IV. ENVIRONMENTAL HEALTH AND LIFE SUPPORT SYSTEMS

A. Introduction

Optimal Environmental Health and Life Support Systems (EHLSS) will protect the crew from inhospitable space and planetary environments and provide transit vehicle and planetary surface cabin environments which emulate Earth-normal conditions for those factors that directly affect crewmembers. These capabilities will alleviate the space environment causes of detrimental effects on crewmembers, thereby allowing mission performance approximately equivalent to human performance on Earth, and normal postflight lives (health and longevity).

Table IV-1 summarizes the life sustaining cabin environmental factors which must be provided by the three major support systems when humans are confined to the closed systems required for transit vehicles, planetary bases, or extra-vehicular (EVA) and extra-habitat (EHA) activities. Mission duration and maximum crew recovery time (in case of aborts) dramatically impact requirements.

TABLE IV-1
CRITICAL HABITABILITY FACTORS

	SYSTEMS PROVIDING CAPABILITY		
FACTORS	ENVIRONMENTAL HEALTH & LIFE SUPPORT	COUNTERMEASURES	MEDICAL CARE
Food	X		C
Water	X		C
Atmosphere	X		C
Waste Management	X		
Toxicology/ Microbiology	X		C
Human Factors	X	X	C

X — Implies the potential for a solution
C — Contingency capability for limited and temporary intervention or treatment

This table is applicable to both Moon and Mars missions; however, the advantages of shorter duration missions and the capability for rapid return from the Moon will allow employment of less sophisticated systems for Moon missions.

B. Constrained Program — Early Missions Without Bioregenerative Life Support

The constrained program[1] for early Mars missions addresses critical issues in the following areas:

- Life Support Systems
- Environmental Health (barophysiology, microbiology, and toxicology)
- Behavior, Performance, and Human Factors
- Radiation Health
- Planetary Protection.

1. Food, Water, Atmosphere, and Waste Management

EHLSS with sufficient redundancy and backups to provide dependable water, food (including nutrient balance) and atmosphere (e.g., gas concentrations, temperature, humidity) are absolutely essential because countermeasures do not exist. If failure occurs, the ability of Medical Care Systems (MCS) to intervene or treat (where it is even possible) is temporary and palliative. Five critical issues (Table IV-2) focus on these life support systems.

Table IV-2
Food, Water, Atmosphere, and Waste

- • • Determine requirements for human waste subsystems
- • • Certify functioning and sufficiency of expendable supplies and physico-chemical regenerative technologies
- • • Certify life support systems capability for providing EVA/EHA surface exploration
- • • Identify food storage, processing and preparation technologies
- • • Determine storage and processing requirements for potable and hygiene water

• • = Required for Moon and Mars

Research Requirements. Research is required to define the acceptable limits of quality and quantity for water, food, and atmosphere, and eventually to provide the science and technology necessary to develop sustainable regenerative (biological and/or physico-chemical) life support systems.

2. Environmental Health

Maintaining humans in confined systems presents a unique challenge, which is exacerbated by extended mission duration, for toxicological and microbiological management issues. Adequate redundancy and backup must be included because optimized MCS (e.g., treatment with antibiotics, drugs) are palliative and can only be utilized for relatively short periods to assure crew mission performance and recovery.

Footnote 1. 17% of the critical questions identified in the discipline plans support a constrained EHLSS program (see Volume II, Table 2).

Critical issues (Table IV-3) focus on microbial contamination and materials (e.g., chemicals, biologicals, and particulates), atmospheric composition, and pressure anomalies that might adversely affect crew health and performance. Environmental standards need to be developed for chronic conditions involving the long-duration of a Mars mission. Monitoring strategies and procedures must be developed for determining which components of the spacecraft internal environment or planetary habitat must be monitored to adequately assess environmental safety, particularly what contaminants are likely to build-up over the long-duration in a closed environment. Sample types, numbers, and sampling frequency, as well as data analysis, must be identified.

Table IV-3
Environmental Health

- •• Establish standards for number and kinds of organisms in water, air, food and on surfaces
- •• Identify crew health, safety, and performance effects of chronic exposure to respirable and nonrespirable particles
- •• Identify effects of atmospheric components on crew physical and psychological well-being
- •• Identify effects on crew physiological responses of interactions between microgravity and off-baseline atmospheric composition, pressure, and temperature
- •• Determine impact of flight-induced physiological responses on crewmember susceptibility to toxic materials, microorganisms, and environmental contaminants
- •• Develop reliable approaches for predicting acceptable exposure levels from limited data
- •• Assess available technology for identifying microorganisms in crew and environmental specimens and how antimicrobial procedures control microorganisms in space
- •• Develop real-time systems for monitoring air quality
- •• Predict (utilizing traditional time exposure and human toxicological data) acceptable values for inhalation and ingestion exposures to chemicals in space flight
- •• Determine effects of space flight on microbes

•• = Required for Moon and Mars

Research Requirements. Ground-based research and space flight experience have established a scientific basis for defining standards for air and waterborne gaseous and particulate microorganisms, and atmospheric composition and pressure. However, information regarding their long-term effects on crew performance and health is insufficient. Enhanced capability (i.e., advanced sensors) for real-time environmental monitoring systems is required to support a Mars mission. Additional research is needed to develop technology for environmental control and monitoring systems for gas composition, pressure, temperature, and humidity. This research and development is required for the cabin environment of planetary bases, spacesuits and transit vehicles.

Human exploration missions will require establishment of standards for the number and kinds of microorganisms in air, water, food, and on surfaces within the spacecraft cabin or planetary habitat. Assessments of the presently accepted or proposed standards, such as the spacecraft maximum allowable concentration (SMAC) values for toxicants, and the maximum allowable counts of microorganisms need to be conducted. Validating the applicability in space of Environmental Protection Agency

(EPA) potable water standards, and EPA and Food and Drug Administration (FDA) standards for food is a necessary step in defining standards for exploration missions.

EVA will be part of any exploration mission scenario, either as a planned activity or in an emergency during transit. Therefore, issues involving the prevention of decompression sickness and acceptable risks for conducting EVA (e.g., venous gas bubbles, bends, Central Nervous System (CNS) effects, and cardiovascular symptoms) must be fully understood. Ground-based research must continue or be accelerated, and flight validation during extended Spacelab missions, on SSF, and at the Moon outpost, will be required before a Mars mission.

3. Behavior, Performance, and Human Factors

For the early Mars mission, critical EHLSS issues (Table IV-4) in habitability and human factors focus on problems involving habitability requirements for transit spacecraft and planetary habitats and human-machine interfaces. Research and technology development for habitability requirements and human-machine interfaces will provide designs that maximize productivity and minimize occupational injuries. MCS, in a manner analogous to Earth operations, will be utilized to treat occupational illness and injuries.

Table IV-4
Human Factors and Habitability Issues

- •• Determine requirements for habitability (e.g., lighting, work/rest schedule) to maximize performance
- •• Determine optimum allocation of functions, including operator discretion, between humans and machines to maximize maintainability and reliability
- •• Determine behavioral correlates of space-induced physiological changes

•• = Required for Moon and Mars

The habitable volume and crew size limitations for transit vehicles and planetary bases, only allow EHLSS that partially provide (e.g., by habitat design) near Earth-normal conditions for factors that impact mental health. However, countermeasures (e.g., crew selection, planned activities, work/rest cycles) may sustain mental health which approaches Earth-normal, allowing acceptable mission performance and postflight recovery. If countermeasures are insufficient and crew mental health and morale degrades, MCS will play only a limited role.

Data on performance assessment and mental workload during missions are limited in scope in areas of task analysis (e.g., experiment errors, lost data, and equipment mishandling due to human-machine interface problems). Some inflight evaluations of workstation design are being performed on Space Shuttle flights to identify the most effective design for utilization in space. Procedures for allocating functions between humans and machines must be developed before embarking on long-duration missions.

Spacecraft habitability problems (e.g., high noise levels and unpleasant odors) have been reported during short-duration space flight. Limited observational data from

Space Shuttle missions (e.g., crews perceive the living space as confined, food as restricted in quality and diversity, lack of privacy and personal hygiene facilities) suggest that significantly improved habitability will be essential for maintaining crew mental health and performance on long-duration missions.

Research Requirements. Ground-based research, aviation research and operational experience, and data from isolated and confined settings have yielded information regarding human performance and productivity. The applicability of this extensive knowledge base for behavior, performance, and human factors designs for operations in long-duration space flight must be thoroughly examined.

A recent report by the National Research Council Space Studies Board (1991) emphasizes the importance of conducting ground-based studies in a variety of research settings in order to understand group performance and functioning. It is their recommendation that studies involve confined groups for three to four years. It is also important to validate the results from analog settings involving laboratories and field experiments (e.g., Antarctic analog) in operational environments (i.e., Spacelabs, SSF, and Moon base).

4. Planetary Protection

Because Mars is potentially hospitable to life, missions to this planet provide an exciting and unique opportunity to increase our knowledge of the origin, evolution, and distribution of life in the universe. Contamination from Earth would obfuscate evidence concerning chemical-biological evolution and the existence of hypothesized extinct and extant species. A planetary protection program is required to protect Mars from biological and chemical contamination as well as to protect Earth from importation of biological materials from Mars.

Requirements and procedures to prevent forward contamination demonstrated on Viking missions must be refined for Mars missions. Policies, procedures, equipment, and facilities to protect against back contamination are less developed (Table IV-5).

Table IV-5
Planetary Protection

- Establish improved requirements to protect Mars from Earth contamination applicable to robotic precursors and human missions (forward contamination)
- Establish requirements for robotic and human exploration to protect the Earth from biological contamination from Mars (back contamination)

• = Required for Mars

Research Requirements. Technology development efforts required to support planetary protection include development of: (1) alternative sterilization methods (e.g., alternatives to dry heat sterilization); (2) remote sealing, verification and monitoring technologies; (3) aseptic transfer technologies; (4) developmental risk analysis methods; and (5) containment technology and appropriate quarantine protocols for the receiving labs on Earth. Robotic missions prior to manned exploration are mandatory. In conjunction with early sample return, plans must be initiated for an Earth-based

Mars sample quarantine (containment and analysis) facility in which samples will be isolated and analyzed. There is a need to form an interagency committee for jurisdiction over planetary protection concerns.

C. Constrained Program - Human Operations in the Radiation Environment of Space

Low level radiation poses a significant health hazard, that becomes more severe with extended exposure duration. Duration of exposure and levels of radiation within transit vehicle and planetary base habitats vary with mission scenario, thereby posing unique mission dependent challenges for design of crew support systems (see Table IV-6).

TABLE IV-6
MISSION SCENARIO SENSITIVE ENVIRONMENTAL FACTORS — RADIATION

MISSION SCENARIOS	SYSTEMS PROVIDING CAPABILITY		
	ENVIRONMENTAL HEALTH & LIFE SUPPORT	COUNTER-MEASURES* *	MEDICAL CARE
(1) Transit Vehicles			
• Mars Missions	X		C
• Moon Missions	X*		C
• EVA	X*		C
(2) Planetary Surfaces			
• Base			
Mars	X		C
Moon	X		C
• EVA			
Mars	X*		C
Moon	X*		C

* — Solar event prediction required
* * — Protectants for radiation exposure
X — Implies the potential for a solution
C — Contingency capability for limited and temporary intervention or treatment

There are neither countermeasures nor totally effective medical treatments for humans exposed to radiation, therefore EHLSS shields are the only means of protecting humans for extended durations in transit or on planetary surfaces. The capability to provide sufficient warning of large solar events should allow unshielded Moon transit; Moon and Mars EVA; and Mars transit vehicles that incorporate shielded sanctuaries.

Similarly a solar event warning capability would enable EHA on planetary surfaces and sanctuary architectures for bases. Shielding with regolith may provide acceptable radiation levels throughout human habitats in planetary bases. Currently, information necessary to quantify health hazards and design effective shielding from HZE is based on empirical models.

The radiation environment of space external to Earth's atmosphere is so hostile to life as we know it that there can be no compromises, and the issues (Table IV-7) must be addressed in the constrained program.

Table IV-7
Radiation Health

- •• Determine the interplanetary radiation environment for:
  - •• Galactic cosmic radiation (GCR) as a function of partial energy, linear energy transfer (LET) and solar cycle for mission profiles
  - •• Maximum flux, integrated fluence, and the probability of large solar particle events (SPE) during any mission
- •• Determine the internal space radiation environment of space vehicles
- •• Develop improved protection from GCR and SPE (proton radiation)
- •• Determine how a radiation field is transformed as a function of depth of different materials
- •• Determine doses related to heavy ions and solar particle flux in deep space
- •• Determine the particle multiplicities of nuclear radiation products
- •• Quantify the biological effects of GCR and proton radiation from SPE
- •• Determine the interaction effects of radiation and hypogravity
- •• Validate ground-based research in space

•• = Required for Moon and Mars

Research Requirements. Required research includes:

- Characterization of radiation environments in transit vehicles
- Determination of the radiation effects of protons and heavy ions on biological systems
- Determination of the risks of stochastic effects (i.e.,cancer and genetic) and acute deterministic effects (e.g., damage to rapid cell renewal systems in bone marrow, gut and skin), and late deterministic effects (e.g., cataracts and CNS damage)
- Development of methods (e.g., pharmacological agents and bone marrow preservation) for protecting against:
- Acute effects that might occur with a very large SPE
- Late effects (in particular cancer) from HZE and proton exposure.

It is critical for NASA to formalize agreements to utilize one or more of the federal accelerator facilities, and to assure that those facilities remain in operation until necessary ground-based research is completed.

In order to develop effective radiation protection, Moon orbitors and rovers must include the capability to quantify GCR and SPE proton levels. They must also include the means to evaluate potential radiation shielding and accommodate experiments to determine biological effects from HZE and SPE exposure.

The primary research thrust should be in prevention of exposure to the maximum extent possible since countermeasures or treatments are not sufficiently developed and might not yield solutions by the time exploration missions are initiated.

D. Constrained Program — Later Missions With Bioregenerative Life Support

The volume and mass of stowage necessary to support crews increases with mission duration and crew size; therefore, hybrid and/or bioregenerative systems will become essential for later Mars missions. The primary difference between "early mission" and "late mission" constrained programs is the exclusion of bioregenerative life support systems from early mission scenarios. If ongoing research programs produce technological breakthroughs in bioregenerative systems or physico-chemical systems meet unforeseen difficulties, it might be feasible and beneficial to use the former in earlier exploration missions.

The constrained program for later Mars missions (i.e., with bioregenerative life support systems) addresses critical issues in the following life sciences areas:

- Life Support Systems
- Plant Biology
- Cell and Developmental Biology
- Radiation Biology.

1. Life Support Systems

Life support designs for Skylab, the Space Shuttle, SSF, and Mir (if one excludes fresh vegetables grown periodically on Soviet missions) are based on stowage of materials before launch and resupply. This has been adequate for short-term Earth orbital and short-duration Moon missions.

Regenerative life support systems based solely on physico-chemical (PC) technologies being developed for SSF and human exploration missions, cannot regenerate food from waste. Eventually, the operational system must include biologically based components utilizing green-plant photosynthesis capable of generating food, oxygen, and potable water, removing carbon dioxide, and using microbial degradation and mineralization of waste. SSF provides an opportunity to develop, test, and gradually introduce regenerative technologies, particularly for water and air, to reduce transportation burdens.

The fundamental strategy of the Controlled Ecological Life Support System (CELSS) Program is to emulate the life-sustaining processes of Earth. However, because of constraints on volume, mass, energy, and crew time, integrated bioregenerative — PC systems will undoubtedly be the most practical for late missions.

Present understanding of the size, volume, and energy required for a total CELSS suggests that for mission lengths of 600- to 1000- days, such systems would not provide significant savings over PC life support systems. However, some fresh food derived from plants may be desirable for nutritional and psychological reasons. For example, Soviet experiences with long duration Mir missions indicate that the presence of living plants and the availability of fresh foods have enormous positive impact on crew psychological well-being and work capacity.

Research Requirements. The major issues (Table IV-8) associated with PC air regeneration include replacement of consumed oxygen, removal of carbon dioxide, and reduction of the amounts of volatile organics and particulates. Major issues associated with PC water regeneration include identification of particulates and solutes in waste water streams that must be processed, establishment of realistic requirements for the product (purified water), evaluation of potential methods of solute removal, and maintenance of long-term water quality in a dynamic recycling system. Issues associated with solid waste stabilization include reduction of volume, containment and removal of off-gases; containment or neutralization of pathogenic organisms; and storage.

Table IV-8
Life Support Systems

Physico-Chemical

- • • Determine best technologies for recycling potable and hygiene water
- • • Determine effects of the space environment on microbial interactions with space systems (especially bioregenerative) and humans
- • • Evaluate and select strategies and techniques to control causes of life support system instability
- • • Evaluate use of mathematical models in system design, simulation, and systems operations
- • • Determine specific caloric, fluid, macronutrient, fiber, and micronutrient requirements
- • • Develop prioritized acceptability criteria for foods

Bioregenerative

- • • Assess CELSS instabilities due to limited volume and intense dynamics
- • • Determine CELSS produced foods to satisfy acceptability criteria
- • • Evaluate extent to which microorganisms in a physico-chemical waste processor may degrade CELSS performance
- • • Establish CELSS system design and operation requirements considering redundancy, subsystem failures, monitoring and control technologies, interaction between bioregenerative and physico-chemical subsystems
- • • Determine sensors required to automate CELSS
- • • Determine available air treatment technologies, CELSS utilization, and development of technologies for space application
- • • Determine acceptable thresholds for revitalized air in an operational CELSS
- • • Determine conditions required for optimizing food generation and water recycling of crop plants
- • • Determine whether extraterrestrially grown crop plants can produce sufficient edible biomass to support humans

• • = Required for Moon and Mars

Human acceptance, nutritional standards, and processing and storage requirements for food were assessed at the highest levels of criticality for research for a Mars mission. It is highly likely that fresh foods derived from plants will be required for extended missions. Many of the high-priority research issues for CELSS development (e.g., storage requirements for potable water and control of microbial films) are also required for pure PC systems (Table IV-8). This life support research is also important to developing technologies essential for environmental health of humans in space.

Investigations must include the possibility that fresh foods, particularly plant-derived foods, will be required to enhance crew morale and mental health and prevent nutritional deficiencies. Such deficiencies could be due to inadequacy of the diet, flight-related changes in nutritional requirements, or crew appetites on long-duration missions.

It is crucial that basic studies be conducted to determine whether safe and sufficient supplies of water, air, and food can be provided by current or developing expendable systems within presently understood constraints of spacecraft storage capacity, crew size, and mission duration. Trade-off studies comparing expendable systems with even partial recycling of water and air using biological systems have the highest priority for research and development in the CELSS Program.

Research on photosynthetic productivity should be cooperatively developed with National Science Foundation (NSF) and United States Department of Agriculture (USDA). Research on waste recycling and food processing should be cooperatively developed with Department of Energy (DOE), USDA, National Institutes of Health (NIH), NSF, EPA, and FDA.

2. Plant Biology

A knowledge of plant gravitational biology (particularly in microgravity and at Moon and Mars gravity levels) is integral to implementation and operation of a bioregenerative life support system in space. Specifically, basic information about plant gravity thresholds and the effects of gravity on nutrition, growth, differentiation, reproduction, metabolism, and photosynthesis provides the fundamental basis for such a system. Therefore, the criticality of these research issues (Table IV-9) in support of exploration missions is directly related to decisions to incorporate a plant-based bioregenerative life support system.

Research Requirements. The United States has had a moderately funded ground-based plant biology program for the past 15 years, and the flight program has been far from robust. As a result, many critical issues pertaining to plant gravitational biology have not been answered, and many life support scientists in the CELSS Program require answers to the same scientific questions as do scientists concerned with more basic questions. For example, what is the gravitational threshold for normal and productive plant growth and development? Can plants go from seed-to-seed-to-seed in the space flight environment? How are crop frequency and size affected by microgravity or other space-related environmental influences? As a result, there is considerable overlap between CELSS and plant space biology.

Many of the plant biology issues assessed as criticality 2 may become criticality 1 if ongoing space-based research reveals additional problems with plant development and physiology and if bioregenerative life support is required during early manned missions.

Table IV-9
Plant Biology

- • • Determine whether plants can reproduce through multiple generations in space or on the Moon or Mars
- • • Determine microgravity and other space-factor effects on single cell or higher plants growth rates; differentiation; anabolic, catabolic and photosynthetic pathways or apparatus; nutrient absorption pathways; support polymer synthesis; chromosomal integrity and behavior during cell division; water transport; transpiration; embryogenesis and life cycle stages in plants.
- • • Determine the threshold levels for gravity effects
- • • Identify perception and response to microgravity differences between species and between tissues
- Determine interaction effects between radiation, environmental factors and microgravity on development of botanical systems

• • = Required for Moon and Mars

3. Cell and Developmental Biology

Space flight experiments to date have not demonstrated debilitating cellular effects from exposure to the space flight environment. However, since inflight experiments have been limited, there is insufficient evidence to draw definitive conclusions. The primary issue (Table IV-10) in cell biology is the requirement to obtain such evidence from a well-controlled flight science program.

Table IV-10
Cell and Developmental Biology

- • • Determine microgravity effects on cells and the influence of magnetic fields and radiation
- • Determine low dose radiation and lowered gravity effects on male and female germ cells
  - -- What events in gametogenesis and early germ maturation are gravity sensitive and how can these results relate to proliferation and differentiation of other individual cell types?
  - -- Can altered gravities affect fertilization and do these results indicate more general mechanisms of membrane alteration in individual cells?
  - -- Which responses are transmitted maternally and which are intrinsic to the developing embryo?
  - -- How do altered gravity levels effect axis polarity and asymmetries of zygotes?
  - -- Are there gravity or other environmental effects that can cause change in gene activation, transcription or translation?

• = Required for Mars
• • = Required for Moon and Mars

E. Robust Program

The robust program for EHLSS would include the following elements:

- An expanded basic research program
  - Accelerated research by expanding the number of principal investigators (PIs) and the diversity of approaches

- An enriched radiation protection program
  - A series of dedicated retrievable biosatellites to collect HZE-based radiation data, including multigenerational data on different species
  - Characterization of solar cycle dependence of space radiation, trapped radiation flux, and energy spectra of electrons
  - Determination of probabilities for GCR-related damage
  - Characterization of mechanisms involved in modulating damage, including utilization of animal models to extrapolate human radiation risks, such as probabilities for different radiobiological outcomes (e.g., cataracts, detrimental genetic development); and utilization of cellular mechanisms to understand whole organism effects

- An expanded life support program
  - Development of life support systems that provide food production for transit vehicles and planetary bases
  - Development of highly automated systems designed with advanced sensors (e.g., immobilized bioactive molecules) and controls that can respond to toxicological and microbiological contamination events
  - Accelerated development of processes to convert non-edible plant waste to edible food ingredients
  - Development and application of genetic engineering

- Accelerated programs to optimize cost-effective design solutions for habitability and performance
  - Sophisticated models and simulators that have the highest fidelity that is technically feasible to establish cost effective design solutions to human factors issues, such as behaviorally and ergonomically-designed systems for providing better habitation and human-machine interfaces
  - Refined anthropometric standards and automated systems for crew communication and training

- An enhanced space physiology program
  - Additional studies to understand physiological and other responses under different atmospheric pressures and compositions, including combustion/flammability, particle deposition and evolution
  - Expanded studies of space flight environmental conditions that influence regulation of temperature, fluids and electrolytes
  - Studies to identify biomarkers for detection of human exposure to contamination

- An accelerated program to develop engineering requirements and determine biological consequences for artificial gravity engineering (e.g., tethers, rotating spacecraft and short-armed or long-radius centrifuges)

- Development of enhanced waste treatment and biological containment systems to delay contamination of Mars and extend the window of opportunity for exobiology studies of Mars.

F. Requirements for Moon Exploration Missions

Because of the relatively short Moon recovery times and mission durations, Moon EHLSS facilities, equipment, and procedures can evolutionarily build in complexity from SSF capabilities until they allow a full scale operational test of Mars mission capabilities. As indicated in the boxed lists in the previous discussion, the only issues for Mars missions that are not required for Moon missions are: (1) planetary protection; and (2) effects of continuous long-duration radiation exposure.