gamma rays. Such damage includes nonlethal but serious impairments. The observed potentiating influence of microgravity on GCR bioeffects requires serious additional study and testing in space. Highly energetic solar protons are both more frequent and less predictable than previously considered. Radiation surveys of GCR flux and energy distribution and related ground-based studies of their radiobiological effects should be performed at the earliest possible time to support future mission planning and spacecraft definition. NASA should develop the in-house capability for radiation risk assessment and should rely on the National Council for Radiation Protection and Measurements (NCRP) for scientific guidance but not for risk management criteria. Uncertainties, now perhaps as much as a factor of 30 or 40, in radiation risks stemming from exposure to GCRs render point

estimates of risk highly problematic; risk assessments should include confidence or credibility intervals to properly inform the more general space community.

Space-based microgravity research is required to improve the quantitative assessment of long-term effects and possible countermeasures. Biomedical research with emphasis on the mechanisms of bone demineralization may permit the development of biological interventions that would be more attractive than the complexity of tethered or rotating space craft. Recent advances in bone growth factors and cytokine research by academic researchers and biotechnology firms and new data on denning (hibernating) bears suggest the feasibility of elegant countermeasures that stimulate the natural control systems for bone formation and remodeling.

Life support systems for long-term missions and planetary settlement will require bioregenerative technologies incorporating both ecological and biotechnology approaches. Analytic systems must be provided for monitoring air, water, and food systems for bacterial or toxic contamination. Standardized methods are required for accounting for consumables, thermodynamics, and recycling to facilitate comparison of competing approaches. Bioregenerative systems offer great promise, but their long-term reliability in the presence of microgravity, radiation, and other factors requires demonstration. Thus, it is prudent to continue development of complementary physical-chemical systems.

Medical care and health maintenance encompass complex and divergent roles. In addition to serving as primary physician, emergency/trauma surgeon, and public health officer, the medical officer may be responsible for monitoring adaptation and administration of supportive countermeasures throughout the mission. While computer-based decision support systems and telemedicine will contribute to diagnosis and treatment, patient care will require additional specific skills, suggesting the development of a team approach.

Not all potentially adverse effects of long-duration space flight, besides ionizing radiation or microgravity effects, can be anticipated or prevented. Preliminary U.S. and Soviet observations indicate small but potentially significant changes in immune, blood, muscle, and sensory-motor systems. Further long-term space-based research on animals and man should elucidate these responses and suggest countermeasures that would become part of the medical armamentarium for space treatment. The medical-care team should be prepared, in conjunction with ground-based support through mission control, to diagnose and treat potential medical-surgical illnesses, injuries, and emergencies as well as manifestations of space adaptation and deadaptation. A better understanding of space pharmacology, pharmacokinetics, and chronobiology is essential prior to any multiyear mission.

Human factors need substantial emphasis, since human behavior under prolonged stress, isolation, and confinement could compromise mission success. The tendency to minimize such potential risks by appealing to "professionalism" should be avoided. Human factors deal with human interactions with engineered systems and thus should be basic to all SEI systems. Behavior and performance issues should be addressed, from the earliest stages of astronaut selection through command structure and conflict resolution. Spacecraft systems must be designed to facilitate human interaction and intervention in off-nominal or emergency situations. While the use of Antarctic analogs appears very promising, it will not be sufficient by itself; again, multiyear testing in low-Earth orbit or on the Moon seems essential as a precursor to Mars missions.

EVA suits are essential to productive work in space or on the Lunar or Martian surfaces. Suit designs must be tailored to fractional gravity and variable surface conditions. High suit pressure minimizes the need for prebreathing and the risk of embolism but creates substantial challenges for designing reliable, flexible joints and dextrous gloves. Manual dexterity is essential to many maintenance or scientific tasks. The need for continuous funding and closer intercenter collaboration in this area deserves highlighting. The synergies and tradeoffs between EVA and robotics require further analysis, as does the development of spacecraft designs suitable for robotic assembly and servicing.

RECOMMENDATIONS: ORGANIZING FOR SEI SUCCESS

In addition to the recent Augustine committee review, space life sciences have been subject to a continuing process of review and evaluation. The process has resulted in a series of detailed reports dealing with scientific, technical, and administrative matters. Our discussion of human support issues would be seriously incomplete if we did not synthesize and interpret, at least briefly, the highlights of these reports as they apply to SEI life sciences organization and management.

NASA Life Sciences must participate actively in the planning and analysis of future missions, but will require more support to play this more active role. Life Sciences now receives less than 1 percent of the NASA budget. Although perhaps adequate for supporting shuttle operations, this leaves little capacity to respond to SEI challenges in ways that are both innovative and sustainable. In contrast with other areas of space science and technology where industry, non-profit laboratories, universities and NASA already form an effective partnership, academics and industrial contractors have been less willing to commit discretionary resources to initiate projects in space life sciences. For industry, this is mainly due to expectations of low funding levels. For academics and smaller organizations, the

problems of scheduling and maintaining priority in accessing space are also significant. Advocating and mounting effective life sciences programs for SEI will require a broader constituency than now exists. Recent comments from industry representatives supporting a primarily life sciences rationale for the Space Station suggest that this constituency is beginning to coalesce.

NASA must develop and maintain the in-house science and technical expertise to lead and critically monitor the technical activities in life sciences, and guide future mission planning and operations. One current example of overreliance on outside experts, without a matching in-house capability, is in radiation protection guidelines. The NCRP's most recent "Guidance on Radiation Received in Space Activities" (issued July 31, 1989), which defines career limits for astronauts underestimates the risk of dying of cancer by factors between 1.3 and 4.0, compared with limits based on the 1990 Health Effects of Exposure to Low Levels of Ionizing Radiation (BEIR V) (NRC) assessment. Thus the NCRP guidelines were obsolete within months of their publication, and NASA and its contractors must develop new guidelines responsive to the new information. The guidelines in turn will be reflected in more precise preliminary planning. However, the acknowledged large uncertainties in radiation protection requirements could render point design analyses virtually useless.

Contractors that provide design services, hardware, and software could, if properly managed, become a valuable resource for leveraging NASA's in-house life science capability. A continuing process of interaction between NASA staff and contractors is required to facilitate the proper mix of life sciences and engineering.

Compartmentalization among research, operations, planning, and contractors should be reduced. While scientific and technical specialties are becoming more narrowly defined, NASA must avoid becoming too narrowly focused in an increasingly multidisciplinary world. For example, the mass and energy needs for GCR radiation shielding strongly affect power and launch requirements, and should be incorporated in the design analysis of any spacecraft configuration intended to generate artificial gravity.

The complexity and long lead times for resolving human support questions mandate long-term NASA support for carefully selected investments in biomedical research. Biologically elegant interventions and countermeasures may offer great leverage and savings in comparison to spacecraft designs intended to create artificial gravity. They could also have far greater capacity for spinoffs that would enrich American society.

Access to flight data is essential for research, verification, and testing. It is also essential for mission planning and spacecraft design. Flight data should be supported by traceable standards and calibration procedures, and made available on a timely basis in a

documented format to facilitate use by NASA, universities, or contractors. Various levels of collaboration with the Soviets seem essential now, particularly the gathering of postmission follow-up data for cosmonauts with more than 75 days of exposure to weightlessness.

SUMMING UP

Human support issues are on the critical path for SEI planning, systems definition, and operations. As noted, key technologies and potential solutions to critical human support issues could evolve from advances being made by the broader scientific and technical communities that are not currently involved in space-oriented life sciences.

In an earlier era, when space research was more consistently and generously funded, NASA was quite effective in establishing and benefiting from broad-based multidisciplinary teams. Institutional barriers and the financially constrained environment of the past 15 to 20 years have substantially reduced the scope of these activities.

Biotechnology and high-temperature superconductivity are areas, for example, where relatively limited investments by NASA could generate major improvements in our ability to refine microgravity countermeasures and radiation shielding. Moreover, the relevant science and technology base is now global, and international participation in life sciences R&D can yield substantial benefits.

It will not be easy to develop effective systems for organizing, managing, and implementing space life sciences programs to meet the long term challenges of SEI. The SEI program can learn from successful technology-based companies whose hallmark is sustained investment in highly productive R&D laboratories—as the corporate labs of AT&T, IBM, GE and Merck demonstrate. Although long-term R&D thrives best when freed from daily operational obligations, interaction and exchange of ideas and staff are essential. This is particularly true for SEI, where no distinct boundary yet exists between important scientific and operational issues.

NASA recognizes the value of complementary diversity and pluralism by maintaining multiple centers of initiative in life sciences. Although overlaps exist, and the transition process from research through sustained operations requires attention, none of the recent assessments of space life sciences suggests consolidating all life science activities at one center. The differing cultural perspectives of operations and more basic scientific research are distinct but essential, particularly for SEI-related programs. Maintaining the proper balance between fundamental and more applied programs is a study in dynamic equilibrium. The roles played by NASA headquarters should be to formulate coherent strategies to achieve this equilibrium and to convey these strategies to policymakers. It should also

encourage more open access to flight experiments and data by all NASA centers, as well as the broader medical community.

The recent debate over the future of the space station has sharpened interest in enhancing the space life sciences knowledge base as a prelude to interplanetary exploration. An even more exciting, ambitious, and ultimately rewarding program is essential to accomplish the needed breakthroughs in human support systems and technology that are needed for SEI success.

ACKNOWLEDGMENTS

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FIGURES

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ACRONYMS

ABCC	Atomic Bomb Casualty Commission
AIAA	American Institute of Aeronautics and Astronautics
AL	Anomalously Large
ALARA	As Low As Reasonably Acceptable
ARC	Ames Research Center
BFO	Blood Forming Organs
BEIR V	Biological Effects of Ionizing Radiation, Five
BMP	Bone Morphogenetic Protein
CELSS	Closed Environment Life Support System
COSPAR	Committee on Space Research
DOE	Department of Energy
DREF	Dose Rate Effectiveness Factor
EPA	Environmental Protection Agency
EVA	External Vehicular Activity
FFRDC	Federally Funded Research and Development Center
GCR	Galactic Cosmic Ray
GEO	GEO-Synchronous Earth Orbit
HTS	High Temperature Superconductor
HZE	High Z, High Energy
ICES	International Conference on Environmental Systems
ICRP	International Commission on Radiation Protection
JSC	Johnson Space Center
LDS	Latter Day Saints
LEO	Low Earth Orbit
LET	Linear Energy Transfer
MI	Myocardial Infarction
MIR	Soviet Manned Space Station
MIT	Massachusetts Institute of Technology
MSFC	Marshall Space Flight Center
MTV	Mars Transfer Vehicle
NAS	National Academy of Science
NCRP	National Council on Radiation Protection and Measurements

NOAA	National Oceanic Atmospheric Agency
NRC	National Research Council
NRL	Naval Research Laboratory
Q	Quality Factor
R&D	Research and Development
RBE	Relative Biological Effectiveness
SEI	Space Exploration Initiative
SPE	Solar Proton Event
SSF	Space Station Freedom
STARPAHC	Space Technology as applied to Rural Papago Healthcare
STS	Space Transportation System
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
UV	Ultra Violet
Z	Charge Number

I. INTRODUCTION

This Note contains the analyses and evaluations of the Human Support panel, one of eight panels created by RAND to screen and analyze submissions to the Space Exploration Initiative (SEI) Outreach Program. In addition to managing and evaluating the responses or submissions to this public outreach program, RAND conducted its own analysis and evaluation relevant to SEI mission concepts, systems, and technologies. The screening and analysis of Project Outreach submissions were conducted on an accelerated schedule between July and November 1990, and involved staff and consultants throughout RAND's departments and research divisions. The panel members also participated in a spin-up process to enhance their familiarity with special SEI programs and concepts. This process involved visits to NASA centers and headquarters, as well as interaction with contractors, academics, and others in the relevant technology areas.

The eight panels created to screen and analyze the submissions encompassed:

- Architectures/Missions
- Automation and Robotics
- Communications
- Human Support
- Information Systems
- Space and Surface Power
- Space Transportation Systems, Launch Systems, and Propulsion
- Structures, Materials, Mechanical Systems, and Extraterrestrial Resource Utilization.

This introduction describes the background of the SEI, the overall methodology used in submission handling and analysis procedures, and some general results and observations.

BACKGROUND

President Bush established goals for manned space flight by announcing a Space Exploration Initiative that includes establishing a permanent base on the Moon and sending a manned mission to Mars within thirty years. The national space policy goals developed by the National Space Council and approved by President Bush on November 2, 1989, were the following:

- Strengthen the security of the United States;
- Obtain scientific, technological, and economic benefits;
- Encourage private sector investment;
- Promote international cooperative activities;
- Maintain freedom of space for all activities; and
- Expand human presence and activity beyond Earth orbit into the solar system.

To support these goals, Vice President Quayle, chairman of the National Space Council, has asked NASA to take the lead in identifying new and innovative approaches that will be required to travel to the Moon and Mars, and to live and work productively on both worlds. Accordingly, NASA began to solicit new ideas and concepts for space exploration that will define promising mission paths for detailed study. The SEI Outreach Program has three principal components:

1. Direct solicitation of ideas from academia, nonprofit organizations, for-profit firms, and the general public;
2. Reviews of federally sponsored research; and
3. A study by the American Institute of Aeronautics and Astronautics (AIAA).

The results of the three efforts listed above were presented to a Synthesis Group chaired by Thomas P. Stafford, Lieutenant General, USAF (ret.). The recommendations[1] of the Synthesis Group are in turn to be reviewed by NASA. From this process, a number of alternative mission paths could emerge, from which NASA may select several for detailed study over the next few years. In addition, the process is expected to yield innovative technologies and system concepts for possible development.

GENERAL OBSERVATIONS ON THE SUBMISSIONS

Our first observation is that the submissions did not appear to contain any new scientific discoveries, although many alerted us to promising areas of science and technology. For example, some submissions suggested applications of high-temperature superconductivity for magnetic shielding of galactic cosmic rays (GCRs). Our analysis showed that recent advances in this technology, in a direction not foreseen by the submitter,

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[1] All RAND fundings were submitted to the Synthesis Group by December 1990 in the form of a series of RAND Working Drafts and briefings. The Synthesis Group report "America at the Threshold" was submitted to Vice President Quayle on May 3, 1991. The report is available from the Government Printing Office.

could facilitate the construction of magnetic shields more powerful than previously thought possible.

The submissions did contain, however, a number of classic ideas that have new implications in the context of the SEI. For example, several submissions included the concept of a spacecraft orbiting at a libration point, a concept that has been proven by NASA's International Sun-Earth Explorer-3, which was put into orbit around the sun-Earth libration point, L-1, in 1978. Libration concepts take on considerable new meaning in the context of potential use as transportation nodes for a Mars mission.

The submissions also contained ideas that had not been heretofore supported by the submitter's organization, which may have been an industrial firm, university, or NASA itself. This is a natural consequence of the priority planning process and resource allocation decisions of each organization. Thus, many of the submitted ideas are not completely new but simply have not received much support.

The submissions sometimes contained ideas that had been buried in the corporate memory of institutions that participated in predecessors of SEI, and part of the analysis process was to recover this memory in a useful way. To illustrate, concepts for magnetic shielding of spacecraft were analyzed 25 years ago, and the hiatus between the last two artificial gravity conferences was 15 years.

Finally, we observe that the submissions were sufficiently diverse to support a wide range of SEI mission concepts and architectures.

THE SUBMISSION PROCESS

Figure 1.1 presents a flow diagram of the Outreach evaluation process. RAND mailed out 10,700 submission packets, in addition to the 34,500 that were mailed out by NASA. A total of 1,697 submissions were received and were initially processed by a subcontractor firm, KPMG Peat Marwick. Of the 1,697 submissions received, 1,548 were judged by Peat Marwick to contain sufficient information for screening by RAND. The screening process selected approximately 183 submissions for more formal analysis. The output of that analysis process is an issue-oriented set of priority submissions and recommendations reported in this and several companion publications.

For further discussion of the sources of submissions and their management by RAND, please see App. A.

THE SCREENING PROCESS

The screening process objectives were to:

- Assure relative insensitivity to the quantity of submissions;

- Select submissions to be analyzed at length;

- Review each submission by at least two technical experts working independently;

- Examine robustness by providing more than one ranking method; and

- Maintain analytic rigor.
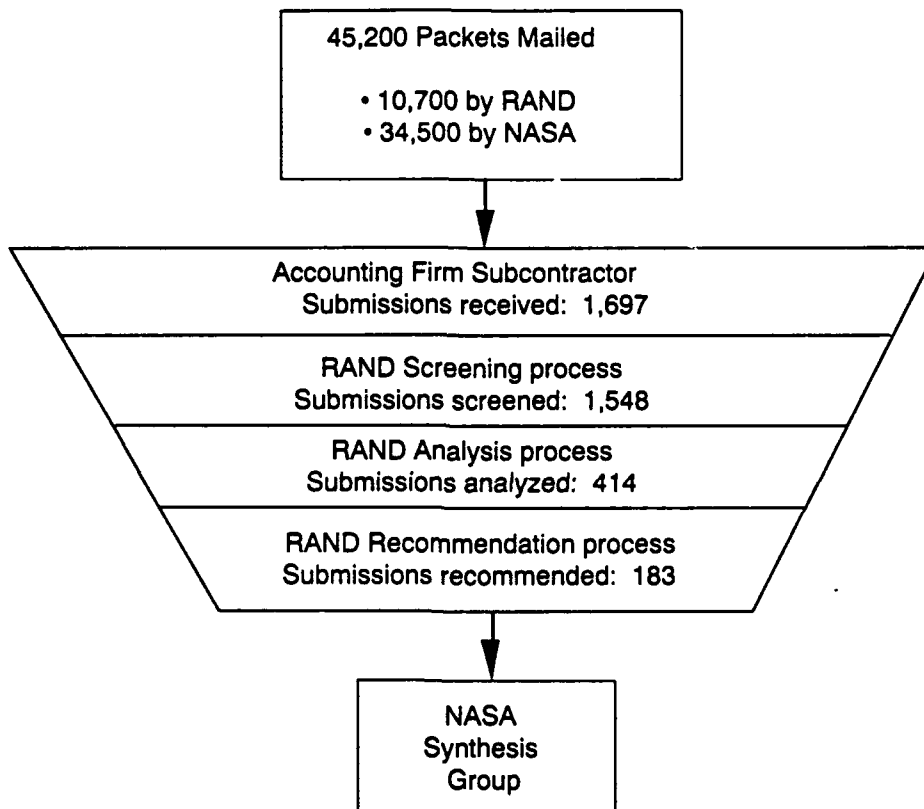
Fig. 1.1 — RAND's Outreach Process

The first objective of the screening process was to assure a good capability to deal with the quantity of submissions, whatever their numbers. Therefore, we constructed a "production line" for processing that would enable insensitivity to the quantity of submissions.

The next task of the screening process was to decide which submissions would be analyzed. We decided that the range and depth of our analysis would have to be a function of (1) the resources available, (2) the perceived quality of submissions across panels, and (3) the relative importance of topics to the overall SEI program.

In the screening process, each submission was reviewed by at least two technical experts working independently. We allowed for robustness by providing more than one ranking method. A related goal was to maintain analytic rigor through the maintenance of tracking systems to enable later analysis of our methodology.

"Multi-attribute decision theory" was used in the screening process, i.e., a group of attributes was used to evaluate each submission. The panels chose to score their various submissions using the same five principal attributes:

- Utility
- Feasibility/technical risk
- Safety
- Innovativeness
- Relative cost

Each panel tailored its own criteria for scoring an attribute according to the panel's specific needs. For example, "safety" meant a very different thing to the Transportation panel than it did to the Human Support panel.

Attributes were independently scored by two or more reviewers on a scale of one to five, with five being the best. Comments and/or written justification for the scoring were input into the text field in the database. We used a widely accepted Macintosh relational database, Fourth Dimension by ACIUS, Inc., for storing and using the various information components of each submission. Formal methods were used as aids to decisionmaking, but human judgment was the ultimate arbiter of those submissions to be analyzed.

A complete discussion of the quantitative means by which panels used their attribute criteria to rank and evaluate submissions is provided in App. A. The specific criteria used by the Human Support panel in assigning attribute scores are also discussed in App. A.

THE ANALYSIS PROCESS

Each panel submitted a preliminary Working Draft to the Synthesis Group on the results of an issue-oriented analysis in its area of technical responsibility. Each Draft and subsequent Note were organized into technical discussions of the important technical

subareas identified by that panel. Where possible, important performance tradeoffs in each subarea were examined quantitatively.

For the Human Support panel, the object of the analysis process was to identify issues and potential options and to show how ideas, concepts, technologies, and recommendations contained in the submissions could assist in meeting the goals of SEI. Thus, it is the combination of the submissions and our analysis of them that is recommended for further consideration by the Synthesis Group. It is important to recognize that even some of the highest-ranking submissions required considerable analysis for their true value to be discerned. When possible, we analyzed the submissions quantitatively within the context of the important unresolved issues in their respective technical areas.

The major human support issue areas we identified were:

- Radiation
- Microgravity
- Life support systems
- Medical care
- Human factors
- EVA suits
- Exercise and conditioning
- Management and organizational issues.

Submissions that arrived with no backup paper, i.e., no detailed substantiating information or documentation, were analyzed in the context of the technical discussions of the appropriate subareas, thus providing necessary background. The majority of submissions did not, in fact, include backup papers, making an extended analytical discussion almost mandatory in most cases.

In terms of the characteristics of the submitters, based on self-designated categories, we found that over two-thirds of all submissions were from individuals or groups of individuals, and that one-third were from organizations.

Of those from organizations, 60 percent were from profit-making firms and about 20 percent were from educational institutions. Appendix B lists the submissions by serial number and title, and App. C provides short descriptions of those selected for analysis.

The process of screening and analyzing submissions was not viewed as a competition among the submitters, but as a means of enriching the base for SEI. In a number of instances, considerable overlap existed among the submissions. Using radiation protection

as an illustration, we found that several submissions recommended a radiation monitoring probe to precisely define the nature of the GCR threat, but only one was specifically selected for analysis. However, the analysis was pertinent to the entire group. This is important because our analysis was informed by data we acquired from the submissions, as well as other sources.

In the human support area, a number of submissions related to the interests and concerns of the American people with regard to nutrition, sex, health, and exercise. Although none seemed to have high priority for SEI at the time, they often demonstrated considerable insight and scientific soundness.

STRUCTURE OF THE NOTE

Section II provides an overview of the priority human support issues that must be resolved for SEI to move forward. We emphasize that an issue-oriented approach was essential to determine how submissions in the human support category could best facilitate SEI progress. Thus, Sec. III deals with the issue of radiation protection. Section IV discusses the issue of microgravity, and Sec. V presents our analysis of life support systems. Section VI deals with issues of medical care. Furthermore, some sections described organizational or management approaches that are most likely to speed the resolution of key issues.

As indicated earlier, App. A discusses the submission handling and evaluation processes and the specific criteria that the Human Support panel used in evaluating its submissions. Appendix B presents a listing of all submissions screened by this panel, and App. C provides descriptive summaries of the submissions chosen for analysis. Appendix D presents a discussion of the evaluation of passive shielding requirements to protect against GCRs.

II. OVERVIEW

In this section, we propose a set of candidate overarching requirements that can help to further the SEI human support goal. We then describe the seven specific areas that enter into considerations of human support. We also touch on several organizational and management matters, and preview our analyses of the high-ranking submissions.

Human survival, tolerance, and performance are design drivers for long-term space exploration. SEI poses human support issues that require an unusually strong collaboration between life sciences and the engineering community for resolution. Furthermore, the time and research costs of resolving these issues, or even of performing the research, development, engineering, and testing in space to properly define alternative ways to resolve them, could be substantial. Also, there is no assurance that enlarging the knowledge base will facilitate resolution: for example, in the area of radiation protection, improvements in the knowledge base have permitted us to sharpen our risk assessment procedures, but, as a result, radiation risk estimates are far more pessimistic now than in the past.

A genuinely multidisciplinary approach to life science issues is essential. Overcompartmentalization will result in unrealistic system configurations and resource forecasts. An uncompartmented approach to life science results in additional flexibility, as well as the opportunity to benefit from a broader scientific and technical community.

It is important to recognize how exposure tolerances and countermeasures relate to three categories of scenarios: baseline, baseline and contingency, and emergency. Baseline, for example, could be a mission duration of two years based on chemical propulsion. A baseline contingency could be a three-year Mars trip that had to be aborted and entailed a safe-return orbit. An emergency might involve an unexpected despin of a rotating spacecraft system. Obviously, all systems should be capable of dealing with contingencies. Dealing with emergencies is more case-specific.

Although it is difficult to be very precise, evidence suggests that human support requirements increase in difficulty with mission duration. Radiation bioeffects, microgravity associated pathologies, and the required quantity of life support expendables all increase with time of exposure during interplanetary flight. Thus, there could be an advantage for architecture concepts that facilitate shorter trip times. But the need for designs to also accommodate the possibility of an aborted mission (baseline contingency) could diminish the magnitude of this advantage. Also, comparisons among different architectures must be informed by knowledge of their ability to meet support requirements for a safe-return orbit.

HUMAN SUPPORT REQUIREMENTS

NASA Life Sciences has adopted as its first primary goal "to ensure the health, well-being, and performance of humans in space." We have recast this goal into three proposed human support objectives for the SEI program:

1. Astronauts will engage in a Mars mission only if the predicted levels of safety, risk, and reliability are acceptable, and there is very high likelihood of their survival in good condition or restorable health.

2. Astronauts will be able to perform their mission tasks productively and effectively, and their performance will not be unnecessarily compromised by physiological responses to the space environment or by countermeasures to mitigate these responses.

3. Astronauts' future careers and health status will not be significantly jeopardized by their exposure to the space environment.

Satisfying the first goal entails careful attention to designing around the various limits to human tolerance. It also implies that predicted *safety* margins and failure rates for human systems should be small or no worse than those permitted for mechanical, chemical, electrical, or other spacecraft systems. We use the term "restorable" because we recognize that a period of adjustment following a long mission may be necessary before full Earth adaptation and equilibrium are achieved.

Satisfying the second requirement involves paying proper attention to conditioning, human factors, behavior, and performance elements to assure that actual human performance best approaches its potential. It implies that astronauts are not showpieces, that they are involved because manned systems can perform critical functions better than unmanned or robotic systems. It also implies that attempts will be made to adhere to the classic Weiner dictum of "the human use of human beings."

Satisfying the third requirement involves paying proper attention to minimizing, avoiding, or countering the delayed deleterious effects that could damage an astronaut's postmission health and career.[1]

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[1] We recognize that such terms as "acceptable, high likelihood, significantly" are subjective until they achieve more precise definition in the context of a specific mission. Our purpose in using these terms is to compel explicit consideration of risks to astronaut survival and performance.

MAJOR HUMAN SUPPORT ISSUE AREAS

As noted, the major human support issue areas we identified were:

- Radiation
- Microgravity
- Life support systems
- Medical care
- Human factors
- EVA suits
- Exercise and conditioning
- Management and organizational issues.

We discuss each issue in broad terms below. We again remark that human support requirements for radiation protection and microgravity countermeasures increase with time of exposure, as do the other factors that influence crew well-being and performance.

Radiation

Radiation poses issues of risk assessment and protection that need to be addressed, since radiation from GCRs and solar proton events (SPEs) imposes the hazards of immediate effects, as well as lifetime career risks. As described later, the precise particle spectra (energies up to 2 GeV), fluences (particles/cm^2), and relative biological effects are not yet well defined for GCRs. The best available radiobiological damage estimates from NASA work using the Berkeley BEVELAC have an estimated uncertainty factor of 30–40, excluding uncertainties in dose estimation.[2] The dose response characteristics of space-associated radiation, for purposes of risk assessment, exhibit increasing risks with increased dose.

Mass shielding using low-atomic-weight materials, such as liquid hydrogen or water, is the most straightforward approach to protection, but the marginal effectiveness of shielding is very low due to fragmentation and the emission of secondary and tertiary particles after collisions with the energetic highly charged ions that constitute the major GCR hazard. Estimates of shielding mass requirements for a five-astronaut Mars transfer vehicle (MTV) habitat range from three to thirty times the mass of the habitat, or 100 to 1000 metric tons, with virtually no margin for safety. A synergistic effect of microgravity on

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[2]The uncertainty factor is subject to considerable debate within the space radiation community. The estimate is taken from the NASA Draft Radiation Health Program Plan of June 1990. It is also included in a report by NASA Administrator R. Truly submitted to Congress in December 1990.

radiation damage has been observed and could further complicate this area. Radiation protection concerns impact spacecraft design, mass-to-orbit, mission duration, and ultimately crew survival and well-being.

Two high-ranked submissions, **#101460** and **#100742**, recommend that spacecraft instrumented with radiation dosimeters be flown beyond the Earth's protective magnetic field and in a trans-Mars trajectory and orbit. This is important because NASA does not now have concrete plans to gather such data within the next decade, and it seems clear that radiation protection questions could delay or cause cancellation of SEI missions.

Although mass shielding is the most direct approach, the use of active magnetic or electrostatic shielding against charged particles also deserves attention. Electrostatic shielding is less attractive than magnetic shielding. One high-ranked submission, **#100699**, proposes that high-temperature superconducting magnets could be far more effective than low-temperature superconductors in providing high magnetic fields to deflect particles from the vehicle. Previous NASA work suggested that magnetic fields of 4.5 tesla in magnitude would be inadequate to deflect heavy, energetic, charged GCR particles. Stimulated by this submission, we found recent data from Japan that imply that new high-temperature superconductors, when operated at liquid helium temperatures, could someday provide fields much greater than this magnitude. We find that levels of 40 tesla and a shield thickness of a meter could protect against even 2 GeV iron ions. However, a number of major problems need to be solved before feasibility can be fully demonstrated. But this is an area where NASA can "piggyback" on developments that are heavily supported by others.

Although protection against occasional SPEs can be provided by storm shelters and warning systems (except during EVAs), recent evidence (during solar cycle 22) suggests that our understanding of flares and solar emissions is still very limited and that the unpredictability and ubiquity of high-energy solar protons is greater than previously thought. SPEs are operational constraints but are also survivable occurrences if a storm shelter and adequate warning are both available.

Microgravity

Microgravity poses issues of physiological deterioration, adaptation, postmission health status, and countermeasures. The microgravity environment of space is responsible for physiological changes in the cardiovascular, musculo-skeletal, neurovestibular, neuromotor, and possibly immunological systems. Cardiovascular deconditioning will impact crews' ability to tolerate high-aerocapture g profiles at both Mars and on Earth return. Loss

of muscle mass could compromise peak strength and endurance, diminishing work load capacity during EVA and emergency egress.

Loss of skeletal mass seems to be irreversible despite substantial research into countermeasures. The fracture threshold is approximately 25 percent lower than normal density and could be approached in missions of two–three years in duration without effective countermeasures. Possible countermeasures include pharmaceuticals, exercise, or artificial gravity, but none has been successfully demonstrated. Enormous progress is being made in the area of bone metabolism, molecular biology, and bone growth factors that could, within a decade or so, cure osteoporosis and incidentally provide effective countermeasures against bone demineralization. Coincidentally, two decades ago, NASA supported research on etidronate, a currently favored drug for treating osteoporosis. NASA could benefit from a greater effort in the metabolic engineering and therapy of bone disorders. The recent discovery that denning (hibernating) bears maintain bone strength during four months of winter inactivity, alluded to in submission #100233, confirms the existence of a natural model for mitigating the effects of microgravity on bone.

Exercise countermeasures used by the Soviets required two to four hours of crew members per day; this was onerous to the crew and would be even more so on longer-duration missions.

Continuous or intermittent artificial gravity configurations have been proposed, ranging from a man-rated centrifuge to specialized spacecraft design. The literature suggests that problems may exist with human ability to tolerate (or adapt to) rotation rates greater than one or two rpm and subsequent readaptation to cessation of rotation. One high-ranked submission, #101270, proposes a coordinated program of Earth and space testing to explore some of these issues. The lack of a suitable Earth-based model implies that a major space test program will be necessary to test both human tolerance and countermeasures.

Baseline spacecraft designs capable of rotational generation of artificial gravity have been made with significant mass and program cost penalties (of 20 to 40 percent) if GCR radiation shielding mass is neglected. Including proper contingencies for shielding mass and a margin for stop-start cycling for EVAs could render artificial gravity systems too complex and heavy to consider. The challenges of designing systems for both 0 and 1 g operation are significant, yet even with the increased design complexity, other problems remain or are introduced. EVA activity would be far riskier, while problems of radiation and habitability remain unabated. Spacecraft dynamics, particularly in a rotating tethered system, pose interesting challenges.

Good long-term data on zero g exposure are not yet available, although proposed collaborative research on the Russian space station MIR could be helpful, as suggested in submission #101270. The maximum Soviet duration in orbit is only one-third of the possible three years for a Mars mission. No integrated model of biological adaptation to zero or partial gravity has yet been developed. In addition to #101270, submission #101271 suggests that a revolutionary approach should be considered that eliminates the need for a long-term program of artificial gravity research and simultaneously solves the radiation protection problem by constructing a massive rotating spacecraft using Lunar or asteroid-derived materials.

Life Support Systems

Life support systems involve issues of reliable, closed, physical-chemical, and/or bioregenerative systems. Current baseline designs for the space station depend entirely on reliable resupply of air and water consumables from the ground. The mass costs are unacceptable for any extended-duration manned missions, either on the Lunar surface or for Mars transit and exploration. While the Soviets believe they could simply stock supplies for a two-year mission, serious long-term exploration requires a commitment to bioregenerative, closed, ecological life support systems. These systems must be capable of recycling and providing air, water, and food, while controlling toxics and bacterial or viral contamination. Stable, robust life support systems are essential to reducing remote outpost dependencies on resupply missions.

In order of complexity, partially closed physical-chemical systems would be first, followed by closed physical-chemical systems, followed by a closed combination of bioregenerative and physical chemical systems.

Pilot plant evaluation, scale-up, and in-space validation must be performed under actual operating conditions, in zero gravity or on the Lunar surface. Lunar validation of such systems should precede any situation of long-term dependency on Mars. Three high-ranked submissions, #101275, #101411, and #101281, touch on important aspects of life support systems.

Medical Care

Medical care involves issues of autonomous medical care and life-threatening emergencies. Experience in analog environments supports the need for comprehensive medical/dental and emergency-care capabilities. While the Lunar surface may be "only" three days away, the ability to stabilize and treat trauma or medical emergencies must be

included. The need is greater on a Mars mission due to the impossibility of rescue or return to Earth in a meaningfully brief period and because any extensive illness or trauma will consume the productive time of multiple crew members, as well as the patient.

The crew should include at least one current, comprehensively trained physician/surgeon, but a team approach will be needed. High-fidelity validation in remote isolated environments is essential, following a progression from hospital, to remote site, to space. Two high-ranked submissions, #100790 and #100776, offer frameworks for addressing these issues in a way that reflects a deep knowledge of NASA and operational space medicine.

The primary medical officer will coordinate or implement the roles of (1) primary physician, (2) specialist on the impact of adaptation and space systems, including countermeasures, (3) emergency/trauma physician, and (4) monitor and possible intervenor in neuropsychiatric/behavioral issues.

Human Factors

Human factors involve issues of human performance and behavior in stressful, isolated, confined environments for extended periods. Crew selection, command structures, conflict resolution, and habitability will affect the crew's productive capacity. Crew selection, compatibility, dynamics, and control structures need extensive research. Not only is little known, but aerospace community interest in this area has been seriously limited. Recent acceptance of the importance of team training and team dynamics (crew resource management) is promising. Excessive reliance on "crew professionalism" has been the hallmark of this area, and open discussion of actual operational problems has been considered detrimental to the space program. (Recent astronaut corps acknowledgment of such problems and their support for further research represent a major breakthrough.)

Meaningful analog studies on Earth and in space are required. While the Antarctic analog could be quite productive, proposals that have the crews wintering over in prepared, established bases substantially miss the point. Abnormal maladaptive behavior due to exposure to toxics may be indistinguishable from psychosis. Senior observers of military and exploration efforts have pointed out that human factors were responsible for mission failure more often than equipment factors.

Spacecraft habitability and ergonomics also require more support and integration into systems design. One high-ranking submission, #100701, suggests a careful study to optimize work performance in space, which, if successful, would improve human performance beyond the present level in space. Another high-ranked submission, #100959, proposed a careful

study of cognitive performance in space based on the evidence that considerable alterations in neural fluid balance and physiology due to microgravity could result in altered performance. This is also consistent with animal studies that suggest that another space hazard, GCRs, could change brain chemistry and ultimately influence behavior.

EVA Suits

EVA suits involve issues of suit design to enable productive work and surface exploration within the restrictions of mass and suit durability. Suit pressure relative to habitat pressure and glove dexterity poses primary design problems. Meaningful work on the Lunar or Martian surface requires mobility. Suit designs must be adapted to fractional gravity and variable surface conditions. Manual dexterity is essential to many maintenance or scientific tasks. High suit pressure minimizes the need for prebreathing and the risk of embolism but creates substantial challenges for designing reliable, flexible joints and dexterous, reliable gloves. Submission #100701 dealt with the ergonomics of work in microgravity. Given the degree of exhaustion reported by the Soviets after three to four hours of EVA, this is an area worth further attention.

Exercise and Conditioning

Exercise and conditioning would act primarily as countermeasures to microgravity-related deconditioning but may also be essential on the Lunar/Martian surfaces. The concept of sufficient gravity, i.e., the existence of a threshold capable of maintaining conditioning, is unverified.

Effective exercise is required to maintain muscle mass and cardiovascular fitness. Whether it will also minimize loss of bone mass is untested. Debilitation could affect survival in emergency egress or ability to tolerate reentry g profiles and subsequent ability to exit spacecraft upon landing. No high-ranking submissions in this category were received, although several that offered small advances in the state of the art were submitted. Exercise may still be essential in a continuous artificial gravity environment. The ability to define exercise prescriptions requires research both on Earth and in fractional g environments. Aerocapture g profiles will be limited by human tolerance.

Management and Organizational Issues

The resolution of management and organizational issues is a necessary condition for solving the difficult problems raised here. Although we received no high-ranking proposals specifically in this area, a number of knowledgeable submissions dealt with these issues

tangentially, reflecting an awareness of several recent studies of space life sciences. Pitts[3]
has documented the historic tensions that existed between life science concerns and the
concerns of an essentially engineering and mission-oriented agency. More recently, a
number of distinguished panels were specifically tasked to review and evaluate the
administrative as well as the technical aspects of space life sciences.[4-7] Their
recommendations are germane to facilitating the extraordinary advances in human support
science, technology, and systems required for SEI success.

NASA has long recognized the value of diversity and pluralism by maintaining
multiple centers of initiative in life sciences. At a strategic level, the 1991 Space Studies
Board report emphasized "the need for a well balanced research program in terms of ground
versus flight, basic versus clinical, and internal versus extramural," in this way endorsing
the concept of multiple centers of life science excellence, each with a somewhat different
orientation. The Robbins Report noted the lack of "an organized and visible space life
sciences constituency to advocate its agenda with individuals who control resources." It also
commented on the relative roles of Headquarters and the Centers and underscored the need
to develop coherent high-level strategies for managing and directing complementary
multicenter activities directed towards long-term space flight. These strategies would
minimize the risks of fragmentation "in terms of organization structures and decision
processes." In addition, it recommended increased outreach activities to the broader
scientific community and universities both to train new investigators and to conduct research
in space life sciences.

Although it is desirable to engage professors and graduate students (as suggested by
The Robbins Report), it is not easy to maintain university-based life science research
programs that involve access to space. As an example, the life science experiments flown on
Spacelab I in June 1991 were initially proposed in the late 1970's, and were based on designs
that relied on cumbersome ground-based rather than space-based data processing, as well as

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[3]J. A. Pitts, *The Human Factor: Biomedicine in the Manned Space Program to 1980*, NASA, Washington, D.C., 1985.

[4]*Exploring the Living Universe: A Strategy for Space Life Science. A Report of the NASA Life Sciences Strategic Planning Study Committee*, NASA, Washington, D. C., June 1988. (Also known as "The Robbins Report.")

[5]Space Studies Board, *A Strategy for Space Biology and Medical Sciences for the 1980s and 1990s*, National Academy Press, Washington, D.C., 1988. (Also known as "The Goldberg Report.")

[6]Space Studies Board, *Assessment of Programs in Space Biology and Medicine 1991*, National Academy Press, Washington, D.C., 1991.

[7]Life Support Management working Group, *Final Report*, June 2, 1989, (also known as "The Smylie Report"). This report focuses on life science management structure roles, responsibilities, and options that are especially pertinent to SEI.

equipment that was essentially obsolete by the time it was flown. Both the uncertainty associated with schedule delays and the maintenance of life science priorities for manned and unmanned flights, and the progressive obsolescence of equipment have been barriers to developing academic careers in these fields.

The critical dependence of successful space exploration on human support/life science issues stands in contrast to the funding support provided in this area. Life science programs have historically received about 1 percent of the NASA budget, a level that permits little surge capacity to anticipate the research and planning needs for SEI. As mission success and productivity ultimately depend on the health, safety, well-being, and productivity of the crew, it is essential to strengthen life science support (as also proposed by the Augustine Committee) and encourage life science participation in early mission planning.

NASA already has significant SEI-related capability in several field centers and substantial staff enthusiasm for intercenter cooperation. Both formal and informal collaboration among groups located at different centers should be promoted to strengthen SEI planning and decisionmaking. Strong collaboration among NASA centers, and between NASA and the broader scientific community, may hold the key to scientific credibility, to better support from the scientific community, and ultimately to mission success.

III. RADIATION PROTECTION

Protecting SEI crews from chronic radiation exposure hazards, both in space and on Lunar or Martian surfaces, poses an enormous challenge to the scientific and technical community. Astronauts in space are exposed to ionizing radiation fields that are more intense and capable of producing injury than those on Earth,[1] since the Earth's atmosphere and magnetic field protect against high doses. An average U.S. inhabitant receives a total of 3.6 mSv a year (360 millirem), but 82 percent of the total burden results from natural exposure, mostly from radon gas in homes. (About 16 percent of the natural exposure comes from cosmic and terrestrial radiation sources.) For the remainder, medical applications account for 15 percent; and the nuclear-fuel cycle, occupational exposure, and fallout account for less than 1 percent and consumer products account for 3 percent, according to BEIR V.

Astronauts in Earth orbit are exposed mainly to protons and electrons that are trapped in the Earth's magnetosphere. Doses increase with time of exposure, altitude, and passage through the South Atlantic anomaly. To illustrate, astronauts on shuttle flight STS-41B, at an altitude of 297 km and an inclination of 28.50 degrees, received an annual dose equivalent of .58 mSv during an eight-day mission, at a yearly rate of 26 mSv. Astronauts on shuttle flight STS-41B, at an altitude of 519 km and a similar inclination, received a dose equivalent of 5.0 mSv during a seven-day mission, at a yearly rate of 260 mSv.

To fix ideas about the possible risks to human health, the latest assessment from the National Research Council-National Academy of Science (BEIR V) projects an 8 percent increase in the risk of dying from cancer for an average American exposed over a day or two to 1 Sv (100 rems) of ionizing radiation and a rate of about 5 percent if the exposure is over a longer period.

Some other relevant exposure quantities are: for the center of the Earth's inner radiation belt, 10 Sv/hr; for a large solar flare, over 1 Sv/hr; for an astronaut exposed to GCRs with minimal shielding, 1.2 Sv/year at the skin surface and .6 Sv/year for deep tissue.

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[1]Much of this material is a synthesis of information found in two publications, NCRP Report No. 98, *Guidance of Radiation Received in Space Activities* and Advances in Space Research, Vol. 9, No. 10, 1989, and *Life Sciences and Space Research XXIII (4) Radiation Biology*. The reader interested in further data and specific citations will find these extraordinarily useful. Much of our discussion of bio-effects is drawn from the sources.

NATURE OF THE PROBLEM

The conventional wisdom until recently was that radiation protection would be achieved by mass shielding and by minimizing the time of exposure.[2] Later, we indicate how computations from NASA and others may be used to infer that shielding masses between 10^5 kg and 10^6 kg or even larger may be required to shield the 30,000 kg habitat portion of an MTV based on limiting the excess absolute lifetime risk of cancer mortality to 3 percent (0.25 Sv/year) for an astronaut who could, because of an aborted Mars mission, be in interplanetary space for a total of three years. Converting these shielding masses into the total mass required to be placed in low Earth orbit (LEO) for an MTV (using a simplified Hohmann transfer), we found that the LEO mass requirements increase from 500,000 kg for the negligible mass shielding case to 1.5×10^6 kg for the case of 10^5 kg H_2O shielding mass, and 9.9×10^6 for the case where 10^6 kg of H_2O shielding is required. We must emphasize that these broad ranges account for uncertainty but do not provide a safety margin.

The large magnitudes of these quantities are convincing evidence that radiation protection is a possible mission-altering or mission-thwarting issue, that alternatives to straightforward passive mass shielding using hydrogen-rich materials need to be considered, and that a reliable set of space radiation dosimetry measurements is needed to provide accurate input data for shielding analysis. These topics are, in fact, the subjects of two strong submissions that pertain to radiation protection.

As we describe later, genuine uncertainties in radiobiology, physics, risk assessment, and the radiation environment suggest that there could easily be more than an order of magnitude of uncertainty in the biological dose equivalent due to GCRs, which would in turn result in an uncertainty in shielding mass that is far more than the factor of ten we have used here. While there is some likelihood that a well-designed radiation health R&D program could markedly narrow the range of uncertainty, there is no assurance that more precise future estimates of the required shielding mass will be less than we presently estimate.

It must be noted that the AIAA preliminary report (pp. 117–120) suggests that shielding against GCRs might entail a mass penalty of 100 tons. Also, the McCormack-Nachtwey radiation article in the 1989 edition of *Space Physiology and Medicine* states, "The weight of increased hull mass or storm shelters may be prohibitive." Finally, the December 1989 SEI databook estimated shielding masses between 60 and 800 metric tons. Thus, there already seems to be support for our observation that straightforward H_2-rich mass shielding

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[2]The past year has seen a change in the direction of recognizing the enormous and uncertain mass penalties associated with passive shielding of GCRs.

to reduce radiogenic doses received by astronauts during a Mars mission may impose enormous, perhaps even unacceptable, mass penalties. This suggests that active shielding and a serious attack on narrowing uncertainty in both the radiobiology and physics of GCR interactions are essential.

THE SPACE RADIATION ENVIRONMENT

Ionizing Radiation—Sources in Space

Space radiation hazards are due to trapped protons and electrons in LEO, particularly the high-energy trapped protons and bremsstrahlung radiation in Geosynchronous Earth Orbit (GEO); high-energy protons, alpha particles, and heavy ions from occasional solar proton events that can reach even LEO but are particularly hazardous outside the Earth's magnetic field; and the energetic protons, alpha particles, and heavy ions that constitute the galactic cosmic rays found in space outside the Earth's magnetic field. For SEI astronauts, particularly if not properly shielded, the most acute hazard is from occasional solar proton events associated with flares that are unpredictable in frequency, intensity, and duration, but that can deliver extremely high doses in short periods of time. An unshielded astronaut would have received 600 rems in deep tissue during the so-called anomalously large (AL) event of August 1972. As described below, exposures of this magnitude would result in prodromal vomiting, fatigue, diarrhea, nausea, and severe bone marrow depletion, leading to infection and death for untreated individuals. Extraordinary events occur a few times during the active portion of the solar cycle, and may possess fluences of $> 10^{10}$ protons/cm^2 for particles with energies > 10 Mev. A large number of these events have occurred since 1989, and in most cases, mission analysts and planners are not yet aware of their scale and frequency.

In deep space, on the Moon, and to a lesser extent on Mars (because of the protecting effect of the Martian atmosphere), chronic radiation exposure from GCRs could initiate potentially fatal neoplasms.

Protons, alpha particles, and heavy ions are all found in GCRs, but charged iron is the most significant particle from the viewpoint of radiation hazard. Although the abundance of iron ions is less than 10^{-3} times the abundance of protons, biological effects depend on energy deposition (or Z^2) and a quality factor that varies with linear energy transfer. As a consequence, charged iron particles have six or seven times the biological effect of GCR protons. GCR ions with energies in the GeV (10^9) nuclear range are major sources of exposure. However, it is likely that rare GCR particles exist with energies in the 10^{18} to

10^{20} GeV per nucleon range, associated with so-called "Centauro" events. There is no statistical basis for estimating the likelihood of encountering such particles, although experiments to search for them have been planned.

We note that GCRs vary with the portion of the solar cycle, being at their maximum intensity during solar minimum. GCRs are considered to be isotropic and spatially and temporally invariant, except for their solar cycle dependence. One high-ranked submission, **Radiation Monitoring on Unmanned Mars Probe (#101460)**, recommends that direct radiation monitoring of both the dose and the energy spectrum of radiation be measured on unmanned probes to Mars to verify our knowledge of GCRs. The submitter, a representative of an organization concerned with radiation protection and measurement, suggests that the doses that might be experienced by Mars travelers is potentially so large that it would be important to reduce the uncertainty in estimates of the radiation field. Another submission, **#100742**, suggested that real-time radiation monitoring be performed on an unmanned space probe, rather than simple track measurements that are mainly useful for assessing the cumulative dose. Both of these submissions establish convincing evidence that careful radiation monitoring should be performed as soon as possible.

To our knowledge, NASA has no firm plans to instrument a spacecraft during the next decade to monitor the radiation field between Earth and Mars. However, such measurements are of high priority for the SEI. Current assessments suggest that GCR spectra are known within about a factor of two but are not uniformly well characterized across the entire solar cycle. Since radiation protection could be a major determinant of mission architecture, it would be important to verify that our knowledge of GCRs, as contained for example in the CREME model of the Naval Research Lab (NRL), is reasonably correct. It would also be useful to obtain a number of radiation measurements during different parts of the solar cycle to determine the spatial and temporal properties of GCRs as a function of solar activity.

Galactic Cosmic Ray Ions

GCRs have low fluences compared to SPE, but the energy deposition per particle is large because kinetic energies are in the relativistic range, and because energy deposition is proportional to Z^2 where Z is the charge number (Z = 26 for iron). Furthermore, heavy ions such as iron are estimated to possess high RBEs for serious radiation bioeffects. The maximum particle flux occurs in the neighborhood of 2GeV/nucleon, but particle kinetic energies as high as 10^{20} GeV/nucleon exist (Centauro events).

GCRs, originating outside of the solar system, consist of ionized nuclei accelerated to high energies. The Earth's magnetosphere and atmosphere shield sea-level locations against GCRs, although there is an altitude and latitude dependence for cosmic ray showers. Astronauts in LEO receive little exposure to GCRs, but operations on the Moon and in interplanetary space would be subject to GCR exposures. Although Mars does not have a magnetosphere, the Martian atmosphere would shield against some GCR particles, and, because GCRs are isotropic in space, operations on planetary surfaces receive only half the free-space flux. In the energy range between 100 MeV/nucleon and 10 GeV/nucleon, GCRs consist of 87 percent protons, 12 percent helium ions, and 1 percent of heavier ions, but as noted, the heavier ions are most troublesome from the viewpoint of radiation protection. The maximum particle fluence rate at solar maximum is about $4 cm^{-2}s^{-1}$, many orders of magnitude below the fluence rates associated with SPEs. GCRs vary with the solar cycle, being somewhat lower in flux when solar activity is high (and the solar wind more powerful). GCR intensity varies smoothly with the solar cycle, the maximum occurring at the minimum of solar activity (solar min) and the minimum occurring at solar max. Calculations have been performed for shielding requirements as a function of solar cycle that utilize a formula using cyclic functions to represent the solar cycle effect. The ratio of solar maximum to solar minimum GCR proton flux ratios is at a minimum of 0.1 at about 10^2 MeV, at about a factor of 0.3 at 1 GeV, and approaches unity at higher energies. Thus there is an important shielding advantage in missions during the solar maximum portion of the cycle if solar proton events can be dealt with properly.

The question of uncertainty in the space radiation environment is important, with factors of two or slightly greater in certain GCR spectral ranges being quoted. However, these uncertainties are small relative to uncertainties in bioeffects or perhaps even in the accuracy of shielding computations. Nevertheless, it is important to determine the GCR spectra accurately, mainly for planning purposes.

Solar Proton Events

While GCRs are expected to be uniform in space and time except for their dependence on the solar cycle (high during solar cycle minimum and low during solar cycle maximum), radiation associated with SPEs is both directional and transient. Feynmann et al. have examined the distribution of events in terms of size versus frequency and have fit a log normal distribution to the frequency distribution of events up to very large fluences.[3] They

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[3] J. Feynman, T. P. Armstrong, L. Dao Cibner, and S. Silverman, "New Interplanetary Proton Fluence Model," *J. Spacecraft and Rocket*, Vol. 27, No. 4, July–August 1990, pp. 403–410.

calculate that a two-year mission would encounter a fluence greater than 7.7×10^{10} p/cm^2 for
E > 10 Mev at a confidence level of 95 percent and a fluence greater than 1.5×10^{10} p/cm^2
for E > 30 Mev and the same confidence level. Heckman et al. classify SPE into three
categories: small events that occur 5–20 times per vear with fluence between 10^5 and 10^7 for
particle energies > 10 Mev, intermediate events that occur three to six times per year with
fluences between 10^8 and 10^9 for energies > than 10 Mev, and extraordinary very large
events (called anomalously large events by Heckman) that occur one to three times per cycle
(mainly during solar maximum) with fluence greater than 10^{10} pcm^{-2}.[4]

An abundance of high HZE particles is also found during the small events. According
to Jordan and Stassinopoulos, a year's exposure to small SPEs results in an equivalent dose
of 30 rem behind a 3g/cm^2 polyethelene shield, compared with .8 rem for a 15g/cm^2 shield,
and a single AL event produces a dose equivalent of 1,000 rem behind a 3g/cm^2 polyethelene
shield, and 223 rem behind a 15g/cm2 shield of the same material.[5] Dose levels behind
aluminum shields of similar thickness are nearly twice as high for polyethelene, a material
that appears to be a good shield candidate for solar protons. Literature before 1990 describes
two extraordinarily large events—an August 1972 event that was monitored by space
measurements, as well as ground and ionospheric instrumentation, and a 1956 event
observed in the presatellite era. However, four unexpected but large proton event periods
occurred during 1989, three of them of the magnitude of the August 1972 event and one
somewhat smaller. Note that 1989 corresponds to the maximum portion of the solar cycle.
An event that occurred during October 1989 exhibited very high fluences at ground level and
was associated with a powerful geomagnetic storm. M. A. Shea[6] recently summarized the
state of knowledge of high-energy proton events. The current solar cycle (22) has been
remarkably active in terms of such events, starting with a series of relativistic events that
were monitored in 1989 after a five-year hiatus and continuing through 1991 (when this Note
was completed). Some of these events have been sufficiently energetic as to be detected by
the world network of muon monitor that can only infer protons with energies greater than 4
Gev. Shea also cites her earlier observation that 15 percent of solar proton events contain
relativistic particles. She prefers the designation "extraordinary" rather than the previously
used "Unusually Large or Anomalously Large" events since they appear to fit the high end of

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[4] G. Heckman et al., "Strategies for Dealing with Solar Particle Events Beyond the
Magnetosphere," *Advances in Space Research*, Vol. 9, No. 10, 1989, p. 275.

[5] T. M. Jordan and E. A. Stassinopoulos, "Effective Radiation Reduction in Space Station and
Missions Beyond the Magnetosphere," *Advances in Space Research*, Vol. 9, No. 10, 1989, pp. 261–274.

[6] M. A. Shea, High Energy Solar Proton Events, Proceedings of Workshop on Ionizing Radiation
Environment Models and Methods, Apr. 16–18, 1991, Huntsville, Ala.

the Feynmann by-normal distribution. Some in the space radiation community may have been mislead by the relative inactivity of solar cycles 20 and 21. In fact, M. A. Shea and F. Smart suggest in a personal communication that there is "considerable evidence that cycles 20 and 21 were relatively benign in terms of solar particle events compared to solar cycles 17, 18, 19, and 22." They also suggest, as do others, that solar particle events are operational constraints that lead to survivable occurrences. The unexpected clustering of powerful proton event periods, after years of relative calm, confirms that our knowledge of these phenomena is far from predictive.[7] This was recently reiterated by G. Heckman of NOAA in a paper delivered at the 1991 ICES meeting.

If astronauts are engaged in EVAs during a solar flare event and are unable to reach a storm shelter or other proper shielding, they could receive enormously high doses of radiation during a short period of exposure. Free space exposures could be thousands of rems under such circumstances. The increasing awareness of the ubiquity of unpredictably high-energy solar protons suggests that the concept of scheduling a mission to coincide with solar maximum to reduce GCR exposures needs serious rethinking.

Warning systems would need to be developed that would monitor solar activity and then predict with high probability the proximal occurrence of significant SPE. These warning systems would require a full complement of solar instrumentation, and could not rely on a datalink between a detector, Earth station, and MTV because of the time required for communication. The MTV, Lunar outpost, and Mars base would need to receive data from space-based solar instruments with minimal delay.

The question of storm shelters remains open. Were it not for the enormous shielding mass required to protect against GCRs, a small storm shelter surrounded by polyethelene would be useful. However, it could be superfluous if GCR shielding of the thickness and type we discuss here is used. In any case, astronauts *must* always be within a short distance of a storm shelter during EVAs unless our ability to predict proton events is close to perfect.

Required Radiation Measurements in Space

As we noted, several submissions recommend that NASA undertake a program of direct radiation monitoring on unmanned probes to Mars to accurately define the radiation field that astronauts may encounter. **Radiation Monitoring on Unmanned Mars Probe (#101460)** stresses the importance of radiation protection given the possibilities of doses that range between .5 Sv and 2.5 Sv per mission from GCRs and the possibility of SPEs that could

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[7]Communication, J. Feynmann, JPL.

provide an additional dose of 1 Sv of exposure (in the absence of a storm shelter). These are large potential doses, and the uncertainty associated with them is also large.

Since NASA has no firm plans within or outside the Radiation Health Program to obtain measurements of both the dose and the radiation responsible for it during the next decade, planning for a Mars mission may be seriously hampered unless such a mission is undertaken. This is especially important in the light of the enormous masses of shielding that may be required, or the need to initiate a program of active shielding that takes advantage of ongoing advances in high-temperature superconducting magnet science and technology. Other submissions also recognized the importance of these measurements, and one proposed that time-resolved data on the radiation field is a prerequisite to long-term space exploration.

RADIATION BIOEFFECTS

Ionizing radiation can produce illness, death, cancer, and genetic damage in humans. Virtually all of the data to define human effects are for low–linear energy transfer (LET) particles, such as Xrays and gamma rays. Low–LET radiation is characteristic of light charged particles, such as electrons, that are produced by Xrays or gamma rays, where the distance between ionizing events is large on the scale of a cellular nucleus. High–LET radiation is characteristic of heavy charged particles (protons, alphas, heavy energetic ions) where the distance between ionizing events is small on the scale of a cellular nucleus. The conventional scientific approach for comparing high–LET and low–LET radiation effects is through a relative biological effectiveness (RBE), which is equal numerically to the inverse of absorbed doses of the two radiations required to produce equal biological effects. The reference radiation is generally 200 kv Xrays. Thus RBE determination requires iso-effect data for both the radiation type of interest and a reference type of radiation. The quality factor (Q) is distinct from RBE, although estimates of Q rely on scientific data for RBE. Q is an LET–dependent factor, used for risk assessment and radiation protection purposes, by which absorbed doses are multiplied to correspond to the biological effect produced by Xrays or low-energy gamma rays. The dose in gamma rays is multiplied by Q to obtain the equivalent in Sv. Conventionally, Qs are used that have been established by the International Commission on Radiation Protection (ICRP) based on a presumed unique relationship between LET in water (in ke V/μm) and Q. Xrays, gamma rays, electrons, and beta particles are assigned a Q of 1, neutron values range between 2 and 10, protons range between 1 and 10, and alpha particles are assigned a Q of 20 (the maximum value). Iron ions found in GCRs are assigned a Q of 20. Thus, the dose equivalent of an iron ion is 13,500

times that of a proton with the identical energy per nucleon, both because of the quality factor and because the energy deposition is proportional to the charge number squared. As a consequence, GCR iron particle effects are six times more potent than GCR protons, although they are only one two-thousandth as abundant.

The paucity of data regarding heavy high-Z, high-energy (HZE) particles cannot be overemphasized. This has been recognized by NASA, which has proposed a radiation health program to gather data in ion accelerators that are operated by the Department of Energy (DOE). However, the data, should they be acquired, would still need to be anchored to the existing human effects database.

Prompt Effects

So-called prompt human effects of radiation, and the corresponding approximate threshold levels are blood count changes (50 rads), skin erythema (>400 rads), prodromal vomiting (100 rads), mortality with no treatment (>150 rads), mortality with minimal medical treatment (>320–360 rads), mortality with supportive medical treatment (500 rads), mortality with bone marrow replacement (1,000 rads), sperm count reduction (15 rads), temporary sperm loss (100 rads), long-term infertility after survival (600 rads), menopause induction (300 rads), and temporary menstrual suppression (300 rads). These prompt effects are significant in the space context because unshielded astronauts who are engaged in EVAs or Lunar or planetary surface activities could be exposed to particles associated with occasional solar proton events, where the fluences of protons and other solar ions could produce exposures of this magnitude.

Prodromal vomiting may occur within a few days after exposure and can be partially countered by antiemetics. However, it could be dangerous to a helmeted astronaut. Major risks of skin damage could also occur as a result of SPE exposure. A simple measure to mitigate the risks of acute bone marrow depression is to bank an astronaut's marrow on the spacecraft, for possible autologous transplantation. This was proposed in NCRP Report 98 and was also the subject of submission #100225, Coping with Radiation.

Prompt or relatively prompt effects, such as those mentioned above, are of primary concern if astronauts are not well shielded and are exposed to solar proton and heavy ion emissions. Delayed bioeffects that must also be considered include radiation-induced cataractogenesis, carcinogenesis, and perhaps even generalized life shortening. These effects could occur even when dose rates are far lower than for the acute exposures postulated above.

Stochastic and Nonstochastic Effects

First we distinguish between stochastic and nonstochastic effects. Stochastic effects are those where *the probability of occurrence* in an exposed population (rather than severity in an affected person) is a function of dose; these effects are often without a threshold value. Hereditary effects and carcinogenesis are generally regarded as being stochastic. In terms of the classic carcinogenesis paradigm—initiation, promotion, progression—by transforming cells stochastically, radiation triggers the initiation process. It can also influence promotion.

Nonstochastic effects are those whose *severity* is a function of dose. For these a threshold may occur; cataractogenesis, nonmalignant skin damage, fertility impairment, and some hemotologic deficiencies fall into this category.

Later we discuss radiation-induced cancer, the principal life-threatening hazard associated with long-term exposure.

Ocular Tissues

The lens, the retina, and the cornea are known to exhibit radiation-induced changes. Cataractogenesis is a key factor in setting exposure limits. Radiation protection guidelines for the astronauts are often driven by the need to restrict eye exposures, primarily associated with cataract induction. The role of radiation in inducing cataracts was discovered soon after the discovery of Xray. In terms of low–LET radiation absorbed by the eye, the low–LET threshold for a single exposure is 1.0 to 2.0 Gy. Prolonged exposure, over periods greater than three weeks, results in cataract formation above a threshold level of 4 or 5 Gy. The probability of some degree of opacity reaches unity, with 7.5 Gy after acute exposures, and protracted doses between 10 and 14 Gy can induce a 100 percent incidence of cataracts. The RBE for mouse cataract induction by protons is close to unity.

Neutrons are assigned a Q of 10 for nonstochastic effects, including cataract induction. Heavy ion studies on animals imply cataract RBEs between 1.5 and 5.0, but other studies suggest RBEs approaching 40 for 570 Mev argon ions. Iron ion-induced cataracts are far more severe than those induced by 60 Co gamma rays at the same dose level, and conversely, the RBE for cataract induction in rabbits seems to be large. The NCRP assumes a Q value of 40 for the heavy ions found in GCRs. NCRP Report 98 estimated that the dose equivalent rate for cataract formation was about 2.5 rem/day for astronauts on the Apollo 17 mission. As noted below, risks of late cataract induction due to HZE exposures could be significant, based on a number of animal studies.

The retina is another sensitive ocular tissue. Light flashes seen by Apollo astronauts were reproduced at Berkeley when HZE particle beams became available. Radiation-induced

effects at low–LETs are seen only at high doses, but a number of phenomena exist that suggest a fundamental difference between the mechanisms of radiation damage for high–LET HZE particles and Xrays or gamma rays. Heavy ions may induce microlesions in the retina that resemble tunnels, and a number of morphological and functional changes have been observed in ground-based and space experiments.

The tracks of heavy ions consist of a wide core of dense ionization that can damage even those cells that are not dividing. The Apollo light flashes were attributed to the traversal of these ions. Todd's estimates, cited in NCRP Report 98, suggest "that HZE particle irradiation could result in a loss of about 3 percent of retinal cells during a 90-day mission." The way in which signals are integrated from groups of photoreceptors implies that a single heavy ion traversal, with fragmentation of the particle track, could cause greater damage than predicted in the base of fluence levels. Certain retinal cells integrate signals from hundreds of photo receptors, and the loss of a single one of these (horizontal) cells would be equal to losing hundreds of photoreceptors. However, other evidence suggests that the cells of the retina can absorb a high level of energy with a low probability of permanent damage. Repair processes seem to be efficient, but a question is posed regarding the possibility of retinal secondary DNA breakdown recurring later in life.

Microlesions

Exposures to extremely low fluences of HZE particles can have important biological effects. Microlesions can be formed in which the localized damage caused by a single HZE particle track consists of a dead cell zone surrounded by mutated cells. A 1954 observation that a single cosmic ray hit resulted in depigmentation of individual mouse hairs stimulated thinking about the microlesion concept and the dramatic differences between the mechanisms of action for HZE particles and low–LET particles. It should be noted that the frequency of HZE particles would be significantly reduced by shielding greater than 20–30 gm/cm^2 of H_2O.

The existence of microlesions implies the detectability of the effects of a single HZE particle. Single HZE particles affect a number of cells, since the radial distance over which an iron ion has high LET is of the scale of mm's, and one particle could clearly kill, damage, or transform a number of cells. Detailed studies of microlesion morphology are not conclusive regarding biological significance, but the concept seems to be reasonable. To underscore the importance of individual HZE particle tracks, we refer to work by Curtis and Letaw, who estimated that during a three-year mission in a heavily shielded vehicle, one-

third of an astronaut's cells would be hit by at least one particle with Z greater than 10, and 6 percent would be hit by at least two such particles.

Thus, individual cells might be at risk of cancer induction, and critical renewal cells and networks might be vulnerable to prompt or delayed damage or inactivation. This seems to be supported by studies of the retina, the brain, and the cornea. Even behavioral changes have been found in mice exposed to low doses of HZE radiation. Neurochemical alterations were also found at levels as low as 10 rads, and the possibility exists that fundamental neural differences exist between HZE and Xray or gamma exposure. Neural effects of HZE particle traversals could impair the ability of astronauts to perform critical tasks, as well as affect their future health status. Although there is only limited data regarding these effects, an obvious need exists to perform further research on animals to clarify these issues.

In general, it appears that the database to support precise risk estimation is surprisingly thin, particularly for effects that have no counterpart in the low–LET literature.

Even for cataract induction, which has been reasonably well studied, experiments using long-lived animal species suggest that late radiation-induced opacification could occur at exceedingly low doses (< .05 Gy), but these effects would not be discernible in a shorter-lived species. Thus the possibility exists that there is no threshold for late cataract induction by HZEs, and decisions about radiation protection limits may thus need to be based on a more precise balance between risks and benefits.

Carcinogenesis

The most serious and well-documented delayed effect of ionizing radiation is the induction of cancer. It is beyond the scope of this section to describe the current state of understanding of radiation-induced carcinogenesis. It is presumed that free radicals and electrons are involved in low–LET carcinogenesis, involving both indirect effects due to free radicals stemming from water irradiation and direct effects due to electrons. Free radicals react with cellular material, and electrons directly excite or ionize cell material by direct interaction with critical molecules. DNA is the most critical site for damage, but other sites may also be important. In terms of cell killing, single- and double-strand DNA breaks, local multiple-damaged sites, and DNA-protein cross-links are implicated as lesions that lead to cell death. Ionizing radiation is a highly efficient cell-killing agent when compared with most other agents, such as UV light, aflatoxin, hydrogen peroxide, etc., using as a criterion the number of lesions per cell per dose of agent to kill 63 percent of exposed cells. High doses of radiation kill cells. Lower doses may damage cells that continue to proliferate, and if the dose rates are low or doses are fractional, DNA lesions may be repaired. This leads to

increased survival, decreased chromosomal aberrations, decreased mutation and transformation rates, and, ultimately, reduced cancer induction. High–LET radiation damage appears to be less susceptible to repair than low–LET damage. Similarly, the presence of oxygen promotes low–LET effects but seems to have little influence on cellular responses to high–LET radiations. Protons are expected to have effects similar to low–LET radiations over a wide range of energies.

Neutrons are particularly penetrating because they are unchanged and interact with the atomic nuclei. The density of ionization in neutron tracks is quite high, resulting in high values of RBE for all biological end points. Neutron biological damage is less dose rate-dependent than low–LET radiation, and in fact may increase at lowered dose rates.

Heavy ions, such as the iron particles found in GCRs, lose energy by electromagnetic interactions as they penetrate matter. They also undergo fragmentation when they strike the nucleus of an atom. Energy is deposited along the core of a particle track, where ionization events are very dense. A larger penumbra of delta rays surrounds the core, where the ionizing event density is low. Thus the traversal of a single heavy ion may affect multiple cells, perhaps in activating or transforming them. Heavy ions produce effects that are little influenced by oxygen levels, fractionation, and dose rate changes that affect low–LET cell damage mechanisms. In terms of tumor induction, studies of mouse Harderian gland tumors suggest RBE values of 30 for iron and argon ions. An important aspect of the work on heavy ions is that LET alone is inadequate to describe RBE. Particles with similar LET but higher charge numbers generally exhibit higher RBEs. However, the data is limited on cancer induction in animal systems and there is no empirical database for human exposure. A number of in vitro studies have been performed to better understand the dependency of neoplastic transformation on LET for different HZE particles as a function of energy, particle type, and cell type.

Although these experiments hold considerable promise, it may be years before a reasonable empirically based prediction model of cancer induction by heavy ions is available that can be used for radiation risk assessment. To a greater extent, then, the situation is far less satisfactory than for low–LET radiation where the extensive human database is matched by years of in vitro and in vivo data gathering. We are pessimistic about the current level of understanding of HZE radiation carcinogenesis. The mechanisms are both different and more complex than for Xrays and gamma rays, and it is not surprising that uncertainties in RBE values of the order of factors of 30 or 40 are cited in the NASA draft radiation health program document and in a report to Congress.

Space Radiation Effects on Plants and Other Organisms

In addition to the effect on human tissue, it will be necessary to define the impact of space radiation, particularly HZE GCR particles, on plants or other organisms that might be included in a bioregenerative system for use on Mars or the Moon, or as part of an MTV life support system. Only limited data now exist for understanding the rate at which bioeffects accumulate in such organisms exposed to HZE particles, but the subject is significant because of the possibility of damage, mutation, and loss of reproductive capacity that might result in exposed plants that are grown in unshielded (or even shielded) enclosures. The possibility exists that HZE particle effects could influence crop yields by reducing reliability and robustness of bioregenerative systems. Arabidopsis thali seeds have been irradiated by heavy ion beams on Earth and have also flown in space. A number of biological end points have been studied, but it is not yet possible to specify the levels at which important effects may occur. However, it appears that only a few hits per cell nucleus can lead to inactivation, and that RBEs depend on particle type as well as LET.

Corn seeds have also been studied in both space and ground-based ion accelerators, and a characteristic imitation was found in both settings. This suggests that plants and seeds may be particularly vulnerable to HZE effects.

Countermeasures might involve the development of radio-resistant plants or even a requirement to shield plants or other organisms against GCRs or SPE. This could be very important on the Lunar or Martian surface where thin enclosures that are selectively transparent may be required for proper plant growth and development. Such enclosures may not have adequate shielding capacity. The situation is simpler for MTVs, if most of the vehicle would be shielded to protect astronauts against GCRs or SPE particles.

Impact of Microgravity on GCR Bioeffects

One possible complication in our ability to develop suitable models for assessing GCR bioeffects using ground-based heavy ion accelerators is the finding that microgravity appears to promote the production of radiation-induced anomalies in the hatching rate and development of eggs of Carausius morosus (a stick insect). A remarkably well-planned space lab experiment was performed in which eggs in monolayers were exposed to cosmic rays in microgravity. An onboard one "g" centrifuge was used to act as a control. Hatching was normal in eggs exposed to the one "g" reference alone. Hits by heavy ions caused body anomalies, and the combined effect of heavy ions and microgravity resulted in a much higher frequency of anomalies. The results using the same stick insect model were confirmed on the BioCosmos satellite.

It has been suggested that microgravity could weaken the processes that repair radiation-induced defects, but the entire issue is open to debate.

RISK ASSESSMENT METHODOLOGIES

NCRP Report 98

Risk assessment for purposes of establishing guidelines both for astronauts and planners is an essential of the radiation protection conundrum. **No specific radiation guidelines have yet been established for SEI missions to Mars**. But NASA, for planning purposes, uses assessments and guidance prepared by the National Council on Radiation Protection and reported in NCRP 98. NCRP 98 suggests the organ dose equivalent limits as shown in Table 3.1 below.

Table 3.1

Dose Limits from NCRP 98

	Blood-Forming Organs(BFO) (Sv)	Eye (Sv)	Skin (Sv)
Career limit	See equations below	4.0	6.0
Annual	.5	2.0	3.0
30 days	.25	1.0	1.5

The career limit is set by the requirement that astronauts should not have an added lifetime risk of cancer mortality greater than some specified level, chosen by NCRP as 3 percent. This compares to the baseline lifetime risk of dying of cancer of about 19 percent for men and 15 percent for women between the ages of 25 and 55. The NCRP career limits (in rems) have been fit by two straight lines, one for males and one for females.

Career limit (males) = 200 + 7.5 × (age 30)
Career limit (females) = 200 + 7.5 × (age 38)

Thus, an entering male astronaut at age 55 could be exposed to a career dose of 4.0 Sv, and an entering female astronaut at age 25 has a life limit of 1.00 Sv. This is more stringent than the 1970 NRC/NAS limit of 4.0 Sv for all astronauts. The 1970 limit was based on limited early results from the ABCC studies of atom bomb survivors, when it appeared that cancer risks were much lower than they now appear to be after over 20 years further follow-up of atom bomb survivors and review of other human data.

BEIR V Risk Assessments

The NCRP limits are based on data and epidemological analysis that were available to the council before the July 31, 1989, publication date of Report 98. The BEIR V report, published in early 1990, formulated a new series of radiation risk assessments that were far more conservative than those in the earlier database used by the NCRP. BEIR V risk assessments differ from earlier assessments because of:

- Longer follow-up of the atomic bomb survivors, the group that constitutes the best source of human data;
- Improved dosimetry based largely on a reworking of the analysis of fission products and transport and shielding for the Hiroshima and Nagasaki bombs; and
- More realistic models for analysis and projection of cancer mortality, particularly use of the relative risk model rather than the absolute risk model.

Thus the BEIR V lifetime excess cancer mortality assessments for an acute exposure, by age and gender, are greater than those in NCRP Report 98 by factors between two and one-half and six, and the 1990 BEIR V risks are between 4 and 15 times greater than the risks estimated using the 1980 BEIR V results, as shown in Table 3.2.

Table 3.2

Ratio of BEIR V to NCRP Estimates for Lifetime Excess Cancer Deaths

Age at exposure	25	35	45	55
Male	3.3	3.7	5.6	6.8
Female	3.0	2.4	3.9	4.3

Note: Comparison for .1 Gy acute exposure.

Revised Career Limits—Preliminary Estimates

When the BEIR V dose-response data are used to determine lifetime career limits for astronauts, using the 3 percent limit and ten-year active career specified by the NCRP, the remarkable differences by age and gender shown in the NCRP assessments vanish, even after reducing the BEIR V cancer estimate by a factor of two to account for a dose rate effectiveness factor (DREF). Table 3.3 illustrates these results:

Table 3.3

Comparison of Career Limits for 3 Percent Excess Lifetime CA Deaths

Male by Age	BEIR V (Sv)	NCRP (Sv)	Female by Age	BEIR V (Sv)	NCRP (Sv)
25	.80	1.63	25	.75	1.02
35	.91	2.38	35	.99	1.78
45	.81	3.12	45	.97	2.51
55	.83	3.88	55	1.05	3.28

Thus, the 1990 BEIR V estimates lead to a career limit that is weakly and nonsystematically dependent on age and gender except that people under 30 are more susceptible. For preliminary purposes, we have chosen .75 Sv as a plausable average value for the career limit.

We have not used the most recent UNSCEAR[8] dose-response estimates, but we anticipate that they would also lead to lifetime career limits that are more stringent than those suggested in NCRP Report 98. A comparison between UNSCEAR and BEIR V in terms of space exposure implications is still necessary. Moreover, the quasi-official status of the BEIR V estimates suggests that they should be taken quite seriously.

We note that the NCRP career limits are intended for planning purposes for orbital missions. It is not clear whether the expected downward revision in career limits that will be required if NCRP's next set of guidance is to conform to BEIR V will also require downward revision for the annual and 30-day limits that may be fixed by nonstochastic criteria.

For long-term deep space flight, e.g., of the order of several years, the .75 Sv cancer-related career limit suggested above becomes the major determining factor in assessing exposures and shielding requirements.

A trans-Mars mission that results in an abort imposes a baseline require.nent at about three years outside the Earth's magnetosphere. A career limit of 75 rems transforms into 25 rems/year (BFO) for the three-year baseline; this value translates into radiation shielding masses between 100 and 1,000 tons or even more for an MTV. A more stringent requirement of, say, 15 rems/year could easily result in shielding masses that are perhaps an additional order of magnitude greater. We emphasize that the large shielding mass range to achieve 25 rems/year is due to genuine uncertainty and does *not* include any safety margin. We also note that the proportionality between dose and time of exposure suggests the importance of space power systems that can markedly reduce transit time. However, a requirement to

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[8]UNSCEAR = United Nations Scientific Committee on the Effects of Atomic Radiation.

maintain a mission abort capability using a safe return orbit could weaken the impact of such a system.

New Approaches to Risk Assessment

The NCRP approach to risk assessment is based on the standard use of a quality factor, Q, to account for differences in stopping power (LET) for different types of particles. The magnitude of Q is based on expert judgment guided by the limited data on RBE for various radiations. The advantage of the Q/RBE approach to risk assessment is that it permits the extension of the extensive human database for low–LET radiation exposure, after combining with animal or in vitro test data for RBEs, to be used to project risks for radiation exposures for which no human data exist. Thus, the traditional approach anchors all risk assessments to the available human data, mainly for Xrays and gamma particles with a Q of unity. Q is assumed to be a function only of LET. By contrast, high-energy particles, particularly alphas or charged heavy ions, have Qs of between 10 and 20.

Curtis et al. have suggested that the risk estimates that are based on Q omit an important effect: that two different particles with the same LET may have different likelihoods for tumor induction. They recommend that attempts be made to gather data for risk coefficients based directly on the number of particles of a specific type that impinge on a unit area of matter, or what they designate as "fluence-based risk coefficients." The advantages of this approach are that it eliminates the need for the low–LET data experiments that are required as the reference point for RBE determination, and that it more naturally corresponds to the biophysics of particle tracks through tissue and organs deposited by high-energy GCR ions. The disadvantages of this approach are that it loses the human exposure database anchor and still requires good data at very low doses for charged particle beams.

Confidence or Credibility Intervals

The surprisingly large reduction in career limits that follows from using the 1990 BEIR V analyses, rather than those developed a decade earlier, and the increasing perception of ionizing radiation as lethal underscores the fragility of a risk-projection model developed at a particular time. Estimates of radiation hazard have been increasing over time, even for low–LET exposures. The NCRP estimates were obviously made during a period of emerging controversy, but the guidelines in Report 98 do not provide the nonspecialist reader with a sense of the magnitude of the uncertainty surrounding the risk projections. If the reductions shown here are a guide, the true credibility interval

surrounding the point estimates in NCRP 98 is distressingly large. They may underestimate cancer mortality risks by factors between two and six, depending on age, gender, and whether the dose is acute or continuous.

Given that the NCRP guidelines are incorporated into occupational standards for astronauts, it would be appropriate if NCRP included the quantitative uncertainties in the underlying models and assumptions upon which their projections rest. This is especially important for situations like SEI or extended high-Earth orbit flights where the ALARA (as low as reasonably acceptable) principle is difficult to apply and where astronauts could be exposed to higher doses of ionizing radiation than in the past. It is also important that planners and designers recognize the true uncertainties in risk radiation projections, since such projections can be instrumental in critical planning decisions about radiation exposures, protection systems, and EVAs. BEIR V uses the term "credibility interval" to designate a subjectively estimated total uncertainty in risk estimates, not merely uncertainty resulting from sampling or measurement error. For GCR radiations, we judge that sampling error effects in the underlying low–LET database are far less important than the many projection errors associated with the uncertainties in the biophysics and radiobiology of high-energy particles as they traverse tissue and organs. If, as suggested in NASA's Radiation Health Program draft, uncertainties as large as factors of 30 or 40 are present in standard risk projection methods, it should be helpful to planners, designers and astronauts that quantitative measures of uncertainty be employed. To illustrate, we believe that guidelines such as the following would be superior to the single-point estimates that NCRP presently uses.

The baseline lifetime risk of dying of cancer is 20 percent in the absence of any space exposure. Our judgment, based on data and expertise, is that a 1.5 percent additional risk would follow from a career limit dose of 38 rems, that a 3 percent additional risk would follow from a 75 rems career limit, and that a 6 percent additional risk would follow from a 150-rem career limit. However, the state of knowledge in this field is such that the limit for the 1.5 percent risk, at the 90 percent level of credibility, is between 20 rems and 80 rems, the 3 percent risk limit is between 40 rems and 140 rems, and the 6 percent risk limit is between 75 rems and 300 rems (using hypothetical but plausible values). Furthermore, these programs are based on data from people who were exposed to radiation many years ago, when cancer treatment was not as effective as it is today or as it is likely to be in the

future. Although our projection methods have tried to take account of this, we believe that certain cancers that are not curable today could be curable in the future and, as a consequence, we may be overestimating the risk of dying of cancer in the future. Furthermore some experts believe that the true uncertainties in our knowledge of radiation injury from galactic cosmic rays or solar emissions could be as a factor of 30 or 40.

A statement of this type would enable NASA and the astronauts to perform sensitivity analyses and make genuinely informed decisions that are not possible using the point estimate approach. We must also consider the more general context in which such information would be used.

Risk Communication and Informed Consent[9]

As described above, there are major uncertainties in our ability to project risks for astronauts who may be exposed to long missions outside the Earth's magnetosphere. Not only risks but uncertainties as well need to be communicated to astronauts who must choose between alternatives and then provide some measure of informed consent to risk. Risks of cancer must also be communicated to planners, designers, and decisionmakers, who could then perform sensitivity analysis. The current approach would make future NCRP-like limits for interplanetary exposure inviolable point estimates and would not permit designers to examine design tradeoffs. At this early stage, where radiation protection is a major issue but is obviously not well defined, such tradeoffs need to be made.

How can astronauts or even nonradiobiologists be considered informed if the best scientific assessment leads to a possible difference of as much as a factor of 30 or 40 for certain radiobiological phenomena, and the NCRP's own guidelines, dated July 31, 1989, are inconsistent with the BEIR V assessment published a few months later by the National Research Council? Given the evidence that even expert judgments may differ by large quantities, uncertainty about risk rather than risk itself becomes the more important concept.

Daniels analyzes the subject of risk and uncertainty in the context of long-duration journeys and suggests that a "fair procedure" is necessary for assessing risks and obtaining informed consent. A "fair procedure" requires more than relying on the experts who participate in NCRP deliberations. The experts should "assess the risks" and provide their

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[9]We refer to the provocative article "Consent to Risk in Space" by Norman Daniels in *Beyond Spaceship Earth*, E. C. Hargrove (ed.), the Sierra Club, 1986.

best quantitative measure of uncertainty to NASA, and NASA, including the astronauts, should then make decisions about risk management, e.g., the appropriate level of excess risk acceptable for a specific mission, and the true uncertainty in judging this level. For example, it may not be appropriate for an NCRP committee consisting of scientists with backgrounds in biophysics and radiobiology to decide (somewhat arbitrarily) that a 3 percent excess cancer mortality is an acceptable rate. An alternative approach would have NASA, including the astronauts, decide appropriate levels of risk after receiving a range of projections (rather than a point estimate) from the NCRP based on the best scientific and epidemologic evidence. Such decisions involve ethical and programmatic considerations where NASA personnel, including the astronauts, have more expertise and personal interest than NCRP-like scientific experts.

The EPA under Secretary Ruckelshaus adopted the policy of distinguishing between risk assessment and risk management. Scientists and technical people perform risk assessments, and EPA staff make policy judgments about risk management. NASA should consider adopting a similar approach as radiation risk and radiation protection become key factors in decisions about SEI. Furthermore, it seems appropriate that NASA adopt a consistent set of guidelines for all types of risk that affect the survival or future health status of astronauts. It is interesting to contrast the NCRP's 3 percent excess cancer mortality (about 1/6 of the baseline cancer mortality) that could be designed into an SEI mission with the stringent approach to reliability that NASA employs for designing nonhuman systems.

Active Shielding

Appendix D describes an approach to evaluating the passive shielding requirements to protect against GCRs. The mass penalties are so large and the degree of protection so uncertain that active shielding should be considered also as an alternative.

Multilayer High Temperature Superconductor (HTS) Protection System (#100699) describes an interesting and potentially significant approach to radiation protection. The essence of the system is the use of high-temperature superconducting materials to produce trapped megagauss magnetic fields that could deflect both GCR and solar flare particles. The suggestion is made that a lightweight HTS multilayered material could be developed that could also be used in outpost or planetary exploration activities that require shielding.

The primary value of the submission is its alerting us to the promise of high-temperature superconductivity, and to compelling us to reconsider the role of active shielding. As discussed in App. D, passive mass shielding against energetic charged GCR

heavy ions can be extraordinarily costly in terms of weight and volume. Furthermore, the nature of the interactions between relativistic iron ions and matter results in a diminishing marginal effectiveness for thick shields. Although this has been recognized for some time, it still appears that passive mass shielding by hydrogen-rich materials is the standard reference system for GCR heavy ion radiation protection.

Since astronauts protected by thick mass shields may still be exposed to reduced doses of energetic charged particles, it would still be essential to understand the potential bioeffects associated with these particles to better define safety margins. Unfortunately, our state of knowledge about the radiobiology of particles in the energy range of interest is limited, although NASA is proposing a radiation health program to elucidate biological and health effects of heavy ions.

It will require an unusually effective research, development, and test program to determine accurate dose response data for defining human health effects. Further, some of the required experiments may need to be performed under microgravity conditions if the synergistic effect of microgravity on radiation bioeffects is confirmed during the LifeSat program. Should it be shown that microgravity increases radiation damage in a variety of in vivo and in vitro models, then it might be necessary to field an elaborate program of space testing to develop data to support more accurate risk assessment.

An attractive concept that could minimize the need for a long, elaborate, and perhaps space-based program of heavy ion radiobiology is to employ active means to prevent these particles from reaching the crew at all.

Electrostatic and electromagnetic shields have been suggested for deflecting charged particles, particularly heavy ions, from an MTV habitat. Electrostatic shielding, suggested in submission #100242, has been studied by a number of investigators. The major difficulty is that the needed electric fields and dimensions are much too large to be practical, with the potential required exceeding the current state of the art in electrostatic field generation by two orders of magnitude. Magnetic shielding is an attractive option, one that has been studied a number of times since the early 1960s. We note that submission #101272 touches on ideas like those included in the high-ranking submission #100699.

The Bernert-Stekly Shield

Physicists at NASA's Langley Research Center have considered a magnetic shield concept first proposed by Bernert and Stekly in a 1965 paper. Earlier it had been found that a confined magnetic field would be more efficient for small vehicles, and an unconfined magnetic field, like the Earth's, would be more effective for extremely large vehicles.

The Bernert-Stekly Mars class shield was designed to deflect solar flare protons in the sub-200 Mev range. It consisted of two concentric spherical shells, each shell supporting a torus-shaped, cryo-cooled, low-temperature superconducting magnet. The original concept proposed an inner spherical radius of about 2m, an outer spherical radius of about 3m, and a perpendicular magnetic field strength of 4 tesla, a level too low to be effective against high-energy GCRs.

The same configuration can be considered today, but the possible use of high-temperature superconducting materials would permit the use of higher field intensities. The significance of high-temperature superconducting materials is twofold: not only do they exhibit superconductivity at higher temperatures than the classical low-temperature alloy superconductors, but, and this is less widely known, they exhibit much greater upper critical magnetic fields at low temperatures. Thus, high-temperature superconductors when operated at liquid helium temperature (4.2°K) can maintain their superconducting properties at much higher fields than do low-temperature superconductors. Therefore, they could be used to produce far more intense fields than the 10 or 15 tesla limit of low-temperature superconductors.

A recent paper by S. Sato et al. of the Osaka Research Laboratories of Sumitomo Electronic Industries describes a series of tests run on a silver-sheathed, bismuth-based, high-temperature superconducting wire. Not only were wires and coils successfully fabricated of $BiPbSrCaCuO$, but a series of measurements were performed at different temperatures to determine current carrying capacity superconducting as a function of temperature and field intensity.

Critical current characteristics of this material at liquid helium temperature seem particularly significant. Superconducting materials lose their large current carrying capacity in the presence of high magnetic fields. For example, traditional Niobium-based alloys show a significant drop when the applied magnetic field is in the neighborhood of 10 tesla. From the Sato et al. results, we observe that the new material's critical current, which is a measure of its superconducting behavior, remains steady at its low field value of about 10^5 amp/cm^2 for applied fields as high as 23 tesla. (Presumably 23 tesla was the maximum steady-state field possible in the Osaka laboratory.)

U.S. and Japanese labs are developing hybrid magnets (resistive and low-temperature superconducting coils) to attain steady fields approaching even higher values in order to further extend the range of fields available for studying material properties. They would permit the study of superconductivity properties at up to 40 tesla in the next few years. Thus the Japanese results are highly suggestive that the low-temperature operation (at

4.2°K) of high-temperature superconducting materials could extend our ability to operate superconducting magnets to much higher fields than is currently possible with conventional low-temperature materials, perhaps reaching levels of 80 to 100 tesla over time.

Scaling Laws

Extrapolating these promising results to 80 tesla is not without risk. But the pace of advance in high-temperature superconductivity is likely to accelerate, and we may discover quite soon whether we are too optimistic. For the present, we assume that fields in the 80–100 tesla range will be possible.

What can be achieved with a superconducting system that can operate in this range? We extend Townsend et al.'s analysis of the Bernert-Stekly geometry. Townsend found that the Bernert-Stekly shield would deflect iron particles only up to energies of 47 Mev/nucleon. For concentric shells of this type with a field intensity B and a separation distance Δ, a suitable scaling law becomes:

$$\frac{.3B\Delta}{2} = \frac{p}{q_e Z}$$

where B is field intensity (tesla)

Δ is shield thickness (meters)

p is particle momentum (Gev/c)

Z is charge number

q_e is electron charge

or

$$\frac{.3B\Delta}{2} = \frac{A}{Z}\left[T^2 + 2M_0C^2T\right]^{\frac{1}{2}}$$

where   A = mass number

T = kinetic energy in Gev

and

M_0C^2 = .939 Gev

From this equation, we find that

BΔ = 40, to shield against 2 GeV iron ions

If a field intensity of 100 tesla can be achieved, then Δ = .4m, and even if a field intensity of only 40 tesla can be achieved, Δ = 1 meter. Thus the dimensions are comparable to the approximately 1 meter Δ of the original Bernert-Stekly shield. Provided that these

orders of magnitude for attainable fields are realistic, this suggests the possibility[10] that an active system utilizing high-temperature superconducting coils operating at liquid helium temperatures could shield against relativistic heavy ions.

Active-Passive Shielding

To assure that adequate shielding would be available in the event of cryogenic or other failure, a safety margin could be provided if the active system was combined with passive shielding.

As we have elsewhere emphasized, considerable uncertainty exists regarding the radiobiological effects of heavy ions and the dimensions of the large purely passive shields that might be necessary to adequately protect astronauts over a three-year mission. Our judgment is that a hybrid active-passive shielding system could better protect astronauts against GCR health effects that might in practice be far worse than we now anticipate. For example, reducing dose equivalent levels to 2.5 rems/year requires a passive shield thickness of between 37 and 370 gm/cm^2 or even more. This should be compared to the roughly 20 gm cm^2 for the Bernert and Stekly shield weight per unit surface area for a low-temperature cryo-cooled superconducting shield. Not only could hybrid shielding provide a better margin for safety, but there is far greater likelihood that major advances in high-field-magnet superconducting technology will occur than in the technology of passive shielding.

RESEARCH, DEVELOPMENT, TESTING

A radiation health program plan has been proposed by NASA Life Sciences that includes a Radiation Biology Initiative to better define the biological effect of SPEs and GCRs. The objectives of the entire program are to develop methods to better characterize space radiation fields in order to predict biological effects; predict the probability of biological effects of space radiation, especially HZE particles; conduct space-based experiments, mainly on LifeSat, to validate the ground-based approaches to predicting biological effects; and most important from the perspective of mission planning and radiation protection, reduce the uncertainty (currently as much as a factor of 30 to 40) to less than a factor of 2 by 1997 and to less than 25 percent by 2010.

It is obvious that the goal of reducing uncertainties to these rigorously low levels, if achievable at all, will require a well-coordinated effort at obtaining HZE radiobiology data

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[10]It is still too early to fully determine the feasibility and effectiveness of this approach, given the large amount of energy needed to form the field initially and the need to shield crew members and spacecraft components from stray magnetic fields using a version of a Faraday cage.

under carefully controlled conditions using DOE accelerators, or perhaps others that may be available in Europe or the Soviet Union. The obvious goal is to develop fluence-based models for dose response and risk assessment.

However, the objective of narrowing uncertainties in human risk assessment to a factor-of-2 level by 1997 must be judged against the recent experience the space community encountered with regard to NCRP Report 98. Between July 1989, when the NCRP guidelines were published, and early 1990, when the BEIR-V assessments were released, the estimated risks of cancer mortality from exposure to ionizing radiation, even for Xrays and gammas, increased by factors of 6 or greater. This suggests that the goal of reducing uncertainty in the HZE case, where virtually no direct human data exist and where there are only a few animal data points, is extraordinarily ambitious.

This is particularly true if one considers the central role of human data in determining occupational limits. Although the concept of a fluence approach to risk assessment fits naturally into accelerator protocols, it is not clear how this approach can be applied to humans. Perhaps it can be used to estimate RBEs, but it seems difficult to suggest an entire new protocol for radiation risk analysis that fails to utilize the available low–LET database.

Nevertheless, it is essential that the BEVELAC or an equivalent heavy ion accelerator be maintained as a radiobiology test facility if any rational attempt at understanding and quantifying HZE bioeffects is to be pursued. Considering the extraordinary record that the Berkeley BEVELAC team has amassed, it seems natural that the facility and the team be given important responsibilities in ground-based HZE studies.

The LifeSat program is viewed as an important element in the Radiation Biology Initiative. A program of space-based radiobiology research is planned for the LifeSat system, an unmanned reusable reentry satellite system capable of flights up to 60 days, with artificial gravity capability and the possibility of flying a variety of orbits that would expose it to various types of space radiation. From the perspective of improving the ability to protect astronauts who may be exposed to GCRs and solar protons, the major impact of LifeSat is likely to be in clarifying the possible interaction between microgravity and radiation on a number of in vitro systems, using either a spinning satellite or centrifuge to provide control data. In addition, fluence, spectra, and dosimetric mapping will provide data for refining dosimetric predictions and system design and performance. The possibility of biological dosimeters will be examined, using such end points as cellular transformations, developmental defects, mutagenesis, alteration and differentiation, inactivation of cellular processes, and modifications of DNA repair. It is presumed that a coordinated program of ground testing will also be performed.

The LifeSat program should not lose programmatic priority since it would enlarge our fundamental knowledge of space radiobiology, and the concept of a biological dosimeter is elegant. Nevertheless, it is not likely that the result of the program will materially narrow the existing confidence intervals in risk assessment, particularly those associated with cancer induction in humans exposed to HZE particles. An exception is the possibility of clarifying the role of microgravity as a GCR radiation enhancer: if the results are consistently negative, this could simplify the process of risk assessment by reducing the need for space testing of animal systems.

CONCLUSIONS

From our exploration of the issues, work being performed by ourselves and others in the scientific and technical community, and the submissions that refer to radiation protection, we are led to the following conclusions and recommendations.

Risk Assessment—NASA should reconsider its approach to risk assessment and radiation guidelines. Our finding that the NCRP career guidelines published in July 1989 were inconsistent with the BEIR V results disseminated in early 1990 and markedly underpredict the lifetime career risks to astronauts suggests that NASA needs its own in-house radiation risk assessment capability to utilize the scientific talents of NCRP fully.

Furthermore, it would be more realistic if NASA performed its own risk management based on risk assessments provided by the scientific community. These assessments must be provided with some measure of the credibility that planners and astronauts can attach to them, perhaps along the lines of the "credibility interval" utilized in BEIR V. In this way, NASA could perform its own sensitivity analyses and tradeoffs. The notion of a 3 percent excess risk of dying of cancer, which would correspond to 25 rems/year for 3 years for a Mars mission (including a mission abort), seems, according to our corrected risk assessment, surprisingly high and probably greater than anticipated failure rates for nonhuman systems. Point designs for radiation protection systems can be misleading, given the large uncertainties that exist in our ability to assess risk. NASA would be better served by requiring that proposed architectures incorporate a range of values determining radiation protection requirements.

In terms of the scientific basis for human risk assessment, the concept of a fluence-based approach seems attractive, but it will be difficult to develop a fluence model using only animal, organ, or in vitro data. Presumably, there will always be the need for a judgment call, either in extrapolating animal data to man or in establishing a quality factor.

Radiobiology—It is generally agreed that the mechanism of action of HZE particles or even energetic protons is quite different from that of classic Xrays and gamma rays— particularly the idea of track structures and the possibility of microlesions. A full set of experiments needs to be performed in ground-based accelerators like BEVELAC to elaborate on these differences. A test of the seriousness with which NASA and DOE view GCR bioeffects in particular and SEI in general is whether arrangements can be made to perform systematic HZE experiments using a range of in vitro and animal models. Space experiments are required primarily to elucidate the possible synergism between microgravity and HZE radiation. More data on plant sensitivity to radiation are also needed to better understand the environmental needs for a bioregenerative system, either on an MTV or a Lunar or Martian outpost. We are pessimistic about radio protectants, but we believe that the possibility of bone marrow banking and autologous transplantation may be worth considering.[11]

Space Environment—More and better data are needed about the space radiation environment between Earth and Mars. This will require that an instrumented probe that can obtain dosimetry data and gather spectra be scheduled within the decade to provide data for planning and scientific purposes.

Shielding—From recent data on high-temperature superconductors operated at 4.2°K, we are optimistic about the possibility of a hybrid active-passive system that would shield against GCRs and SPEs. It may be some years before the feasibility and configuration for such a system can be determined, but a preliminary assessment suggests two advantages:

- A probable, significant mass advantage over fully passive shielding, unless a liquid or slush hydrogen shield material is used; and
- A nearly fail-safe system that would provide excellent protection, virtually independent of the fluence level, and that would revert to a passive shield in the event of loss of cooling capacity.

Finally, we must refer to an extraordinarily provocative submission entitled **The Spinoff Is the Payoff (#101271)**. This submission touches on a number of important areas

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[11]Radio-protectants are compounds that mitigate the effects of radiation exposure. They have been studied for years in the context of protecting soldiers and others from nuclear weapons effects. Although they have a theoretical basis, their success in the laboratory is limited, and they are often associated with serious side effects. It does not appear likely that they would be useful on a continuing basis during a long interplanetary journey. But, they could ultimately play a role in a comprehensive radiation protection system.

and provides a rationale for a radical alternative involving the use of Lunar and asteroid material for radiation shielding. From the perspective of radiation protection, the submission suggests a two-meter-thick radiation shield made of sand, gravel, or dirt mined on the Lunar surface via an extraterrestrial mining and manufacturing infrastructure. The submission derives from the work of G. O'Neill and the Space Studies Institute.

Although we suspect that hybrid shielding may prove to be the most effective approach, we must emphasize that our current estimate of space radiation hazards is at levels that make even a meter-thick shield appear to be inadequate. Nevertheless, this proposal suggests that the scientific community may not nail down both radiation protection requirements and microgravity countermeasures in a way that will permit rigorous planning and design with suitable margins of safety. Should this occur, this alternative approach would then offer a novel way to proceed that would also provide other advantages in terms of building an infrastructure for space.

IV. MICROGRAVITY

BACKGROUND

The Quintessential Space Issue?

The microgravity (μ-g) problem—how best to enable humans to cope with the microgravity of space, the partial gravity of the Moon (.17 g) and Mars (.38 g), and return-to-Earth gravity, with minimal impact on health and performance—may be the quintessential SEI human support issue, although ionizing radiation exposure may be more decisive in determining SEI feasibility. Our relatively benign experience with microgravity during the era of manned spaceflight, which defied early predictions of major injury to lungs, brain, heart, etc., confirms the robustness of human physiology and homeostasis. However, we may have already reached the limit of human tolerance to microgravity with a Soviet one-year orbital exposure in which the only effective countermeasure was rigorous exercise.

As SEI moves forward and plans for space exploration are realized, far more comprehensive and perhaps even radical countermeasure approaches could be implemented. They could range from combinations of exercise, conditioning, and sophisticated pharmaceuticals (some not yet developed) to complex, rotating, tethered spacecraft systems.

Observations of humans in orbit have shown that the microgravity environment of orbital flight is responsible for many physiological alterations, including several that are potentially injurious. Changes, some significant, have been found in cardiopulmonary, muscular-skeletal, neurovestibular, neuro-motor, hematological, immunological, biochemical, and hormonal parameters.[1] Many of these changes are temporary and result from adaptation to weightlessness by organ systems that operate at new setpoints. But even if postmission recovery is complete, a number of adaptation responses could impact mission effectiveness by impairing the ability to respond to emergencies or sudden changes in mechanical force loading. For example:

- Cardiovascular deconditioning could diminish the ability to tolerate aerocapture g profiles at both Mars and Earth return, as well as the ability to perform effectively shortly after reaching the Martian surface.

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[1]See A. E. Nicogossian, C. L. Huntoon, S. L. Pool, Space Physiology and Medicine, 2d ed., Lea & Febiger, Philadelphia, 1989, for an up-to-date discussion of weightlessness.

- Muscle mass loss could reduce peak strength and endurance that would be required for optimal EVA performance and emergency activities.
- Irreversible skeletal mass loss and demineralization could increase the likelihood of bone fractures in the absence of effective countermeasures. This could occur postflight or even when undergoing mechanical loads associated with Martian "g."
- Calcium supplements and increased calcium washout could result in increased risk of kidney stone formation.
- Orthostatic tolerance decreases, as reflected in occasional increases in heart rate, decreased pulse pressure, and spontaneous tendencies toward fainting, would impair the ability to function properly after landing on Mars.
- Space motion sickness due to the lack of a gravity vector to orient the neurovestibular system and a resulting sensory conflict that occurs when the head is moved, sometimes debilitating and lasting for the first few days of a mission, affect 50 percent of all space travellers but are self limiting.

A number of other microgravity effects have been observed that do not now appear to be associated with significant increased risk, although the data are too limited to be very definitive. Fluid shifts away from the lower extremities are in this category, as well as reduced plasma volume, decreased red cell mass, and subtle changes in the immune system.

One high-ranking submission, **Cognition, Problem-Solving, and Memory in a Microgravity Environment (#100959),** proposed to investigate the hypothesis, as yet untested, that altered cognitive performance could accompany cerebral fluid shifts and chemistry changes owing to weightlessness. Further, postural changes have been observed that, although not particularly ominous, suggest that the sensory motor responses that have evolved on Earth may not be suitable for long-term exposure to microgravity. Cardiac dysrhythmias have also been observed in both U.S. and Soviet astronauts, primarily during EVAs, but their significance has not been determined.

Simulating Microgravity

There is only a partial correspondence between the responses evoked during ground-based (or even aircraft-based) studies and responses to μ-g that occur in space. Bed rest, particularly head-down tilt, offers a partial simulation of fluid shifts, muscle and bone unloading, and cardiovascular deconditioning. Water immersion simulates g force unloading, fluid redistribution, and reduced plasma volume, as well as acute renal and circulatory

phenomena. Parabolic flight in an airplane offers 30-second intervals of 0 g separated by 30-second intervals of 1.8 g that can be utilized for short-term sensory motor task studies. Sequential combinations of bed rest followed by centrifuge have been used to test a series of countermeasures to show that tolerance to + g acceleration degrades after bed rest.

However, there is no complete analogue to spaceflight exposure to microgravity. Furthermore, long-duration simulations using volunteers pose ethical problems. As a consequence, monitoring and test programs in space are required to gather the physiological and countermeasure response data needed for rational design.

Countering the Effects

A number of countermeasures have been either utilized or proposed to avoid or mitigate the physiological effects of chronic exposure to microgravity. In many cases, the costs could be high in terms of side effects or resources. The Soviets claim that cardiovascular capability can be sustained using a rigorous four hours/day exercise regime, a program that seems onerous and unsustainable.

A number of agents have been used to combat the symptoms of space motion sickness, but virtually all have side effects that may restrict their utility. Rotating spacecraft would provide an artificial gravity force to minimize any long-term μ-g effects, but rotational effects on neurovestibular function and task performance could limit permitted rotational rates or hamper the ability to adapt to, or recover from, a rotating environment. Further, the mass penalty and design complexity of a properly configured rotating spacecraft system, including realistic radiation protection, could be far greater than is generally recognized.

Finally, there are two additional concerns regarding the bioeffects of micro- or partial gravity. The first is the observed increase in GCR ionizing radiation-induced bioeffects described in Sec. III, and the second is the impact of non-Earth g on plant growth and productivity, a factor that could influence bioregenerative life support systems. These are two areas where further elucidation would be accomplished by space testing of nonhuman systems.

RECENT OBSERVATIONS AND CURRENT PRACTICE

The Data Problem

The longest-duration U.S. orbital flight, Skylab 4, occurred in 1974 and exposed three astronauts to microgravity for 84 days. In contrast, 30 Soviet cosmonauts experienced weightlessness during orbital flights where durations were between 75 and 366 days. Thus U.S. astronauts have had far less microgravity experience than the Soviet cosmonauts,

particularly during the past 15 years. In addition, the limited number of test subjects (the small "N" problem) and limits on the ability to gather in-flight data hamper our understanding of SEI-relevant microgravity effects, despite the productivity of the Skylab Biomedical Program. The Soviets appeared to collect some systematic biomedical data, but only limited amounts have been shared with NASA investigators. Furthermore, there are difficulties in analyzing the data that have been shared because Soviet test protocols do not always comply with U.S. standards in terms of instrumentation, crew compliance, and experimental design. Furthermore, the Soviets have treated the sharing of this data as a technology transfer issue.

A NASA document prepared by its Life Sciences Division, March 29, 1989, "USSR Biomedical Program Preliminary Review of Long-Duration Manned Mission," summarized the views of Soviet scientists. The conclusions were that (1) a one-year orbital stay is the existing limit today, given available countermeasures, and six months is the optimum stay-time from the viewpoint of productivity, (2) the scientific database is too small to draw meaningful conclusions, (3) "operational prescriptions" are not at hand, and (4) an accelerated understanding of physiological mechanisms is essential for developing new countermeasures or improving existing ones. This last conclusion seems unavoidable, particularly as we consider the possible configuration of a spacecraft that can transport crews to Mars and back to Earth.

If continuous artificial gravity is necessary, then the MTV configuration will be more complex and costly than if a combination of pharmaceuticals, exercise, and perhaps even intermittent g is found to be acceptable. But the data are not yet able to help us distinguish between these alternatives.

We next review the highlights of U.S. and Soviet findings with regard to skeletal, muscle, heart, and neurovestibular responses to extended weightlessness. These are the areas with greatest potential, we judge, to affect missions and therefore require long lead-time R&D programs.

Bone

Bone demineralization and the resulting susceptibility to fracture are presently viewed as the most critical limiting factor in longer-term human exposure to microgravity. Although the data are limited and highly variable, a consistent picture emerges of a continuing loss of calcium, phosphorous, and other essential elements accompanied by a reduction in bone density. U.S. long-term data from Skylab (up to 84 days) and Soviet data from a number of orbital missions (up to 366 days), supplemented by the results of long-duration bed rest

studies, show that total body calcium is lost at the rate of .3–.4 percent per month and that weight-bearing bones (the calcaneus) experience density losses of between 1 and 5 percent per month.

Five-year follow-up data of the Skylab crew indicates that bone density does not recover its preflight values. U.S. analysis of Soviet data obtained for the hip, spine, tibia, and calcaneus indicates no relationship between bone loss and the duration of flight. Variability in Soviet data may result from individual differences, countermeasure differences in both prescription and compliance, and differences in measurement techniques and instrumentation. (Neutron activation, D/T scan and densitometry, and single and dual photon methods were all used for inferring bone density.)

Losses in bone density of 25–30 percent are generally associated with increased risk of fracture. Thus bone density losses during a Mars mission could result in high risks of injury when the skeletal system is loaded mechanically on the surface of Mars or Earth.

Cardiovascular

Cardiovascular effects appear rapidly during exposure to microgravity, triggered by the rapid headward shifts of 1–2 liters or more of body fluid. Cardiovascular compensation occurs quickly. The heart stroke volume decreases by about 12–15 percent after first increasing within the first 24 hours. The heart rate increases, but cardiac output changes slightly. Lung vital capacity decreases, leg blood flow increases, and exercise capacity is observed to decrease in some flights and remain unchanged in others. Soviet data imply a 100 percent increase of postflight orthostatic hypotension and a decrease in exercise capacity upon return to 1 g. Ventricular tests indicate that cardiac function and heart muscles do not deteriorate, that cardiac wall thickness remains unchanged, and that the left ventricular mass undergoes a 10 percent decrease but rapidly reaches its preflight values. The question of effective countermeasures against cardiac deconditioning is still open, except for general agreement on the utility of exercise and proper fluid and nutritional status. The Soviets have space tested a variety of heart drugs, but it is not entirely clear whether U.S. cardiologists would concur in their use.

Muscle

Muscles are not adequately loaded by microgravity, particularly the antigravity muscles that counteract gravity by maintaining upright posture. As a result, partial atrophy, loss of mass in leg and back muscles, and reduced leg muscle tone are seen. Leg mass loss may also be related to fluid shifts toward the head and loss of body water. After

only one month in space, 20 percent of leg muscle strength and 10 percent of arm muscle strength are lost, even with exercise. Leg circumferences decrease by several centimeters. However, muscle losses appear to reach a plateau if adequate exercise is performed and are generally reversible upon return to Earth. Long-term bed rest studies indicate that the longer atrophy exists, the longer the time needed to reverse it by exercise and electrostimulation. According to Sandler of NASA's Ames Research Center, lack of use of muscles for periods beyond four months may result in the inability of full restoration of muscle fibers that have degenerated, and very long term disuse atrophy could be irreversible because fat and fibrous tissue could replace muscle fiber.

Other Systems

Although there are other observed physiological responses to extended exposure to microgravity, it does not now appear that they would be mission altering or would require other than an evolutionary approach, except perhaps for the neurovestibular system.

There are little long-term data on the influence of weightlessness on the vestibular system. This system relies on the semicircular canals, which sense angular acceleration of the head, and the otolith organs, which sense linear accelerations. It has been suggested[2] that microgravity-induced changes in calcium metabolism could affect vestibular function because the primary mechanism for otolith functioning is provided by small calcium carbonate crystals (otoconia) whose composition and frequency could be altered by changes in calcium levels. It is also speculated that nervous system plasticity, the ability to adapt to different environments, could be affected by long-duration weightlessness. The fact that the Soviets have experienced a 2 to 3 percent incidence of postflight neurovestibular disorders may also be significant, although detailed data have not yet been published. Sensory motor visual and sleep data have been gathered via observation and anecdote, that indicate occasional difficulties in motor performance, vision, posture maintenance, and stability. These difficulties occur both during flights and during the process of adapting to Earth g.

Clearly, space motion sickness is the most common and severe vestibular disorder. As discussed below, vestibular tolerance will influence the maintenance of artificial gravity using a rotating habitat.

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[2]See B. Lichtenberg,"Vestibular Factors Influencing the Biomedical Support of Humans in Space," in D. Lorr, et al. (eds.), *Working in Orbit and Beyond: The Challenges for Space Medicine*, Science and Technology Series, Vol. 72, p. 9.

Adaptation and Deadaptation

Upon return to Earth, Soviet cosmonauts have exhibited the following signs of deconditioning, presumably due to adaptation to weightlessness:

- Weakness and fatigue;
- Dizziness and vestibular discomfort associated with sharp head movements;
- Increased perspiration;
- Limitations in motor function and coordination;
- Decreased orthostatic stability;
- Problems in perceiving the spatial orientation of the body;
- Tachycardia; and
- Reductions in bone and muscle mass and tone, red cell and blood volume, and cardiac stroke volume.

U.S. astronauts have displayed these symptons as well. Some could impair the ability to perform effectively on reaching the Martian surface. Although there is anecdotal evidence that a rigorous exercise program reduces the period of readaptation to Earth g, it seems unlikely that countermeasures could properly eliminate all of these deficits without introducing potentially serious side effects. It must be noted that a rotating habitat, i.e., a tethered system or a rotating hollowed-out asteroid, could virtually eliminate these problems, and could be designed to minimize rotational deadaptation by extending the period of angular deceleration prior to Mars arrival.

Current Countermeasures

Both the U.S. and Soviet space programs utilized a series of countermeasures to prevent or mitigate the effects of weightlessness and to improve the ability of crew members to cope with changes in g levels.

A number of medications have been used to eliminate or reduce the severity of symptoms due to space motion sickness, and it is likely that evolutionary progress in this area will continue. Phenergan now seems favored as an anti-emetic, but several traditional motion sickness remedies have been tested, including combinations of scopalomine, promethazine, ephidrine, and dexedrine. Although I. M. Phenergan is an improvement over previous treatment, the challenge remains to develop protocols (including selection and training) that also permit astronauts to perform effectively during the first few days of space

flight, when nearly 50 percent of crew members show some level of neurovestibular dysfunction.

A still unresolved issue is how weightlessness influences the distribution, disposition, and action of virtually all medications, and how proper drug doses and levels can be determined. The use of saliva to infer pharmacokinetic behavior is promising, but additional work is needed to define dose and schedule for virtually any type of pharmaceutical intervention.

The Soviets have used several drugs for treating cardiovascular deconditioning, including beta blockers. Antidiuretics have been used to counter postflight orthostatic intolerance, and salt and water loading is used on recovery days to increase plasma volume and prevent orthostatic intolerance. The Soviets also use a chibis suit, designed to provide lower-body negative pressure, occasionally in-flight and prior to return to Earth.

An anti-g suit to prevent the pooling of blood and to maintain brain circulation is worn during reentry, and a penguin suit that places axial load on the musculoskeletal system is worn through all waking hours. The Soviets are also reported to have used some form of biphosphonate to counter bone demineralization, but no data are currently available.

Exercise and Conditioning

Both the U.S. and the Soviet programs have made extensive use of exercise as a countermeasure to minimize muscular atrophy and cardiopulmonary deconditioning. Maintenance of work capacity will also be essential for the performance of EVA tasks. The assessment of countermeasures will be in terms of their ability to maintain peak oxygen uptake, strength, and muscular endurance. However, precise data on the effects of long-term microgravity are not yet available. Thus, the ability to define an "exercise prescription" remains one of the long-sought goals of space medicine.

A variety of cycle ergometer, treadmill, and bungee cord devices have been used in flight. While the Soviets credit regimens of four hours per day with minimizing cardiac deconditioning and minimizing postflight orthostatic intolerance, committing that much time to exercise has been onerous to the crew. The extent of protection is difficult to assess, but recently concluded (December 1989) data-exchange agreements with the Soviets may permit standardization and more meaningful assessment of their data. However, the exercise required to preserve the ability to tolerate the g stresses associated with aerorecapture at Mars or Earth still cannot be estimated accurately.

Greenleaf at NASA's Ames Research Center has also reported a decreased thermal transport ability, post bed rest, which could reduce overall work capacity as deconditioning

progressed. This could be significant in a program that required frequent EVAs for assembly or maintenance.

Mathematical models have also been developed to study the parallel physiological responses of muscle, connective tissue, and bone for adaptive changes due to various levels of disuse and exercise. These models suggest that high-force activities may be more effective than low-force endurance activities. This leads to the hypothesis—yet untested but expressed in the Vernikos White Paper—that hypergravity exercise at 2 g (in a centrifuge) might be more effective than long-duration exercise regimens and normal or fractional g levels. Again, access to flight will be required to verify the models that could be valuable in SEI mission planning.

More extensive exercise programs are currently being developed to assure that all major muscle groups are actively and sufficiently exercised during the daily workout routines to be incorporated in the extended Duration Orbiter program. Whether they will prove sufficient for the antigravity muscles of the back remains to be seen. Unfortunately, prior to the space station, flight durations will not be sufficiently long (greater than 30 days) to gather data on the effect of exercise protocols on preservation of bone mass and bone strength. More precise quantitative measurements of bone density of the spine, as well as biochemical analysis, will be required to describe and define the time course of various deconditioning modes and the effectiveness of various countermeasures.

ARTIFICIAL GRAVITY

The Rotational Analogue

Should continuous artificial gravity be required for a Mars mission, it will most likely be provided by rotating the MTV habitat. One submittal, **Magnetically Induced Artificial Gravity (#101273)**, suggested as an alternative that astronauts wear clothing constructed of magnetically susceptible fabric. Combined with a properly aligned magnetic field that would be maintained within the spacecraft, this would in effect create an effective surface magnetic force on the torso to replace the missing gravity body force. Although the idea is ingenious, we were concerned over its feasibility, the likelihood that the magnetic forces acting on the torso would not be properly distributed or oriented, and the possibility of injurious bioeffects due to the magnitude of the required field strengths.

If artificial g through rotation is required, the fundamental relation is

$$a = r\omega^2$$

where a is centrifugal acceleration, r is radius, and ω is angular velocity.

In general, the designer of a continuously rotating system will be restricted in the choice of each of these variables. Limitations on tolerance and habitability would restrict a and ω, and mass, complexity, and dynamic control factors would limit r. First we look at a and ω. The upper limit value for a would be 1 g, but the lower limit is not known. The scientific consensus is that three years of exposure to μ-g is too long using present countermeasures. Although there are limited human data at 10^6 g for periods up to 366 days, programs of space, Lunar testing, or both, supported by Earth-based partial simulations, might be required to determine the proper level for human exposures up to three years. We have recently learned[3] that Soviet cosmonauts have already requested permission to experience a year and a half exposure to μ-g on MIR, but Soviet space officials are undecided about a flight of such an extended duration.

If extended and truly productive stays on the Moon and Mars are anticipated, it will ultimately be necessary to gather long-term human data at .17 g and .38 g. Such data can only be obtained in orbit with a rotating system or on the Moon. If a Lunar outpost is built, astronauts could be monitored (without hampering their activities) to detect signs of g-related health and performance effects. If these alterations are serious and countermeasures are ineffective, crew members could be sent home if necessary. A Lunar centrifuge could be developed to simulate Martian g, although we suspect it would be a difficult endeavor.

Mars is more difficult over the long run. Should it be shown that long-term exposure to Martian g is inconsistent with productive human settlement (even with permissible countermeasures), then it will be necessary to rethink the ultimate configuration and function of a Mars colony. The approach suggested in the highly ranked submission **The Spinoff is the Payoff (#101271)** suggests an alternative involving a rotating large habitat (asteroid) in an orbit around Mars.

If one can interpolate between micro g and Earth g from the combined Soviet and U.S. experience, exposures at .17 to .38 g might be tolerated for periods of the order of months. However, it may be desirable to develop orbital-based rotating spacecraft systems that would operate at a variety of rotational speeds for long-term human testing of toleration, performance, and countermeasures. Although the Lunar surface also offers an opportunity to perform extended observations at 1/6 g, an orbiting variable-rotation rate system would be more versatile. It is possible that monitoring could be scheduled to interfere only minimally with other mission activities. But the possibility also exists that monitoring and testing

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[3]Personal communication, V.M. Surikov, deputy director, Research Institute of Machine Building, Moscow, 1990.

could demonstrate impairments to health or performance that cannot be prevented or treated adequately.

Tolerance to Rotation as a Limiting Factor

Experience shows that high rates of rotation produce temporary debilitating neurovestibular disorders. There are only limited data, virtually all taken on Earth, to assist decisions about ω, the angular velocity. Rotating room experiments were performed by Graybiel, Kennedy, Lackner, and others at Pensacola and Brandeis in the 1960s and 1970s. The results showed that rotation rates of 5.4 rpm provoked severe motion symptoms in virtually all subjects, that subjects rotating at 2 rpm exhibited only mild symptoms, and that 1 rpm subjects exhibited virtually insignificant vestibular effects. These experiments involved a continuously rotating room approximately six meters in diameter, in which test subjects lived for periods of up to two weeks. Over time, most subjects showed increased tolerance to rotation even in the 4 to 6 rpm range. However, readaptation posed a new problem: After subjects had adapted to the rotating environment, they were unable to adapt quickly to a nonrotating environment, especially at the higher rates. This suggests that an artificial gravity system operating at a higher angular speed might need to deaccelerate slowly as Mars was approached for astronauts to perform with minimal neurovestibular deficit during the first few days on the Martian surface. From these studies we judge that rotation rates of the order of 1 or 2 rpm, corresponding to the limit of human tolerance without pronounced adaptation or readaptation symptoms, are prudent choices for preliminary planning studies.

We must note that rotating room experiments are performed in Earth g, and subjects are exposed to additional acceleration due to rotations that are only in the .01 to .1 g range. Thus background Earth g levels are much larger than the rotational values. Experiments that combine rotation with zero g have been performed using the parabolic flight profile of a specially adapted KC 135. The zero-g durations are less than 30 seconds and are proceeded by an equal length exposure to 1.8 g. Although 40 cycles/day can be observed, there is little that these tests can illuminate about long-term effects. Thus there are major limitations on either the rotating room or parabolic flight as proper simulation modalities for rotating spacecraft.

On the positive side is the finding that subjects in a rotating room who are exposed to a stepwise increasing level of rotation and coriolis force appear to undergo fewer episodes of motion sickness than if they are accelerated more abruptly. This suggests that, in practice, it might be desirable to increase or decrease the angular velocity over long periods, perhaps

days or weeks. A fundamental safety concern is the ability to respond to emergencies. An astronaut rotating at > 4 or 5 rpm may require several days to properly readapt to a nonrotating environment, such as a planetary surface, or after an emergency despin in space in order to perform an EVA. Thus the ability to perform effectively during an emergency could be seriously hampered.

Another uncertain area is the ability to perform new tasks while undergoing rotation. Observations indicate that rotating room subjects learn to self-limit their motion to avoid head movements that induce discomfort, but such learning may take considerable time. Coriolis forces are generated when astronauts or others move in a rotating environment. These forces are sensed by the neurovestibular system in ways that lead to conflicting stimuli. Thus they are highly nausea-producing. Experiments on Skylab and parabolic flight suggest that the nauseagenic potential decreases in micro g, and that ground-based training could improve tolerance to cross-coupled angular motions.

Despite the apparent limits of the rotating room as a model for space, it offers the possibility of facilitating understanding about tolerance to rotation and perhaps even as a tool for screening or training crew members. But the inadequate status of the human rotation database and the inability to perform Earth-based studies to properly simulate both coriolis force and background g effects over longer periods of observation are major impediments to realistic planning. Determining the proper range of design parameters for a rotating spacecraft could entail an elaborate program of space experimentation. Without performing a detailed study, we are still impressed by the scale and complexity that such a program would require.

Parameters and Penalties

For preliminary planning and to grasp the magnitude of the mass requirements, it is useful to explore the impact of varying α and ω on an artificial g system. We assume that restrictions on α and ω would eliminate a single rotating habitat as a serious candidate. Note that $\alpha = 1$ g and $\omega = 1$ rpm results in a radial distance of 896 meters between the axis of rotation and a rotating compartment. A tethered approach, in which two compartments separated by a distance of hundreds of meters translate and simultaneously rotate about a common axis, is the most plausible concept.

L. Lemke[4] of Ames Research Center formulated a simplified set of equations for preliminary evaluation of tethered spacecraft that permit tradeoff estimates and sensitivity

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[4]Unpublished manuscript.

analysis to be made. We consider a rotating spacecraft system consisting of two masses, m_1 and m_2, separated by a tether of length l. The system is required to be capable of undergoing N start-stop rotational cycles, where N must definitely be greater than two, probably greater than four to account for midcourse corrections, and perhaps six or eight for contingencies that might involve EVAs. Lemke's tether is not capable of supporting compression, but others have considered systems in which the masses m_1 and m_2 (containing habitat, cargo, power system, etc.) are separated by structures that can sustain both tension and compression. We believe Lemke's explicit formulation can be used for both types of systems.

Lemke's first-order scaling laws are the following:

$$\frac{\Delta M}{M_0} = \left\{ 1.045 \left(\frac{NF\phi}{\omega I_{SP}} \right) + \left[\frac{m_1 \lambda}{m_2 \, fS_t} \left(\frac{F_g}{\omega} \right)^2 \right] \right\} + .075$$

where ΔM is the artificial g mass penalty; M_0 is the baseline system mass without artificial g; N is the number of start-stop cycles; F is the artificial gravity level in units of g; $\phi = [4/(1+M_2/M_1)]$, a shape factor; I_{sp} = the specific impulse of the rotation jets; ω is the angular velocity; m_1, m_2 are the masses at each end of the tether; λ = the tether density; and FS_t is the tether's design tensile strength.

The Lemke relation, after choosing numerical values for strength and propulsion parameters, simplifies to:

$$\frac{\Delta M}{M_0} = 9.1 \times 10^{-3} \times \frac{F}{\omega} \times \frac{m_1}{m_2} \left\{ \frac{N}{1 + \frac{m_1}{m_2}} + .048 \frac{F}{\omega} \right\} \frac{F}{\omega} + .075$$

Unless m_1/m_2 is very large, the first term in the brackets is larger than the second. The first term reflects the mass penalty associated with the fuel required to spin and slow the system. Its magnitude is thus proportional to N. The second term in the bracket reflects the additional mass penalty associated with the length and cross-sectional area of the tether.

Lemke estimates $\Delta M /M_0$ to be about .2 for N = 4, F = 1, and ω = 2 rpm. Doubling N to 8 or halving ω to 1 rpm would result in a value approaching 30–35 percent. Doubling N to eight to account for a more prudent strategy and halving ω result in a value greater than 40 percent, beyond the limits of accuracy of the simplified linearized analysis. Thus a plausible mass penalty for artificial gravity could easily be in the 40 percent or 50 percent range, a range somewhat higher than suggested by advocates of a tethered system.

Unfortunately, planners and analysts have not yet considered the impact of realistic radiation shielding on the mass and dynamic of a tethered system or the optimal division of function and mass between the two rotating compartments if the radiation shielding mass is in the 10^5-10^6 kg range. Although more precise analysis must be done, our initial estimates are that a highly asymmetric configuration ($m_1 >> m_2$), corresponding to radiation shielding for one compartment, leads to exceedingly large mass penalties for artificial gravity that must be added to the mass of the baseline system.

Not only is it too early to properly set the values of α and ω, and by design, r for a rotating system, but the range of parameters and strategies that might be employed to properly optimize artificial g have not been determined. A rational systems analysis would consider a plausible range of systems parameters to develop mass and systems requirements over the entire range. Choosing exceptionally favorable sets of values or neglecting realistic radiation protection could lead to distorted or unrealistic predictions. For example, the assumption that Lunar or Mars gravity is suitable for a multiyear mission could lead to overly optimistic projections, as would the choice of an unrealistically large constant rotation rate. Unfortunately, there seems no easy way to develop a set of specifications for α and ω without a large space testing program, either in orbit or on the Moon.

From mass considerations alone, independent of the complex problems of structure, dynamics, and control, it appears that artificial g poses enormous engineering challenges.

Simulating Artificial Gravity

Mars Mission Gravity Profile Simulation (#101270) suggests a combined program of ground-based and space-based testing to address the issue of whether artificial gravity is required for a manned mission to Mars. The simulation is configured as an eight-phase program involving considerable cooperation between the United States and the USSR. Each phase is intended to simulate some portion of the g profile associated with a Mars mission. Primary use of MIR as a currently available testbed for physiological g monitoring is proposed, while crew transfers to and from MIR are to be provided by the U.S. STS. Although not included within the eight-phase simulation, the final stage could involve the planning and construction of an international variable gravity facility, possibly to be linked to MIR by a tether.

The eight phases are:

(0)   Baseline data taken at 1g on Earth;

(1)   Crew launch from USSR, rendezvous/dock and MIR transfer;

(2) MIR space station activities for 180 days outbound Mars simulation;

(3) STS launch from Kennedy Space Center, rendezvous/dock with MIR, MIR crew transfers to STS, return to Edwards AFB and crew transfers to Ames Research Center;

(4) Simulation of Mars activities at Ames Research Center for 30–40 days (presumably after debrief and physiological checkout);

(5) Crew transfer from Ames to Kennedy S.C. to STS, STS launch, rendezvous/dock with MIR, transfer to MIR;

(6) MIR space station activities for 180 days, inbound simulation;

(7) Crew transfer to descent vehicle (STS), land at Edwards, crew transfer to NASA Ames; and

(8) Postlanding recovery, debrief and physiological checkout.

The submittal clearly recognizes the omplexity, time, cost, and schedule issues associated with a program to develop a variable-gravity research facility. Therefore it proposes such a program as a potential evolutionary option.

The submission proposes that astronauts be taken to Ames Research Center for extensive ground testing that would simulate Martian g for stays up to 450 days. A series of simulation protocols would be employed at Ames that would mimic the .38 g level of Mars. They include a tilt table (at 22°) and control panel, sitting in a partially flooded habitat, standing in a fully flooded habit, performing treadmill exercises underwater to simulate Mars EVA, performing exercises in a zero-gravity tilted exercise trainer, sleeping on a horizontal bed, and performing so-called overhead activities at one g. The notion of permitting a limited portion of test time to be spent in true one g, such as sleeping offsite, transportation, and other overhead activities, could make the long test program more palatable to astronauts.

Unfortunately, only bed rest studies (either head-down or head-up tilt) are able to provide (partial) long-term analogues to space flight, or Lunar or Martian g. The other proposed ground-based simulation modalities permit only limited test duration, introduce substantial nonphysiological elements into protocols, or are simply not proven methods for simulating variable g. A sequential protocol in which the same crews move from space to lab to space and undergo monitoring in each environment is attractive, but the ground-based portion does not seem properly realistic. One possible advantage, however, is that the testing of astronauts rather than volunteers in long-duration experiments could simplify the issue of informed consent.

Artificial Gravity White Paper

It is interesting to compare the above submission with a related proposal, not submitted to RAND, that was developed at the NASA Ames Research Center. J. Vernikos of NASA Ames recently reviewed requirements for microgravity testing and countermeasures.[5] She expressed the view that a dual pathway for testing should be maintained before design decisions for the MTV are set. One pathway would involve the development of intermittent gravity protocols incorporating the proper combination of g, duration, and exercise activity to mitigate risk or prevent injury. This path would rely heavily on ground simulations, primarily bed rest combined with periods of 1 g or greater to formulate the best combination of g loading, activity, and time to enhance bone, muscle, and cardiovascular conditioning. Vernikos also alluded to a mathematical model developed by R. T. Whalen of Ames and based on Skylab and Soviet data showing that walking plus a minimum level of .7 g was required to maintain bone mass. A short-arm centrifuge could be employed at both Ames Research Center and Space Station Freedom (SSF) to provide intermittent g conditions.

The other pathway involves continuous artificial gravity. According to Vernikos, ground simulation via studies using tilted platforms (-6° tilt for micro-g, 10° tilt for .17 g, and +22° tilt for .38 g) could assist in evaluating or screening countermeasures, but it would be useful to construct a man-rated variable artificial g facility (VGF) in space using SSF as a platform. The scale of the resources needed to build and operate such a platform, particularly one based on a tether concept, could be quite large. It is difficult to envision interest and support for a VGF at a decisionmaking level. Even the use of SSF to test artificial gravity using a less costly short-arm centrifuge seems to have limited priority within NASA, given the current plans to employ the planned SSF centrifuge initially for space processing experiments, rather than for testing bioeffects. Vernikos also proposed that a Lunar-based centrifuge be considered should Lunar g (.17 g) be found inadequate. She further recommended a subscale, unmanned, artificial gravity spacecraft experiment to explore the dynamics of tether operations.

The Vernikos white paper is more realistic about the limitations of ground simulation than the submission **Mars Mission Gravity Profile Simulation (#101270)**; however, its reliance on SSF as a space platform for artificial gravity testing could introduce foreseen and unforeseen delays in implementing a suitable test program.

The use of MIR with or without STS and the possibility of a cooperative program between the United States and Soviet Union to develop baseline values for microgravity

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[5]Vernikos, J., *Artificial Gravity White Paper*, September 12, 1989.

effects and to initiate test protocols to mitigate these effects in orbit seem highly desirable, given the present tenuous status of SSF and the urgent need to obtain such data. The ground-based simulation approaches proposed in the submission are either limited or unproven, except for the use of bed rest. There would be little value, we judge, in long-term but problematic ground simulations of Mars g, given the enormous uncertainties regarding long-term microgravity effects and countermeasures.

A combination of the ground-based simulations described in the Vernikos white paper and the space-based approach described in the submission would enable the United States (and the Soviet Union) to proceed with a more effective program for exploring solutions to the microgravity question.

Should NASA adopt the recommendations of the Augustine panel that the space station be modified primarily to gain longer-duration life science data and that microgravity processing be given lesser priority, then the unmodified Vernikos proposal could be far more promising than it now appears.

FUTURE COUNTERMEASURES

A Natural Role for Genetic Engineering

Bone is in a constant process of renewal and growth (remodeling), even in full-grown adults. The bone remodeling process involves a balance between the formation of new bone and the dissolution (resorption) of old bone into minerals and other constituents. Although the physiological role of bone remodeling is still obscure, it is thought that it facilitates the maintenance of bone strength (newly formed bone has fewer microfractures than old bone) and promotes the role of the skeleton as a source of minerals.

New Directions

Fragmentary evidence from observations of astronauts and subjects undergoing bed rest studies implies that weightlessness and inactivity both result in elevated urinary excretion of calcium, phosphorous, and hydroxyproline, even when mineral supplements are taken regularly. Hydroxyproline is significant because its presence in urine proportional to the rate of bone resorption. Under normal circumstances on Earth, bones that are used and loaded by gravity forces are able to signal via biochemical messengers that osteoblasts should produce new bone to compensate for the loss of old bone resorption. In weightlessness or bed rest, signals induced by mechanical loads may be lacking, and new bone formation is unable to keep pace with the rate of bone loss. As a consequence, bone loses density and ultimately becomes prone to fracture.

The past decade has seen great advances in understanding the cellular basis of the remodeling process. These advances are just beginning to show clinical rewards in terms of the isolation and synthesis of biochemical compounds (growth factors) that have the ability to switch certain bone cells on and off.[6] An example of progress is a genetically engineered human growth factor called Bone Morphogenetic Protein 2 (B.M.P.2) that has been tested in animals and is scheduled for human trials soon. A series of other B.M.P.'s derived from calves, cows, and humans is being developed and tested in animal studies.[7] In addition, other growth-controlling proteins that can stimulate bone growth by amplifying the number of cells involved in bone formation are being readied for clinical trials. In some of these trials, growth factors would be combined with collagen and/or ceramic, inserted into breaks and used to repair bone fractures. Ultimately it seems likely that disorders of the bone remodeling process such as osteoporosis, a disease that results in 1.5 million fractures and health-care costs of 10 billion dollars a year in the United States, will be successfully treated. Even today, drugs such as insulin growth factor are being prepared to treat animal models of osteoporosis.

The possible use of bone growth factors is somewhat analogous to the use of erythropoetin to treat certain types of anemia. It has been known for years that red cell production in mammals is controlled by a complex protein formed in the kidney in response to tissue oxygen levels, but it required modern genetic engineering methods to isolate this protein and to synthesize it in ways that could be adapted to commercial production. The methods for probing the chemical composition of growth control factors are widely available, as well as the facility of biotechnology to synthesize and produce them in quantities that permit their use in treatment and prevention. It thus seems probable that a number of pharmaceutical agents will be available during the next decade that will control the growth and activity of the cells that mediate bone formation (osteoblasts) and bone resorption (osteoclasts). However, the possibility that bone formation is primarily influenced by local rather than systemic factors could make the search for a pharmaceutical approach more difficult than if controls are mainly systemic.

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[6]See Canalis, E., et al., "Growth Factors and Cytokines in Bone Cell Metabolism," *Annual Review of Medicine,* Vol. 42, 1991, pp. 17–24.

[7]E. L. Andrews, "Artificial Bone Being Developed to Repair Breaks,"*New York Times*, National Edition, October 24, 1990, p. A-1.

Old Directions

NASA researchers studying weightlessness and others studying osteoporosis have been engaged for years in understanding and attempting to treat bone demineralization using an earlier medical paradigm. It was recognized that a class of chemical compounds called biphosphonates absorb bone crystals and can reduce the rate at which osteoclasts are able to participate in the resorption process. One such biphosphonate, etidronate, has no serious side effects and has the ability to impair the resorption of newly formed bone. Recent clinical studies have shown that some etidronate protocols may inhibit osteoclast-mediated resorption without overly depressing the rate at which new bone is formed. This differs from the action of other agents that have been used to control resorption, where it appeared that bone formation itself decreased because of feedback loops that regulate the balance between resorption and formation rates. Bone density stabilized (for those agents) at a lower level than for etidronate. Preliminary etidronate data indicate that bone density seems to increase with time. Moreover, more advanced variants of etidronate are being tested abroad that could have even greater ability to reduce resorption without adversely affecting the process of mineralization. One limitation of this approach is that older bone is more fracture-prone than newer bone, so that depressing resorption without activating formation could result in a higher rate of microfractures.

The Control Factor Approach

Although the biphosphonate line of attack has short-term promise, it is worth understanding the etiology of osteoporosis associated with age, disuse, or weightlessness. It is generally thought that mechanical forces on bone and surrounding tissue regulate the formation of bone by stimulating the local production of messenger proteins that control the rates of activation, resorption, and formation of new bone. If mechanical stimuli are missing or if the control process is impaired, then bone density will decrease, leading to elevated fracture risk. This is analogous to the role that kidney oxygen levels play in stimulating the production of erythropoetin which, in turn, sets the rate of erythrocyte production by bone marrow. Patients with kidney disease are often unable to produce sufficient quantities of erythropoetin to signal the bone marrow to continue red cell production, and, as a result, anemia occurs despite the availability of iron. Thus, erythropoetin treatment bypasses the early parts of the control loop and overcomes the inability to respond to oxygen levels. Similarly, bone growth factors could substitute directly for the missing stimuli of gravity loading and would directly control the remodeling process. Important research questions are

the relationship between local and systemic controls, and whether a systemic control can properly regulate local remodeling.

For astronauts, the significance of reducing resorption rates without simultaneously modifying the feedback loop between resorption and activation is that newly formed bone is less prone to fracture, and a reduced resorption rate alone could result in the predominance of less desirable older bone. Over the short run, biphosphonate could be effective, but unless a method to promote new bone formation is utilized, the risk of fracture after a multiyear exposure to weightlessness could be high.

It is of interest to observe that bed rest studies supported by NASA were not promising with regard to the ability of etidronate to reduce the loss of bone material, although high doses of etidronate appeared to slow the rate of bone resorption associated with disuse osteoporosis. These same studies suggested that exercise, the ingestion of calcium and phosphorus supplements, and calcitonin treatment were also not successful in reversing bone demineralization in bed rest subjects.

In an abstract way, biphosphonate treatment is a far less elegant approach to treating or preventing defective bone remodeling than the use of growth factors, but the efficacy of the new approach still remains to be verified.[8] Perhaps a combination of agents like etidronate to slow bone resorption and control factors to activate bone formation will be successful. But it seems likely that agents to regulate the entire remodeling process will ultimately be employed. The discovery of a naturally occurring example, discussed below, of the process of growth control seems particularly encouraging.

The Hibernating Bear: Bone Remodeling and Inactivity

Submission #100233 (Untitled) recommended (in an extraordinarily cryptic way) that consideration be given to the process of bear denning (hibernation) as a model for inactivity and the control of bone demineralization. Although not cited in the submission, we found a recent journal article[9] that provides encouraging evidence that in one instance, months of inactivity and the accompanying decreased mechanical loading of skeleton did not produce disuse osteoporosis. Studies of bone and calcium metabolism in black bears were performed during summer, winter (the denning season), and spring. Serum calcium concentrations did

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[8]Arthritis Institute project officers recently (1990) initiated a meeting, jointly sponsored by NASA and NIH, to encourage NASA participation in advanced studies of bone and muscle, but it is too early to determine the outcome in terms of NASA/NIH collaborative research.

[9]T. Floyd, et al., "Calcium and Bone Metabolic Homeostasis in Active and on Denning Black Bears (Ursus Americanus)," *Clinical Orthopaedics and Related Research*, No. 255, June 1990, pp. 301–309.

not change—although the animals remained metabolically active but recumbent—and the bears did not excrete urine or feces during their denning season. Bone biopsies demonstrated that even after four months of skeletal inactivity, bone formation and bone mass were unchanged from their summer values. They also indicated that the remodeling process, in which osteoclast-mediated bone resorption balanced osteoblast-mediated bone formation, did not stop. After spring arousal, when bears again become active, large increases in mineralization and bone formation rates were detected, presumably as a result of regional strain differences within the skeleton that were missing during the denning season. It is hypothesized that these differences could now generate remodeling signals in the loaded portions of the bear skeleton.

The relevance of the bear data is the demonstration that disuse or bone unloading does not inevitably lead to bone density loss but could also result in simultaneous bone resorption and formation. It seems likely that hibernating (denning) bears produce regulatory substances, probably similar to the various bone growth factors described above, that continue to promote osteoblast-mediated bone formation despite the lack of mechanical skeletal loading.

These findings, combined with the dramatic progress being made by biotechnology firms in unraveling the various feedback loops and chemical messengers that control bone formation and loss, provide convincing evidence that NASA should broaden its research agenda to properly exploit these advances. It seems likely that the next decade will see major breakthroughs that could be adapted to preventing microgravity-induced bone demineralization. And the limited research and development costs to NASA associated with this approach could lead to enormous resource savings for SEI when compared with the complex system requirements for maintaining artificial gravity. We believe that R&D on both paths should be supported, but the net payoff to SEI of bone growth-control research could be very large. Furthermore, it would also demonstrate NASA's commitment to maximizing the spinoff impacts of SEI. Certainly, the spinoff value of artificial gravity research on American society would be far less profound than the possibility of ameliorating osteoporosis and improving the treatment of bone disorders.

It is realistic, nevertheless, to expect that a program of exercise and conditioning, perhaps performed under intermittent g in an exercise centrifuge, may still be needed to counter cardiovascular, pulmonary, and muscle dysfunction.

CONCLUSIONS

The data are not yet available to support decisions on the proper strategy for countering or avoiding the effects of microgravity. Although bone demineralization is the critical limiting factor for SEI, there could be other long-term exposure effects that might require more varied and sophisticated countermeasures than we or the Soviets employ or envision.

The United States, for SEI to proceed successfully, desperately requires hands-on experience in long-duration space flight. This would enable data to be acquired that are either not available or insufficiently precise for planning purposes. The recommendation in submission **Mars Mission Gravity Profile Simulation (#101270)** to join forces with the Soviets in a joint MIR-STS program to monitor human responses to microgravity and countermeasures seems both appropriate and possible with reasonable expenditures of time and resources. It should be taken seriously, particularly in conjunction with the ideas for ground simulation expressed in the Vernikos artificial gravity white paper. Waiting for the space station to be available for longer-term studies of human physiology could markedly delay the acquisition of design data.

NASA, we judge, must pursue a dual-path R&D approach, as recommended in the Vernikos document. One path would be the further development of artificial gravity as an option, but with far more realistic consideration of the dynamics, structures, and control issues that would arise when realistic habitat designs include proper mass allowances for radiation protection systems. Originally, the space community was skeptical about artificial gravity. It was concerned that the provision of continuous artificial gravity could increase the complexity and the costs of SEI to perhaps unacceptable levels. More recently, a greater willingness to consider the possibility of a rotating system for transportation to Mars has emerged. Our judgment is that the space community's original instincts were correct: Continuous artificial gravity must be viewed as a technology of last resort, to be employed only if a well-coordinated program of countermeasure research does not bear fruit. Even countering the possible microgravity enhancement of bioeffects could be avoided without invoking artificial gravity.

We are far more optimistic about the other path, which would combine exercise and conditioning, perhaps with intermittent gravity, with state-of-the-art pharmaceutical agents, including some likely to be formulated during the next decade. This path would enable NASA to benefit from the great progress being made in developing genetically engineered counterparts to the natural substances that control bone growth.

Bone growth control is a major spin-on/spin-off opportunity. By spin-on we mean that NASA should monitor current advances in bone therapy, particularly those involving growth control substances, and collaborate with laboratories and biotechnology firms in adapting promising agents to space needs and planning, and executing trials using bedrest simulations. Thus a relatively small NASA investment in this area could lead to enormous payoffs for SEI. By spin-off we mean the possibility that NASA's own work, or even the work of its grantees, collaborators, and contractors, could enhance further progress in medical care.

To properly capture the spin-on/spin-off benefits, NASA would need a genuinely multidisciplinary team, preferably located at one center, that encompasses medical expertise, endocrinology and bone metabolism expertise, exercise physiology expertise, systems engineering expertise, and expertise in the molecular biology of bone growth factors. This latter specialty area is missing from the current NASA mix of skills, although there are scientists at both Ames and JSC who are knowledgeable about aspects of bone metabolism and growth.

In terms of the impact on the feasibility or cost of SEI, the combined countermeasure approach would be far more attractive than continuous artificial gravity. Our preliminary analysis of artificial gravity suggests that it could lead to mass penalties approaching 50 percent and cost penalties perhaps in the same range, and that it would introduce major technical difficulties that have no counterpart outside of SEI. Since it would not benefit from related work being done outside SEI—little spin-on might be expected. It would also have little spin-off potential. A properly configured countermeasure program, along the lines sketched here, holds greater promise of success and at a much lower NASA expenditure of time and resources.[10]

The remarkable finding that denning bears do not lose bone density during four months of inactivity suggests that a model of the process we are seeking to achieve in space actually exists in nature. Identifying the bone growth control substances that are involved, and relating them to those being isolated in the laboratory, could be a major step forward. But NASA and its contractors need to broaden and diversify their research and development portfolios to gain the proper leverage from these exciting results. The concept of spin-on/spin-off represents a management approach for SEI that could maximize the participation

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[10]It must be emphasized (see Medical Care section) that unanticipated consequences to chronic weightlessness might arise that would require diagnosis and treatment by crew member specialists.

of a broader scientific community, minimize total system costs, and enhance the social benefits from SEI research and development.

V. LIFE SUPPORT SYSTEMS

Stable, robust, regenerative life support systems are essential to reducing remote outpost dependencies on resupply missions. The cost and difficulty of transporting water or food to the Lunar or Martian surfaces are sufficiently large as to make the economics of surface-based closed systems quite attractive despite initial large mass costs. Pilot plant evaluation, scale-up, and in-space validation must be performed under actual operating conditions in microgravity or on the Lunar surface. Full-up testing and verification of such systems should precede any situation of long-term dependency on Mars.

Current baseline designs for SSF entirely depend on reliable resupply of air, water, food, and filtration consumables from the ground. A legacy of the shorter missions of the Skylab and Shuttle era, the physico-chemical approach dominates present mission planning activities but is incapable of supporting the projected long-term missions. In terms of daily consumables, an astronaut requires about 2.5 kg of water for drinking and food preparation, about 1.2 kg of food, and about 0.8 kg of oxygen. Nitrogen make-up may require 1–2 kg per day. There is a substantial range of estimates for hygiene and domestic water use of up to 18 kg per person per day. While recycling efficiencies of at least 90 percent are targeted, they have not yet been fully developed or demonstrated. (Our review of the literature finds substantial divergence of requirements.) Attempts to estimate total mission support requirements appear to underestimate minimal mass requirements. It is clear that there is a need for a standardized method of accounting for mass consumption, utilization, thermodynamics, and recycling performance claims.

It is recognized that the launch mass costs could be unacceptable for any extended-duration manned mission, either on the Lunar surface or for Mars transit and exploration. While the Soviets believe they could stock supplies for a two-year mission (a three-year mission should cover the contingency of a low-energy safe return orbit), long-term exploration requires a commitment to bioregenerative, closed, ecological life support systems. (Given the realities of the Soviet agricultural economy, it is difficult to imagine their allocating the specialized scientific resources to study the food production for such a small population.) These life support systems must be capable of providing and recycling air, water, wastes, and food, while controlling toxics and bacterial, viral, or fungal contamination.

KEY ISSUES

The key issues for life support systems are:

- Air revitalization, water purification, and waste management;
- Food production;
- Control of contaminants and toxic substances;
- Human ability to monitor, modify, and control the system;
- Consequences of the space environment for plant biology;
- Launch mass versus resource recycling; and
- Test and verification of working systems.

NASA's requirements are unique. Presently they are the only customer for much of the specialized research necessary to support systems development. While the fields of plant biology and genetic engineering have much to offer, most university and commercial research is directed toward agricultural scale applications concerned with crop yield and agricultural productivity. The few sparsely supported groups have made substantial progress. Work performed during the 1980s demonstrates steady improvement in estimates of the cumulative launch mass crossover from closed physico-chemical to biorcgenerative life support systems. Yet claims that bioregenerative systems now appear to break even against physical-chemical systems with food resupply after mission scenarios of four to five man-years remain to be demonstrated.

PLANT BIOLOGY, REPRODUCTIVE AND FUNDING CYCLES, AND TECHNOLOGY

Plant biology and cell division have well-defined cycles. Even aggressive, ambitious, well-funded programs cannot accelerate the time required for plant growth and reproductive cycles. The issues and options available to NASA and the program paths and required resources are well understood and documented. Because these issues were subjected to multiple, extensive analyses under the Pathfinder Program and subsequently the Smiley Committee, there is little new to be added to this area. While research and development efforts in bioregenerative systems hold great promise, generous funding and staffing could yield substantial savings in future operating costs. Failure to provide adequate support now could reduce the options available to future missions, especially those characterized as "Lunar colony" or "early to Mars."

This area suffers from the proverbial Catch-22 of developing technologies: little funding is available to perform development work for potential missions, yet not enough time remains to develop technology once a mission is defined.

Several competing philosophies can be identified. The first of these is the mechanist's versus the biologist's. NASA's operational experience base is exclusively with physico-chemical systems—essentially a mechanistic approach. Green plants are viewed as unreliable by some members of the aerospace community. This may mirror their experience with house plants and landscaping. The role of plants (and algae and microbes) in processing and balancing atmospheric gases is of such a large scale that it is easy to overlook. Perhaps the key to altering perception in this case is to point out the vast scale of the varieties of plant life that function together to establish a "symbiotic" or "ecological" system. The variety and diversity of plant species is such that they provide a robust system with virtually no opportunities for single point failures. The classic notion of a "food chain" is best replaced with the concept of a "food web." Biology, left to itself with adequate nutrients, water, and energy (light), is remarkably resilient. The plants of the Earth's natural ecosphere have maintained a life-sustaining balance since long before man ever considered creating a controlled enclosed environment, in fact, long before mankind was even aware of nature's subtlety and complexity. This perspective is well represented by elements within NASA's Life Sciences' research program that have focused on global ecology and artificial ecosystems. Earth is clearly the ultimate ecosystem, and creating a stable, reliable, miniaturized version is required for the establishment of long-duration outposts or settlements in space.

Among the biologists there are also at least two contending groups—characterized as ecology or biotechnology. The breadth of the related issues is well stated in the preface to the 1988 COSPAR meeting on "Natural and Artificial Biosystems":

> The scientific and technological interests of this group of investigators range from the study of in situ natural ecological systems, the development of biotechnology systems, through the generation of data on natural and artificial ecosystems by remote sensing technologies, to the development of artificial ecosystems. Underlying the studies presented are the participants' interests in developing life support systems for the use of human crews in space.
>
> It is anticipated that by increasing our knowledge of how the Earth's natural ecosystems function, we will gain insights into the requirements and function of artificial bioregenerative systems that will be used in space, either in orbit or on planetary surfaces. In turn, the development of bioregenerative systems may provide information leading to fuller definition of how natural systems function.

While some phenomena are of a grand scale, involving global systems with enormous biodiversity, they can be difficult to study or model on a comprehensive scale. Simplifying assumptions must often be made or elements isolated to provide smaller systems amenable to detailed analysis and study. At the extreme, biotechnology can focus on the molecular biology or energy efficiency of specific species. Recreating stable large ecologies from component parts cannot be taken for granted.

The most prominent current example of an "artificial ecosystem" is the Biosphere II project in Oracle, Arizona. It is the largest and most ambitious project to attempt to create and maintain a balanced and self-sufficient closed environment over a period approximating a Mars mission (two years). The scale of this project (3.15 acres, 7.5 million cubic feet, 3,800 species of plants and animals) is such that no one should mistake its being the demonstrator for the "first Mars colony," but it offers unique opportunities for studying atmospheric gas dynamics and plant biology and biochemical processes on an unprecedented scale. It fully acknowledges the role of human intervention in establishing and maintaining its balance: Man is explicitly the "keystone predator." As a large-scale, integrated test bed with a complex energy and food web, it is unique.

The biotechnologists are pursuing a more closely controlled approach where single species are being intensively studied, whether in genetically engineered plants or in bioreactors and fermentation processes. The energetics of plant growth and food production are being carefully analyzed in terms of available photosynthetic photon flux. While increases in light intensity at carefully controlled wavelengths have been demonstrated to affect plant growth and food yields, a great deal of work, some of it conducted in zero or partial gravity, is yet to be performed. As it is widely recognized that the physical stresses of gravity or wind affect plant growth and the formation of material in trunks or in stalks, the use of plant resources to produce cellulose- and lignum-based structures or edible food materials awaits evaluation in partial and zero-g environments.

The diverse approaches hold great potential for the development of highly productive plant species. Integrating the various species into a stable, robust ecological system offers unprecedented opportunities for conflict between species, but also unprecedented rewards, as already demonstrated in the "green revolution" (the high-yield, low-labor agriculture achieved during this past century).

TOXICOLOGY, BIOLOGICAL CONTAMINANTS, AND PSYCHOTIC BEHAVIOR

The control of toxic substances has always been of substantial concern in the closed spacecraft environment. The extended duration of the proposed missions will impose even

greater requirements for monitoring and control of possible toxic substances and infectious contamination. There is a body of literature that suggests that many exploration expeditions of the past 100–500 years failed because of subtle, but deadly, cases of toxicity, which were often manifested in apparently psychotic behavior that may have had its roots in organic poisoning (Holloway). The most promising submissions in the life support area are described below.

Biosensors: The Heart of the Life Support System in Space (#101411)

Biosensors use a biological molecule such as an enzyme or antibody mated with more classic transducer technology to form a sensitive, highly specific system. These sensors could have a critical role in the detection of toxic chemicals or bacterial or viral pathogens in the life support systems. They could be incorporated in monitoring or control systems for spacecraft or EVA suit, portable life support systems. Stable, reliable means of monitoring are essential to control systems. Sensors capable of real-time monitoring and eliminating the need for large-scale analytic chemistry equipment and the related trained operating personnel (and the subsequent demand on crew time) are essential for long-duration operation of life support systems.

Ground-Based Prototypes for Bioregenerative Life Support Testing (#101269)

This submission proposes that ground-based prototypes be built to facilitate full-scale evaluation of hybrid systems of partial physico-chemical life support systems integrated with bioregenerative systems. Due to the low level of funding in the past, elements of the problem, such as food production, and waste recycling, have been studied separately, and integrated systems testing has been quite limited. The construction of airtight large-scale test facilities would enable studies of CO_2 absorption and sequestration in soil and plant materials, as well as yield a better understanding of atmospheric gas balances under varying light and temperature conditions. The submittal proposes the use of soil bed reactors for trace gas absorption and extensive instrumentation for monitoring atmospheric gases and potable waste system and irrigation water quality.

Variety in Biological Life Support Systems (#101281)

Stability in biological systems is a function of the size of the system and the diversity of plants in that system. The submittal expresses concern that volume and mass considerations will tempt designers of bioregenerative life support systems to use a relatively small number of plant species. Then, if even one species were to fail in some way via disease, pest, or genetic damage, the entire ecosystem could collapse. The submittal reiterates the importance of designing the ecological systems with a wide variety of complementary species

that are capable of performing the life support function. While a processing chain would be susceptible to the failure of single species, a processing web could be far more robust.

Hydrogen Peroxide for Mars Commodity (#101275)

Hydrogen peroxide, H_2O_2, is proposed as a multipurpose chemical storehouse for breathing oxygen, water, and energy for a Martian base. Made from indigenous water and electricity from a central power facility, it could be used for a range of applications as: (1) a fuel for rovers or a mono- or bi-propellant, (2) a high explosive for mining, (3) an antifreeze solution, or (4) a variety of manufacturing processes in metallurgy, cement production, or ceramics. The submission argues that energy may be the critical limiting resource at the surface of Mars.

VI. MEDICAL CARE

The ability to maintain crew health and the capability to manage illness and injury will be critical for long-duration manned missions. A significant physical or mental illness or in-flight death could severely limit mission capabilities and jeopardize mission success. Given the relatively small crew size currently envisioned for exploration missions, the operational impact of injury or illness incapacitating even a single member of the crew would be catastrophic.

The maintenance of crew health can be assured only by utilizing a systems approach encompassing the triad of modern medicine: prevention, diagnosis, and therapy. This approach applies to both the crew members and their environment. Components of this systems approach include medical certification, crew selection, preflight health stabilization, in-flight medical capabilities, physiological countermeasures, and rescue and recovery. Equally important are life support issues, such as spacecraft environmental monitoring, contamination containment and control, and disposal of toxic or contaminated substances.

KEY ISSUES

The key issues in medical care are:
- Crew selection and training, cross training, and skill maintenance;
- Verification of emergency care and surgical support procedures and systems;
- Systems autonomy versus the "stabilize and transport" option;
- Establishment of physiologic norms;
- Shelf life of pharmaceuticals and blood products; and
- Impact of patient care on total crew time and mission.

The history of exploration on Earth has demonstrated repeatedly that mortality and morbidity related to illness and injury have accounted for more failures of expeditions and impediments to settlement than the failures of transportation systems. Many of the early long-duration exploration missions of the oceans (Magellan, Vasco de Gama) were severely affected by medical problems.[1]

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[1]Daniel J. Boorstin, *The Discoverers*, Random House, New York, 1983, p. 261; and Eric Newby, *The World Atlas of Exploration*, Crescent Books, New York, 1985, pp. 75–76.

The primary medical officer will be responsible for diverse roles that will be complex and demanding:

- Public health officer/primary physician;
- Monitoring space adaptation and administration of support countermeasures throughout the mission;
- Emergency/trauma surgeon; and
- Monitoring and possible intervention in neuropsychiatric/behavioral issues.

Such responsibilities also require a comprehensive perspective on the possible impact of spacecraft systems on human health. Given the diverse roles and the need for specific technical skills, such as those of a medical or laboratory technician, nurse, and surgical assistant, a team approach will be essential.

The practice of environmental medicine and traditional aerospace medicine usually involves a normal subject (i.e., patient) in an intermittently abnormal environment. Conventional medicine usually involves an abnormal subject in a normal environment. True space medicine presents a worthy challenge: a chronically abnormal patient in a continuously abnormal environment. This challenge requires the development of interdisciplinary teams consisting of crew members, physicians, engineers, managers, and life scientists from various organizations, both internal and external to the space agency.[2] Extended-duration missions also pose unique challenges regarding the stability of blood products, pharmaceuticals, and reagents for modern laboratory analysis. They also require the availability of diagnostic instruments and analyzers that operate in space with stability and reliability.

A sustained effort is required to solve current and anticipated problems associated with space medicine. Mission managers are beginning to recognize that the human link in the chain may be the most vulnerable. Without a high-priority, sustained, integrated effort, significant biomedical issues will preclude the timely accomplishment of an extended space station, Lunar base, and/or manned mission to Mars or, at the very least, force acceptance of higher-risk mission scenarios than necessary.

The goal of a space medical facility is to provide preventive, diagnostic, and therapeutic capabilities consistent with current and anticipated U.S. clinical medical practice

[2]J. S. Logan, "Health Maintenance on Space Station," D. Lorr, V. Garshnek, and C. Cadoux (eds.), *Working in Orbit and Beyond: The Challenges for Space Medicine*, American Astronautical Society, Vol. 72, Science and Technology Series, 1989, pp. 87–99.

standards.[3-5] The objectives are to ensure the physical and mental health and safety of the crew during routine operations; prevent mission alteration or termination secondary to an illness/injury; maximize crew performance by reducing crew downtime due to illness/injury; to the extent possible, prevent an in-flight death; and in case of in-flight death, provide capability of storage and return of the body to Earth. It should also support the acquisition and analysis of data on long-term space adaptation critical to developing the prerequisite scientific knowledge to support future missions.

THE MEDICAL RISK

Analysts define risk as the product of the probability of an event and the consequences of that event. For manned space flight, medical risk is defined as any illness or injury requiring significant mission alteration, termination, or evacuation of the patient. While many operational analogs have been statistically analyzed in an attempt to quantify the medical risk for extended spaceflight, none of the analogs is comprehensive.[5] These include the Soviet and American space experiences, U.S. Air Force and Navy air crew members, Navy submarine crews, operation "Deep Freeze" personnel (Antarctic), and general populations matched for age and sex with the U.S. astronaut population. The data are highly variable but still suggestive. The Soviets have required two rescues in 137 man-months of extended-duration space operations, which yields a risk of 1.41 evacuations per year for an eight-man crew per/year. Medevac experiences from the Antarctic show 102 evacuations between 1982 and 1987 for a 12 percent risk per eight-man crew/year. Navy data for all ships for a nine-month period of 1987 show 990 evacuations for 60,000 man-years, again yielding a 13 percent risk per eight-man crew/year. However, most epidemiologists agree that the quantitative application of ground-based analog data to space is rather tenuous. Yet the inability to accurately quantify the medical risk in space prospectively should not prevent a common sense approach to in-flight health-care systems design.

While quantitative risk approximations are imprecise, design guidelines based on qualitative risk assessments can be developed. Three general types of medical/surgical conditions could affect the crew. The first consists of medical/surgical conditions, which will be more likely in microgravity than on the Earth. Given the physiology of adaptation to

[3]Newby, pp. 75–76.
[4]Logan, "Health Maintenance."
[5]B. D. Nelson, R. M. Gardner, D. V. Ostler, J. M. Schulz, J. S. Logan, "Medical Impact Analysis for the Space Station," *Aviat. Space Environ. Med.*, Vol. 60, No. 2, February 1990

weightlessness (e.g., calcium washout), the risk of a kidney stone is higher in space than on the ground. The second consists of those conditions more likely in the occupational setting of a spacecraft, independent of the effect of microgravity. An example is decompression sickness or trauma. Because the crews will be transitioning between higher and lower ambient pressures (spacecraft to space suit), they will have a greater risk for developing decompression sickness. A crush injury or trauma secondary to rapid decompression during an EVA would bridge the categories. The third consists of the routine medical/surgical conditions that are expected in a patient population matched for age and sex with a long-duration crew.[6]

In addition to the statistical (quantitative) and qualitative approach, the significance of mission impact must be considered in any discussion of the medical risk. The cost of being unprepared must be addressed. Although the probability of an in-flight myocardial infarction (MI) may be low, the impact would be significant. With proper equipment on board, an uncomplicated MI could be adequately treated. Other low-probability occurrences, such as penetrating head trauma, might not be treatable without a large medical infrastructure. Therefore, in-flight coverage should be provided if a low-probability event could be treated with little additional capability or expertise, especially if the event would have profound mission or health consequences. Specifying crew training and facility requirements is further complicated because high-probability events will have minimal impact, while the less probable events may have the greatest mission impact.

Classically referred to as triage, possible medical/surgical conditions group into three classes: (1) those expected to resolve with little or no formal care; (2) those likely to deteriorate or be fatal without adequate care but that can be expected to stabilize, improve, or recover with appropriate equipment, capability, and expertise; and (3) those likely to be fatal despite all reasonable efforts in the in-flight environment. Class 1 conditions are expected to be most prevalent. Unambiguous Class 3 problems, although the most dramatic, should be infrequent. Concentrating the majority of resources to support Class 2 conditions assures the greatest positive impact on mission success and clinical outcome.[7]

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[6]C. A. Raymond, "When Medical Help Really is Far Away," *Journal of the American Medical Association*, Vol. 259, April 22/29, 1988, pp. 2243–2244.

[7]B. A. Houtchens, *Emergency Surgery and Critical Care to Support Human Exploration of the Inner Solar System, Final Report*, NASW-4519, July 31, 1990.

SYSTEM REQUIREMENTS AND CAPABILITIES

Overall Needs

A space-based health-care system must provide baseline medical coverage. Design cannot be entirely driven by numerical projections of the medical risk for each condition. A strong analogy to the rural hospital setting is evident: The only medical facility in an area is obliged to provide initial evaluation and management for any problem that is presented, regardless of whether or not it was anticipated.[8] The functional requirements for an in-flight medical facility to support low Earth orbit (LEO) manned operations have been described.[9] It is assumed that space medical requirements for SEI missions will be an extension and augmentation of LEO capabilities but will reflect the fact that distance and orbital mechanics may preclude the evacuation option.

From LEO stations to Lunar bases, relatively prompt transport to definitive care on Earth is possible, provided all of the following are true: (1) adequate **initial** evaluation and patient stabilization is possible, (2) the necessary level of supportive care can be provided **during** the transport, and (3) the return flight profiles (G-loads) are tolerable for a physiologically **compromised** patient.[10] Beyond Lunar bases, successful patient evacuation becomes highly unlikely. Medical self-sufficiency becomes more critical.

The principal determinant of outcome for significant in-flight illness or injury is the primary medical officer on site, provided that proper support, equipment, and trained personnel are available.

System Flight Equipment

The major constraints to the design of in-flight health-care systems are weight, volume, power, cost, and time. Weight, volume, and power are critical constraints in the design of all flight systems. The increasingly complex bureaucratic procedure for flight certification of hardware requires the "freezing" of technology 8 to 12 years prior to intended use. Delays of this magnitude might be perceived as intentional barriers to entry rather than a meaningful process intended to assure safe and reliable operation in flight. The three- to five-year product cycle of advances in medical instrumentation technology and

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[8]B. A. Houtchens, "Emergency Surgery and Critical Care to Support the Space Exploration Initiative," RAND Outreach Submission 100776, August 7, 1990; and B. A. Houtchens, "Health Care Systems Definition, Testing, Training and Support For SEI," RAND Outreach Submission 100790, August 7, 1990.

[9]Space and Life Sciences Directorate, *Medical Requirements of an Inflight Crew Health Care System (CHeCS) for Space Station Freedom*, National Aeronautics and Space Administration, Johnson Space Center, March 5, 1990.

[10]Houtchens, *Emergency Surgery*.

expertise is tantamount to forcing the utilization of equipment and procedures no longer used by reference medical centers on Earth. (Corporate product cycles in highly competitive industries are now about 18–24 months. A one-step lag may be tolerable for NASA, but a greater lag is inexcusable.) Funding mechanisms and procurement practices, as well as disclosure of proprietary technology, have been an impediment in this area. The paucity of resources for design, development, validation, and test stands in stark contrast to the resources committed to the development and certification of flight hardware.

As in any spacecraft system, flight components should be modular to facilitate easy replacement, repair, and operation. A complex conflict arises between the desire to use commercially available diagnostic analyzers and instrumentation that have been verified and well accepted by the clinical medical community and the need for equipment that will be safe and reliable in space. While the option to "fly-bridize" (hybridizing for flight or "flight hybrid") is initially appealing, substantial redesign at both the component and system level is often required to meet current NASA materials, electronics, thermal, and microgravity constraints. In fact, the safety, reliability, and operational standards currently required for commercially available medical hardware are very stringent. Such hardware must function effectively and safely in environments ranging from operating rooms to jet aircraft. However, each piece of hardware must be reviewed stringently in the context of the space environment. Fortunately, only minimal modification of certain types of medical hardware is required for satisfactory operation in microgravity. Given the relatively few hours of in-flight operation anticipated in medical hardware, current NASA reliability, materials, electronic, and thermal requirements should be relaxed for medical equipment already meeting strict government standards. An example is the case of a medical device that was flight certified for STS with minimal modification because it already met existing stringent government standards. In contrast to this, chemistry systems and pressure transducers may require special attention to assure reliability and stability in microgravity.

Since NASA's operating environment and requirements are substantially different from those of clinical medicine, NASA should not expect, much less depend upon, investments made by commercial companies to supply the clinical market. Defining a suitable balance still remains a challenge.

Selection criteria should include traceability of standards and calibration, ease of maintenance, low consumables requirements, nonlabor intensive operation, and minimal reliance on the expertise of the operator to obtain clinically valid information and data. Instruments to be used for special studies could entail other even more stringent requirements. Analyzers and instruments should also be interfaced to the onboard

computers and data communications system. Fortuitously, these requirements parallel development in systems for hospital-based clinical laboratories.

A systems approach to baseline medical coverage has identified 22 subsystems generic to any in-flight health-care system.[11] They are (1) anesthesia, airway management; (2) blood, blood products; (3) central supply; (4) consultative support, telemedicine; (5) dental care; (6) fluid administration, intravenous therapy; (7) fluid containment, medical suction, liquid collection; (8) hyperbaric treatment; (9) imaging diagnostics, Xray; (10) informatics and communications, medical decision support; (11) laboratory diagnostics; (12) minor treatment, eye, ear, nose, throat; (13) morgue, body bag; (14) pharmacy; (15) physical examination diagnostics; (16) physiologic monitoring; (17) sterilization; (18) surgery; (19) surgical workstation/patient restraint; (20) transport, resuscitation, stabilization; (21) ventilatory support, mechanical ventilator; (22) waste management.

PERSONNEL: BACKGROUND, TRAINING, INFRASTRUCTURE, ORGANIZATION

The primary medical officer should be a surgeon who is well trained and current in the required clinical procedures. The minimum training for anyone assigned to provide management of a broad spectrum of emergency surgical diseases, trauma, and surgical critical care is general surgery. With adequate access to a proper knowledge base and remote consultation, a properly trained and clinically current[12] general surgeon could function as an emergency physician or general internist. The reverse is generally not true.[13] Surgeons can be cross-trained to perform other mission-essential duties such as research or station keeping.

With the assistance of remote specialty consultation, a crew surgeon would be expected to provide initial evaluation and intervention, and the continuity of care for a broad spectrum of potential illness and injuries. A background most compatible with these responsibilities includes formal training in the following: diagnosis and treatment of common acute medical and surgical emergencies (including operative decompression of intracranial hemorrhage and fixation of fractures); critical-care medicine, including the management (with required consultation) of cardiac, pulmonary, infectious diseases, and renal problems; diagnostic and interventional radiology skills, including percutaneous drainage of fluid collections; anesthesiology skills; preventive medicine; and research skills.

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[11]Houtchens, *Emergency Surgery*.

[12]There should be both requirements and mechanisms for physician astronauts to maintain clinical currency, although the present cadre of physician mission specialists could view this as a threat to future flight opportunities.

[13]Houtchens, *Emergency Surgery;* and Houchens, "Health Care Systems."

Of approximately 250 university-associated medical centers, only about 20 percent provide this range of clinical opportunities, and none provides background in operational space medicine. To meet this need, NASA should identify and establish ongoing collaborative relationships with several university-associated or free-standing training programs that offer a favorable spectrum of clinical training opportunities in general surgery/trauma/critical care and are willing to become and remain familiar with the operational space medicine environment. A potential syllabus for a "pilot" program in crew surgeon training should be defined and evaluated in the immediate future.[14] The issues associated with dysfunctional behavior and the possible necessity for psychopharmacological intervention must also be considered during training of the primary medical officer. In addition, the mission commander or other members of the crew should be able to deal with behavioral problems.

A NASA/medical center program should be established to provide ongoing training for space physicians in the areas of general surgery, trauma management, critical care, and other relevant areas. From this cadre of trained, clinically current medical experts, at least one space physician should be assigned to every SEI crew. The cadre of space medical specialists should participate actively with mission planners, senior management, and the aerospace engineering community. Because of the unusual significance of human support problems for SEI, they should have major responsibility and authority in medically relevant decisions and in defining, developing, and validating space-based medical systems. The cadre's proper organizational relationship to the astronaut office remains to be developed to minimize the possibility of conflicts of interest.

DECISION SUPPORT SYSTEMS: ARTIFICIAL INTELLIGENCE, PROTOCOLS, AND TELEMEDICINE

Decision support systems based on artificial intelligence, validated treatment protocols, and telemedicine can be used to support the medical personnel on site. In addition to computer-based onboard diagnostic and treatment protocols and "expert systems" logic to guide decisionmaking, the on-board medical personnel could be supported by the use of "telemedicine." Via electronic links to the ground, the chief medical officers will have access to "live" operational medicine and clinical specialty consultation upon request. However, as distance from Earth increases, all the following will increase: (1) the time delays in telemedicine communication circuits, (2) the need to provide more comprehensive diagnostic and therapeutic services on site (especially in the absence of a capability to provide timely transfer to definitive care on Earth), and (3) the feelings of "isolation" and of "being cut off"

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[14]Houtchens, *Emergency Surgery*; and Houchens, "Health Care Systems."

from mainstream medicine that discourage rural community physicians on Earth. Despite the inconvenience associated with the first, it is predicted pressures associated with the last two that will make telemedicine more important rather than less.[15] "Virtual reality" techniques could also permit on-board personnel to view actual surgical procedures or obtain consultative support.

Submittals **#100776** and **#100790** emphasize that clinically validated protocols have become increasingly important in guiding evaluation and management of critically ill or injured patients. Ideally, protocols eliminate actions demonstrating little or no value while preventing omission of actions known to be of benefit. This reduces the cost of care, minimizes the medical infrastructure required to provide care, and maximizes quality of care. Patient differentiation, therapy content, therapy process, and outcome criteria are key elements addressed by critical-care protocols. University medical centers are the only settings developing these essential elements. While protocol development should be based within clinical institutions, NASA sponsorship of that development would offer the space agency an opportunity to take a leadership role in defining what is and is not efficacious in acute-care medicine in the space environment. Given that most protocols would evolve from ground-based practice, a potential limitation is the variability introduced by microgravity and the limited information on pharmacodynamics to guide drug therapy in space.

NASA has been active in telemedicine projects ranging from the ATS-6 satellite program in Alaska in the early 1970s to the STARPAHC program with the Papago Indian tribe and the Indian Health Service in Arizona in the mid-1970s, and recently took the lead in establishing a Telemedicine Spacebridge to Soviet Armenia to provide expert consultation to Armenian physicians caring for victims of the massive earthquake in December of 1988. Despite the success of the project, no additional demonstration projects are planned by NASA. Telemedicine could be one of the cornerstones of clinical space medicine. It is essential that the technology and procedures be refined and improved at the earliest opportunity.

Long lead-time schedules are implicit in the development of medical flight hardware. A five- to seven-year lead time is planned for hardware developed for SSF. However, a similar time span may be necessary for comprehensive clinical-care protocol development and verification. Citing the experience of the LDS Hospital in Salt Lake City, submittals **#100776** and **#100790** indicate that compliance for most protocols exceeds 90 percent; however, every time a new algorithm is introduced, compliance drops. It is difficult to

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[15]Houtchens, *Emergency Surgery*; and Houchens, "Health Care Systems."

predict the impact of seemingly "minor" alterations in treatment protocols before testing in the clinical environment. Significant lead time is required to develop safe, efficacious clinical-care protocols. An early start on these tasks could provide the opportunity to incorporate the experience in ongoing operations and mission planning.

TESTING AND VALIDATION

While simulations are helpful in the development of space medicine systems, no medical device, technique, or procedure should be considered "qualified" until subjected to critical evaluation with real patients. Sufficient lead time should be provided in testing schedules to correct deficiencies by effecting design changes. The appropriate clinical "test beds" are not found within NASA or aerospace engineering corporations or "support contractors." They are found in university medical centers and biomedical engineering departments.[16] Testing such protocols may introduce some "Human Subject Committee" problems.

Furthermore, the obsolete turnkey approach to system design, development, and testing should be replaced by one where an ongoing interaction between NASA Life Sciences and contractors is encouraged, although at the risk of complicating organizational and procurement arrangements. If possible, lines of responsibility and authority should be merged to both cost and performance surprises. In these ways the likelihood of a Hubble-like episode could be minimized.

CONCLUSIONS

The human link in the chain may be the most vulnerable. As space exploration progresses towards longer-duration missions, space medicine will become more critical to mission success. Without a high-priority sustained effort, significant biomedical issues may preclude the timely accomplishment of SEI missions. Even with serious attempts at anticipating and resolving medical problems by NASA and the broader medical community, it is likely that new, unexpected problems will arise during a multiyear mission. Successful solution of these problems will require the involvement of a far more extensive network of biomedical specialties than there is at present.

Given that expertise in critical-care planning and medical hardware development does not reside in NASA or traditional aerospace engineering support contractors, the NASA Life Sciences staff, particularly those involved in manned space flight, should develop ongoing collaborative arrangements with established university medical centers and biomedical

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[16]Houtchens, *Emergency Surgery;* and Houchens, "Health Care Systems."

engineering departments. These arrangements could be both formal and informal and would serve to familiarize others with operational space medicine (4). They would promote excellence and critical thinking during the initial specification and design of systems and hardware, the formation of clinical protocols, and the testing/validation of not only the individual devices and protocols, but the resultant clinical-care systems as well.

VII. HUMAN FACTORS: BEHAVIOR AND PERFORMANCE

The field of human factors focuses on human capabilities, behavior, and performance while interacting with engineered systems and environments. Its scope is far broader than the classic perception that human factors deals primarily with cockpit displays and ergonomics. The success of long-duration missions will be highly dependent on human factor considerations, which must be designed in, not merely added on. Crews will be operating in a stressful, isolated, and confined environment for extended periods. Crew selection, command structure, conflict resolution procedures, and habitability will affect the crews' productive capacity and could compromise mission success or limit mission goals. The costs of neglecting human factors can take the form of labor-intensive operations, high workload and fatigue, increased mission costs, and higher rates of human error. While constant reference is made to the future use of "highly automated" systems, the crew must be able to manage off-nominal and emergency situations. When crew size is small and the operating environment stressful, the cognitive demands of large, complex, and dynamic nonlinear or digital systems quickly outstrip the control capacity of the unaided human. These problems are far from trivial—they can be life threatening.

The term "human factors" has been loosely (and inappropriately) applied to all aspects of manned as contrasted to unmanned spaceflight activities. It does not deal with the physical health of the crew per se. Rather, it connotes a number of factors, as described below.

KEY ISSUES

The key issues in the study of human factors are:

- Crew selection, compatibility, and conflict resolution;
- Command structure;
- Human interaction with engineered systems, including management of off-nominal and emergency situations;
- Behavior and performance;
- Habitability; and
- Analog environments.

As the space environment is often referred to as stressful, the primary psychological stressors are listed here so as to make the concern more tangible and facilitate analysis to develop approaches for minimizing them.

- Social isolation;
- Physical confinement in small habitable volumes;
- Continuous perception of risk;
- A wide range of social, emotional, and physical deprivations;
- Monotonous surroundings, lack of variety, and change;
- Lack of separation between work and nonwork settings;
- Inability to leave the work group or setting;
- Lack of privacy;
- Limited role opportunities; and
- Complete dependence on technological infrastructure.

The example—not entirely facetious—of what a two-year mission might entail has been put forth: check into a small hotel room, invite six to eight of your friends up for drinks, now stay there for two years. Yes, you get to go out into an Arctic desert for two to four weeks after a year, room service can probably offer more variety than will be available on the spacecraft, but the confinement and monotony will bring out many unanticipated tensions. Providing meaningful, stimulating activities for the crew will be a serious challenge.

Crew selection, composition, compatibility, dynamics, and control structures need extensive research. Not only is little known about these issues in stressful, confined, long-term, and isolated environments, but aerospace community interest in this area has been limited. While recent acceptance of the importance of team training and team dynamics (crew resource management) is heartening, it is only a beginning. Excessive reliance on "crew professionalism" has been the hallmark of this area and open discussion of actual operating problems has been considered detrimental to the space program. Recent astronaut corps acknowledgment of problems and their support of further research are major breakthroughs. Leadership and management on board has traditionally assumed a military model, which must be reconsidered for future exploration activities. Considering the possibility of multinational crews with substantial cultural differences, the high probability that few crew members will have had military training (barring a return to the draft) means that the issues of command structures and individual rights will require substantial attention. Command structures may change during different portions of the mission. Issues concerning the locus of

control between flight personnel and mission control must be resolved. On-board training and skills maintenance among cross-trained crew members for highly infrequent but potentially life-threatening anomalies also pose a challenge.

Meaningful analog studies are required, both on Earth and in space. While the Antarctic analog could be quite productive, proposals that have the crews wintering over in prepared, established bases substantially miss the point.

Spacecraft habitability and ergonomics also require more support and integration into systems design. Minimum volume standards, as well as communications and privacy issues, require further research. It is well known that overcrowding is highly correlated with aggression and violence.

Another area where tradeoffs are needed is the acknowledged desirability of multiple missions for crew members, the ensuing benefits associated with learning from experience, and the potential risks of cumulative exposure to space-related radiation or microgravity. Although a single "flags and footprints" mission does not pose this problem, it becomes more important for a continuing program of exploration and infrastructure building.

RADIATION AND HUMAN FACTORS

It should also be noted that the Soviet literature raises the issue of the effects of radiation on spacecraft operator performance in the following areas: learning and retention of discriminations, transfer of skills to a new situation, delayed responses, attention, motor activities, object manipulation, solution of various mechanical problems by "insight" or "intellect," and conditioned avoidance response. Work is reported from the U.S. Armed Forces Radiobiology Institute that highenergy iron particles (galactic cosmic rays) (at 600 MeV/amu) have been found to alter behavior in rats after doses as low as 10 rads. The sensitivity to iron particles was 10–600 times greater than to gamma photons. An impairment in the regulation of dopamine release in the caudate nucleus (a motor center in the brain), lasting at least six months, was also found and correlated with performance deficits.

SUBMITTALS

Two submittals were highly pertinent to issues in human factors. **Cognition, Problem Solving, and Memory in a Microgravity Environment (#100959)** raises the issue "Have adequate studies been done on humans?" on the stated topic. In fact they have not, and anecdotal recitations by several astronauts on the degree to which they found themselves dependent on checklists for tasks with which they were highly familiar and similar tales of attention difficulties suggest that this is not a frivolous suggestion. The

submittal reviews the adaptation processes to microgravity at the biochemical and physiological level to make the case at the cellular level that the possibility exists for perturbation of central nervous system tissue and particularly brain tissue in the hippocampus and cerebral cortex. An array of studies to test cognition, problem solving and memory are proposed for examination in two environments, weightlessness and artificial gravity, on board the same space vehicle. If particular deficits are detected, then measures can be taken to design for the problem in terms of operational procedures.

Space Ergonomics: Optimization of Work Performance in Space (#100701) touches on an area that was widely studied during the Apollo era but has been sparsely supported subsequently. In space, muscles produce forces without the natural antagonism provided by gravity. Relatively little is known about the efficiency of human motion in the zero-gravity environment. Often altering the technique of task performance alters both the local muscle stresses and the systemic stress on the cardiopulmonary system. Different methods to execute the same tasks may be more energy-efficient than others, and the optimal technique on Earth (or in the MSFC neutral buoyancy tank) may not be the most energy-efficient for the same task performed in space. In light of the fatigue experienced by the Soviet cosmonauts after three to four hours of EVA, this is an area worthy of further study. There has also been a strongly felt need for more specific guidelines for designers working in the Space Station Freedom environment, and this need will become even greater on future projects requiring substantial construction and assembly in space.[1]

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[1]Space and Life Sciences Directorate, *Medical Requirements*.

VIII. CONCLUSIONS

CAN HUMAN SUPPORT REQUIREMENTS BE SATISFIED?

The core human support issues—radiation protection, microgravity, life support, medical care, human factors, and EVAs—pose challenges to the entire community interested in the success of SEI. We are confident that a broadly based endeavor, probably involving substantial levels of international cooperation, could resolve these challenges in ways that will facilitate the success of SEI. However, an early and unusually well-planned, coordinated, and funded program will be necessary for NASA to assure the high levels of reliability for human support systems that are demanded for systems of a primarily engineering nature.

We reiterate the human support requirements stated in Section II:

1. Astronauts will engage in a Mars mission only if the predicted levels of safety, risk, and reliability are acceptable, and there is a high likelihood of their survival in good condition or restorable health.

2. Astronauts will be able to perform their mission tasks productively and effectively, and their performance will not be unnecessarily compromised by physiological responses to the space environment, or by countermeasures to mitigate these responses.

3. Astronauts' future careers and health status will not be significantly jeopardized by their exposure to the space environment.

Only if these requirements are satisfied will NASA achieve its stated human support goals of ensuring "the health, well-being and performance of humans in space." Despite our optimism that these goals can be achieved, we are concerned that the 1989 NCRP radiation protection guidelines are inconsistent with the 1990 NAS/NRC BEIR V risk assessment. NCRP guidelines would, if followed, permit SEI crew members to be exposed to radiation over their careers that could result in 4 to 16 percent excess lifetime cancer mortality compared with the 3 percent limit endorsed by the NCRP. Even 3 percent may be excessive as a planning target, especially when compared with planning targets for the reliability of other NASA systems. We are also concerned by apparent underestimates of realistic GCR radiation shielding mass in NASA and contractor studies of artificial gravity, as well as

compartmentalization between systems that may be intimately connected, such as radiation shielding and artificial gravity. Another issue is the timely use of unmanned space probes to better characterize the space radiation environment.

Our radiation protection analysis underscores the drawbacks of passive shielding as a means to reduce GCR and SPE bioeffects to acceptable levels. Mass penalties of 10^5 to 10^6 kg for a four-person MTV seem excessive, but such values are necessary for a three-year mission with a maximum GCR-only dose rate of 25 rems/year within a habitat. This corresponds to a 3 percent excess lifetime risk of cancer mortality.

Hybrid active/passive shielding, if successfully developed, seems more attractive than pure passive shielding, especially since it minimizes reliance on uncertain radiobiological data. We were impressed by preliminary data from Japan indicating the possibility that high-field superconducting magnets fabricated of high-temperature superconducting materials could operate in a low-temperature (4.2°K) mode, but much remains to be done to confirm the feasibility of this approach.

As we noted, uncertainties in the understanding of space radiation exposures are so large that point designs of conceptual radiation protection systems are virtually useless or misleading, particularly those that assume future research will show only favorable findings. It would be far more realistic to design systems that reflect the true high level of uncertainty. Further, planners must consider the complex and potentially significant interactions among different systems, including radiation shielding, artificial gravity, microgravity countermeasures, habitability design and performance, life support systems, and EVAs. More generally, the interactions between human support and mission/architecture activities deserve greater attention. Quantitative estimates of human support needs will become drivers for the overall mass requirements for insertion into low Earth orbit.

Outreach As a Continuous Process

Regarding the Outreach process, we believe that many scientists and engineers who could contribute to SEI may not be adequately aware of the relevance of their R&D to the Mars mission. Two illustrations are biotechnology firms and other research groups developing bone-growth factors for treating bone disease, and the high-temperature superconductivity materials research in Japan. Investigators at Los Alamos, MIT, and Florida State, for example, could make significant contributions as part of the new NSF-sponsored National Magnet Laboratory.

Furthermore, a focused future effort to gather submissions from university students and staff, as well as from non-U.S. sources, could broaden the level of interest and the richness of the base of human support submissions.

Finally, we emphasize the importance of access to space as the primary way to gather human support data or to demonstrate the reliability and robustness of concepts that pass the screen of ground-based simulations. As we have noted, the entire area of microgravity, including countermeasures or artificial gravity, requires long-duration observations of both human and plant bioeffects.

In closing, we judge that the Outreach process has already been fruitful in terms of the submissions and analyses described here. A continuing Outreach program could be even more useful in the future as a way to broaden the R&D base and to stimulate innovative solutions of SEI problems.

Appendix A

SUBMISSION HANDLING, EVALUATION METHODOLOGY, AND CRITERIA
FOR EVALUATING SUBMISSIONS

Submitters were asked to select the appropriate category for their ideas from among those listed in Table A.1. The table shows that all categories received a fair number of submissions. Of the 1,697 submissions received, 149 (less than 9 percent) were judged to be incapable of being screened. Another 105 submissions were received after the cutoff date of August 31, 1990.

Table A.1
Submissions Distributed by Category

Category	Screened	Not Analyzed
Architecture	290	1
Systems	52	0
Transportation	350	0
Power	138	1
Human support	156	2
Processing	75	3
Structures	119	1
Communications	45	1
Automation	52	1
Information	21	1
Ground support	28	0
Others	194	4
Undetermined	28	134
Total	1548	149
Received after 8/31/90	105	

A submission was ruled incapable of being screened if it (1) was marked as classified or proprietary or (2) contained no supporting information of any kind. A submission marked as either proprietary or classified was automatically destroyed by the subcontractor. In such cases, the subcontractor noted who destroyed it, the date, and any particulars, then informed the submitter of the destruction of the submission and the reason for it.

As shown in Table A.2, the majority of submissions (63 percent) came from individuals, with 22 percent coming from for-profit firms and 5 percent from educational institutions. The relatively few submissions from educational institutions may have been a problem of timing, because Project Outreach's publicity and submission process began in the

summertime, when most lower-level schools are closed and most universities have reduced staffs and enrollments.

Table A.2
Sources of Submission

Source	Submissions	
	Number	% of Total
Individuals	1,061	63
For-profit firms	381	22
Educational institutions	89	5
Nonprofit organizations	72	4
Other	46	3
Groups of individuals	48	3
Total	1,697	100

Nevertheless, Project Outreach generated broad national interest. All of the states except Alaska, Arkansas, and Wyoming were represented, as were five foreign countries—Argentina, Australia, Canada, Israel, and Scotland. Interestingly, 40 percent of the submissions came from three states—California with 26 percent, Texas with 9 percent, and Florida with 5 percent.

NASA personnel also contributed to Project Outreach: Submissions were received from the Johnson Space Center, Goddard Space Flight Center, Marshall Space Flight Center, Lewis Research Center, Ames Research Center, Jet Propulsion Laboratory, Langley Research Center, the Reston Space Station Program Office, and the Stennis Space Center. A total of 121 submissions were received from NASA locations.

SUBMISSION FORMAT

Submitters were asked for a two-page summary and simple outline of their idea. Submitters were also given the option of submitting an additional ten-page backup explanation of their idea. Only 22 percent of the total submissions included backups. This had implications for the analysis process, which we discuss below.

SUBMISSION HANDLING

Because of time constraints, RAND was obliged to follow an abbreviated six-month schedule. Figure A.1 shows the flow of the process we developed and implemented for

handling the submissions. Our task involved simultaneously processing the submissions, developing a methodology, training the panels, and building the software. This time frame allowed no margin for error.
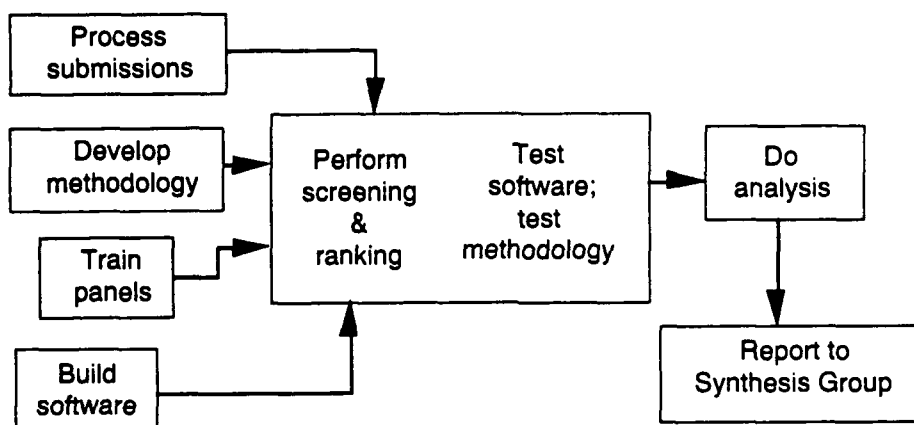

Fig. A.1—Flow of Submission Handling

SUBMISSION DATABASE

For each submission, pertinent background information was logged into the database, including the unique ID number of the submission, the reviewer, the date, the name of the panel performing the review, and the title or subject of the review. To remove bias from the process, the panels did not have information concerning the submitter's name or organization. Reviews of the submissions were entered in a text field. Each reviewer was required to briefly explain the reasons for scoring a submission as he or she did.

PANEL RANKING OF SUBMISSIONS

Primary Ranking Method[1]

Submissions were ranked initially using a method based on weighted sums of five attribute scores. In this case, the attribute weightings were numbers between zero and one that summed to one over the five attributes. These weightings represented the consensus of each panel concerning the relative importance of the attribute for the panel's particular technology/mission area.

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[1]We refer to "Decisions with Multiple Objectives: Preferences and Value Tradeoffs," by R. L. Keeney and H. Raiffa, John Wiley & Sons, New York, 1976, for a review of ranking methodologies and a discussion of advantages and pitfalls. They use the term "additive" to refer to our cardinal method, and "Lexicographic" for the method we designate as ordinal.

Table A.3 presents the screening process weights determined by each panel for each of five common attributes. Each submission received a composite score, computed by summing over all attributes the product of the attribute score (1–5) and its weight. Thus rankings represent the overall score of a submission relative to all the submissions within its panel. Rankings by composite score can be sorted within the Fourth Dimension database and recomputed using different attribute weights to perform sensitivity analysis.

Table A.3

Screening Process Weights Determined for Each Panel

Panel	Utility	Feasibility	Safety	Innovativeness	Cost
Architecture	0.30	0.30	0.15	0.20	0.05
Transportation	0.30	0.25	0.25	0.05	0.15
Power	0.25	0.25	0.25	0.10	0.15
Human support	0.40	0.25	0.08	0.25	0.02
Structures	0.30	0.25	0.20	0.10	0.15
Robotics	0.30	0.25	0.01	0.04	0.20
Communications	0.50	0.25	0.01	0.04	0.20
Information	0.29	0.23	0.11	0.20	0.17

Prioritized Ranking Method

To test the robustness of the screening process, each panel also ranked submissions using prioritized attribute ranking methods. In ordinal ranking, the *most important* (primary) attribute is selected, and submissions are ranked according to their scores for that attribute alone. Submissions with equal scores on the primary attribute are then ranked by their score on the next most important, or secondary attribute. The panels found that it was rarely necessary to use a third attribute to rank all the submissions by this process. The prioritized ranking of a submission can then be compared with its general ranking results to determine if there are significant differences. The lack of significant differences in the two ranking systems would indicate that the results are somewhat robust.

In addition, a secondary prioritized ranking was created by reversing the order of the first two attributes in the primary ranking. Thus, if safety was the most important and utility the second most important attribute for a given panel, the order was reversed. This provided a further check on robustness. It must be noted that Human Support panel members ranked submissions with the expectation that the cardinal method would be

decisive in screening. Furthermore, the drawbacks of the ordinal scheme are described by Keeney and Raiffa, and were reinforced by simulations performed by the Outreach team.

Comparison of Methods

Figure A.2 shows an example comparison of the results of the rankings from the Structures panel submissions. The vertical axis represents the primary rank of a submission, and the horizontal axis measures its prioritized rank. The intersection points of these rankings are shown by small black boxes or squares. The figure contains a 45-degree line from the origin out through the total number of submissions. Submissions that had the same primary rank and the same prioritized rank would fall directly on the 45-degree line. The "best" submission for this panel would be the one closest to the origin, because it would be the one that ranked first in the primary ranking or first in the prioritized rankings, or first on both. Thus, the closer that each of the small black boxes falls to the 45-degree line, the better the congruence of the two ranking methods. Figure A.2 shows that the dark blocks representing the top 20 or 25 submissions are in the lower left-hand corner, indicating good agreement. The agreements of the two ranking methods become less congruent as one moves out into the lower-ranked submissions, which is to be expected.
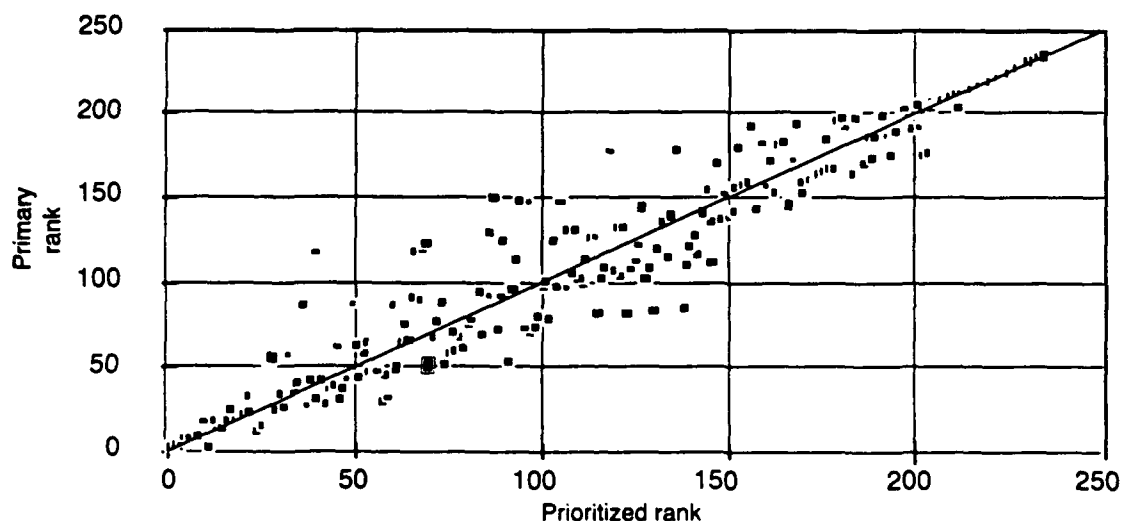

Fig. A.2—Example of Primary Versus Prioritized Ranking

Table A.4 compares the percentage of common submissions found in the lists of the top 20 submissions as created by the three ranking methods just discussed. The left-hand column shows the percentage of submissions that appeared on both the primary and

"primary prioritized" lists; it indicates that the percentage of overlap of the top 20 submissions on both lists ranged from 75 to 85 percent. The right-hand column shows the commonalties among three lists: the primary rankings, the "primary prioritized" rankings, and the "secondary prioritized" rankings discussed above. This comparison was made as a more stringent test of robustness; it also reveals a fairly high correlation among the three ranking methods.

This correlation gives confidence in the consistency of the evaluation method used to screen submissions. It shows that whether we extracted the top 20 submissions using the prioritized or the primary methods, they would still be nearly the same.

However, it must be emphasized that the screening methodology was used to assist but not to support decisionmaking.

Table A.4

Comparison of Ranking of Top 20 Submissions for Each Panel

| Panel | Percentage of Submissions Appearing on | |
	2 lists[a]	3 lists[b]
Architecture	75	40
Transportation	75	35
Power	85	75
Human support	80	55
Structures	85	80
Communications	85	55
Robotics	85	55
Information	80	80

[a]Primary and prioritized.
[b]Primary, prioritized, and reverse prioritized.

Appendix B

LIST OF ALL HUMAN SUPPORT SUBMISSIONS

Table B.1

List of All Human Support Submissions

Submission ID	Title/Subject
100071	Water Purifying Pipes
100225	Coping with Radiation
100226	Hiccup Therapy
100228	Urine, Fecal, Odorless, Squeegeeless Dry, Disposal System
100229	Preservation of Lower Leg Muscle Strength and Calcium During Space Flight
100230	Biosphere Life Support System
100231	Astronauts Strength Maintenance/Promotion and Funding of the American Space Stat
100233	Untitled
100235	Plant Bioreactors as Part of a Life Support System
100236	Exercise in Space
100237	First Aid in a Space Suit
100238	Space Medicine at Orbital Station
100239	Space Medicine at Lunar Station
100240	Health Applied Learning (HAL)
100241	Physical Rehabilitation in a Variable Gravity Space Facility
100242	Megavolt Electrostatic Cosmic Radiation Shield
100245	ID Micro-electronic Dog Tags
100249	Human Survival Factors on the Moon or Mars
100250	The Tremometer
100251	Analog to Isolated and Confined Environment of Long Duration Space Missions
100252	Centrifugal Force for Artificial Gravity
100253	How to Build a Space Colony in Two Years and Save Money
100254	Safety PoDual
100255	Use of Ambient Radiation in Water Recycle Treatment
100256	Summary of Innovative Concepts to Mission and System Architecture for NASA
100257	Memories
100258	Self-Sheathing Syringe
100259	Waste Processing
100260	Permanent Space Existence
100261	Production of O_2 Using Mars Atmospheric CO_2
100262	Water in Food and its Effect on Life Support Mass Balances
100263	Artificial Gravity and Sleeping Cylinder
100264	Expendable Regeneration Using Supercritical Absorbents
100265	Oxygen Production for the Moon Base
100266	High Density Chemical Thermal Storage System
100267	An Artificial Intelligence-Based nulation of Social Environmental Interactions
100268	Water Disinfection with In-Situ Generated Hydrogen Peroxide
100269	Inflatable Life Support Module
100270	Microbial Fuel Cells to Quantify Low Bacterial Concentrations in Water
100271	G-Suit
100272	Bioregenerative Life Support
100273	Self Sealing Air Lock

Submission ID	Title/Subject
100274	Advanced Heat Pump Cycles for Space Station Heat Rejection Systems
100275	High Lift Heat Actuated Solid-Vapor Heat Pump for Simultaneous Refrig and Water
100276	Trace Contaminant Removal by Complex Compounds and Pretreated Activated Carbons
100278	Lunar Food Production Module
100280	Multigenerational Space Explorers
100281	Semicontinuous Balanced Ecological Life Support System
100282	Human Mass Measurement in Space Flight
100396	Mars Space Exploration: Project Flatboard
100403	Space Radiation Environment
100416	Pre-Colonization Study on Project Mars
100421	Closed Ecological Life Support Systems
100445	Green House
100590	The Dual Bike Multi-Exercise Equipment
100591	Mechanical and Spatial Approaches for Accommodating Sexual Activity in Low Gravity
100640	Solid-Medium Space Agriculture
100641	Human Factors
100642	Untitled
100678	Space Medicine
100679	Direct Use of Urea in Astronaut Diets
100680	Single-Gas Cabin and Suit Atmospheres
100681	Radiation Protection
100682	Terrestrial Testing of Water Reuse Systems Suitable for Moon and Mars Application
100683	Biocatalytic Design by Chemical Modification
100684	Monitoring Plant Stress in CELSS
100685	Plant Productivity in CELSS
100699	Multilayer HTS Protection System
100701	Space Ergonomics: Optimization of Work Performance in Space
100709	Remote Subsurface Imaging of Random Media
100725	Magnetic Levitation and Human Dynamics
100726	CO_2 Reduction via the Bosch Process for Lunar Base or Mars
100727	Improving Astronaut Health by Reducing the Deconditioning Effect of Spaceflight
100728	Lunar/Mars Logistics Support Station
100742	Real-Time Monitoring of the Charged and Neutral Particle Environments in Space
100775	Life in Space
100776	Emergency Surgery and Critical Care to Support the Space Exploration Initiative
100777	Phytopharmaceuticals for Extended Missions: Establishing a Reference Base
100778	Entomological Protein Supplements for Extended Missions: Evaluating Acceptability
100790	Health Care Systems Definition, Testing, Training and Support for SEI
100798	Crew Autonomy
100806	The Beginnings of Life in Space
100807	Extended Duration Companionship
100808	Space Reproduction
100816	Bread Maker
100840	Electronic Companion
100841	Robotic Dentistry
100854	Space Saving Habitats
100876	Space Exploration Diet
100953	Integrated Life Support System for Moon and/or Mars Space Base
100954	Integrated Life Support System for Space Station
100955	Integrated Life Support System for Mars Space Ship
100956	Selection of a Closed-Ecology Life Support System

Submission ID	Title/Subject
100957	Dehydrated Food Packages
100958	Personal Environment Assurance Pod
100959	Cognition, Problem-Solving, and Memory in a Microgravity Environment
101043	Role of Nursing in Space Exploration
101044	High Acceleration Adaptation
101045	Disabled Veterans Astronaut Program
101046	Technology for Growing Plants in Space
101047	Transformation of Martian Atmosphere into the Oxygen and Fuel
101048	Recycling of Waste Water and Filtration
101049	Production of Artificial Water
101050	Gravity Production
101051	Production of Air
101052	Recyclable Personal Items
101053	Fast Growing Fruits and Vegetables
101054	Purification of Air
101055	Sanitary Facilities
101056	The Use of Plasma Arc Technology for Space Life Support Systems
101076	EVA-Friendly Space Suits
101083	Joint Biological Research Module
101198	MHD Shielding
101267	Food Animals in Biological Life Support System
101268	Aquatic Plant Waste Recycling System
101269	Ground-Based Prototypes for Bioregenerative Life Support Testing
101270	Mars Mission Gravity Profile Simulation
101271	The Spinoff Is the Payoff
101272	Magnetic Shielding for Manned Lunar and Mars Missions
101273	Magnetically Induced Artificial Gravity
101274	Computerized Immediate Language Translator System
101275	Hydrogen Peroxide for Mars Commodity
101276	Zero Gravity Toilet
101277	Plants that Grow Without Soil for Oxygen Recycling and Air Purification
101278	Recovery of Oxygen and Carbon from Carbon Dioxide Using Electrolysis
101279	Self-Contained Earth-Type Ecosystem for Interplanetary Transfer Vehicle
101280	Expanded On-Board Spatial Sound System
101281	Variety in Biological Life-Support Systems
101316	Non-Polluting Real Time Analytic Systems for Space/Lunar Facility
101343	Potential Martian Biological Hazard
101363	Imaginative and Intuitive Nutrition
101364	Static Isometric Suit
101365	Crew Relationships
101366	Conception to Birth
101411	Biosensors: The Heart of the Life Support System in Space
101413	Critical Human Requirements Data Base for Space Exploration
101415	Creation of Life Support Environments
101416	Store Materials at Space Station for Later Recycling
101417	Integrated Life Support System for Space Station
101418	Integrated Life Support System for Mars Spaceship
101419	Gravity Selectable Centrifuge Spacecraft
101460	Radiation Monitoring on Unmanned Mars Probe
101461	Enhanced Gravity on the Lunar Surface
101462	The Super Oxygen Maker

Submission ID	Title/Subject
101463	Humans and Aircraft Operations in Rarefied Atmosphere
101470	Mars Seeding Project
101477	Automatic Tester of Dynamic Visual Acuity
101526	Orbiting Mars Biological Laboratory
101527	Human Factor Considerations for Space Living
101544	An Experimental Model for Extraterrestrial Agriculture and Food Resources
101577	Centrifugal Habitats for the Moon and Mars
101578	Life Support
101606	Space Station Freedom Water Storage
101607	The Use of Helmet-Mounted Displays in Space and Its Implications
101608	Human Powered Centrifuge for Space
101657	Space Suit

Appendix C
SUBMITTAL SUMMARIES

1. **Health Care Systems Definition, Testing, Training and Support for SEI (#100790)**

This submission addresses the problem of establishing the right kind of program to ensure adequate definition, design, evaluation, testing, training, implementation, and operation of an in-flight health-care delivery system.

Two points in the submission deserve special mention: (1) the importance of linking the development of in-flight treatment protocols and the evaluation of potential equipment to university medical centers rather than NASA or aerospace contractors; and (2) the importance of having the right personnel as crew members, and the critical importance of training.

2. **Emergency Surgery and Critical Care to Support the SEI (#100776)**

This submission is an excellent summary of the salient points of the delivery of state-of-the-art medical care in flight. It makes the case for surgical training and the currency of crew medical officers, as well as for the development of supporting infrastructure.

3. **Multilayer HTS Protection System (#100699)**

Astronauts outside the Earth's magnetosphere may be exposed to ionizing radiation from energetic charged particles associated with occasional solar emissions and continuous galactic cosmic rays (GCRs). The most straightforward way to shield against these particles, particularly those in GCRs, is to use passive mass shielding. However, the mass penalties are large and uncertain. Another approach is a system to maintain a magnetic field of sufficient strength that even heavy charged particles in the relativistic energy range could be deflected from the vehicle. This submission proposes that high-temperature superconducting materials, in a layered configuration, could be part of a magnetic system for shielding against energetic ions. Our analysis suggests a two-layer system could be effective if such materials are operated at liquid helium temperature, and that a combined passive-active system could provide an additional safety margin.

4. **Radiation Monitoring on Unmanned Mars Probe (#101460)**

There is considerable uncertainty in our quantitative understanding of radiation protection beyond Earth orbit. Uncertainties exist in (1) the spectra and fluxes of ionizing particles, (2) the ability to predict the interaction of these particles with matter including shield materials, and 3) the effects on the health and well-being of astronauts. This

submission proposes an instrumented probe be sent to Mars to gather data on the characteristics of the space radiation field between Earth and Mars. This is significant because such an instrumented spacecraft has nevel been flown, and NASA has no firm plans to initiate such an experiment within the decade. Data from such a probe would help establish the magnitude of the radiation protection issue in a far more precise and convincing way than is presently possible.

5. Biosensors: The Heart of the Life Support System in Space (#101411)

Biosensors use a biological molecule such as an enzyme or antibody mated with more classic transducer technology to form a sensitive, highly specific system. This submission suggests that these sensors could have a critical role in the detection of toxic chemicals or bacterial or viral pathogens in the life support systems. They could be incorporated in monitoring or control systems for spacecraft or EVA suit, and portable life support systems.

6. Ground-Based Prototypes for Bioregenerative Life Support Testing (#101269)

This submission proposes that ground-based prototypes be built to facilitate the full-scale evaluation of hybrid systems of partial physico-chemical life support systems integrated with bioregenerative systems. Due to the low level of funding in the past, elements of the problem such as food production and waste recycling have been studied separately, but integrated systems testing has been quite limited. The construction of airtight large-scale test facilities would enable studies of CO_2 absorption and sequestration in soil and plant materials, as well as yield a better understanding of atmospheric gas balances under varying light and temperature conditions. The submittal proposes the use of soil bed reactors for trace gas absorption and extensive instrumentation for monitoring atmospheric gases and potable, waste system, and irrigation water quality.

7. Variety in Biological Life Support Systems (#101281)

Stability in biological systems is a function of the size of the system and the diversity of plants in that system. The submittal expresses concern that volume and mass considerations will tempt designers of bioregenerative life support systems to use a relatively small number of plant species. Then, if even one species were to fail in some way via disease, pest, or genetic damage, the entire ecosystem could collapse. The submittal reiterates the importance of designing the ecological systems with a wide variety of complementary species that are capable of performing the life support function. While a processing chain would be susceptible to the failure of a single species, a processing web could be far more robust.

8. **Mars Mission Gravity Profile Simulation (#101270)**

A fundamental issue in extended-duration space flight is the degree to which it may be necessary to provide artificial gravity via a rotating spacecraft system, countermeasures against microgravity, or both. The submission proposes a coordinated ground-based program to perform enabling research that would help define the magnitude of the microgravity problem and investigate some simple approaches for dealing with it. Unfortunately, the submission does not include a proposal to study tethered manned space flight. Furthermore, there is only a tenuous correspondence between some of the ground-based protocols and practice.

9. **Space Ergonomics: Optimization of Work Performance in Space (#100701)**

This is a field that had been widely studied during the Apollo era but sparely supported subsequently. In space, muscles produce forces without the natural antagonism provided by gravity. Relatively little is known about the efficiency of human motion in the zero-gravity environment. Often altering the technique of task performance alters both the local muscle stresses and the systemic stress on the cardiopulmonary system. Different methods to execute the same tasks may be more energy-efficient than others, and the optimal technique on Earth (or in the MSFC neutral buoyancy tank) may not be the most energy-efficient for the same task performed in space. In light of the fatigue experienced by the Soviet cosmonauts after 3–4 hours of EVA, this is an area worthy of further study. There has also been a strongly felt need for more specific guidelines for designers working in the Space Station Freedom environment, and this need will become even greater on future projects requiring substantial construction and assembly in space.

10. **Cognition Problem-Solving, and Memory in a Microgravity Environment (#100959)**

This submittal raises the issue of "Have adequate studies been done on humans?" on the stated topic. In fact they have not, and anecdotal recitations by several astronauts on the degree to which they found themselves dependent on checklists for tasks with which they were highly familiar and similar tales of attention difficulties suggest that this is not a trivolous suggestion. The submittal reviews the adaptation processes at the biochemical and physiological level to make the case at the cellular level that the possibility exists for perturbation of central nervous system tissue and particularly brain tissue in the hippocampus and cerebral cortex. An array of studies to test cognition, problem solving, and memory are proposed for examination in two environments, weightlessness and artificial

gravity, on board the same space vehicle. If particular deficits are detected, then measures can be taken to design for the problem in terms of operational procedures.

11. Hydrogen Peroxide for Mars Commodity (#101275)

Hydrogen peroxide, H_2O_2, is proposed as a multipurpose chemical storehouse of breathing oxygen, water, and energy for a Martian base. Made from indigenous water and electricity from a central power facility, it could be used for a range of applications as a fuel for rovers or a mono- or bi-propellant, a high explosive for mining, an antifreeze solution, a disinfectant, or a variety of manufacturing processes in metallurgy, cement, or ceramics. Energy may be the critical limiting resource at the surface of Mars.

12. The Spinoff Is the Payoff (#101271)

There are a number of informed scientists, such as G. O'Neill of the Space Studies Institute, who believe that both artificial gravity and radiation protection pose issues that might take enormous resources and time to resolve, and that conventional solutions will be too costly and complex. This submission proposes that a large spacecraft be assembled in space using material obtained from asteroids or from mining the Lunar surface, which could serve as a thick radiation shield. The spacecraft, presumably hundreds of meters in diameter, would then be rotated at less than 2 rpm to provide artificial gravity. It would travel to a Martian orbit where it would act as a base for travelers to the Martian surface. This approach reflects a deep pessimism regarding the conventional approach to a Mars mission and considerable optimism over the idea of building infrastructure to mine the Moon and asteroids and ultimately to inhabit interplanetary space.

Appendix D
SHIELDING MASS FOR A MARS TRANSPORT VEHICLE

Abstract: A range of plausible radiation shielding masses is estimated for a Boeing MTV weighing 30,000 kg. They vary from a low-mass estimate of 10^5 kg to an upper-mass estimate of 10^6 kg. It may be decades before this uncertainty can be adequately narrowed.

The major source of ionizing radiation, in terms of possible injury to crew, is energetic heavy ions in galactic cosmic rays (GCRs) and solar protons. It is assumed that a storm shelter will be available, as well as adequate warning for crews to avoid exposure to protons from extremely intense solar flares that occasionally occur. The principal hazard is the induction of fatal cancers over an astronaut's lifetime.

Because GCRs are isotropic, shielding must be provided over all solid angles. Thus we can assume for preliminary analysis purposes that uniform shielding must be placed on the entire surface of the MTV habitat module. It may be possible to fine-tune shielding by using hydrogen-rich consumables and waste as auxiliary shields, or by fiddling with configurations and the relative position of the propulsion system and fuel. However, the range of *true* uncertainty is so large that such fine-tuning may be a decade or two premature.

Liquid hydrogen is the best shielding material in terms of effectiveness and weight. However, it must be ruled out by the fundamental rules of safety. In terms of relative effectiveness, the mass ratios are 1:5:11 for shields made of liquid hydrogen/water/aluminum based on computations for a particular allowed exposure that corresponds to 25 rems/year to internal (blood-forming) organs.

NASA TM 4167, 1990 (*Estimate of GCR Shielding Requirements During Solar Minimum* by Townsend et al.), is the best source of computed data on shield thickness from a physics perspective. It also assesses the impact of uncertainties in the underlying physics.

Another NASA document (*Draft Radiation Health Program Plan*, June 1990, LSD, OSSA, NASA, WASH) is useful as a guide to NASA's views of the range of radiobiological uncertainty in radiation risk assessment. This document suggests that radiobiological uncertainties today could be as large as a factor of 30 or 40. It also suggests that a dedicated research effort could narrow uncertainties to a factor of two by 1997 and to negligible levels by 2010.

According to TM4167, uncertainties in physics and the space environment GCR spectrum could easily lead to an underestimate of radiation exposure of a factor of two or

more. If we combine this with a factor that corresponds to the square root of the 30 or 40 times uncertainty factor in radiobiology, we could obtain, very roughly, a factor of 10 or more in the uncertainty regarding the effective radiation dose received by sensitive internal tissue and blood-forming organs.

This is bad enough. What is even worse is the nature of the interaction of heavy relativistic GCR ions with shielding material. Fragmentation and secondary and tertiary collisions result in a virtual cascade of ionizing radiation. As a result, increasing shield thickness is very inefficient in reducing effective radiation exposure.

We considered the Boeing MTV crew module that can accommodate four or five crew members. According to Boeing D615-10004, this module is approximately a cylinder of height 9m and diameter of 7.6m, corresponding to a surface area of

$$\frac{\pi D^2}{4} + \frac{\pi D^2}{4} + \pi DL$$
$$= \frac{\pi}{2} \times 7.6^2 + \pi \times 7.6 \times 9$$
$$= 300 \text{ M}^2$$

For a water shield, TM4167 computes a shield thickness of about 3.5 gm/cm^2 based on an allowable dose of 50 rems/year to internal organs, and a shield thickness of about 35 gm/cm^2 based on allowable dose of 25 rems/year to internal organs. Unfortunately, the 50 rems/year allowable dose is based on an analysis by the National Council on Radiation Protection (NCRP Report 98, June 1989) that is now known to be too high by at least a factor of two for a long-duration (2–3 years) Mars mission. This factor of two is obviously dwarfed by th⁻ factor of 30 or 40 that NASA believes is the present range of uncertainty in radiation tissue damage from GCRs.

Therefore the most plausible *low* estimate of shielding thickness is 35 gm/cm^2 of H$_2$0. Unfortunately, as noted above, there is a highly nonlinear relation between dose uncertainty and shield thickness uncertainty. TM4167 demonstrates that a dose reduction from 50 to 25 rems/year requires an order of magnitude increase in shield thickness. TM4167 does not attempt, for various technical reasons, to compute a shield thickness for the case where the effective dose must be reduced even further to account for true uncertainties in both physics and biology, i.e., for the case where the 25 rems/year dose is still too high.

For the sake of round numbers, we can say that the credibility interval is probably between a lower shield thickness of 35 gm/cm^2 and an upper shield thickness of 350 gm/cm^2. The upper level is highly uncertain and is probably too low, using the computations in TM4167 as a guide.

Therefore, we need to consider a range of shield weights between:

$$300 \times 10^4 \times 35 \text{ gm and } 300 \times 10^4 \times 350$$

or between

$$100{,}000 \text{ kg and } 1{,}000{,}000 \text{ kg}$$

Since the module (exconsumables) weighs 30,000 kg, this suggests that the required mass of shielding is between *3* and *30* times the mass of the crew module for this specific configuration. These numbers are not so surprising. People at both NASA headquarters and Langley have alluded to an upper estimate of 1.8×10^6 kg for a certain Boeing MTV design, and the December 1989 support document for the 90-day study includes estimates of this magnitude for passive shielding mass.

REFERENCES

1. Boorstin, Daniel J., *The Discoverers*, Random House, New York, 1983, p. 261.

2. Newby, Eric, *The World Atlas of Exploration*, Crescent Books, New York, 1985, pp. 75–76.

3. Logan, J. S., "Health Maintenance on Space Station," in Faughnan, B., and G. Maryniak, (eds.), *Space Manufacturing 6, Nonterrestrial Resources, Biosciences, and Space Engineering, Proceedings of the Eighth Princeton/AIAA/SSI Conference*, American Institute of Aeronautics and Astronautics, Washington, D.C., October 1987.

4. Logan, J. S., "Health Maintenance on Space Station," in Lorr, D., V. Garshuek, and C. Cadoux (eds.), *Working in Orbit and Beyond: The Challenges for Space Medicine*, American Astronautical Society, Vol. 72, Science and Technology Series 1989, pp. 87–99.

5. Nelson, B. D., R. M. Gardner, D. V. Ostler, J. M. Schulz, J. S. Logan, "Medical Impact Analysis for the Space Station," *Aviat. Space Environ. Med.*, Vol. 60, No. 2, February 1990.

6. Raymond, C. A., "When Medical Help Really is Far Away," *Journal of the American Medical Association*, Vol. 259, April 22/29, 1988, pp. 2243–2244.

7. Houtchens, B. A., *Emergency Surgery and Critical Care to Support Human Exploration of the Inner Solar System, Final Report*, NASW-4519, July 31, 1990.

8. Houtchens, B. A., "Emergency Surgery and Critical Care to Support the Space Exploration Initiative," RAND Outreach Submission 100776, August 7, 1990.

9. Houtchens, B. A., "Health Care Systems Definition, Testing, Training and Support For SEI," RAND Outreach Submission 100790, August 7, 1990.

10. Space and Life Sciences Directorate, *Medical Requirements of an Inflight Crew Health Care System (CHeCS) for Space Station Freedom*, National Aeronautics and Space Administration, Johnson Space Center, March 5, 1990.

11. Hunt, W. A. , J. A. Joseph, and B. M. Rabin, "Behavioral and Neurochemical Abnormalities after Exposure to Low Doses of High Energy Iron Particles," *Advanced Space Research*. Vol. 9, No. 10, 00 (10)333–(10)336, 1989.

BIBLIOGRAPHY

Advances in Space Research, Vol. 19, No. 10, 1989.

Curtis, S. et al., *Fluence-Related Risk Coefficients Using the Harderian Gland Data as an Example*, to be published in *Advances in Space Research*.

Floyd et al., "Calcium and Bone Metabolic Homeostasis in Active and on Denning Black Bears (Ursus Americanus)," *Clinical Orthopaedics and Related Research*, No. 255, June 1990, pp. 301–309.

Lawrence Berkeley Laboratory, *Manned Exploration of Deep Space, Cosmic Particle Biology and Health*, University of California, February 1989.

Letaw, J. R. et al., *Galactic Cosmic Radiation Doses to Astronauts Outside the Magnetosphere in Terrestrial Space Radiation and its Biological Effect*, P. D. McCormack et al., (eds.), Plenum Press, 1988.

National Council on Radiation Protection and Measurements, *Guidance on Radiation Received in Space Activities NCRP Report Number 98*, NCRP, Bethesda, MD, July 31, 1989.

National Research Council, *Health Effects of Exposure to Low Levels of Ionizing Radiation (BEIR V)*, National Academy Press, Washington, D.C., 1990.

Reitz, G. et al., *Influence of Cosmic Radiation and / or Microgravity on Development of Carausis Morosus, Advances in Space Research*, Vol. 9, No. 10, 1989, pp. 161–173.

Sato, K. et al., *High-Jc Silver-Sheathed Bi-Based Superconducting Wire*, Paper MM-1, 1990 Applied Superconductivity Conference, Snowmass Village, Co., September 24–28, 1990.

Townsend, L. W., *HZE Particle Shielding Using Confined Magnetic Fields, Journal of Spacecraft and Rockets*, Vol. 20, No. 6, November–December 1983, pp. 629–630.

Townsend, L. W. et al., *Radiation Protection Effectiveness of a Proposed Magnetic Shielding Concept for Manned Mars Missions*, SAE Technical Paper #901343, 20th Intersociety Conference on Environmental Systems, Williamsburg, VA, July 9–12, 1990.

Vernikos, J., *Artificial Gravity White Paper*, September 12, 1989.