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Guidelines and Capabilities for Designing Human Missions

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TABLE OF ACRONYMS

ADS	altitude decompression sickness
AG	artificial gravity
ALARA	as low as reasonably achievable
ALS	advanced life support
BEO	beyond Earth orbit
BPR	biological and physical research
Btu	British thermal unit
CD	crew day
CH	crew hour
CHeCS	crew health care system
CME	coronal mass ejection
CMO	crew medical officer
CPR	Critical Path Roadmap
CRM	cockpit resource management
CWS	caution and warning system
DCS	decompression sickness
DO	dissolved oxygen concentration
ELISA	enzyme-linked immunoassay
EMS	Emergency Medical Service(s)
ETO	Earth-to-orbit
EVA	extravehicular activity
GCR	galactic cosmic radiation
GFE	government-furnished equipment
Gy	Grays
Gy-Eq	Gray-equivalent
HCD	human-centered design
IC	integrated circuit
IMLEO	initial mass in low-Earth orbit
IMS	intravehicular maintenance system
IR	infrared
ISS	International Space Station
IT	information technology
IVA	intravehicular activity
kg/p/d	kilograms per person per day
LEO	low-Earth Orbit
LET	linear energy transfer
LMLSTP	Lunar-Mars Life Support Test Project
MDO	multidisciplinary optimization
MJ/CD	millijoules per crew day
MSIS	Man-System Integration Standards (NASA-Standard-3000)
NC	noise criteria
NCRP	National Council on Radiation Protection and Measurements
NIOSH	National Institute of Occupational Safety and Health
OASPL	overall sound pressure level
OSHA	Occupational Safety and Health Administration
ppb	parts per billion
ppm	parts per million
psia	pounds per square inch, absolute
PTS	permanent threshold shift
RBE	relative biological effectiveness
SAS	space adaptation sickness
SMAC	spacecraft maximum allowable concentration
SOMS	Shuttle Orbiter Medical System
SMS	space motion sickness
SPE	solar particle event
TDD	technology-driven design
TTS	temporary threshold shift
UV	ultraviolet
WHO	World Health Organization

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1 OBJECTIVES

These guidelines and capabilities identify the points of intersection between human spaceflight crews and mission considerations such as architecture, vehicle design, technologies, operations, and science requirements. In these chapters, we will provide clear, top-level guidelines for human-related exploration studies and technology research that will address common questions and requirements. As a result, we hope that ongoing mission trade studies will consider common, standard, and practical criteria for human interfaces.

1.1 SCOPE

The human element is likely the most complex and difficult element of mission design because it significantly influences every aspect of mission planning—from basic parameters, such as duration, to more complex trade-offs among mass, volume, power, risk, and cost. Engineers, who rely on precise specifications in data books and other technical references, can be frustrated when dealing with the uncertainty and the variability of designing for humans. When designing for the human element, more questions arise than definitive answers. Nonetheless, we do not doubt that the most captivating discoveries in future space missions will necessitate human explorers.

Beyond a cause-and-effect statement, human-driven requirements are highly variable because of destination, operational environment, mission objectives, and more. Often a precise quantification of parameters for a human mission is difficult without further study or arriving at a precise definition of a specific mission architecture. Each mission design requires several iterations as the effects of the crew on the system architecture (and vice versa) coalesce. We thus see this document as a tool that mission designers can use to understand the many trade-offs inherent in planning a human spaceflight mission.

In the following pages, we will convey the key drivers on human safety, health, and performance as simply as possible. By integrating this information into mission trade studies, mission planners can better address the most important human needs. We will make every attempt to deal only with materials necessary to mission designers in the conceptual design phase. The finer details of human and crew accommodations in the vehicle design are not within the scope of this document.

1.2 BACKGROUND

We have distilled guidelines and recommendations from personal experience and a good number of sources. Since many comprehensive sources are already available, we will not attempt to recreate these. A majority of the chapters include detailed reference lists.

We will approach the difficulty of designing for the human presence by briefly describing the fundamental concepts and definitions required for making decisions and by considering (where possible) the design trade-offs of current alternatives. When uncertainty arises, we will present the pros and cons of the alternatives, the best-worst boundary conditions, and other caveats for making the best decision. With such an approach, we envision that this document will become only the first step of many towards understanding the human element of the space mission.

The objectives for this document are to:

- Synthesize the current thinking of experts who have spent considerable time considering future missions in and beyond low-Earth orbit (LEO);
- Provide an lucid overview of the key human requirements and considerations that drive the success of a crewed mission;
- Clearly introduce some problems that must be solved or resolved in developing human mission planning; and
- Supply mission planners with the tools required to make decisions appropriate to a given mission, without exhaustively cataloging all possible designs for all possible missions.

Finally, this document is intended to supplement the many excellent texts that address the complex issues involved with designing future human missions. These publicly available texts are listed in the References section at the end of each chapter.

1.3 GROUND RULES AND ASSUMPTIONS

Safe and affordable human systems are feasible for future missions. A space-faring human crew, working cooperatively and in concert with intelligent systems and robotics, is needed to answer the greatest questions about our solar system and the universe beyond. For this document, we assumed the set of boundary conditions described in Table 1.1.

Table 1.1: Boundary Conditions

Remote destinations	Includes libration points, Moon, and Mars
Mission duration	50–100 days or 500–1000 days
Transport durations	5–10 days (near Earth) or 90–180 days (Mars)
Transport cargo frequency	Monthly (near Earth) or every 2 years (Mars)
Human/robot options	Stand-alone, cooperative, or local/remote telepresence (*see* Table 1.2)
Tasks	Planetary/astronomical sciences, assembly, maintenance, contingencies, and commerce
Primary safety criteria	Near-zero risk to public on Earth
Mission safety criteria	Return all crewmembers alive without serious injury or illness
Assembly/maintenance criteria	Spacecraft stable and viable for productive work
Science success criteria	Majority of tasks completed
Overall success criteria	No major impediment to subsequent missions
Budget	Generally flat across NASA for the foreseeable future
Mass, volume, and power	Severely constrained delivery mass
International participation	Likely

Human Capabilities

Although robots and artificial intelligence can achieve specific tasks better than humans can, and vice versa, robots that are as intelligent and as capable as humans do not yet exist. Automation alone cannot achieve the desired scenarios within a reasonable timeframe. While automated systems are appropriate, the following human capabilities may well enable otherwise difficult or completely impossible missions:

- **Productivity**: Use of the human brain's creative and cognitive abilities enables rapid, real-time, and on-scene decisions that overcome time delays and data bandwidth limits.
- **Reliability**: Adaptive and proven capability of humans for manual response to unforeseen, unique, and non-repetitive activities.
- **Cost and mass**: Less need to expend resources on complex, redundant, and fully automated designs.

For this reason, we emphasize the essential capabilities of humans throughout this document. The options and impacts of possible human and robotic roles are included in Table 1.2.

Table 1.2: Exploration Implementation Options

Robot Method	Human Role	Site Access	Data Scope	Relative Cost	Hardware Repair	Safety Risk
Remote teleoperation	Earth-based control	Lowest	Lowest	Low	None	None
Fully automated	Earth-based monitoring	Low	Low	Low-medium	None	None
Local teleoperation	Orbital habitat	Low	Low-medium	Medium	None	Low
Local teleoperation	Lander habitat; no extravehicular activity (EVA)	Low	Low-medium	Medium-high	None	High
Variable autonomy	Lander habitat; no EVA	Low	Medium	Medium-high	None	High
Variable autonomy (pressurized garage)	Lander habitat; no EVA	Low	Medium	Medium-high	Partial	High
Variable autonomy (can be docked to habitat)	Canned mobility; i.e., no EVA	Low-medium	Medium	High	Partial	Highest
Precursors only	Space-suited humans on foot	Medium-high	High	Medium-high	Full	Medium
Variable autonomy (total crew access)	Space-suited, transportable humans with rovers	Highest	Highest	Highest	Full	Medium-high

1.4 REFERENCES

Note: Each chapter of this document includes both cited and recommended references. Where possible, NASA or general access Web addresses are provided. These references should be considered as part of the general reference library for any mission designer or planner.

[1] Charles J and Critical Path Control Panel. *Critical Path Roadmap Baseline Document*. Johnson Space Center Bioastronautics Research Division; latest revision October 2000. (Available as a PDF on the public access Web site: http://criticalpath.jsc.nasa.gov/CP_Baseline.pdf.)

[2] Griffin B, Spampinato P, and Wilde R. “Chapter 22: Extravehicular Activity (EVA) Systems.” In: Larson W and Pranke L, editors. *Human Spaceflight: Mission Analysis and Design*. New York: McGraw Hill; p 707–757. 2001.

[3] Parker JF Jr and West V, editors. Report No. NASA-SP-3006, *Bioastronautics Data Book*. 2nd ed. Washington, DC: NASA Scientific and Technical Information Office. January 1973.

[4] Calvin M and Gazenko O, editors. Report No. NASA-SP-374, *Foundations of Space Biology and Medicine,* Vol 1–3. Washington, DC: NASA Scientific and Technical Information Office. January 1975.

[5] Connors M, Harrison A, and Akins, F. Report No. NASA-SP-483, *Living Aloft: Human Requirements for Extended Space Flight*. Washington, DC: NASA Scientific and Technical Information Branch. 1985. (Available on the public Web site: http://www.hq.nasa.gov/office/pao/History/SP-483/cover.htm.)

[6] “Operations Concept Definition for the Human Exploration of Mars.” Lyndon B. Johnson Space Center. May 2000. Internal document. Available to JSC users only.

[7] Stuster, J. *Bold Endeavors: Lessons from Polar and Space Exploration.* Annapolis (MD): Naval Institute Press. 1996.

[8] Eckart, P, editor. *The Lunar Base Handbook: An Introduction to Lunar Base Design, Development, and Operations*. 1st Edition. New York: McGraw-Hill Companies. 1999.

[9] Committee on Advanced Technology for Human Support in Space, National Research Council. Catalog No. 5826, "Advanced Technology for Human Support in Space" Washington, DC: National Academy Press. 1997. Available in HTML on the NAP Web site: http://www.nap.edu/books/0309057442/html/index.html.

[10] Hoffman S and Kaplan D. Report No. NASA-SP-6107, "Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team." July 1997.

[11] Drake B. Report No. SP-6107-ADD, "Reference Mission Version 3.0 Addendum to the Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team." June 1998.

[12] Report No. TP-1999-209371, "Mars Reference Mission – Surface Activities." December 1999.

[13] Report No. NASA-RP-1045, "Physiological basis for spacecraft environmental limits." 1979.

Table 1.3: Recommended Web Sites

Web Site Address	Subject
http://advlifesupport.jsc.nasa.gov	Advanced Life Support
http://advtech.jsc.nasa.gov	Advanced Technology Integration Group
http://ares.jsc.nasa.gov/HumanExplore/intro.html	Human Exploration Science Office
http://ares.jsc.nasa.gov/HumanExplore/Exploration/EXLibrary/EXdocindx.htm	Exploration library compiled by the JSC Exploration Office
http://criticalpath.jsc.nasa.gov	Critical Path Roadmap
http://jsc-web-pub.jsc.nasa.gov/fpd/shfb/Msis/MSIS_home.htm	Man-Systems Integration Standards (MSIS)
http://peer1.nasaprs.com/peer_review/prog/prog.html	Biological and Physical Research (BPR) Program Plans and Requirements Documents
http://spaceresearch.nasa.gov/research_projects/resplans.html	BPR Plans and Documents (new version)
http://srhp.jsc.nasa.gov/	Space Radiation Health Project home page
http://www.jsc.nasa.gov/xa/advanced.html	EVA Exploration Requirements and Rationale

2 RISK IN HUMAN EXPLORATION MISSIONS

A risk is frequently described as any event, action, or outcome that threatens success. Indeed, every space exploration mission has risks. In addition to physical risks to the crew and the vehicle, other risks must be acknowledged and integrated into mission planning.

2.1 KEY CONCEPTS

- **Cost risk**: Risk resulting from budgetary issues, including unplanned expenditures or inadequate funding.
- **Programmatic risk**: Risk created by political, management, or technical challenges.
- **Biomedical risk**: Risk resulting in loss of crew safety, health, or performance to the degree that mission success or crew survival is compromised.
- **Mission success**: Maintaining crew safety, health, and performance; carrying out key scientific goals; returning selected specimens or data; and completing public outreach activities.

2.2 FUNDAMENTAL GUIDELINES

While specific requirements will be addressed in subsequent sections, the following high-level requirements will address the fundamental needs of a human crew:

- ***Providing for subsistence-level human needs entails considerable mass expense.***
- ***Optimum performance requires optimum conditions.***
- ***The most carefully selected and well-trained crewmembers will never be superhumans.***

Although mission mass and cost will always be an important goal, we recommend that basic crew requirements be addressed for what they are—needs. Cost-effectiveness cannot be the sole measure of success in mission design. We can only obtain superior results and future mission success by creating a state of mind and value system that emphasizes the safety, comfort, and productivity of crewmembers over mass and cost.

2.3 MISSION SUCCESS

Mission success requires that we consider factors beyond the mission. NASA has established an overarching priority for risk mitigation. NASA's priority is that:

1. Public safety is paramount because the public must not be injured by any NASA activity, including launch phase malfunctions and return to Earth of hazardous materials (such as nuclear power sources or dangerous planetary specimens), or by longer-term consequences (such as environmental damage).
2. Safety for crewmembers, who are exposed to high risks because of spaceflight, is the second most important safety concern.
3. Safety for employees, to ensure a safe and healthful workplace, is also a key NASA value.
4. Safety of high-value equipment, as public investments in space exploration, takes fourth place.

Other mission goals, such as science return, must therefore fall lower in priority compared to the safety of the human crew.

A recent study[2] considers the current state of readiness for exploration missions with a human crew. The key finding of this study, which was conducted by a panel of learned experts who interviewed NASA personnel, is not startling to many who face the problems of crew health, safety, and performance daily. The basic findings of the committee are:

(1) Not enough is yet known about the risks to humans during long-duration missions, such as to Mars, or about what can effectively mitigate those risks to enable humans to travel and work safely in the environment of deep space; and (2) everything reasonable should be done to gain the necessary information before humans are sent on missions of space exploration.

This stark finding—regardless of how feasible a human-rated exploration vehicle may be—suggests that we cannot absolutely guarantee the health and safety of a space-faring crew. The challenge facing mission planners and medical operations personnel then becomes one of risk management: how do we address the risks with the greatest potential impact to crew health and to mission success?

Biomedical Risks

Foremost among the issues associated with a human exploration mission are the biomedical and life support risks of the spaceflight environment. These risks are described in the *Bioastronautics Critical Path Roadmap* (CPR), a strategic plan for reducing risks to human health and safety in long-duration spaceflight.[1] By virtue of its comprehensive approach to the risks of human spaceflight, the CPR[1] provides a:

- Guide for prioritizing research and technology;
- Framework for assessing progress in mitigating risks;
- Way to track effective risk-mitigation strategies; and
- Means to determine acceptable levels for identified risks.

Panels of academic and government experts were convened to identify critical risks and a set of core questions in 12 different disciplines as listed in Table 2.1. This work benefits from the consensus of a broad cross section of the academic and scientific community. As summarized in Table 2.1, the CPR[1] has prioritized 55 critical risks and 343 critical questions that must be addressed to ensure the success of missions that require an extended human presence. Investigation and research to address these risks is supported by the National Space Biomedical Research Institute (a consortium of 15 universities) and by NASA's Office of Biological and Physical Research. While the original proviso of the CPR[1] embraced missions beyond LEO, current NASA funding levels and management direction necessitate that the focus now be limited to near-term and immediate mission needs.

Approaches to Avoid

Although some activities are inherently dangerous, no human endeavor is completely free of risk. Space exploration is arguably dangerous; because human space exploration may threaten the lives of many people at taxpayers' expense, NASA is expected to take every possible measure to reduce risk. Despite this, reducing the crewmembers' risk to zero is nearly impossible, and any reduction often comes at significant cost.

Occasionally, the following solutions have been advanced to circumvent the more difficult decisions in mission design and risk management. These solutions can be deceptively simple and unrealistic if they are not examined carefully. We thus provide, below, a brief discussion of each to discourage this kind of thinking in future mission design and planning.

- **Accepting current risk**: Just because a relatively large number of candidates, despite the danger and personal risk, are willing to journey to Mars or beyond does not mean that mission, programmatic, and personal risks can be ignored.

- **Crew selection**: Carefully selecting a crew for extraordinary resistance to the dangers and difficulties of the space environment is not feasible. Statistics refute this for at least two reasons: (1) if the top 10% of individuals are selected by a series of 20 independent scales, at least 10^{20} individuals must be tested to find one person who would rate in the top 10% of all 20 scales; and (2) variability in the human population is not sufficient to provide significant protection against the many challenges of exploration missions. This is because we—from geniuses to religious leaders to sports stars—share many of the same traits and are subject to many of the same weaknesses.

Table 2.1: Distribution of Severe and Very Serious Risks Across the CPR Areas

Risk Type [1]	Area	Risk
Type I (severe)	Bone Loss	■ Acceleration of age-related osteoporosis
	Human Behavior and Performance	■ Human performance failure because of poor psychosocial adaptation
	Radiation Effects	■ Carcinogenesis caused by radiation
	Clinical Capabilities	■ Trauma and acute medical problems
Type II (very serious)	Advanced Life Support (ALS)	■ Inability to maintain acceptable atmosphere in habitable areas ■ Inability to provide and recover potable water ■ Inadequate supplies (including maintenance, emergency provisions, and edible food) ■ Inability to maintain thermal balance in habitable areas ■ Inability to adequately process solid wastes ■ Malnutrition due to inability to provide and maintain a bioregenerative system ■ Inadequate stowage and disposal facilities for solid and liquid trash generated during mission
	Food and Nutrition	■ Malnutrition ■ Unsafe food systems ■ Human performance failure due to nutritional deficiencies
	Bone Loss	■ Fracture and impaired fracture healing
	Cardiovascular Alterations	■ Occurrence of serious cardiac dysrhythmias ■ Impaired cardiovascular response to orthostatic stress
	Human Behavior and Performance	■ Human performance failure because of sleep and circadian rhythm problems
	Muscle Alterations and Atrophy	■ Loss of skeletal muscle mass, strength, and/or endurance ■ Inability to adequately perform tasks ■ Inability to sustain muscle performance levels to meet demands of performing activities of varying intensities
	Neurovestibular Adaptation	■ Impaired neuromuscular coordination and/or strength (gait ataxia, postural instability) ■ Disorientation and inability to perform landing, egress, or other physical tasks, especially during/after g-level changes
	Radiation Effects	■ Damage to central nervous system from radiation exposure ■ Synergistic effects from exposure to radiation, microgravity, and other spacecraft environmental factors ■ Early or acute effects from radiation exposure
	Clinical Capabilities	■ Toxic exposure ■ Altered pharmacodynamics and adverse drug reactions
	Multisystem (Cross-Risk) Alterations	■ Postlanding alterations in various systems resulting in severe performance decrements and injuries
	Environmental Health	■ Allergies and hypersensitivity reactions from exposure to the enclosed spacecraft and other environmental factors ■ Inability to maintain acceptable atmosphere in habitable areas due to environmental health contaminants ■ Inability to provide and recover potable water due to environmental health contaminants

[1] The type assigned to each risk depends on the level of uncertainty, both concerning knowledge of the risk itself (i.e., its occurrence and severity) and concerning its mitigation status.

- **Crew privation**: Many of the more complex issues of human space missions cannot be solved simply by supplying the absolute basics and nothing else. In planning any long-duration mission with a human crew, the argument of "separating needs from greeds" is a fallacy. In fact, any mission beyond LEO cannot supply crews with the quality of life they have enjoyed on Earth. Even the most creative concepts and innovative approaches do not diminish basic crew needs. The pressure to reduce mission cost is constant, but the risk to mission success and crew survival does not justify underestimating human needs and overestimating human abilities to cope with privation.

Through careful risk assessment and risk management, we must establish a strong record of mission success. If humans are to overcome the limitations of crewless exploration and explore the key scientific questions of our time, space-faring crews must return safely from their missions—and in good shape.

From the perspective of mission success, any mission should be considered a failure if the crew and the data they obtain do not return to Earth. Nor can we subject the public to knowledge that, during a mission, crewmembers have become sick from radiation exposure or are suffering from stress, privation, and a long isolation from Earth.

Risk-Management Schemes

Numerous means exist to mitigate or minimize the risks of human space missions within the mission design process. Examples include:

- **Public protection**: The public must be protected against harm from departure and return disasters (e.g., debris, fire, and contamination) through fault tolerance, range safety devices, and the safe location of facilities.

- **Precursor information**: Risk reduction depends on advanced knowledge of environmental conditions, performance of engineering products, and human response. Minimizing unknowns—through a balance of ground demonstrations, in-situ robotic sampling, and realistic in-space rehearsals—ensures mission success and safety.

- **Automated asset deploymen**t: To meet the basic goals of safe scientific exploration and commercialization, the amount of time required and the risk introduced during setup and to maintain life support systems should be minimized. Basic life support should be automatically deployed, and the crew must be able to verify a system as being operational or repairable prior to commitment and use.

- **Design risk out**: To minimize reliance on error-prone and time-intensive human or procedural controls, the primary means of risk mitigation should involve designing out risk (e.g., fail-safe redundancy, material selection, load margins, automation, inherent reliability, and test verification). Normal design criteria require two-fault tolerance for crew-safety critical functions.

- **Maintenance design**: Maintenance can be a complementary means to restore fault tolerance, noncritical functions, and crew/vehicle safety. Because resupply at remote destinations is limited by orbital mechanics, transport time, and mass and volume constraints, maintenance provisions must be available on site. Tactics to ensure efficient and safe maintenance include: advance deployment of spares, component commonality, in-situ manufacture, low-level repairs, autonomous training and procedures, and robotic implementation and preventative attention. Unless impractical, all equipment that may require maintenance will be located internally; and whenever possible, all external items should be detachable so they can be moved to the cabin interior for repair. In general, crew time and logistics demands must be minimized and conducted under the safest possible conditions.

- **Hazard isolation**: Because life-threatening failures may occur, remote placement of hazardous materials, redundant containment, and cleanup materials are a few options for reducing risk. A crew should be able to avoid or secure hazardous devices and work zones before entering an area.

- **Safe havens**: The crew must be protected from the deleterious effects of exposure to temporary or prolonged environmental hazards, such as decompression, temperature extremes, natural or artificial radiation, and prolonged microgravity. When conditions exceed space suit or habitat protection capabilities, a safety shelter (e.g., rover, portable enclosure, or hardened habitat zone) is necessary. To be effective, the shelter must combine practical shielding technologies with limited exposure times, avoidance of harsh/hostile conditions, supplementary shelters, and systems for advance warning. Long-term sheltering may be necessary in the event of a permanent spacecraft decompression or another non-repairable failure of the life support system. Such catastrophic events cannot be handled by an emergency return to Earth or by wearing an EVA suit for years or months at a time. Finally, considerable planning must be devoted to the crew facilities in such a shelter.

2.4 REFERENCES

[1] Charles J and Critical Path Control Panel. *Critical Path Roadmap Baseline Document*. Johnson Space Center Bioastronautics Research Division; latest revision October 2000. (Available as a PDF on the public access Web site: http://criticalpath.jsc.nasa.gov/CP_Baseline.pdf.)

[2] Ball JR and CH Evans, Jr., editors. *Safe passage: astronaut care for exploration missions.* Committee on Creating a Vision for Space Medicine during Travel Beyond Earth Orbit, Board on Health Sciences Policy, Institute of Medicine. Washington, D.C.: National Academy Press, 2001 (Also available as an electronic publication from the National Academy Press Web site: http://www.nap.edu/catalog/10218.html.)

3 HUMAN-RATED VEHICLE REQUIREMENTS

The spacecraft serves as a crew's first line of defense against the hazardous space environment. NASA has identified design requirements to ensure the safety and reliability of human-rated exploration vehicles. The most important requirements, fully addressed in NASA *Human Rating Requirements*,[1] are reprinted below.

3.1 GENERAL

Requirement 1: The vehicle shall be designed, built, inspected, tested, and certified to specifically address the requirements for human rating.

Requirement 2: The vehicle design, manufacture, and test shall comply with report JPG 8080[3] and with applicable military standards. Where alternative approaches are used, verification shall be provided that the alternative approaches meet or exceed the performance of accepted approaches.

Requirement 3: The vehicle crew habitability and life support systems shall comply with *Man-System Integration Standards* (MSIS) NASA Standard-3000[2] and with NASA spaceflight health requirements for crew habitability and life support systems design.

Requirement 4: A successful, comprehensive flight test program shall be completed to validate analytical math models, verify the safe flight envelope, and provide a performance database prior to the first operational flight (i.e., flights other than for the specific purpose of flight test) with humans on board.

Requirement 5: Spacecraft operations in proximity or docking with a crewed vehicle shall comply with joint vehicle and operational requirements so as to not pose a hazard to either vehicle. Provisions shall be made to enable abort, breakout, and separation by either vehicle without violating the design and operational requirements of either vehicle. Crewless vehicles must permit safety-critical commanding from the crewed vehicle.

3.2 SAFETY AND RELIABILITY

Requirement 6: The program shall be designed so that the cumulative probability of safe crew return over the life of the program exceeds 0.99. This will be accomplished through the use of all available mechanisms including mission success, abort, safe haven, and crew escape

Requirement 7: A crew escape system shall be provided on future (e.g., post-Space Shuttle) Earth-to-orbit (ETO) vehicles for safe crew extraction and recovery from in-flight failures across the flight envelope from prelaunch to landing. The escape system shall have a probability of successful crew return of 0.99.

Requirement 8: For ETO vehicles, abort modes shall be provided for all phases of flight to safely recover the crew and vehicle or permit the use of the crew escape system. For beyond-Earth-orbit (BEO) missions, spacecraft and propulsion systems shall have sufficient power to fly trajectories with abort capabilities and to provide power and critical consumables for crew survival. Trajectories and propulsion systems shall be optimized to provide abort options. When such options are unavailable, safe haven capabilities shall be provided.

Requirement 9: If a flight termination (range safety) system is required for future (e.g., post-Space Shuttle) ETO vehicles, the vehicle design shall provide for safe recovery of the crew.

Requirement 10: All critical systems essential for crew safety shall be designed to be two-fault tolerant. When this is not practical, systems shall be designed so that no single failure shall cause loss of the crew. For purposes of this requirement, maintenance can be considered as the third leg of redundancy so long as mission operations and logistics resupply permit it.

Requirement 11: Vehicle reliability shall be verified by test(s) backed up with analysis at the integrated system level prior to the first flight with humans on board and verified by flight-based analysis and system health monitoring for each subsequent flight.

Requirement 12: The performance and reliability of all critical software shall be tested on a flight-equivalent avionics test bed across the entire flight envelope. Independent verification and validation methods shall be used to confirm the integrity of the software testing process.

3.3 HUMAN-IN-THE-LOOP

Requirement 13: The vehicle shall provide the flight crew on board the vehicle with proper insight, intervention capability, control over vehicle automation, authority to enable irreversible actions, and critical autonomy from the ground.

Requirement 14: The flight crew shall be capable of taking manual control of the vehicle during all phases of flight. The vehicle shall exhibit Level I handling qualities as defined by the Cooper-Harper Rating Scale (a scale used to determine how effective aeronautical modifications are).

Requirement 15: The spacecraft displays and controls design shall be based on a detailed function and task analysis performed by an integrated team of human factors engineers with spacecraft displays and controls design experience, vehicle engineers, and crewmembers. Solutions in this design area shall not be limited to those solutions derived from experience with Shuttle if newer or alternative concepts are applicable.

Requirement 16: Mission design, including task design and scheduling, shall not adversely impact the ability of the crew to operate the vehicle.

3.4 EMERGENCY PROVISIONS

To protect crew health and vehicle operation, the vehicle architecture must include the following safety systems and features:

- A smoke detection system that provides nontoxic fire suppression and by-product cleanup;
- A system that will detect cabin depressurization, seal affected areas, and help determine the location and cause of a seal breech. Ideally, the system would be able to automatically seal the breech and repressurize the area. If the breech cannot be sealed automatically, the crew needs to be able to safely enter the depressurized area wearing EVA suits;
- Methods to detect and clean particulate, chemical, and biological contamination;
- Contingency consumables, to allow time for failure correction or mission extension due to resupply or return skip cycle;
- Early return for untreatable health or vehicle emergency;
- Multiple escape paths; and
- Preservation of alternate ingress path.

Caution and Warning System

The caution and warning system (CWS) is of particular importance to prevent or manage an emergency. This is because it warns personnel of impending danger, alerts an operator to a critical change in system or equipment status, reminds the operator of a critical action(s) that must be taken, and provides advisory and tutorial information. The following guidelines are distilled from *MSIS* Section 9.4[2] on displays. The CWS must:

- Provide standard alarms using both visual and auditory information for the following:
  - **Class 1 (emergency)**: A life-threatening condition requiring an immediate and predefined action to protect the crew.
  - **Class 2 (warning)**: Conditions requiring immediate correction to avoid loss or major impact to the mission, or to avoid potential loss of the crew.
  - **Class 3 (caution)**: Conditions of a less time-critical nature, but with potential for further degradation if crew attention is not given.
- Consider alarm's frequency, intensity, alerting capability, and discriminability. Verbal alarms should be designed for maximal intelligibility, considering speech characteristics, intensity, message content, and repetition.
- Allow rapid CWS recovery to default and ensure that the CWS remains operational during power failures or other anomalies.

3.5 REFERENCES

[1] van Laak, J. “Human-Rating Requirements.” 1998. Internal document. Available to JSC users only.

[2] Booher, C. “Man-Systems Integration Standards, NASA-STANDARD-3000.” 1992. Available at http://standards/msfc.nasa.gov/default.htm.

[3] Report No. NPG 7120.5A, “Section 4.0 Risk Management“ found in Program and Project Management Processes and Requirements.” 1998. Available in HTML on the NASA Web site http://nodis3.gsfc.nasa.gov/library/displayDir.cfm?Internal_ID=N_PG_7120_005A_&page_name=main.

[4] “JSC Design and Procedural Standards Manual.” Johnson Space Center. 1991. Internal document. Available to JSC users only.

4 ARTIFICIAL GRAVITY

The concept of creating artificial gravity (AG) was first popularized by Wernher von Braun, Arthur C. Clarke, and others many years ago. Stanley Kubrick's 1968 movie "2001: A Space Odyssey" brought this concept to the forefront of public interest, although gaps in fundamental knowledge and research mean that AG cannot yet be considered viable. More than 30 years of sporadic activity in AG research has not elucidated the fundamental operating parameters for a countermeasure.

As indicated in the CPR[1] (section 2.3.1), current measures for preventing the deleterious physiological effects of microgravity have been only partially successful for orbiting missions that may last 10 to 90 days. Certainly, further countermeasure development is required for missions lasting 1000 days or more.

4.1 KEY CONCEPTS

Countermeasures that rely in part on AG are still under consideration. Although the rotation of an exploration spacecraft or component is not a panacea and cannot ameliorate radiation exposure, isolation, confinement, and environmental homeostasis, it may offer significant promise. Many of the trade-offs and considerations for AG countermeasures are addressed in the *1999 Artificial Gravity Workshop Proceedings*,[2] a multi-day meeting of life sciences, engineering, and medical experts discussing AG.

- **Countermeasure**: Any preventive or mitigating measure—whether a form of exercise, a drug or nutritional supplement, or a more complex mechanical device—that addresses the most severe physiological and psychological risks of human spaceflight. A countermeasure must also meet stringent specifications for use in flight, where resources and crew time are equally scarce.

- **Operational performance**: Level of crew performance that must be maintained during a mission and that relies, in part, on countermeasures. Unfortunately, sufficient empirical information is not yet available to qualify the level of performance required for crew performance during a Mars or another long-duration mission.

- **Rotational AG**: The primary approach to providing AG (as opposed to linear AG), which involves rotation of all or part of the spacecraft to produce constant or intermittent levels of gravito-inertial force.

- **G-transition**: The physiological and psychological process of adapting to different gravity environments, as may be introduced when applying intermittent AG.

The goal of an AG countermeasure should be to maintain the level of operational performance required during and after flight, and to minimize the irreversible changes that are likely to compromise the long-term health and safety of the crewmembers.

4.2 BENEFITS

An AG countermeasure could potentially reduce or eliminate the physiological changes associated with microgravity. These changes include a spectrum of health issues: loss of bone-mineral density and the associated increase in renal stone risk; muscle atrophy; cardiovascular deconditioning; orthostatic hypotension; and sensorimotor and neurovestibular alterations as well as perceptual illusions.

AG and exercise combined with diet control and/or pharmacologic supplements might prove to be the optimal mitigation for certain health risks faced by crews on long-duration, exploration missions. In addition, AG would provide some benefit to life support systems; i.e., continuous or intermittent rotation would reduce the levels of floating particulates in the air, thereby reducing the risk of potential microbiological and/or toxicological hazards. It can also simplify the performance of common tasks that are complicated by microgravity (or another hypo-g environment), such as materials handling, surgery, sleeping, cooking, and excretory function.

4.3 CURRENT LIMITATIONS

The lack of systematic research on AG raises significant questions on the appropriateness of AG for exploration missions—questions that cannot be answered by speculation or theory alone.

The following summarizes recommendations from the 1999 Artificial Gravity Workshop as to the most crucial actions required before any type of AG can be certified as an operational countermeasure:

1 Implement a rigorous research and development project to investigate rotational AG. The desired outcome should be a multisystem countermeasure against the detrimental health and performance effects of long-duration, exploration-class spaceflight.

2 Determine optimal design characteristics for an AG countermeasure facility that will best promote human health and performance.

3 Support the upgrade of existing ground and flight research sites and facilities as needed to perform fundamental activities.

4 Promote community participation of and communication among experts from life sciences fields, human factors, international space agencies, mission and vehicle design, crew representation and training, and rehabilitation.

More specifically, research is needed to fully characterize the physiological response to gravity environments between 0g and 1g and the cumulative effects of g-transitions. Optimal designs require data on the human response to the varying characteristics of rotating AG environments (e.g., radius and angular velocity). Acceptable standards must be defined to maintain the level of operational performance required during and after flight, and to minimize irreversible changes that are likely to compromise the long-term health and safety of a crewmember.

Indeed, the timeframe required to develop an AG countermeasure is rather significant. If we hope to apply AG during the next few decades of space missions, we need to begin human-subject studies on AG in space as soon as possible. An Earth-orbiting space vehicle equipped with a short-arm centrifuge could be used to study the effects of rotating AG environments (from 0.38g to 1g) on human physiology. Even smaller-scale experiments that use the International Space Station (ISS) as a test bed would yield significant progress our understanding of the design and operational parameters of AG.

The following statement summarizes the current state of an AG countermeasure:

While AG shows significant theoretical and intuitive potential as a multisystem countermeasure, considerable research and development effort is required before it can be considered for a complex, long-duration mission.

4.4 DESIGN CONSIDERATIONS

A number of approaches have been considered for designing an AG countermeasure, each of which involves trade-offs between amplitude (g-level), duty cycle (how often and for how long), angular velocity, rotation arm, and other key variables. The following is an attempt to distill the key considerations and alternatives.

One confounding factor of any rotational environment, whether constant or intermittent, is the so-called gravity gradient, which may cause untoward operational effects and significant discomfort to crewmembers.

The physics of rotational AG means that the gravity experienced by a crewmember varies directly with the distance from the center of rotation. A crewmember exposed to a 1g vector in a 4-meter radius centrifuge could experience 1g at the feet but only 0.5g at the head.

Intermittent AG

One approach involves using a short-arm centrifuge to produce intermittent AG. With this approach, AG might be applied only during crew sleep time or as a means of human-powered exercise.[4] But intermittent AG represents a significant unknown because it introduces a number of g-transitions between the desired level of g and the current “ambient” levels in the spacecraft or on the expedition surface, which may be marked by a host of adverse cardiovascular effects. For example, tests of other countermeasures using intermittent lower body negative pressure show that crews repeatedly experienced the malaise, facial edema, and other symptoms resembling postflight orthostatic hypotension (a condition that may result in fainting or near-fainting upon egress). Intermittent AG may produce similar problems, keeping the crew in an uncomfortable or even a dangerous state of constant physiological adaptation.

Continuous AG

Continuous AG may also have drawbacks. We do not know how well the central nervous system can adapt to the constantly varying sensory stimuli introduced by this type of rotating AG. Coriolis forces created by rotation give the illusion of angular motion (usually roll or pitch) whenever the head is moved outside the plane of rotation. In many subjects, this movement causes severe nausea and vomiting. Whether the effects would be eliminated over time as the subject adapts to AG is unknown. Additionally, long-term exposure to continuous rotating AG may alter how a subject readapts to Mars or Earth gravity or to microgravity.

4.5 REFERENCES

[1] Charles J and Critical Path Control Panel. Critical Path Roadmap Baseline Document. Johnson Space Center Bioastronautics Research Division; latest revision October 2000. Available as a PDF on the public access Web site: http://criticalpath.jsc.nasa.gov/CP_Baseline.pdf.

[2] Paloski WH, & Young LR (1999). Artificial gravity workshop: Proceedings and recommendations. NASA/NSBRI Workshop Proceedings. Available at mvl.mit.edu/AG/ag-overview.html.

[3] Diamandis P. "Countermeasures and Artificial Gravity." In *Fundamentals of Space Life Sciences*, Volume 1, Churchill S, editor. Malabar, FL: Krieger Publishing Company. 1997.

[4] Meeker L et al. "A human-powered, small-radius centrifuge for space application: a design study." *Survival and Flight Equipment Association Journal.* 26(1):34-43. 1996.

[5] Smith M, Wercinski P, et al. "A Conceptual Design Study of a Variable Gravity Spacecraft" in *Space Exploration Projects Center Report*. Moffett Field, CA: NASA/Ames Research Center. July 1990. Internal document. Available to internal users only.

[6] Stone R Jr. Report No. NASA-SP-314, "An overview of artificial gravity." Presented at the Fifth Symposium on the role of the Vestibular Organs in Space Exploration. Pensacola, FL; p 23–33. August 1970.

[7] Vernikos J. "Artificial gravity: intermittent centrifugation as a spaceflight countermeasure." *Journal of Gravitational Physiology*. 4(2):13-16. July 1997.

[8] Young L. "Artificial gravity considerations for a Mars exploration mission." *Annals of the New York Academy of Sciences*. 871:367-78. May 28, 1999.

5 RADIATION

Radiation in the space environment remains one of the greatest risks to human health. (This risk is further described in the CPR[1]). Crewmembers are exposed to two types of radiation: ionizing radiation and nonionizing radiation. The radiation environment fluctuates considerably over time and location, which means that a crew will likely require different protections or countermeasure approaches over the course of a long-duration mission.

5.1 KEY CONCEPTS

One definitive source for understanding the radiation environment and the human-driven requirements is the MSIS[2]. In addition, requirements for ionizing radiation received during spaceflight are set by the National Council on Radiation Protection and Measurements (NCRP). Limits for human exposure to nonionizing radiation in space were modified from guidelines provided by the American Conference of Governmental Industrial Hygienists.

Table 5.1 characterizes the key sources of radiation that affect human safety, health, and performance. More common examples of ionizing radiation include human-made sources of x rays, nuclear reactors, and radioactive nuclides; as well as natural sources of galactic cosmic radiation (GCR), solar particle events (SPEs), and particles trapped in naturally occurring magnetic fields. Examples of nonionizing radiation sources include infrared (IR) light, radio waves, and ultraviolet (UV) light.

Table 5.1: Characteristics of Radiation Sources in the Space Environment [a]

	Form	Source	Sphere of Influence	Frequency	Description
Ionizing	SPE	Natural	Outside vehicle, in space or on planetary surface	Unpredictable but infrequent with high intensity	Produced by dynamic solar events, such as solar maximum
	Trapped particles	Natural	Localized outside of vehicle	Constant with moderate intensity	Found within Earth's magnetic field, in polar regions, on other planetary surfaces and in deep space
	GCR	Natural	Ubiquitous and penetrating throughout universe	Constant with low intensity	Permeates the galaxy and moves with speeds approaching that of light
Nonionizing	Technology sources	Artificial	Inside vehicle	Constant, low levels	Derived from human-made equipment or devices
	Solar UV		Outside vehicle and inside through some windows	Constant, relatively high levels	Produced by solar corona

[a] Adapted, in part, from Table 2.1: Sources of Space Radiation.[3]

Ionizing radiation is of particular concern because it directly damages the genome as it traverses the cell nucleus. It also indirectly damages the genome by producing free radicals and by transducing signals between adjacent cells within the body.

- **Acceptable risk**: Currently, dose limits are designed to ensure a less than 3% probability of excess cancer death. The "as low as reasonably achievable" (ALARA) principle is used to stay well below these limits.[4,5]
- **Deterministic (non-stochastic) effects**: Physiological effects (e.g., acute radiation sickness, damage to central nervous system, or cataracts) of radiation exposure for which the severity is related to the level of exposure; that is, these physiological effects occur only above dose thresholds.[4]
- **Stochastic effects**: Physiological effects (e.g., cancer, hereditary effects, or neurological disorders) for which the probability is related to the level of exposure and can occur long after a mission is complete; that is, the probability of occurrence is proportional to the dose received.[4]

- **Radiation dose**: Measure of energy absorbed by a unit mass of living tissue, expressed in grays (Gy) or rads (100 rad = 1Gy).[4]
- **Linear energy transfer** (LET): The energy loss rate or stopping power of a given radiation type that is one means of attenuating radiation. Generally, sources are defined as low-LET or high-LET.[4]
- **Relative biological effectiveness** (RBE): Ratio of radiation doses with different LET, resulting in the same biological effect.[4]
- **Gray-equivalent**: Indicator of deterministic injury, where RBE × dose[6] = Gy-Eq.
- **Quality factor** (Q): An LET-dependent, defined protection quantity based on judgment of RBE for protection purposes.[4]
- **Dose equivalent** (H): Indicator of stochastic risk, where Q × dose[4,6] = H, in units of Sv or rem (100 rem = 1 Sv).

5.2 NONIONIZING RADIATION CONSIDERATIONS

The MSIS[2] clearly defines the parameters that contribute to nonionizing radiation exposure within the spacecraft. Exposure of crewmember eyes and skin to the Sun are limited for UV light, “blue light,” visible, and IR wavelengths, as indicated in Table 5.2. Scientific experiments and observation through spacecraft windows impose technical specifications for color-balanced light transmission that permit high intensity of sunlight at some nonionizing wavelengths.

Table 5.2: Limits for Exposure to Nonionizing Sunlight in Space [a]

Mechanism	Solar irradiance exposure time limit [a]
Retinal thermal	3 sec
Retinal photochemical	5 sec
IR exposure	10 min
UV exposure	8 hr

[a] From *MSIS* Figure 11.11.3.1.4-2.

5.3 IONIZING RADIATION CONSIDERATIONS

Regulatory requirements have been established for LEO operations to control stochastic and deterministic radiation effects.[4,6] The current limit of no more than 3% excess cancer death in crewmembers originates from comparisons to other occupational injuries and analogous populations.[4,6] Accepted sex- and age-dependent cancer risks limits are currently expressed in terms of dose equivalent.[4] On the basis of more recent cancer risk evaluations, the recommended limits (Tables 5.3 and 5.4)[4] have been greatly reduced for LEO operations. Deterministic effect limits pertain to three particularly sensitive tissue—ocular lens, skin, and blood-forming organs—over 30-day, annual, and lifetime periods.[4]

All radiation protection measures and approaches must also adhere to the U.S. regulatory requirements; i.e., exposure must be ALARA. Mission planners and radiation personnel must demonstrate that ALARA has been achieved in the designs used and the operations conducted in space.[4,6]

Unlike LEO, which is often dominated by trapped radiation, deep space exposure is dominated by GCR.[4,6-9] Currently, insufficient data exist on the biological effects of GCR, which means that specific exposure requirements for deep space operations have not been established.[4,6] Quantities and limits defined for LEO operations are normally used for all mission studies, but scientific and regulatory communities can hardly be expected to retain these standards when concrete planning for BEO missions commences in earnest.

Table 5.3: Recommended Organ Dose Limits for Deterministic Effects (All Ages) for LEO Operations [6]

	Bone marrow (Gy-Eq)[a]	Eye (Gy-Eq)	Skin (Gy-Eq)
Career	—	4.0	6.0
1 year	0.50	2.0	3.0
30 days	0.25	1.0	1.5

[a] Gy-Eq or Gray-equivalents.

Table 5.4: Career Effective Dose Limits [a]

Age at exposure	Effective dose (Sv)	
	Female	Male
25	0.4	0.7
35	0.6	1.0
45	0.9	1.5
55	1.7	3.0

[a] Limits are based on 3% excess lifetime risk of fatal cancer in LEO operations.[6]

5.4 UNCERTAINTIES IN EXPOSURE RISK ESTIMATES

Uncertainties in health risk estimates for space radiation are derived from several sources, the greatest of which is the human health risk data that comes from the two detonations of nuclear weapons during World War II. Uncertainty for these data arises from uncertainty in dosimetry, in statistics from the limited survivor population, in projection of the fatal cancer risks over the lifetime remaining, and in relationship of these risk estimates for this population to other national/ethnic groups. Further uncertainty enters in applying the high-dose-rate risk coefficients to low-dose-rate exposures, to the RBE for other radiation types, and to the estimation of dose to specific tissues from space radiations for a specific mission.

Detailed analysis has shown that the main limitation of shielding design for deep space results from uncertainty in applying the known risk coefficients—with their associated uncertainty—to the space exposures and not to the related evaluation of the exposure conditions. The greatest uncertainty arises from the uncertainty in the RBE of different radiation types (or quality factor), while the remaining uncertainty in risk coefficients from other sources is comparable to the uncertainty arising from the estimation of LET-related dose contributions in specific tissues for the specific space shielding.

5.5 RADIATION COUNTERMEASURES

No single method can completely protect crewmembers from the effects of space radiation. Thus, the overall approach applies three methods:

- **Design, technology, and shielding**: Controlling the radiation reaching specific tissues through shielding and selection of exposure conditions.
- **Operational methods**: Controlling exposure based on individual sensitivity (currently age and gender) and by judicious operational scheduling.
- **Biomedical countermeasures**: Controlling select symptoms through medical intervention or prevention.

These three methods must be implemented throughout the entire cycle of mission planning, shield design, operations, and biological treatment and controls. In the ensuing sections, these principles are considered in more detail. Table 5.5 summarizes the results of a detailed analysis conducted to quantify the potential improvements in operational capacity that may result from adhering to these principles.

Table 5.5: Estimates of Safe Days Gained in Space from Different Forms of Mitigation

Mitigation approach	Estimate of days gained	Comment
Improved risk assessment	200 – 400 days	Cost-effective approach using data collection and research
Shielding	50 – 300 days	Light-mass materials identified; risk assessment data needed to improve approach
Advanced propulsion	100 – 300 days	Large advantage, if achievable
Crew selection	50 – 300 days	Age, sex, and genetic selection not ethical; role of sensitivity to GCR not established at this time
Biological countermeasures	0 – 1000 days	Needs revolutionary research to achieve
Solar cycle avoidance	100 – 200 days	Reduces launch windows to decrease SPE threats

Design, Technology, and Shielding

Exposures can be reduced for specific missions through planning, technology choices, and shielding. As shown in Table 5.5, a number of approaches are or should be available to limit radiation exposure to space-faring crews. For example, although limiting the launch windows to coincide with solar cycle variations reduces GCR exposure, it also introduces a rising risk of SPE exposure. Advanced propulsion systems might reduce the transit times. Shielding against the radiation environment involves the entire spacecraft, meaning that apparently simple design choices (e.g., aluminum structures as opposed to polymer composites) can have adverse effects on radiation exposures.[8,9] Shielding during every aspect of the mission is necessary to ensure crew safety, health, and performance. For example, the minimal protection afforded by space suits and rovers (due to mobility requirements) necessitates that careful attention be devoted to developing a shelter for SPE storms.

Operational Methods

First, the judicious scheduling of missions and activities may allow crewmembers to simply avoid exposure when radiation levels are known to be high. Also, the duration of exposure during high levels or rates should be minimized to the greatest extent possible. Second, monitoring the environment and making short-term predictions of radiation events is important. Personnel monitoring (using cabin dosimeters or body-worn dosimeters, for example) provides for cumulative tallying against career limits and may help guide medical treatment in the event of an exposure.

Biological Countermeasures

Biological countermeasures for radiation must work for extended periods, be effective for high-LET radiations, and lead to minimal side effects. A combination of pharmaceutical radioprotectants, antioxidants, and enzymatic modifiers might reduce health risks.[10,11] Other approaches that have been considered (but may not necessarily be adopted) include:

- Select for radio-resistant individuals (select-in) and reject radio-sensitive individuals (select-out);
- Pharmacological protection (prophylactic or postexposure);
- Genetic therapy; and
- Genetic modification and cloning (so-called designer crews, which may surpass ethical limits).

5.6 FUTURE DIRECTIONS

Providing adequate radiation protection for crews on long-duration missions outside of Earth's protective magnetic field is a major challenge to NASA, one for which no effective and affordable solution has been found.

In the following paragraphs, we suggest advances that can drive the capability of radiation protection forward. An increased commitment to research and testing of mitigation techniques is required to enable mission scenarios beyond LEO.

Design and Shielding Technologies

Shielding affects the entire vehicle and the habitat designs. Space radiation interacts with all structures and equipment, modifying the radiation to which humans and devices in the interior are exposed. To perfect efficient and affordable shielding, all human-rated structures must be approached with a radical perspective on design development.[8,9]

In the past, materials research has focused on requirements for functional use (e.g., high mechanical strength per material mass) without regard to the property of radiation protection per material mass. Adding this criterion requires a new multi-functionality. Also implied in this new multifunctional approach is the need for new design methods—in which multiple disciplines are addressed in the design process, and in which the need for multi-disciplinary optimization (MDO) processes, including radiation-shielding requirements, is emphasized. The parameter space in the design process will reveal that MDO solutions are radical departures from conventional approaches.

Increased emphasis on MDO processes will place requirements on tools for shield analysis. Concomitant to the development of such tools is experimental testing of required databases and computational methods to validate solutions. High-fidelity, physics-based models, together with ample model validation in laboratory test facilities (including the Booster Application Facility and Alternating Gradient Synchrotron at Brookhaven National Laboratory, and the proton accelerator of the Loma Linda University), will become increasingly important as well.

Operational Methods

Temporal variations in the space radiation environment have been and can be used to reduce crew exposure. Operational solutions include:

- Improved propulsion systems that limit transit time for crews;
- Protective spacecraft design;
- Shielded habitats; and
- Personal shielding.

GCR, the primary constraint on planning deep space operations, is reduced in magnitude during periods of maximum solar activity. This reduces the need for shielding of crew areas.

While GCRs are reduced, the probability of an SPE increases. SPEs are sporadic events, lasting only a few hours or days, so that crew exposure can be minimized with a limited-volume shelter. Unfortunately, the mass of such a shelter would be quite large. Scientists have suggested that the water reservoir for a spacecraft could serve as shielding material, but the mass required to protect against an SPE (based on the largest event in recent history) would be very great indeed. The potential disadvantage of an SPE shelter is that it may not be readily accessible during certain mission events, such as EVA or surface exploration. In this case, the limiting factor is the time required to reach the shelter and the availability of timely warning systems. Even an adequate warning system may allow only 1 to 2 hours for crewmembers to seek shelter within proscribed radiation exposure limits. Any advance in warning systems would permit a larger range of human exploration activities.

The largest SPEs are associated with coronal mass ejections (CMEs). Providing an effective early warning capability, alarm system, and shelter would nearly eliminate any threat from SPEs. Future sensors should detect shock acceleration from a CME, providing up to about 8 hours warning before the shock wave arrives at human operation areas. Clearly, the predictability of SPE radiations is in need of continued research and development.

Biological Countermeasures

Genetic variability will play an important role in understanding risk estimates and developing biological countermeasures. Many mechanisms that underlie mutation, repair, and cell signaling have now been explained. The relatively new analysis technique using gene micro-arrays will permit scientists to study the expression of literally thousands of genes and the role of those genes in the genetic response to radiation. Bioinformatics methods (using computational tools and databases in relation to biological, medical and health data), which are currently in development, will allow expedient analysis of micro-array data.[17] Individual differences will also be important in the development of biological countermeasures and for understanding the potential effectiveness of such countermeasures. Important ethics issues will have to be addressed to determine how such knowledge can appropriately be applied to human spaceflight.

5.7 REFERENCES

[1] Charles J and Critical Path Control Panel. *Critical Path Roadmap Baseline Document*. Johnson Space Center Bioastronautics Research Division; latest revision October 2000. Available as a PDF on the public access Web site: http://criticalpath.jsc.nasa.gov/CP_Baseline.pdf.

[2] Booher, C. “Man-Systems Integration Standards, NASA-STANDARD-3000.” 1992. Available at http://standards/msfc.nasa.gov/default.htm.

[3] Letlaw J. “Radiation Biology.” In *Fundamentals of Space Life Sciences, Volume 1*. Churchill S, editor. Malabar, FL: Krieger Publishing Company. 1997.

[4] NCRP Report No. 98, “Guidance on Radiation Received in Space Activities.” Washington, DC: NCRP. 1989.

[5] NCRP Symposium Proceedings No. 3, “Acceptability of Risk from Radiation—Application to Human Space Flight.” 1996.

[6] NCRP Report No. 132, “Radiation Protection Guidance for Activities in Low-Earth Orbit.” 2001.

[7] Space Studies Board. “HZE: Particle Effects in Manned Space Flight.” Washington, D.C.: National Academy of Sciences. 1973.

[8] Wilson JW, Miller J, Konradi A, and F Cucinotta. *Shielding Strategies for Human Space Exploration*. NASA CP-3360. December 1997.

[9] Wilson JW, Shinn JL, Tripathi RK, Singleterry RC, and others. “Issues in Deep Space Radiation Protection.” *Acta Astronautica* 49:289-312. 2001.

[10] Strategic Space Radiation Health Program Plan, NASA Office of Life Sciences and Microgravity Applications, Washington D.C. (1998). Available at http://srhp.jsc.nasa.gov.

[11] Space Studies Board. “Review of NASA's Biomedical Research Program.” Washington, DC: National Academy Press. 2000. Available on NAP Web site: http://www.nationalacademies.org/ssb/biomedmenu.htm.

[12] Space Studies Board. *Radiation and the International Space Station: Recommendations to Reduce Risk*. Washington, DC: National Academy Press. 2000.

[13] Lawrence Berkeley Laboratory. LBNL Report No. 40278, “Modeling Human Risk: Cell and Molecular Biology in Context.” Washington, D.C.: U.S. Department of Energy, 1997.

[14] Space Studies Board. “Radiation Hazards to Crews of Interplanetary Missions.” Washington, DC: National Academy Press. 1996. (Available on line at http://www.nationalacademies.org/ssb/besrmenu.html.

[15] *Radiation Protection Guides and Constraints for Space-Mission and Vehicle-Design Studies Involving Nuclear Systems.* Washington, DC: National Academy Press. 1970.

[16] *Radiobiological Factors in Manned Space Flight.* Washington, DC: National Academy Press. 1967.

[17] “Patents In The Bioinformatics Field: Releasing The Gene Genie.” Alex Wilson, Bioinformatics Group, Bristows, Bio-Science Law Review. 17 October 2002.

6 ROUTINE AND EMERGENCY MEDICAL CARE

Since humans made the earliest orbital flights, space medicine has been tasked with ensuring a successful mission in which the crewmembers return safely to Earth. A successful mission relies on three interdependent elements—the spacecraft system, the human crewmember, and the environment—each of which is driven by the central objective of crew safety, health, and performance.

The function of the human in the spaceflight environment is a continuum that begins with stringent selection, training, and preflight monitoring of the crew, is followed by comprehensive in-flight monitoring and intervention as needed, and is completed with postflight monitoring and rehabilitation. The environmental element is closely related to that of the crew and takes into account internal and external monitoring factors (refer to Chapter 11 for further information).

These responsibilities encompass both the routine medical event that may occur during the course of a normal mission and the emergency care necessitated by an accident or another mission contingency. Elements of this specialty include medical monitoring and certification, health maintenance and countermeasures, medical intervention, psychosocial support, and environmental health monitoring. As a result, needs for medical equipment, crew training, and ground support are considerable. Since standard terrestrial clinics rely on a suite of bulky, resource-intensive diagnostics and therapeutics, these needs are greatly influenced by the mass, volume, and power restrictions of the spaceflight environment.

6.1 KEY CONCEPTS

- **Countermeasure**: Any preventive or mitigating measure—whether in the form of exercise, a drug or nutritional supplement, or a more complex mechanical device—that addresses the most severe physiological and psychological risks of human spaceflight.

- **Countermeasures system**: An element of the crew health care system (CHeCS) that is prescribed by flight surgeons for counteracting the most detrimental psychological and physiological effects of microgravity (see Chapter 4 on Artificial Gravity for a detailed discussion of this approach).

- **Crew medical officer** (CMO): One or more members of a crew who are designated as the lead for managing any medical issues that may arise in flight. The CMO currently receives up to 18 hours of medical training, which is comparable to the training received by an emergency medical technician.

- **Environmental health system**: One element of the CHeCS that permits crew or ground personnel to monitor microbial and chemical contamination of the atmosphere and water, and of the radiation environment.

- **Health maintenance system**: One element of the CHeCS that provides:
    - In-flight preventive, diagnostic, and therapeutic medical care; and
    - Patient stabilization and transport for serious medical situations.

- **Medical event**: Occurrence of significant illness or injury, normally requiring an evacuation, an emergency room visit, or a hospital admission (as applied to the operational environment).

- **Space medicine**: The program of comprehensive health care that is necessary to ensure a healthy, safe, and productive crew; a successful mission; and the prevention of detrimental mission and long-term health consequences.

Figure 6.1 shows how space medicine relies on many disciplines to meet its objectives.

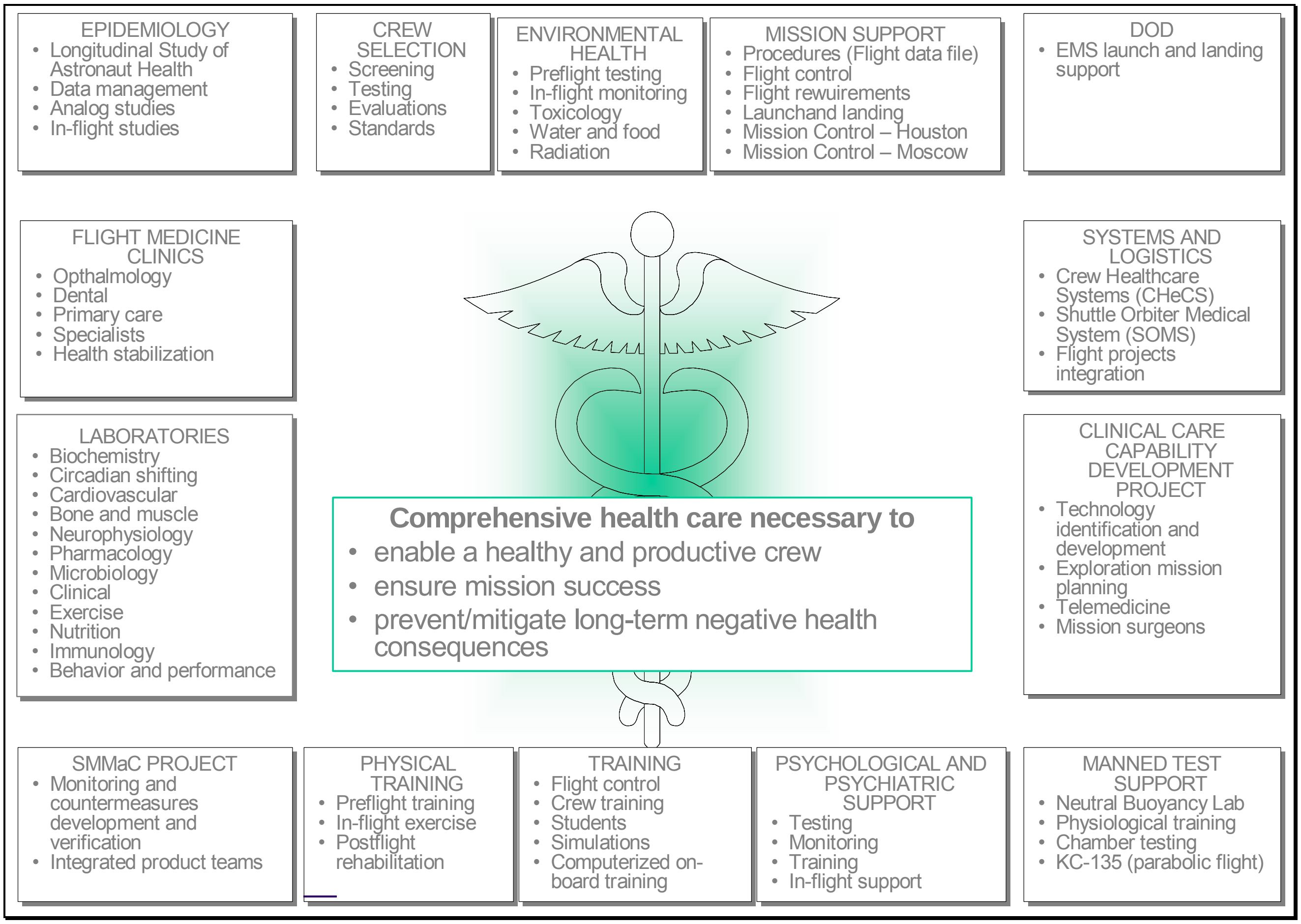

Figure 6.1: Elements of Space Medicine

6.2 RATES OF INCIDENCE

While the U.S. spaceflight program has rarely—if ever—been compromised by a medical event during a mission, such an occurrence is likely.

The probability of significant illness or injury occurring during future human missions is high. These estimates even exclude the singular dangers of the space environment; e.g., radiation exposure, immune system depression, and untoward physiological adaptations.

> ***The probability of significant illness or injury occurring during a 2.5-year mission with six crewmembers is about 0.9 incidents per mission—or nearly every mission will be confronted with such an event.***

If we use the same data sets to estimate the number of events requiring intensive care, again ignoring the untoward effects of the spaceflight environment, the probability that such an event will occur during a Mars mission is about one incident for every three missions. Undoubtedly, the spaceflight environment itself will increase these rates.

Analog Medical Data

In fact, analysis of illness and injury rates for analog populations (e.g., data from astronaut longitudinal, submarine crew, Antarctic winter-over, and military aviator studies) reveals that a medical event during a mission is increasingly probable. These analog populations are a valuable source of data because spaceflights generally involve a small population and correspondingly small limitations on medical data. Detailed analyses, performed by researchers at the NASA/Johnson Space Center, reveal that analog populations suffer many of the physiological and psychological conditions faced by spaceflight crewmembers, with some exclusions as described in Table 6.1.

Despite these exclusions, analog populations furnish an important source of data on the types and rate of incidence for illness or injury that could occur during a human space mission. Table 6.1 shows a ranking of all of the medical events or complaints compiled from over 20 years of analog data.

Table 6.1: Ranking of Medical Events or Complaints from Analog Data [a,1,2]

1	Injury and toxic exposure (poisoning)
2	Digestive system
3	Musculoskeletal
4	Respiratory
5	Mental disorders
6	Signs and symptoms (ill defined)
7 – 9	(tie) Infectious / circulatory / genitourinary
10	Skin and subcutaneous tissue
11	Nervous system and sense organs
12	Neoplasms
13	Endocrine / metabolic / nutritional and immune
14	Blood and blood-forming organs

[a] Unpublished data from Billica et al., NASA/Johnson Space Center.

Crew Medical Data

Medical data from human spaceflight is equally instructive, despite the markedly smaller population size. Analysis of medical complaints recorded during 89 Space Shuttle missions (from 1981 to 1998) and covering 508 crewmembers during 4443 cumulative flight days reveals that an overwhelming majority of any space-faring crew will experience some change in performance—even if it relates to normal physiological adaptation. Data show:

- 79% reported space motion sickness (SMS).
- 98% reported some medical symptom, including:
  - 67% reported headache;
  - 64% reported respiratory complaints;
  - 59%reported facial fullness;
  - 32% reported gastrointestinal complaints; and
  - 26% reported musculoskeletal complaints.

Both spaceflight and analog data analyses inform current estimates of incidence both for the ISS and for future spaceflight missions.

Despite every possible attempt to minimize the risks of human spaceflight, the flight environment remains a hostile one for humans. Microgravity brings considerable physiological effects, including SMS, neurovestibular effects, bone mass loss, cardiovascular deconditioning, musculoskeletal deconditioning, and psychological effects.

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[1] Expect less musculoskeletal-related injuries in spaceflight because the analog environments have increased exposures (cold, numbers of people, injury risk, etc.).

[2] Expect increased skin and circulatory injuries, and possible metabolic/nutritional/immune events in spaceflight because the space environment has increased hazards (e.g., microgravity, closed environment, radiation, age of crew, etc.) that are not found in analogous environments.

The cabin environment may expose a crew to hypoxia, decompression, toxic releases, extreme temperatures, radiation, etc. Confinement, isolation, a difficult workload, stress, danger, and noise can also create difficult psychosocial adaptation problems. Medical emergencies may include burns, trauma, cardiac life support, infections, food poisoning, and a host of other injuries.

Each mission must address and be prepared to manage a wide spectrum of medical concerns during mission operations. Among these are medical events affecting mission timeline or objectives; damaged spacecraft or injured/ill crewmember(s); catastrophic events impacting vehicle integrity and crew survival; and Class 1 alarms (fire, toxic atmosphere, cabin depressurization).

6.3 EMERGENCY CARE

The practice of emergency medicine in space is confounded by severe restrictions on vehicle and personnel resources. Current medical operations rely on nonphysician crewmembers, who have minimal medical training and experience, and who are supported by extensive communications with Earth-based medical personnel. Thus, the alternatives are (1) stabilization of the injured crewmember to allow medical evacuation or (2) complete diagnosis, treatment, and rehabilitation (also known as the “stand and fight” concept).

Medical Evacuation

Medical evacuation from orbit is not unprecedented. In 1976, the Russian *Salyut* 5 space station was abandoned 49 days into a 54-day mission for intractable headaches; on *Salyut* 7, in 1985, a medical evacuation for sepsis/prostatitis occurred 56 days into a 216-day mission; and in 1987 on the Russian space station *Mir*, there was a medical evacuation for cardiac dysrhythmia 6 months into an 11-month mission. There have been several missions where various conditions did not result in medical evacuation, but could have: spacecraft fires in 1971, 1977, 1988, and 1997; a possible kidney stone in 1982; hypothermia during EVA in 1985; psychological stress reaction in 1988; spacecraft depressurization in 1997; and a toxic atmosphere in 1997. Other medical events in the U.S. space program include a rescheduling of an Apollo 9 EVA due to medical causes, Type 1 decompression sickness (DCS) in the command module pilot during Apollo 11, a urinary tract infection in one of the crewmembers during Apollo 13, a cardiac dysrhythmia in a crewmember during and after a lunar EVA during Apollo 15, and chemical pneumonitits due to nitrogen-tetroxide inhalation on reentry during the Apollo-Soyuz Test Project.

Onboard Care

Any complex interplanetary mission generally eliminates the option of medical evacuation to Earth. Instead, the focus of an emergency medical system becomes autonomy, intelligence, and reliability. The transition to missions of increasing length or to more dangerous operations—e.g., significant "hard hat" construction in space —intensifies the need for autonomous emergency medical care. A crewed mission to Mars, for example, would be beset by communication delays of up to 40 minutes round trip. In such a scenario, emergency support from the ground is not feasible.

6.4 DESIGN CONSIDERATIONS

Planning and designing all of the elements of a CHeCS for a long-duration mission is extremely difficult due to the large number of medical conditions that might occur. A problem may present across all or several crewmembers, and any number of problems may occur a number of times during a mission. For this reason, “traveling light” on a future Mars or lunar mission is just not feasible.

For a Mars-type mission, the minimum mass of a crew health care system for a habitable vehicle is estimated to be at least 1000 kg (approximately 2205 lbs) for equipment and 500 kg (approximately 1102 lbs) for consumables, with a total low-estimated volume of 4 m^3 (or about 13 ft^3).

A lunar base would need to be similarly stocked, although the possibility for an evacuation to Earth should reduce the mass and volume of the base slightly.

Consider the complexity and resource-intensive nature of a terrestrial emergency room, in which a team of doctors, nurses, laboratory technicians, pharmacists, radiologists, and pathologists work in concert using an extensive suite of medical equipment to diagnose and treat critically ill or injured patients. During current ISS expeditions, the crew of three includes up to two CMOs who have received medical training equivalent to that of an emergency medical technician. Future missions, which may benefit from a larger crew, will still be confounded by limited medical training and clinical experience, along with severe resource limitations to diagnose, treat, and rehabilitate a fellow crewmember. Even exploration crewmembers, who possesses all relevant mission-critical skills (mechanical and electrical engineering, geology, astronomy, etc.), will have to handle medical emergencies of all sorts under extremely stressful conditions.

Clearly, the resource-limited environment of spaceflight means that the operational concept for onboard care must substitute careful planning and innovation for the many resources of a terrestrial care setting. Vital decisions must be made quickly, with little forgiveness for error. To complicate matters, all equipment and supplies in a "space hospital" must be stowed in the tightest configuration possible to maximize the available space and ensure safety in microgravity—unlike in a hospital emergency room where equipment and supplies are readily at hand, powered up, and in a high state of readiness.

6.5 MEDICAL TECHNOLOGIES AND INVENTORY

Crews on long-duration missions will clearly need the support of intelligent medical systems as they attend to routine and emergency medical needs. In this scenario, intelligent systems act as physician-equivalent helpers or provide logistical support during routine care. Below are examples of the various technologies required to create such intelligent medical systems:

- **Visual programming shells/interfaces for knowledge capture**: Allow physicians and other medical experts to transfer their knowledge for computer-based training and databases, diagnostic aids, decision-support tools, medical protocols, multimedia training, and other support systems.
- **Team coordination/management protocols**: Use linked palmtop computers or other means to ensure adequate emergency medical response.
- **Rapid data entry and comparison**: Allows comparison of data with existing records for rapid diagnostic support, permitting more natural, simpler access or interaction with medical knowledge.
- **Data visualization techniques:** Provide large amounts of complex medical data that are easy to understand and manipulate, which allows questions about the data to be easily and intuitively investigated in an interactive fashion.
- **Physiological simulation models**: Support development of protocols and procedures for emergency medical response.
- **Detailed individual physiological models**: Guide protocol for the administration of pharmaceuticals and to assist prediction of treatment effects.
- **Real-time decision support and "just-in-time" training tools**: Unobtrusive means that permit emergency treatment by nonphysician crewmembers.
- **Intelligent tutoring applications**: Tools that assist the development of onboard medical training for long-term missions, especially those that use a multimedia case-study approach.
- **Automated systems for delivering aspects of emergency care**: Guidance or completion of select medical tasks that allow crewmembers to attend to other tasks.

The health care system for supporting a crew on a 2.5-year mission to Mars would require extensive inventory and availability of numerous medical consumables. In addition to the more commonplace diagnostic and treatment equipment and countermeasures included in current systems, any future system would rely on cutting-edge tools (including software, hardware, and consumables) to guide crewmembers with limited medical knowledge and to minimize or eliminate invasive procedures, as outlined below:

- Noninvasive, in-vivo biosensors and clinical laboratory equipment for monitoring blood chemistry (e.g., calcium ions, electrolytes, proteins, lipids, and hormones as well as cellular components);
- Real-time, in-vitro biosensors and clinical laboratory equipment for monitoring bodily fluids and exhaled gas chemistry;
- Implantable/injectable/ingestable biomedical sensors;
- Pharmaceuticals with a long shelf life (approximately 3 years) and/or the capability to produce pharmaceuticals during the mission;
- Telemedicine systems for orbital and near-Earth or near-Moon consultation and mentoring;

- Laboratory diagnostic equipment (e.g., clinical chemistry, hematology, pathology, microbiology, hematology, and endocrinology);
- Imaging diagnostics equipment (e.g., radiographic, magnetic resonance, and ultrasound);
- Minimally invasive or noninvasive monitors (e.g., electrocardiograph, blood pressure, and oxygen saturation);
- Equipment and protocols for in-flight diagnostic equipment that use minimal consumables (cytometer, delayed-type hypersensitivity testing ("skin test"), enzyme-linked immunoassay (ELISA) system, blood collection and distribution, and a cell culture and challenge system);
- Equipment and protocols to provide rescue, resuscitation, stabilization, and transport;
- Fluid therapy systems including infusion pumps, on-site production of sterile fluids, nutritional support, and blood and blood component replacement.
- Medical waste management system;
- Advanced medical storage systems for samples, pharmaceuticals, and other perishable items;
- Microsurgery/microtherapeutics equipment and protocols;
- Methods for monitoring the radiation environment and dose received (e.g., active, solid-state, bio-, and personal dosimetry);
- Radioprotectants and methods for monitoring pharmacological treatments for radiation exposure; and
- Methods for real-time, autonomous monitoring of air, water, and food for microbial and chemical contamination.

7 PSYCHOSOCIAL INTERACTION

Human exploration crews of the future will be beset by many challenges that will affect their performance, including transitions between g-environments, isolation and confinement, significant crew autonomy, significant lag times for communication to Earth, increased exposure to the physical environment (especially radiation), and decreased perceptual stimulation.

Although we are gaining experience with long-duration crew deployments in LEO (with Shuttle-*Mir* and the ISS), we know little about maintaining a long-duration presence beyond LEO. To some extent, Earth-based analogs (e.g., nuclear submarine deployments, Antarctic missions, and naval research vessels) identify and address crew performance issues expected during long-duration missions. (See Chapter 6 for a comparison and contrast of the analog populations.) These analogs have shown that increased isolation and confinement typically result in increased crew psychological and social problems. The following is a brief description of these issues.

7.1 CREWMEMBER PERFORMANCE

Crewmember performance can be compromised by many aspects of a mission, including:

- Microgravity-induced neutral body posture;
- Physical and biomedical changes;
- Sleep-wake cycles and sleep deprivation;
- Work schedules;
- Isolation and confinement;
- Metabolic costs of EVA; and
- Space adaptation sickness (SAS), although SAS should occur during the initial transition into a different gravity environment and will diminish over time.

Scheduling

Experience with Skylab, *Mir*, and the ISS shows that precisely choreographed schedules for crew work can be problematic during long-duration missions and can be exacerbated during interactions with Mission Control personnel. The present approach for the ISS is to use standard duty schedules that permit regular personal time and rest days. Other important considerations for crew scheduling include:

- Balancing both overload and underload of crew schedules. Excessive workload results in stress, fatigue, attention deficits, and decreased motivation.
- Instituting in-flight refresher training and performance assessment during the long en route portion of the mission.
- Considering rotating duties to maintain crew skills and to decrease boredom.
- Most importantly, ensuring crewmembers have some authority to determine or modify their schedules.

Quality of Sleep

Sleep disturbances (primarily insomnia and decreased sleep quality) have often been reported in confined environments. Even with moderate sleep and disruption of normal circadian rhythms, concentration, vigilance, decision-making, motivation, and skilled performance decrease. Spacecraft design (e.g., noise, vibration, illumination); habitability (e.g., private crew sleep areas), operations (e.g., disruptive communications with Mission Control), and work cycle design should support “normal” sleep periods to prevent disruption of the crewmembers’ circadian rhythms. This will provide zeitgebers (the external physical, temporal, and social cues that regulate circadian rhythms) to regulate crew internal clocks.

7.2 CREW INTERACTION

Exploration missions in particular will require a high degree of group cohesion and cooperation. Individual crewmembers will need strong interpersonal skills because of the requirement to live and work together in a small, confined environment for long periods. Traditionally, crew selection has focused on individuals with strong technical skills and competence; but in addition to these abilities, individual personality characteristics must be emphasized. This is because crew interactions will relate to issues associated with overall crew functioning and compatibility—including crew size, gender, age, culture, competence, and leadership.

Culture

Human missions likely will continue to be composed of an international crew. No culture-based problems are expected since individuals will continue to be selected from a specific subset of the population and, therefore, will have common ground. Although provisions may be required to accommodate the special cultural needs of particular crewmembers, the entire crew should be expected to conform to a single culture. So an official mission language must be selected, and all crewmembers must receive training to be proficient in that language.

The entire crew should perform mission training together for enough time to allow cultural differences to be addressed before departure. During the mission, crewmembers should have equal status based on crew position and not on national origin.

Crew selection should be focused on individuals with characteristics that lend themselves to group cohesiveness and cooperation. In addition to a strong task and team orientation and highly perceived competence, individuals should demonstrate strong social and interpersonal abilities and have introversion/extroversion balance. Particular attention should be paid to selecting the leader. The leader of the first expeditionary force must have both strong leadership abilities and superior interpersonal skills (i.e., be mature, competent, and experienced rather than “action-oriented”).

Crew Performance

Crew performance, as distinguished from the performance of individual crewmembers, relies on the formation and maintenance of a cohesive team that extends over multiple years of training and continues for the duration of the mission.

A number of factors affect crew team performance. These include: knowledge, skills, attitudes, motivation, performance strategies, and personality characteristics of individual crewmembers; group factors (e.g., size, cohesiveness, leadership); and environmental factors (e.g., mission tasks, risks). Important considerations for mission designers include built-in training approaches. Among these are to train:

- All crewmembers to identify and manage conflicts and stress during the mission;
- The crew to protect against “groupthink,” a situation in which maintaining group harmony prevents critical thinking (groupthink may lead to poor or unsafe decisions, which are of particular concern because outside communications are so restricted); and
- Crewmembers in cockpit resource management (CRM) methods (i.e., individual crewmembers must behave assertively for the protection of the entire team, including questioning a leader’s decision).

7.3 COMMUNICATIONS

The isolation, confinement, and distances of long-duration missions yield unique communications issues. Distance will prevent real-time communications, so procedures are required to regularly communicate important information in a store-and-forward fashion. Examples of store-and-forward communications include periodic computer-to-computer transmissions and scheduled crew tapings for public outreach.

Direct crewmember-to-crewmember communications also change. This occurs because microgravity and the artificial atmosphere alter speech, and fluid redistribution alters communication cues such as facial expression and body position. Equipment noise also interferes with communications (see Chapter 11 on Crew Environment, section 11.2) within the cabin. Given the unique circumstances of a human exploration mission, electronic communication will take on added significance.

Communications difficulties between the crew and Mission Control will be exacerbated. The isolation and confinement of missions often mean that crew frustration is directed toward ground personnel. The design considerations listed below—together with established, formal, and structured protocols—will address some of these problems. Crew and ground controller training can offset potential problems.

In summary, communications must provide regular access to crewmembers without constantly intruding on them or interfering with onboard operations.

Design Considerations

- Communications should include full-motion video, audio, and computer-based modes.
- New video compression techniques are required to provide error-free transmission of "television-like" video quality. Recent advances in optical communications require further refinement before these techniques can be integrated into planning for future human missions.

Transmitting quality video is a significant requirement, necessitating robust communication systems. Overcoming the considerable transmission distances of exploration missions in turn affects spacecraft power, mass, sizing, and operations.

- Audio communication has fewer transmission demands than video communication. Synchronized audio and video communication are nonetheless required. Existing systems must be extended to accommodate this requirement.
- Regular computer-to-computer transmissions (e.g., email, burst, text, graphics, telemetry) will be required. An autonomous communications system should be considered.
- Crew-to-family and crew-to-medical communications that are both secure and regular are required.
- Regular near-real-time crew communications are required for public outreach and education in which the crew shares their experiences.
- Regular communications between the crew and scientists on Earth are required, especially during surface operations. Moreover, allowing direct access between a ground-based “science team” representative and the on-board science officer should also be considered.

7.4 EMERGENCIES AND CRISES

Danger is inherent in the space environment and is particularly relevant to any exploration mission, where unique emergencies or crises—some severe and life-threatening—may arise from external or crew-related issues. The individual response to external threats includes both generalized physiological reactions and individual responses. Beyond a certain level, however, the elicited response impairs performance and training becomes critical. Training provides crewmembers with skills to reduce specific threats and to provide effective responses to threat situations. Specific coping strategies can also be learned. Considerations for individual and team performance during an emergency or crisis include:

- Consider modifying crew selection criteria to include specific personality characteristics that are stress-adaptive. When selecting the crew commander, consider leadership behavior during a crisis.
- Address the team response to threats with comprehensive training and simulation.
- Remember that an internal threat, perhaps imposed by another crewmember, is also a possibility. Psychological disturbances increase during long-term confinement and isolation, and negative events on Earth may trigger depression or grief. Decisions are required to determine when and how events on Earth should be communicated to a crewmember.
- Prevent potential psychological problems and, when required, intervene effectively. Prepare crewmembers to recognize and understand possible psychological problems they may experience. Also, give them training in generalized stress reducers (e.g., meditation, relaxation, biofeedback) and in the value of regular exercise.
  - Train the mission commander in crew behavior assessment and intervention techniques.
  - Train the CMO in psychological intervention and countermeasures.
  - Train crewmember families to increase their sensitivity to psychological issues, and provide regular support and counseling to crewmember families during the mission.
- Consider the possible death of a crewmember during a mission, which would require the remaining crew to manage psychological and physical demands. Define procedures to manage this event, using the experience of analog populations (e.g., U.S. Navy vessels at sea; Antarctic during winter-over) as a guide.

7.5 CREW STRUCTURE AND AUTHORITY

The crew should be directly involved in formulating the mission plans. Organizational structure and authority within and between the crew and other organizations must be addressed.

Leadership is formalized and based on the perceived competence of the leader with formal supporting roles. The mission commander will undoubtedly be selected from the ranks of experienced crewmembers, but crewmembers should be allowed to nominate mission commanders.

Authority is often shared on space missions between Mission Control-based personnel and the onboard crew. The long distances associated with exploration missions may make this difficult. Onboard centralization of authority and crew autonomy should be increased, with ground-based personnel focusing on long-range issues.

Crew Work Roles

Crew work roles also influence crew structure. Crew roles should be evaluated and defined specifically for each mission. Consider assigning complementary roles or functions to a crewmember, without introducing task overload. The four functional crew work roles are:

- **Flight operations** (e.g., mission command; guidance, navigation, and control; flight engineering; systems management; communications).
- **Scientific investigation** (e.g., data collection, analyses, mission science goals). Although not essential to mission completion, science tasks may be the primary justification for an exploration mission.
- **Environmental support** (e.g., vehicle and habitat maintenance, logistics management): With a small crew, these roles can be combined with flight operations responsibilities.
- **Crew support** (e.g., medical operations).

7.6 RE-ASSIMILATION ON EARTH RETURN

An exploration crew must remain together for five or more years through initial selection, mission training, and the mission itself. When the mission is completed and the crew returns to Earth, each crewmember will need to be re-assimilated into the life left behind. The separation imposed by the mission and the subsequent re-assimilation can disrupt a crewmember's family. The following considerations will ease the re-assimilation of exploration crewmembers:

- When selecting the exploration crew, familial characteristics must be considered (e.g., should crewmembers be married or unmarried; should crewmembers have young children still at home?).
- Fundamental relationships will be significantly strained by an exploration mission. Consider providing support structures for the duration of the mission to help sustain those involved in the mission.
- During the mission, family members must fulfill their own needs (with the spouse accorded primary responsibility). Other forms of supporting relationships need to be fostered and maintained throughout the entire mission. All crewmembers will face difficult issues associated with missing family occasions and burdening the spouse with added responsibilities.
- After the mission, family roles will need to be redefined and reestablished. Emotions such as frustration, resentment, guilt, and depression can affect the re-assimilation process. The spouse, who managed the family during the mission, has established family rules and may feel uncomfortable giving up primary authority and modifying established behaviors.

7.7 REFERENCES

[1] Connors M. Report No. NASA-SP-483, *Living Aloft: Human Requirements for Extended Spaceflight*. Moffet Field, CA: Ames Research Center. 1985.

[2] Holland A. "Psychology of Spaceflight" in *Human Spaceflight: Mission Analysis and Design*. New York: McGraw-Hill, Inc.; p 55–91. 2000.

[3] Stuster J. *Bold Endeavors: Lessons from Polar and Space Exploration.* Annapolis, MD: Naval Institute Press. 1996.

8 ANTHROPOMETRY AND BIOMECHANICS

Anthropometry and biomechanics seek to improve human performance by understanding the physical characteristics of the human body. Among the characteristics are: dimensions, range of joint mobility, locomotion and translation capability, physical strength in whole and in part, and functional capabilities (e.g., ratcheting, cranking, arm pushing and pulling, leg lifting and lowering, wheel turning, and upper and lower body exertions).

8.1 KEY CONCEPTS

Designers must be aware of likely variations in body dimensions when they build cockpit seats, EVA and escape suits, internal vehicle and habitat architecture, tools, and other items of hardware. They also need to know ranges of joint movement and information about strength required for certain tasks. Speed and methods of locomotion in microgravity and reduced gravity, under EVA-suited conditions, are needed both by suit designers and by the designers of the habitat through which the suited crew must move. This is particularly true if a mission calls for crewmembers to spend any considerable length of time suited up while attempting to repair a problem.

Unfortunately, most existing data on anthropometry and biomechanics were gathered in Earth's gravity. Very little information is available from microgravity, and there are no measurements for reduced-gravity environments.

There is a real need to understand the costs, benefits, and political implications of limiting crew physical size. Attempting to build equipment to accommodate all people between a 5th-percentile Japanese female and a 95th-percentile American male may not be wise. Such a wide spectrum in strength and physical dimensions will undoubtedly increase the cost of manufacturing the equipment necessary for a mission. But will limiting size really decrease cost or make components more interchangeable or easy to use? There is also a misconception that a person in the 5th percentile for stature is also in the 5th percentile for arm reach or shoulder strength. If we limit our population by size, we will diminish the pool from which we can choose crewmembers. The characteristics desired for a crewmember are a cocktail of many parameters, of which size is only one.

Those responsible for the design and sizing of space modules, EVA suits, and other equipment must consider the user population. To accurately fit 90% of the general population, a range of users is specified from the 5th percentile to the 95th percentile for several critical body dimensions. From there, the range can be narrowed to allow for more consistency and interchangeability in, for example, EVA suit parts. There is a cost associated with accommodating 90% of the adult population, however. In Table 8.1, the variation within each dimension can be as high as 58.4 cm (23 in). The choice for EVA, for example, is to (a) develop custom-made suits for each crewmember, (b) modify operations to accommodate all crewmembers (e.g., no suited EVA), or (c) greatly restrict user size (e.g., to from 45th to 55th percentile). This last approach may be difficult or impossible to achieve if we try to accommodate a multicultural crew of both genders, however. There is a need to perform a cost/benefit analysis on all possible options, and to consider the possible political dimensions of such restrictions.

Table 8.1: Examples of Critical Body Dimensions [a,b]

Dimensions	5th Percentile	95th Percentile	Range
Stature	148.9 cm (58.6 in)	190.1 cm (74.8 in)	41.2 cm (16.2 in)
Sitting height	78.3 cm (30.8 in)	99.5 cm (39.2 in)	21.2 cm (8.4 in)
Arm reach	65.2 cm (25.7 in)	88.2 cm (34.7 in)	23.0 cm (9.1 in)
Chest circumference	30.3 cm (11.9 in)	89.4 cm (35.2 in)	59.1 cm (23.3 in)

[a] Information is from MSIS (reference 5).[1]

[b] No data are available on sitting leg reach, although this measurement could be an important design factor.

Currently, the U.S. space program selects crewmembers using the following dimension criteria:

- **Pilots:** 162.5 cm (64 in) to 193.0 cm (76 in).
- **Mission Specialists:** 148.6 cm (58.5 in) to 193.0 cm (76 in).

8.2 DEFINITION OF CREW POPULATION

Current NASA standards[1] provide data for both the 5th-percentile Japanese female and the 95th-percentile American male projected to the year 2000. This does not necessarily define the crew population, however. These data are meant only to characterize the size variation of people across the world. Potential user sizes for specific beyond-LEO missions have not been determined. The Anthropometric Initiative document prepared by NASA's Flight Projects Division (1999)[2] demonstrates that different organizations use different databases and techniques to measure the crew population. This has resulted in widely varying measurements. It would therefore be best to consolidate all anthropometric data so that a single well-defined and well-maintained database can represent the relevant crew population.

8.3 ANTHROPOMETRIC DESIGN CONSIDERATIONS

There are three approaches for fitting a design to the user. Not all approaches may be suitable for all designs, however. These approaches are:

- **Single size fits all**: A single size may accommodate all members of the crew. For example, everyone can use a passage if it is designed for the largest person. A workstation, with a switch within the reach limit of the smallest person, will allow everyone to reach it.
- **Adjustable**: Adjustable hardware, such as the hardware found on car seats, can accommodate most of the user population when a single size cannot be selected.
- **Custom-build**: Individually fitted items may or may not be the right solution. Clothing and eyeglasses are examples of items that require a certain amount of custom fitting. Custom-built items are more expensive, however, and could increase overall mission costs.

Variability in Human Body Size

- **Microgravity effects**: Without the loading effect of gravity, the human physique is altered. The following must be considered when designing equipment for use in microgravity (refer to Figure 3.2.3.1-1 in the MSIS[6]):
    - Height increases by about 3% due to spinal elongation. More complete studies of this effect need to be done, especially for long-duration missions.
    - The relaxed body naturally assumes an S-shaped posture. Studies have not quantified this, however, and this does not account for large individual differences in posture.
    - Changes in circumference, associated with fluid shifts and losses, have been subjectively noted but have not been accurately measured.
    - Because of bone and fluid losses, body mass reduces by about 3 to 4%. The rate of change and the time to reach steady-state conditions have not yet been fully elucidated.
- **Partial-gravity effects**: No studies have been done to characterize how body dimensions change in a partial-gravity environment. Research must be done before equipment is fitted for use during crewed planetary and lunar missions.
- **Duration effects**: The effects of ultra-long-term exposure to microgravity and reduced gravity on body dimensions are not known.
- **Effects of returning to Earth**: Data need to be compiled from prior and future missions to document the effects caused by returning to Earth—e.g., how long it takes to recover body mass, mobility, and the time to recover from joint limitations (mobility-related impairment due to muscle atrophy, bone loss, etc.).

Strength

Several aspects of human strength should be understood and considered when designing equipment for the space environment. These include:

- **Maximum strength**: The ability to generate maximum voluntary muscular tension and apply it to an external object;
- **Endurance**: The amount of work that can be performed at a given level of effort, isometrically or isotonically and under submaximal and maximal conditions;

- **Functional strength**: The ability to perform tasks—e.g, gripping, grasping, turning a knob, hammering, pushing, pulling, carrying, and building; and
- **Tool-specific strength exertions**: The use of tools—e.g., screwdrivers, hammers, and ratchets—to maximize strength applied to a task.

Unfortunately, current design standards[1] do not provide all the necessary data for designing space hardware or tools. To allow 90% of the user population to adequately operate the tools provided, the tools should be designed for the *minimum* capability of the user population and be able to withstand the *maximum* capability of the user population. Additional data on a user population's maximal, functional, and tool-specific strength must be acquired before this goal can be achieved.

Much data in this area are based on Earth's gravity environment. Strength data are needed for reduced-gravity environments and long-term missions, since evidence indicates that muscles atrophy in reduced-gravity environments.

Effects of EVA Suits

Studies[4,5] show that wearing a space suit reduces strength capacity by about 40%. In addition, for industrial operations, current National Institute of Occupational Safety and Health (NIOSH) guidelines recommend that the allowable capability be at or about 30% of maximum capabilities. Hence, strength requirements for EVA-related operations may need to be based on similar guidelines. Equipment may also be developed to safely augment human strength to counteract the effects of the suit.

8.4 REFERENCES

1 Astronaut Selection Criteria. Available in abbreviated form on the public Web site: http://spaceflight.nasa.gov/shuttle/reference/factsheets/asseltrn.html.

2 Internal document, unavailable; contact authors for information.

3 Morgan D, Wilmington, R, Pandya, A, Maida, J and Demel, K. Report No. NASA-TP-3613, "Comparison of extravehicular mobility unit suited and unsuited isolated joint strength measurements." 1996.

4 Pandya A, Maida J, Aldridge A, Hasson S and Woolford B. Report No. NASA-TP-3206, "The validation of a human force model to predict dynamic forces resulting from multi-joint motions." 1992a.

5 Pandya A, Maida J, Aldridge A, Hasson S and Woolford B. Report No. NASA-TP-3207, "Correlation and prediction of dynamic human isolated joint strength from lean body mass." 1992b.

6 Booher, C. "Man-Systems Integration Standards, NASA-STANDARD-3000." 1992. Available at the NASA Web site http://standards/msfc.nasa.gov/default.htm.

9 CREW ACCOMMODATIONS

The best exposition of design considerations for crew accommodations is found in the chapter on crew accommodations in Stilwell, et al.[1] The mass and value factors presented here and used in the resource model (see Appendix D for complete instructions) are taken directly from the resource model described in that chapter.

9.1 KEY CONCEPTS

- **Crew accommodations**: Those elements of mission supplies, hardware, and software that most directly serve human needs throughout every phase of a mission, including:
  - Galley, food system, and wardroom;
  - Sleep accommodations and crew quarters;
  - Personal hygiene facilities;
  - Clothing systems;
  - CHeCS;
  - Emergency provisions;
  - Recreation equipment;
  - Maintenance equipment;
  - Housekeeping and waste disposal;
  - Photographic equipment; and
  - Restraints and mobility aids.
- **Potable water**: Water required for drinking, food preparation (typically food rehydration in prior missions), and oral hygiene. Potable water is subject to the most stringent requirements for contamination because it is to be ingested by the crew.
- **Hygiene water**: Water primarily for external use, such as body cleansing, with similar—but slightly less stringent—requirements for contamination.

9.2 RESOURCE MODEL

We have adapted the crew accommodations resource model found in the above-referenced chapter[1] by creating an Excel spreadsheet that permits the user to make mission-specific calculations and comparisons of mass and volume requirements for 11 systems. ***We will provide detailed instructions for using this model in Appendix D and encourage everyone to use it.***

The greatest value of this model is that it relies on a comprehensive set of baseline assumptions for crew needs, depending on the mission type selected:

- **Shuttle-like mission**: Generally a short, 2-week mission with little need for self-sufficiency.
- **Station-like mission**: An approximately 3-month or more mission that can take advantage of Earth resupply and proximity but could benefit from some self-sufficiency.
- **Lunar base**: Expected to last about 6 months to 1 year, where moderate self-sufficiency is needed.
- **Mars habitation module**: Occupied for an extended period of time of 6 to 8 months in transit and up to about 2 years on the surface, where considerable self-sufficiency is required.

Although these mission types are used to make all calculations for the model, the user can easily adjust specific factors to best approximate the mission design under consideration.

For example, an exploration or habitation mission will almost certainly require a clothes washer and dryer. Supplying complete sets of clothes for the duration of a mission, as we do in current space missions, is not feasible. By default, this model assumes a washer/dryer system is not appropriate for Shuttle- or ISS-like missions, but the clothing mass for lunar/Mars missions assumes cleaning and reuse of clothing. The baseline assumptions for each mission type are just that—assumptions. Certainly, there are some good reasons for including a clothes washer/dryer for an ISS-like mission. The goal of this spreadsheet is to allow users to accurately explore trades in crew accommodations.

9.3 WATER, FOOD, AND FOOD PACKAGING

Water

Water provisions are divided into potable (ingestible) and hygiene water. Potable water is used for drinking, food preparation (typically food rehydration in prior missions), and oral hygiene. Hygiene water is primarily for external use, such as body cleansing, and as with the potable water, cannot be contaminated with high-levels of contaminants. Table 9.1 summarizes the amount of water allotted per crewmember per day for different operational states.

Table 9.1: Summary of Water Consumption per Crewmember for Different Operational States

Type of Water	Operation States	Water Consumed per Crewmember per Day
Potable	Nominal	5.16 kg (11.35 lbs)
Potable	Off-nominal or otherwise degraded	2.84 kg (6.26 lbs)
Hygiene	Nominal	23.4 kg (51.59 lbs)
Hygiene	Off-nominal	8.18 kg (18.03 lbs)
Hygiene	Degraded	5.45 kg (12.02 lbs)

Water temperature is another important factor because of its food, cleansing, and drinking uses. The water system must be able to provide potable water in the following temperature ranges:

- Cold water at 4 °C ± 3 °C (40 °F ± 5 °F);
- Ambient water at 21 °C ± 5 °C (70 °F ± 10 °F); and
- Hot water up to 65.6 °C (150 °F).

Crew hygiene water temperature must be adjustable from 21 °C (70 °F) to 45 °C (113 °F).

Energy Requirements

The energy requirements of the crew will depend on the individual needs of the crewmembers, their lean body mass, and the amount of physical work they are to perform. Crewmembers who frequently conduct EVAs, for example, will require more food than crewmembers who do not conduct EVAs since more demanding physical work is typically associated with an EVA.

The caloric requirements for an exploration-class food system are calculated based on the World Health Organization's (WHO's) requirements,[10] provided below, for the 1g environment found on Earth. Unfortunately, caloric requirements for any hypogravity environment are not known, and the activity level of future missions may exceed those assumed by the WHO guidelines.

- **Men** (30 to 60 years): Activity (1.7) * (11.6 W + 879) = kcal/day required
- **Women** (30 to 60 years): Activity (1.6) * (8.7 W + 829) = kcal/day required

where W = mass (kg) and the activity level is assumed to be medium, ranging from 1.0 to 2.0.

Assuming an average body mass of 70 kg, the WHO model estimates an individual would need a caloric intake of 10.834 MJ a day.

Food System Mass

The mass of a food system will depend heavily on the food's degree of hydration, which is largely a function of the type of food chosen and the method of storage. Fresh foods can contain as much as 95% water, while dry foods (grains) can contain as little as 12% water. We have provided additional information regarding food mass in Tables 9.2 and 9.3.

Table 9.2: Historical, Near-term Food Masses [a]

Parameter	Mass (kg/CD)	Water Content	Volume (m^3/CD)	Comments
Intravehicular activity (IVA) food, dry weight	0.674	0%		
Food provided for Shuttle [b]	0.8	20%	0.002558	Dehydrated
	1.818		0.004045	Packaged, with water content
	0.227			Packaging alone
	1.591	58%		Fresh, no packaging
Food provided for ISS [c]	2.3		0.006570	Packaged, with water content
	1.955	66%		Fresh, no packaging

NOTE: CD: crew day (based on 6 crewmembers) and IVA.

[a] Data based on Bourland (1998) and Vodovotz (1999).

[b] Shuttle food systems do not meet nutritional requirements estimated for long-duration spaceflight. While the diet meets all minimum nutritional requirements, it exceeds the limit for sodium and iron for a microgravity diet. Note that the Shuttle food system does not use refrigeration.

[c] Data provided are based on an ISS assembly-complete diet. Food is provided as 50% frozen products. For a 540-CD (six crewmembers for 90 days) food supply, 1.84 m^3 of refrigerated storage is required.

Table 9.3: Food Quantity and Packaging [a]

Parameter	Assumptions			Source
	Lower	Nominal	Upper	
IVA, dry weight (kg/CD)	0.54			Lange and Lin (1998)
		0.674		Bourland (1998)
IVA human metabolic water production (kg/CD)		0.335		Derived from Lange and Lin (1998)
IVA (MJ/CD)		11.72		Hall and Vodovotz (1999)
EVA added [b] (kg/Y)		+0.026		Derived from Lange and Lin (1998)
EVA added [b] metabolic water production [kg/Y]		+0.016		Derived from Lange and Lin (1998)
EVA added [b] (MJ/crew hour (CH))		+0.563		Lange and Lin (1998)
Packaging [c] (kg/kg)		100%		Hanford (1997a)
Crew time (CH/d)	1			Lane (1999), from Shuttle
		3		Hunter (1999); see above
			9	Kloeris et al. (1998) from Lunar-Mars Life Support Test Project (LMLSTP) Phase III data

CD; CH (based on six crewmembers).

[a] The listed food values are "as shipped" and before the addition of any hydration fluid (water).

[b] EVA requirements are in addition to any IVA requirements.

[c] Packaging accounts for individual food packages, trays, food storage lockers, and other associated secondary structures.

In addition to the mass of the food itself, packaging is required to protect the food from degradation and contamination. This packaging includes exterior food wrappings, which may divide foods into individual servings, stowage containers—such as lockers—and secondary structures to house the stowage. In total, these can easily double the mass of the food system.

Historically, packaging masses are available for two applicable food systems. An empty food locker on board the Shuttle has a mass of 6.4 kg (14 lbs). Filled, this locker holds up to 42 individual meals for an overall mass of

24.5 kg (54 lbs) (Bourland, 1999). Perchonok (2002) reports that a loaded ISS food locker for Phase II averages 5.5 kg each and contains nine meals with snacks (equivalent to 1 day of food for three ISS crewmembers). For a 1000-day, six-person Mars mission, assuming a 10:1 vehicle-to-payload ratio, food packing would add 3 metric tons to the 30 metric tons of vehicle and fuel in the initial mass in LEO.

Although waste will depend on the type of food and preparation used, the waste mass could be quite large. For example, during the 10-day menu test conducted for the LMLSTP Phase III, total food waste—including preparation, plate waste, and unused food—was 42% of all waste.[6]

The equipment mass needed to process food for four crewmembers is estimated to be about 655 kg (1,444 lbs).[4] This is a very preliminary estimate, however.

Transit Portions

The journey between Earth and Mars is approximately 6 to 8 months each way. Assuming that the food items provided for this journey will be shelf-stable, prepackaged foods resembling ISS provisions, the mass of food per crewmember will be about 1.83 kg (4 lbs) a day.

Assuming six crewmembers and a transit time of 225 days, approximately 2.5 metric tons of prepackaged food will be required for a single transit between Earth and Mars. If we also assume a 10:1 vehicle-to-payload ratio, food will increase the mass of the transit vehicle, including fuel, by about 25 metric tons. Clearly therefore, considerable overall mission-mass savings can result from finding ways to reduce the mass of the food system.

Plants, which offer the greatest opportunity for self-sufficiency and, possibly, cost reduction for long-duration missions, also pose some of the greatest unknowns.

Future Directions for Food Systems

As planning for human exploration missions beyond LEO evolves, new technologies in food science and food processing will be necessary. Because an exploration crew will not have access to regular resupply, a complete 3-year diet for six crewmembers must be included as part of the mission specifications. Some technologies that will be important for such future missions beyond LEO are described below.

The food system model described previously is only one system that might be proposed for a Mars mission. Any food system would have the following basic requirements:

- **Prevention of microbial contamination**: Microbes adversely affect food safety and quality, producing changes in freshness, color, texture, and flavor. Therefore, the food system must be free of disease-causing and quality-affecting microbes, including yeasts, fungi, molds, protozoa, bacteria, viruses, and other organisms.

- **Adequate nutrition for each crewmember**: Calorie intake requirements will vary from crewmember to crewmember, and will be affected by the amount of physical work each crewmember performs. For example, a crewmember must consume more food to meet the physical demands of EVAs. As we better understand the effect of long-duration space missions on crew health, the recommended nutrient levels may be revised.

- **Food quality**: This parameter can have a tremendous impact on crew morale and performance, which requires a highly acceptable and varied system.

These requirements cannot be met without additional research, however. For example, the first requirement —that the food system be free of microbial contamination—may not be possible in all circumstances. Shelf-stable items that have been vacuum-packaged in plastic and irradiated will remain microbe-free indefinitely, but a diet that is composed of such foods would be nutritionally incomplete if not augmented by fresh items. Hence, many mission designers have proposed that ultra-long-duration missions, which cannot rely on resupply of fresh foods from Earth, should include one or more growth chambers for plants that will provide foods that cannot be made shelf-stable or that contain important nutrients that do not survive processing or storage. But the warm, moist, nutrient-rich environment of growth chambers also encourages microbial growth and variety. Due to depressed immune system function, which is a response to space travel, and the increased rate of microbial mutation, which may result from the unique radiation environment, we cannot be certain that "farming in space" will not engender both plant and human diseases and adversely affect the safety of the expanded ecosystem. (This is a general concern, but some evidence suggests that human-associated organisms would not compete well with the stable microflora of these systems and, hence, the systems would not be significant reservoirs of these organisms.[12])

The requirement for adequate nutrition may also prove challenging. It is almost certain that shelf-stable items will not provide sufficient nutrition alone to adequately support the crew on an ultra-long-duration mission beyond LEO. Supplements would help supply nutrients that are not provided by shelf-stable food, but there is no guarantee that an augmented diet would provide important micronutrients. Frozen food is an attractive supplementary food item, but the mass of a passive freezer and the amount of frozen food required for an ultra-long-duration mission may be prohibitive. Additionally, frozen food that is stored at commercial temperatures is only palatable for about a year. Salad components cultivated in a growth chamber would be an excellent food supplement, but they would also add significant mass to a mission. Because the consequences of crop or seed failure—or even the destruction of a frozen foods due to freezer failure—would be catastrophic, mission designers cannot rely exclusively on crops or food refrigeration. A complete set of shelf-stable food would therefore need to be packed in the event of the failure of other food sources. Considerably more in-flight experience with these methods of provisioning is required before crewmembers can depend on such methods for core nutritional needs. It would also be unreasonable to expect that, within the next half century, the addition of necessary “space farming” equipment and supplies would reduce mission mass significantly.

Ultra-long-duration, Shelf-stable Foods

Shelf-stable foods that use high-quality, palatable ingredients are important to maintaining a healthy crew diet throughout a long-duration mission. Currently, we have no ability to store a varied and acceptable diet for 3 to 5 years, as would be required by Mars mission scenarios. All new food items developed for long-duration missions should be low in sodium and derive less than 35% of total calories from fat. Although breads and a few other food items can be made with very long shelf lives, a large variety of foods in a balanced diet currently falls far short of the mark. New and emerging food-preservation technologies and/or packaging methods, such as those listed below, may extend food shelf life:

- irradiation;
- sonication;
- electromagnetism;
- pressurization;
- chemical additives;
- biotechnology;
- microbial sources
- pulsed light;
- dehydration;
- special packaging; and
- freezing.

The treatments used must be food-specific, due to individual differences in food composition and mode of spoiling. Food palatability and variety also require improvement. If crewmembers find the food unpalatable, they may consume inadequate amounts of nutrients and, as a result, suffer from poor health or morale.

Advanced Packaging for Food Storage and Preparation

The galleys on the Shuttle and ISS account for about 75% of the trash produced during a mission; and about 50% of trash dry mass (about 0.5 kg per crewmember every day) comes from the plastic packages for individually wrapped meals. Approximately 25% of the mass of individually packaged food rations is packaging material that is neither biodegradable nor recyclable. Waste packaging from the Shuttle is returned to Earth for disposal, and waste packaging from the ISS is incinerated upon reentry of a spent Progress vehicle into Earth’s atmosphere. Since these disposal options would not be possible during exploration missions, a serious waste management problem would result. One solution is to develop new food-packaging technologies that use biodegradable or readily recyclable materials and yet still allow for the food items to achieve a 3- to 5-year shelf life.

Theoretically, the waste stream coming from the galley could be reduced to near zero if waste products could be transformed into objects that would be useful later in a mission. This would also have the net effect of eliminating the need to carry those objects on board the spacecraft. On the outbound trip, for example, plastic packaging materials could be redissolved or remelted and then molded into “Erector set”-like components that could be used to construct tables, chairs, and other items that have little use in microgravity but would be useful on Mars. Holding racks, sample containers, rover parts, and geological tools—essentially any item of use on a lunar or a planetary surface—could be manufactured from recycled materials. As a result, the mass of an intravehicular maintenance system (IMS), which would normally be stocked with a veritable hardware store of supplies, could be reduced if replacement items such as pipes, connectors, and mechanical patch materials could be produced with recycled materials during the mission. Even if the recycling process was only partially successful, decreasing the amount of unusable waste as well as decreasing the size of the systems used to process and store that waste could easily reduce the overall vehicle mass by many metric tons.

Another solution is to create larger, crew-sized packages. The quantity of trash would decrease, minimizing the need for onboard trash storage and treatment facilities and reducing the burden on downstream support systems. Additional advantages of family-style dining could include a decrease in the amount of food required per person by reducing food waste and making better use of leftovers. Larger-sized meals are not currently being used because researchers have not found a way to transfer food from larger pouches to individual food holders in 0g. Any new packaging design would need to be thoroughly tested on the Shuttle or the ISS before it could be incorporated into a future beyond-LEO mission. Assuming that we will eventually develop “family-style” dining techniques and instruments, the whole galley concept and all of its hardware must be changed to take full advantage of “family-style” dining. Ovens, dishwashers, bulk storage, cooking and eating utensils and containers, and refrigerators and freezers must be redesigned to accommodate the larger packages.

9.4 GROWTH CHAMBERS

Fresh salad crops grown during a long-duration mission would provide variety, texture, and color to an otherwise dull diet. Crewmembers would realize both nutritional and psychological benefits from consuming salad crops. Researchers are developing an advanced life support system for future missions that would hydroponically grow crops and process them into edible food ingredients or table-ready products.

The processing equipment for such a system should be highly automated, reliable, and safe; and it also should minimize crew time, power, water, mass, and volume. The equipment must be suitable for use in 0g or hypogravity (e.g., 0.38g on Mars) as well as in hermetically sealed habitats.

The stay on Mars will be approximately 600 days. A plant chamber for growing food could be housed in full racks such as those already used on the ISS. As the crops mature, the rack would supply ingredients that would supplement the core diet of prepackaged foods. In addition to providing nutrition, such a system might benefit air and water recycling as well as waste removal.

In the distant future, a Mars base or another ultra-long-duration facility could allow a stay of 5 to 10 years. A multitude of plants could be grown at such a base, but more than half of the diet would still likely rely on shelf-stable foods. The food system would use food-processing procedures and equipment to convert crops to bulk ingredients. These food products could be stored or used immediately, thereby augmenting ingredients supplied from Earth. The risks and sustainability of crop systems for life support are still largely unknown, and we need continued testing with crops as supplementary dietary items before relying on in-situ farming to provide a primary food source. If successful, such a system could produce mass savings over 5 to 10 years.

Mars colonization, with a stay of more than 10 years, may rely primarily on plants grown in situ for the majority of the diet (approximately 90% of the food, by dry mass). The mass of farm equipment and growth facilities required to create such a self-sufficient base, and that will operate without the danger of crop disease or failures, is currently unknown. Such a food system would be integrated with the air revitalization, water recovery, biomass, solid processing, and thermal control systems. System designers will need to consider the availability of power, volume, and water as they develop the entire food system.

Hypothetical Diets for Long Durations

Tables 8.3 and 8.4 present diets that assume differing availability of crops grown at the site of a base or colony. In both cases, the menus are designed to be used as a unit for meeting the crew’s nutritional needs.

NASA’s Advanced Life Support Program proposes a 20-day crew diet using crops as shown in Table 9.4. The edible masses of the main crops, which will be harvested to support the 20-day diet, are calculated per CD and for a crew of six people for 20 days. This menu averages roughly 11.72 megajoules per crew day (MJ/CD), uses a wide variety of crops, and provides a high degree of closure. With respect to closure, the majority of the resupply mass is oil—a substance that is necessary for nutrition but is not produced efficiently from higher crops.

Table 9.4: Twenty-Day Diet Using All Potential Food Crops [a]

Crop	**Average Consumption** (kg/CD)	**Menu Consumption** (kg) [b]
Soybean	0.086	10.4
Wheat	0.24	28.8
White potato	0.20	24.2
Sweet potato	0.20	23.7
Rice	0.029	3.5
Peanut	0.013	1.5
Tomato	0.22	26.6
Carrot	0.041	5.0
Cabbage	0.0038	0.5
Lettuce	0.024	2.9
Dry bean	0.013	1.5
Celery	0.013	1.5
Green onion	0.048	5.7
Strawberry	0.016	2.0
Pepper	0.049	5.9
Pea	0.0075	0.9
Mushroom	0.0011	0.1
Snap bean	0.010	1.2
Spinach	0.040	4.8
Crop subtotal	1.25	150.7
Water [c]	2.20	263.3
Resupplied foodstuffs [d]	0.37	44.6
Total	3.82	458.6

NOTE: CD (based on one crewmember).

[a] The listed food values are "as shipped" and before the addition of any hydration fluid (water). Derived from Hall and Vodovotz (1999).

[b] Quantity is based on six crewmembers over 20 days.

[c] Water data are for hydration, cooking, and food preparation only. Water for cleanup and water tankage is not included.

[d] Oil is included as a resupply item. No frozen or refrigerated foods or packaging are included in this calculation. Resupplied food is about 20% moisture by mass.

A second 20-day crew diet is shown in Table 9.5. Again the edible masses of the main crops, as harvested to support the 20-day diet, are calculated per CD for a crew of six people for 20 days. This menu also averages 11.72 MJ/CD. Unlike the previous formulation, the diet plan in Table 9.5 produces only salad and carbohydrate crops on site, because these crops are the most efficient of the higher plants considered here. Most protein is primarily resupplied in the form of shelf-stable meat.

Table 9.5: Twenty-Day Diet Using Salad and Carbohydrate Crops [a]

Crop	Average Consumption (kg/CD)	Menu Consumption (kg)[b]
Soybean	n/a	n/a
Wheat	0.22	25.8
White potato	0.17	19.8
Sweet potato	0.18	21.5
Rice	n/a	n/a
Peanut	n/a	n/a
Tomato	0.21	24.6
Carrot	0.040	4.8
Cabbage	0.0025	0.3
Lettuce	0.021	2.6
Dry bean	0.013	1.5
Celery	0.0075	0.9
Green onion	0.034	4.1
Strawberry	n/a	n/a
Pepper	0.031	3.8
Pea	0.0038	0.5
Mushroom	0.0013	0.2
Snap bean	0.010	1.2
Spinach	0.040	4.8
Crop subtotal	1.0	116.4
Water [c]	2.1	253.7
Resupplied foodstuffs [d]	0.5	57.5
Total	3.6	427.6

NOTE: CD (based on one crewmember).

[a] The listed food values are “as shipped” and before the addition of any hydration fluid (water). Derived from Hall and Vodovotz (1999).

[b] Quantity is based on six crewmembers over 20 days.

[c] Water data is for hydration, cooking, and food preparation only. Water for cleanup and water tankage is not included.

[d] Oil is included as a resupply item. No frozen or refrigerated foods or packaging are included in this calculation. Resupplied food is about 20% moisture by mass.

9.5 WASTE MANAGEMENT

Based on current waste production levels, each crewmember can be expected to produce about 1 kg (2.2 lbs) of dry trash per day, primarily from the use of habitation systems and crew supplies. For a 1000-day, six-person Mars mission, this would come to 6 metric tons of trash in addition to the 60 metric tons of vehicle and fuel for the initial mass in low-Earth orbit (IMLEO), assuming a 10:1 vehicle-to-payload ratio. The waste weight estimates for several mission profiles are provided in Table 9.6.

Table 9.6: Estimated Waste Mass for Different Mission Profiles [a]

Waste Component	**Transit** (180 days)[b]	**Independent Exploration** (600 days)[c]	**Exploration Mission** (600 days)[d]	**Extended Base** (10 years)[e]	**Extended Base** (10 years)[e]
Dry human waste	0.720	0.720	0.720	0.720	0.720
Inedible plant biomass	0.404	1.874	5.507	7.486	13.787
Trash	0.556	0.556	0.556	0.556	0.556
Packaging material	7.908	7.122	5.866	4.341	1.185
Paper	1.164	1.164	1.164	1.164	1.164
Tape	0.246	0.246	0.246	0.246	0.246
Filters	0.326	0.326	0.326	0.326	0.326
Miscellaneous	0.069	0.069	0.069	0.069	0.069
Subtotal	11.390	12.080	14.450	14.910	18.050
Grown food	0.000	1.740	6.000	7.500	14.172
Packaged food	4.044	3.642	3.000	2.220	0.606
Total	15.434	17.462	23.450	24.630	32.828

[a] All units are based on a six-person crew.
[b] Profile is based on a packaged foods diet model.
[c] Profile includes the cultivation of salad crops.
[d] Profile is based on a low-carbohydrate diet model.
[e] Profile is based on an all-plants diet model.
Refer to Appendix B for the details of each waste component.

Solid Waste System Requirements

Table 9.6 provides estimates of types and quantities of waste that must be handled during a variety of mission profiles. Important considerations include:

- Containment and sterilization of wastes;
- High-fidelity systems that will satisfy different constraints of various missions;
- Multifunctional systems that can be used for various missions;
- System models that will identify mission resource recovery needs; and
- Various waste processing subsystem integrated with the water recovery and air revitalization subsystem.

DESIGN CONSIDERATIONS

- **Ease of use**: A bodily-waste management system should be simple and quick to use, as well as readily available for emergencies (e.g., vomiting or diarrhea). As a design goal, the facilities should resemble equivalent Earth-based facilities, and should require approximately the same amount of time to use.
- **Redundancy**: A beyond-LEO mission can be doomed if the bodily-waste management system fails and a functioning alternate, redundant system is unavailable.

Trash Management

A trash management system designed for an ultra-long-duration mission should rely heavily on recycling and reuse. Plastics, which make up the majority of dry waste, could be remolded into a variety of useful items (e.g., air filters, replacement parts, or even basic Erector-set-like components) that could be used to build larger items. Through in-flight and on-surface recycling of trash, it is conservatively possible to reduce the IMLEO of a Mars vehicle by at least 45 metric tons, or about 10% of total vehicle mass, based on a 425-metric-ton vehicle. The possibility of in-flight waste recycling is contingent on additional research into recycling techniques and advanced reusable materials, however. Currently, techniques for recycling in microgravity or reduced gravity have not been developed. Before a trash recycling/reuse system can be incorporated into a future mission design, extensive testing on both potential systems and materials must be conducted on both the Shuttle and the ISS.

Based on a Mars mission profile such as the one described above, approximately 1.5 metric tons of trash will remain unrecoverable. This type of trash also requires a carefully designed management system.

DESIGN CONSIDERATIONS

- **Location of trash receptacles**: Selection and placement of trash receptacles must be based on crew activities. Several small receptacles placed throughout the spacecraft may initially save crew time, but will ultimately cost time if crewmembers must gather trash from the receptacles and transport it to a central receptacle.

- **Separation**: The crew will sometimes have to manually separate biologically active trash (e.g., leftover food) from plastics, metals, and other materials to facilitate the stowage, recycling, or disposal of trash. In some cases, separation will be carried out automatically using equipment—such as dishwashers, clothes washers and dryers, and showers—but crewmembers will still need to clear filters or empty traps.

- **Manipulation**: Every effort should be made to automate trash management. This will not only reduce the amount manual manipulation crewmembers must perform, but it will also reduce the trash volume through compaction.

9.6 PERSONAL HYGIENE

Good grooming can enhance self-image, improve morale, and increase the comfort and productivity of the crew. Personal hygiene includes whole or partial body washing, oral care, and hair cutting, grooming, and shaving. Adequate and comfortable personal hygiene and body-waste management facilities have been high on the list of priorities for participants in prior space missions, but will become even more important during future long-duration missions. The lunar missions conducted in the late 1960s and 1970s were short, but crewmembers were extremely bothered by the lunar dust that was carried into the lunar module. In the absence of a significant atmosphere on the Moon, extremely fine dust was electrostatically attracted to the EVA suits and could not be brushed off. After crewmembers returned to the module and reintroduced air, tiny dust particles fell off their suits and got into everything.

Frequent whole-body cleansing will become a critical part of personal hygiene during future planetary missions if highly effective dust control methods cannot be developed. Terrestrial personal hygiene practices and procedures may require some modifications, due to equipment limitations and water supply restrictions, but the experience should be as simple as possible. Wet wipes are sufficient for whole-body cleansing during short-duration missions, such as the Shuttle, but showers are vital for longer flights. The *Mir* shower had a watertight, rigid wall that surrounded the user and prevented water from leaking into the rest of the cabin. Cosmonauts were allowed 10 liters of water per shower, which were then returned to the water reclamation system for extraction and reuse. Skylab had a soft-walled, collapsible shower that earned a reputation for being so difficult to use and clean that it was rarely used. A rigid-walled shower would therefore be the better choice for a long-duration mission.

Design Considerations

- **Ease and comfort of use**: Ideally, the personal hygiene facility should be as easy to use as a ground-based facility, while still taking into consideration mass restrictions and water reclamation needs. Experience with the Skylab shower design revealed that a personal hygiene facility will be used less frequently if it is awkward and uncomfortable, or if it requires an inordinate amount of time to set up and use.

- **Privacy**: Privacy for partial- and whole-body cleansing, including dressing and undressing, is essential—particularly if the crew is composed of men and women.

- **Microgravity considerations**: Water and debris, such as hair, do not fall to the floor in microgravity as they do on Earth. So water and debris collection poses an engineering and operational problem for crewmembers. For example, taking a shower in microgravity requires a handheld vacuum to remove the buildup of water and soap on the body, particularly near the face. Activities, such as showering, that require relatively little time on Earth can take a lot more time and be far less relaxing in microgravity. This can have a negative impact on mission schedules and personal motivation to use personal hygiene equipment.

- **Restraints**: Crewmembers can exert an inordinate amount of effort and energy stabilizing themselves if restraints are not provided. The restraints should be compatible with the personal hygiene operation and environment. For example, foot restraints used in a whole-body wash facility should not be damaged when exposed to water and should prevent slipping in wet environments.

Clothes and Cleaning Rags

Current LEO missions return soiled garments to Earth for cleaning, and the ISS crews rely on periodic deliveries of fresh clothes. This will not be possible during a beyond-LEO mission. A 1000-day, six-person Mars mission would require at least 2 metric tons of clothing—even if crewmembers wore each garment for a week—if there was no clothes-washing system. This estimated weight does not include the 1350 kg (2976 lbs) of house-cleaning disposable wipes, such as are currently used by the space program, and packaging that would be added to the waste management system. Obviously, an ultra-long-duration mission requires a system for washing and drying both clothes and cleaning rags. Assuming a 10:1 vehicle-to-payload ratio, a cleaning and drying system could save 34 metric tons in overall vehicle mass by reducing the amount of clothing that must be included in the mission and by replacing disposable wipes with reusable, washable cleaning rags.

Design Considerations

A washer/dryer system for use in a microgravity or hypogravity environment does not now exist. A great deal of research and development, followed by significant testing on board the Shuttle and the ISS, must occur before such a system can be incorporated into a beyond-LEO mission. The resulting technology could be considered enabling, however, since it is unlikely that a Mars mission would be undertaken if clothes could not be cleaned en route.

9.7 INTRAVEHICULAR MAINTENANCE SYSTEM

Technologies for system repair are essential both to mission success and to mass and cost reduction. The complexity of a Mars vehicle, the long mission duration, the high probability of equipment failure, the communication distances of up to 20 minutes each way, and the impossibility of resupply all make a complete IMS one of the most critical components of a Mars mission. Similarly, an adequate IMS is also critical for long-duration Moon missions. The IMS should include tools, replacement parts, hoses, wire, connectors, supplies, methods for mocking up integrated circuits (ICs) through programmable ICs, decision-support and expert systems, troubleshooting drawings or procedures, and other electronic tools.

Sizable mass and volume savings can be made by designing a minimal-mass, yet complete, IMS. For example, development and use of ultrasonically cured patching materials and adhesives might reduce the number of pipes, panels, and other replacement parts that would need to be stocked. The ability of crewmembers to manufacture some components during the mission would also reduce mass and cost.

Current state-of-the-art, in-flight maintenance systems are insufficient for a Mars mission. Generally simple tasks—e.g., plumbing and soldering—become more challenging in a microgravity or reduced-gravity environment. A great deal of development and in-flight testing on board the Shuttle and the ISS must be done for materials and techniques before true mass savings from IMS technology can be realized.

Design Considerations

- **Uniform materials**: Repair materials should be carefully selected before vehicle design begins to ensure that uniform materials are used throughout the vehicle, making it easier to replace and manufacture parts during the mission.

- **Expert advice**: Any IMS should be highly usable and as intelligent as possible. The IMS should have a computer interface, or some other intelligent device, that would provide crewmembers with expert advice and guidance for troubleshooting and repairs.

9.8 REFERENCES

1 Stilwell D, Boutros R, and Connolly J. “Chapter 18: Crew Accommodations” in *Human Space Flight: Mission Analysis and Design*. New York: McGraw Hill Companies. 1999.

2 Connors MM. *Living aloft: Human requirements for extended spaceflight.* NASA SP-483. Moffet Field, CA: Ames Research Center. 1985.

[3] Golub M and Wydeven T. Report No. NASA-TM-103888, "Waste Streams in a Typical Crewed Space Habitat: An Update." February 1992.

[4] Hunter J and Drysdale A. "Concepts for Food Processing for Lunar and Planetary Stations," SAE paper 961415, 26th International Conference on Environmental Systems, Society of Automotive Engineers, Warrendale, PA. 1996.

[5] Hunter J. Department of Agricultural and Biological Engineering, Cornell University, Ithaca, New York. Personal communication. May 24, 1999.

[6] Kloeris V, Vodovotz Y, Bye L, Stiller CQ, and Lane E. "Design and Implementation of a Vegetarian Food System for a Closed Chamber Test," *Life Support and Biosphere Science* 5:231-242. 1998.

[7] NASA-STD-3000. *Man-Systems Integration Standards*. Revision B. Houston, TX: Johnson Space Center. July 1995.

[8] Stuster J. *Bold Endeavors: Lessons from Polar and Space Exploration.* Annapolis, MD: Naval Institute Press. 1996.

[9] Vodovotz Y, Bourland C, and Rappole C. SAE Paper No. 972363, "Advanced Life Support Food Development: A New Challenge." Presented at the 26th International Conference on Environmental Systems. 1997.

[10] World Health Organization (WHO). "Energy and Protein Requirements." *Technical Report Series 724, Report of a Joint FAO/WHO/UNU Expert Consultation.* Geneva: World Health Organization. 1985.

[11] Wydeven T. Report No. NASA-TM-84368, "Composition and Analysis of a Model Waste for a CELSS." September 1983.

[12] Morlaes A, Garland J, and Sim D. "Survival of potentially pathogenic human associated bacteria in the rhizoshpere of hydroponically grown wheat." *FEMS Microbial Ecology* 20:155-162. 1996.

[13] Bourland CT. "Advances in food systems for space flight." *Life Support Biosph Sci* 1998;5(1):71-7.

[14] Vodovotz Y, Bourland C, Kloeris V, Lane H, Smith SM. "Critical path plan for food and nutrition research required for planetary exploration missions." *Hum Perf Extrem Environ* 1999 Oct;4(2):56-9.

[15] Lange and Lin (1998): Lange, K. E., and Lin, C. H. (1998) "Advanced Life Support Program: Requirements Definition and Design Consideration." Lyndon B. Johnson Space Center, Houston, Texas. Internal document. Available to JSC users only.

[16] Hall, P., and Vodovotz, Y. Lyndon B. Johnson Space Center, Houston, Texas. Personal communication, 10 May 1999.

[17] Hanford, A. J. (1997a) "Advanced Regenerative Life Support System Study." Lyndon B. Johnson Space Center, Houston, Texas. Internal document. Available to JSC users only.

[18] Stein TP, Leskiw MJ, Schluter MD, Hoyt RW, Lane HW, Gretebeck RE, LeBlanc AD. "Energy expenditure and balance during spaceflight on the space shuttle." *Am J Physiol* 1999 Jun;276(6 Pt 2):R1739-48.

[19] Hunter, J. (1999) Department of Agricultural and Biological Engineering, Cornell University, Ithaca, New York. Personal communication, 24 May 1999.

[20] Kloeris V, Vodovotz Y, Bye L, Stiller CQ, Lane E. "Design and implementation of a vegetarian food system for a closed chamber test." *Life Support Biosph Sci* 1998;5(2):231-42.

[21] Perchonok M, Bourland C. "NASA food systems: past, present, and future." *Nutrition* 2002 Oct;18(10):913-20.

10 ARCHITECTURE AND HABITABILITY

The following description of facilities addresses specific considerations for designing and configuring the human-rated spacecraft or habitat. General issues concern how much volume to devote to each function, where to place the facility, and how to demarcate functional areas within a limited pressurized volume. At present, we do not fully understand the amounts and types of space required for an exploration crew (likely composed of international members) that will be confined together for long-duration missions. These factors are also looked at, in some detail, in Chapter 9 on Crew Accommodations.

10.1 KEY CONCEPTS

The architecture of any spacecraft must address the following needs and considerations, a number of which are described below. To begin with, several functions/facilities must be defined including:

- work areas,
- "public" recreational areas that are shared by the entire crew, and
- individual crew private areas.

Architecture must also consider crew privacy and the need for personal space, especially given the public nature of a long-duration exploration mission. This design aspect relates to personal volume, the ability to control or personalize space with family photographs, books, tapes, and the need for private time during communications with family and flight surgeons. (We have addressed this further in Chapter 9 on Crew Accommodations, section 9.7.) Individual privacy needs are also determined by individual characteristics and culture. Given volume constraints, it is more efficient to provide only shared interior space; but private space becomes more important as mission duration increases. So facilities to meet the need for individual privacy and public interaction should be balanced.

10.2 OVERARCHING ISSUES

Any system design should be based on the smooth flow and logical sequence of activities. The most efficient layout is usually to place crew stations adjacent to each other, when they are used sequentially, or in close coordination. However, adjacent positions might cause two crewmembers to get in each other's way, thereby degrading their performance and possibly preventing their safe egress during emergencies. Attention needs to be given to the volume of traffic expected in any given area.

Activities such as communications, sleeping and rest, and mental concentration are adversely affected by noise (see Chapter 11 on Crew Environment, Section 11.2). Clearly, therefore, activity centers that generate significant noise levels should not be placed adjacent to centers adversely affected by noise.

Ambient illumination may interfere with activities in an adjacent area. Some areas, such as windows used for outside viewing and crew quarters during sleep hours, are dimly illuminated. These areas should be placed away from those requiring bright illumination, or light-blocking barriers should be provided to separate areas.

Vibrations and jolts disturb personal activities such as relaxation and sleep. Crew areas requiring a quiescent environment should be isolated from sources of vibration.

10.3 TOTAL HABITABLE SPACE

There is currently no method to determine, with absolute certainty, the amount of habitable space needed per crewmember for missions beyond LEO.

> ***Until better data are available, designers should plan on allocating a minimum of 16.99 m^3 (600 ft^3) of usable space per crewmember.***

Hatches and Doors

- **User size**: The size of the hatch and door opening should accommodate the largest crewmember, plus any equipment to be transported.

- **Suited crewmembers**: Internal doors are normally only used by unsuited IVA crewmembers. In some cases, however, passages and doorways must be large enough to accommodate a suited EVA crewmember.

- **Traffic considerations**: Internal doors and hatches are points of potential traffic congestion. Special attention should be given to the placement of doors and hatches to help avoid this problem.

Windows

- **Glare, dark adaptation, and light-sensitive activities**: Bright interior illumination could reflect from window surfaces and degrade visibility. It could also interfere with the dark adaptation necessary for celestial viewing. Similarly, exterior light through windows could interfere with light-sensitive activities, such as sleeping, use of cathode ray tube displays, or tasks requiring dark adaptation. Interior and exterior light-control devices, special window materials, and careful placement of windows throughout the spacecraft or habitat are ways to avoid these problems.

IVA Mobility Aids

- **Method of use**: Previous experience has shown that mobility aids, such as handrails, are not used for hand-over-hand translation. They are instead used primarily to control body orientation, speed, and stability. After crewmembers gain confidence in free-flight translation, they mainly use fixed-mobility aids at free-flight terminal points or while changing direction. Padding or kick surfaces should therefore be considered at free-flight terminal points.

- **Use in emergencies**: IVA mobility aids may have to be used by space-suited crewmembers during emergency conditions. Therefore, the aids should be located to accommodate bulky garments with reduced joint movement and clearance. (Refer to Chapter 3 on Human-Rated Vehicle Requirements, section 3.4, and Chapter 10 on Architecture and Habitability, section 10.3, for related information.)

- **Operator stability**: Restraints should be available around workstations where the operator must remain stable or must use two hands to performance certain tasks (e.g., viewing through an eyepiece, operating a keyboard, or repairing a circuit).

Interior Decor

- **Personalization**: The ability of crewmembers to personalize certain portions of their environment can boost morale. This option should be limited to the individual's personal quarters, however. A simple way to personalize quarters is a bulletin board on which a crewmember could display photos or other memorabilia.

Orientation and Layout

In a 1g or hypogravity environment, the orientation of objects within an area is not a particular problem. The pull of gravity determines how we position our bodies. We orient our surroundings based on our perception of up and down. In microgravity, where gravity and acceleration are imperceptible, orientation becomes arbitrary. No gravity cue defines up or down, and orientation is defined primarily through visual cues that are controlled by the system designer. The orientation within a particular crew station is referred to as a local vertical. Several orientation factors should be considered when designing for the microgravity environment, including:

- **Work surfaces**: Microgravity expands the number of possible work surfaces (walls, ceilings, and floors) within a given volume. This could result in a number of different local verticals within a module.

- **Training and testing**: Some of the working arrangements that will occur in microgravity will not be easily duplicated on Earth. Pre-mission training and testing will not fully prepare crewmembers for what they will face in flight. Facilities and equipment will be necessary to conduct additional training during a mission. (See Chapter 15 on Planning for Human Operations, section 15.1 for further consideration of training needs.)

- **Disorientation**: We are accustomed to forming mental images of our environment with a consistent orientation derived from gravitational cues. We locate ourselves and objects according to these mental images. If we view the environment in an unusual orientation, our mental images are not supported. This makes us disoriented, causes us to temporarily lose our sense of direction, decreases our overall performance, and, in the case of spaceflight, may engender SMS.

Visual cues are needed to help crewmembers quickly orient themselves and create a more familiar view of the world. These visual cues, such as the edges of a window, should define some sort of horizontal or vertical reference plane. (Of the two, a horizontal cue is more effective.) Further research is presently being conducted by NASA to determine additional guidelines for the design of visual-orientation cues.

10.4 CREW QUARTERS

The design and layout of private activity and sleeping quarters for an individual crewmember can significantly affect the crewmember's quality of life:

- **Mission duration and privacy**: As missions become longer, the need for privacy increases—as does the space required for each crewmember. The need for privacy is determined by individual and cultural factors. The level of introversion or extroversion is an individual trait. While privacy is a culturally universal need, cultures vary in how private space is implemented or in expectations of privacy. The need for privacy becomes more pronounced for all crewmembers as missions become longer, particularly if crewmembers must endure a confined spacecraft or habitat.

"Hot-bunking," where crewmembers sequentially occupy the same sleep space, should be avoided—even though the practice might reduce the overall mass and volume of a spacecraft or habitat. Each crewmember needs to have at least some individual space, and there will be times when all crewmembers might simultaneously need to take some time off or to sleep.

Depending on the design, dormitory sleeping arrangements might be acceptable if individual bunks can be created and used as places of retreat.

- **Communications**: A two-way audio, visual, and data communications system must be provided between the crew quarters and other module areas. The system must also adequately alert occupants in crew quarters of emergency situations.

- **Environmental controls**: Individual lighting, ventilation, and temperature controls need to be provided in crew quarters. These controls should be adjustable from the bed.

- **Noise control**: The noise-dampening systems in crew quarters must meet all requirements described in Chapter 11, Crew Environment, section 11.2.

- **Compartment size**: Without additional research, the amount of dedicated, private volume that needs to be assigned for each crew quarters during long-duration missions cannot be definitely determined. The internal dimensions should be sufficient to comfortably accommodate the largest crewmember, however.

For conceptual designs, the following should be considered as minimums:

- ***1.50 m^3 (53 ft^3) for sleeping;***
- ***0.63 m^3 (22 ft^3) for stowage of operational and personal equipment; and***
- ***1.19 m^3 (42 ft^3) for donning and doffing clothing.***

These volumes do not include the crew quarters structures or the additional space needed for a desk, a computer and communications system, trash stowage, personal grooming, medical equipment and supplies required for convalescence, and an area for off-duty activities.

10.5 GALLEY AND WARDROOM

Meals can considerably enhance the quality of crewmembers' lives. In addition to satisfying nutritional needs, mealtimes can offer a chance to rest and socialize, while also providing a familiar reminder of normal Earth living. The social benefits of sharing a meal are significant. Researchers suggest that crewmembers should plan to eat at least one meal a day together to maintain group cohesion.

Design Considerations

- **Food consumption locations**: Ideally, it should be possible to consume food virtually anywhere in the habitat without undue difficulty. Work schedules and other pressures may make it desirable to eat while engaged in various work activities. However, having a comfortable group dining space—called a wardroom in Navy and space applications—is very important for ultra-long-duration missions. To reduce overall spacecraft mass and volume, a wardroom does not need to be a separate, dedicated room. It can also double as a conference room or as another group activity space.

- **Restraints**: Restraints need to be provided for crewmembers, food, utensils, cooking equipment, and other loose items in the galley and wardroom.

- **Cleaning**: Surfaces in the galley and wardroom must be fully accessible for cleaning and sanitation, and the surface texture should be easy to wipe clean. Permanent bactericidal surface coatings have been developed in recent years. Further research should be done to determine whether these recently developed, permanent bactericidal surface coatings will be useful in the space environment.

10.6 EXERCISE FACILITIES

A well-outfitted facility for exercise is needed to combat the harmful effects of microgravity or hypogravity on the human body. Exercise also provides recreation and helps to maintain crew morale. Exercise facilities should include strength-training equipment that will provide the muscle enhancement and increased-strength benefits of weightlifting, and different types of aerobic exercise equipment, to increase cardiovascular strength and capacity.

Design Considerations

- **Vibration and noise**: Most exercise equipment is noisy and causes vibration. It should therefore be isolated from the crew quarters, science and spacecraft systems, and instruments affected by vibration.

- **Potable water dispenser**: Drinking water that has been cooled below ambient temperature should be readily available during exercise.

- **Cooling**: Perspiration does not drip from the body in microgravity, but rather pools on the body or floats into the atmosphere. In 1g, convection causes warm air around the body to rise, but in microgravity this will not occur. Adequate airflow is the most effective means of cooling in 0g. Absorbent clothing and other techniques can also help control perspiration.

10.7 RECREATION FACILITIES

As crewmembers travel far from Earth on ultra-long-duration missions, they will need generous amounts of time for recreation. Although the fast-paced Shuttle mission may be scripted almost down to the minute, long-duration crewmembers cannot keep up a high level of work for many months or years at a time without ample opportunities to relax. One of the favorite recreations in prior space missions has been gazing out of the window at Earth, but this may be less interesting given the stark interplanetary space or the bleak surface of a planet. A generous supply of recreational items for individual and group entertainment—e.g., games, books, music, and audio-visual materials—is necessary.

Photographic Equipment

Since the first human spaceflights, crewmembers have recorded their experiences in space—from Earth and Moon observations to daily in-flight activities. These videos, movies, and photographs transmitted or returned to Earth are the public's most obvious return on their investment in the space program. Many crewmembers also find photography an enjoyable pastime. Future beyond-LEO exploration missions will probably include high-speed, high-resolution video and still digital cameras, allowing the images to be rapidly transmitted back to Earth.

10.8 STOWAGE FACILITIES

Stowage difficulties have plagued many LEO flights due to sheer mass and the logistics required to inventory and locate stowed items. Facilities can be located at particular crew workstations, ready for immediate use, or kept in a separate stowage area apart from normally occupied areas.

The Shuttle-*Mir* Phase I Program demonstrated the difficulty of finding little-used items, such as tools, written procedures, and supplies. A method for tracking the location and status (e.g., health and functional state) of these items, such as by embedding a small microchip with an integral micro-transmitter, may help crewmembers locate them, thus preventing failures from propagating from system to system while the missing item is sought.

Design Considerations

In most cases, items should be stored in an area that is as close as possible to where the items are used. There are cases, however, when this would be impractical. A central storage point can make inventory tracking a simpler task, while also maximizing the space allotted for stowage. A combination of techniques is probably best. For example, food for a day's meals might be stored in a galley pantry, but the bulk of food supply might be stored in a central facility. Considerations for the IMS are addressed in Chapter 9 on Crew Accommodations, section 9.7).

11 CREW ENVIRONMENT

11.1 KEY CONCEPTS

- **Noise criteria** (NC): Rating of ambient noise that typically represents as a family of curves. NC was developed to quantify how room noise affects speech communications.
- **Comfort zone**: The range of environmental conditions in which humans can achieve thermal comfort.

11.2 ACOUSTIC NOISE

The many detrimental effects of a noisy environment on crewmembers include:

- Physical damage to the sensing organs of the ear, resulting in permanent or temporary hearing loss;
- Speech and communication interference, resulting in potentially unsafe operating conditions; and
- Psychological stress, possibly resulting in hypertension, loss of sleep, fatigue, irritability, loss of productivity, distraction, increase of errors in judgment, and decreased morale.

Although the most severe of these effects are associated with the loudest noise levels, even moderate noise levels over extended periods can cause auditory damage and hearing loss. Hearing loss affects individuals differently, with some individuals more sensitive to sound and other individuals more susceptible to physical damage. Hearing loss is classified as either a temporary threshold shift (TTS) or a permanent threshold shift (PTS).

Unlike industrial workers, spacecraft crews cannot escape their noisy work environment after the workday is over. Conversely, we would not expect machines—such as the punch presses or saws used in factories, Industry, or other high-noise work environments—to be used on crewed spacecraft or habitats.

Acoustic Environment

Because of the 24-hour-per-day, 7-day-per-week exposure of spaceflight crews to their environment, space vehicles are required by NASA to meet more stringent noise requirements than the Occupational Safety and Health Administration (OSHA) levies on Earth workplaces for an 8-hour day. In addition to the consideration of 24-hour-a-day exposure, NASA spaceflight requirements also vary depending on the duration of a mission.

In the past, failure to maintain reasonable levels in extended-noise-exposure situations has led to many cases of hearing loss. For example, hundreds of U.S. Navy personnel have experienced significant hearing loss during submarine and ship missions. This has led to the U.S. government having to spend millions of dollars annually to pay for hearing aids for veterans. In another example, a very high percentage of *Mir* cosmonauts experienced TTS, and several cosmonauts with PTS were disqualified from further spaceflights.

> ***Hearing protection provides some small amount of relief. But since it is only comfortable to wear for a few hours, it does not provide a permanent solution for a 24-hour-a-day noise problem.***

On vehicles or in habitats, noise is generated by fans, pumps, compressors, motors, environmental systems, actuators, exercise equipment, and rotating machinery, as well as by the equipment supporting computers and science experiments. Any vehicle has hundreds of noise-making items. The cumulative noise emissions, along with the acoustic characteristics of the enclosed space, create the habitable volume's acoustic environment. Vibration isolation, sound containment, sound dampening, and machinery balancing are some of the measures available for quieting these sources. Unfortunately, success has been limited to date—mostly because of the lack of attention to acoustics in the design phase of hardware.

In terms of duration, some noise producers operate continuously and some operate intermittently. To characterize a noise environment that is produced by differing numbers of continuous and intermittent sources, a time-weighted average of the noise is taken over a period of time. We denote the equivalent sound pressure level or noise dose as $\mathbf{L_{Aeq}}$ For a typical Earth-based workday, the duration is 8 hours; for spacecraft environments, the applicable integration period is 24 hours.

Acoustic Specifications for Mission Durations of Four Months

The ISS, which hosts relatively long-duration missions lasting as many as four months, is used below as our model of acoustic requirements during space missions. The unit used to denote noise level (dBA) relates noise to

20 microPascals, the lowest noise level that the average 18-year-old male human can hear. For a standard 8-hour workday, NIOSH recommends an average noise level of less than 85 dBA, with hearing protection required for personnel exposed to levels of 85 dBA or higher. NASA standards are necessarily more stringent, because most noise in space is continuous for 24 hours a day. For Shuttle flights that last no longer than two weeks, Flight Rules call for hearing protections when noise levels reach 74 dBA. For the ISS, Flight Rules state that hearing protection must be used at and above 67 dBA. A breakdown of the hearing protection requirements for ISS is provided in Table 11.1.

Table 11.1: ISS Hearing Protection Requirements Versus 24-hour Noise-Exposure Levels [a]

	L_{Aeq24} (dBA) [b]										
	65-66	67	68	69	70	71	72	73	74-75	76-77	>77
Required hours per day of hearing protection	0	2	7	11	14	16	17	19	20	21	22 (full time)

[a] From internal document.

[b] Hours are in addition to 2-hour exercise period.

The above exposure limits, where hearing protection is specifically required, address the concern of crew hearing loss. NASA stipulates additional requirements to address the concerns of speech communication effectiveness and psychological effects, ensuring that the noise levels in space vehicles do not approach the noise levels specified in the Flight Rules.

The *ISS Flight Crew Integration Standard* (internal document only) recommends additional limits on the acoustic environment for the crew's habitable volume, as given below:

- Impulsive noise—i.e., noise with duration less than 1 second—shall not exceed 140 dB.
- Infrasonic noise shall be less than 120 dB in the frequency range from 1 to 16 Hz for a 24-hour exposure.
- The reverberation time in areas where crewmembers must communicate by voice shall be between 0.4 and 0.6 seconds for sound in the 1000 Hz octave band.

In addition to the L_{Aeq24} noise exposure limits, NASA ISS specifications include individual limits on the noise emitted into the crew's habitable volume by ISS modules, payloads, and government-furnished equipment (GFE). These specifications are divided into continuous and intermittent emissions.

Frequency content is important, because humans are more sensitive to noise in specific frequencies. Noise that interferes with speech falls within a limited range; and high spikes or levels in some frequencies can be very annoying and can dominate overall broadband noise level concerns. Specifically, these criteria do not address the spectral shape of the acoustic environment. To satisfy the need for a more comprehensive and rigorous specification, NASA uses NC curves that were developed to quantify how room noise affects speech communications. A partial set of the NC curves is provided in Figure 11.1.

Continuous Noise Emission Limits

- Modules in the US segment of the ISS shall not exceed NC-50 at the center of the module's habitable volume, including noise emitted by the integrated GFE. Also, the sleeping environment shall not exceed NC-40. The Russian segment modules have roughly equivalent but different requirements that, for clarity, we will not discuss.
- The complement of payload racks in a given module shall not exceed NC-48 when evaluated at the center of a module's habitable volume. To implement this specification, the NASA Payloads Office has specified that each payload rack shall meet the NC-40 criteria when measured 0.6 meters (2 ft) from the loudest point on the rack. Furthermore, to meet this requirement, rack integrators specify a sub-allocation to individual payloads that is typically close to NC-32.

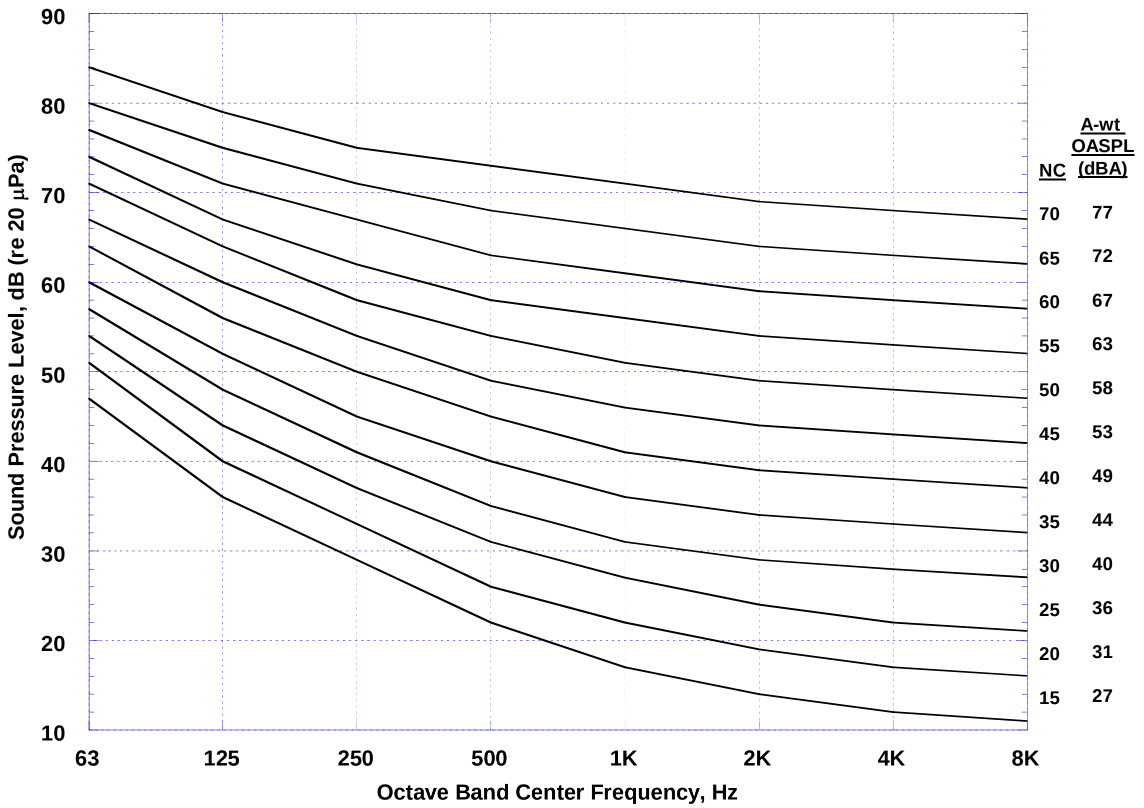


Figure 11.1: NC Curves ^{x} Used in Noise Emission Specifications. To use the NC curves, compare the acoustic emission of the item, measured at the specified location using a Type 1 microphone, a measurement microphone using the American National Standards Institute (ANSI) guideline for acoustical emissions, and analyzed into octave frequency bands using appropriate filtering or spectral analysis, with the appropriate NC curve. Sound pressure level in decibels (no weighing) in each frequency band measure must be equal to or lower than the corresponding values of the appropriate NC curve.

- Noise emitted by nonintegrated GFE shall not exceed the NC-40 criteria when measured 0.6 meters (2 ft) from the loudest point on the GFE.

Intermittent Noise Emission Limits

Table 11.2 specifies the intermittent noise emission limits for ISS payloads and nonintegrated GFE. The limits apply to measurements performed 0.6 meters (2 ft) from the loudest point on the item. Items that have operational durations longer than 8 hours must comply with the continuous noise limits stated above.

Acoustic Risk Mitigation and Countermeasures

Ground-based testing, empirical predictions, and on-orbit measurements are all used in conjunction with remedial actions and countermeasures to maintain a safe acoustic environment on the ISS. First, ground-based testing is conducted on all noise-producing hardware to ensure compliance with specifications. Test data, when combined with calculations and assumptions about equipment installation and reverberation effects, predict the acoustic environment at any stage during a mission. Second, on-orbit measurements are taken to verify that the acoustic environment is appropriate. These on-orbit measurements use sound level meters to measure acoustic spectra and frequency-weighted sound levels at specific locations. Acoustic dosimeters are also used to measure the L_{Aeq} noise exposure levels. As a final safety precaution, on-orbit audiometry is performed in addition to the pre-mission and post-mission audiometry to monitor the hearing sensitivity of the crew.

Table 11.2: Intermittent Noise Emission Limits [a]

Maximum Noise Duration (per 24-hour period)	**A-wt OASPL** (dBA) [b]
8 hours	≤ 49
7 hours	≤ 50
6 hours	≤ 51
5 hours	≤ 52
4 hours	≤ 54
3 hours	≤ 57
2 hours	≤ 60
1 hours	≤ 65
30 minutes	≤ 69
15 minutes	≤ 72
5 minutes	≤ 76
2 minutes	≤ 78
1 minute	≤ 79
Not allowed	≥ 80

[a] Data from internal documents.

[b] A-wt OASPL: A-weighted overall sound pressure level is the sound pressure level, including acoustic energy at all frequencies. Contributions from various frequency bands are weighted according to the A-weighting scale that approximates the response of the human ear for high levels of noise.

Noise emission problems are fixed on the ground whenever possible; but if a problem is identified on orbit, that problem is reviewed and fixed on orbit with remedial actions, such as vibration isolators and sound-absorbing or sound-blocking materials. As a last resort, acoustic countermeasures are used; e.g., passive bulk and molded earplugs and active noise control headsets.

Design Considerations

For mission durations that exceed 1 year, a low level of ambient noise in the vehicle or habitat environment must be achieved on the order of NC-50. Although these levels are achievable, consideration of acoustics must be included in the design phase. While simple features—such as well-placed absorbent panels, equipment isolators, and sound absorbers—are efficient and easily incorporated approaches to include in the design phase, they are also expensive or impossible to employ to an existing vehicle. And the fact that the vehicle might not be accessible, if out of Earth orbit, means that the vehicle must not require remedial actions.

From an acoustic load perspective, we recommend that the crew be provided with a quiet place, in which they will not have to use hearing protection, to recover from the higher acoustic levels of the working space. It would be desirable to design the sleeping quarters as well as a recreation or meeting area to be especially quiet so that the crew can relax and unwind there. To help with this, the emerging field of active noise control could be used to eliminate low-frequency noise within these spaces, while more traditional methods might be used to handle high-frequency noise.

11.3 ACCELERATION, VIBRATION, AND IMPACT LIMITS

The maximum deceleration load on the crew after long-duration microgravity exposure is 5 g.

11.4 CABIN PRESSURE

To assure crew safety, performance, and health, internal pressure and air composition in habitable elements must be carefully selected. Atmospheric pressure and composition can critically affects the construction strength of a habitable vehicle and of EVA systems and, therefore, can strongly affect overall mission cost.

A main function of controlling the pressure and composition of the atmosphere is to maintain oxygen partial pressure somewhere between hypoxic and oxygen toxicity or flammability limits. Table 11.3 shows normal oxygen (normoxic) pressures and concentrations at sea level.

Table 11.3: Oxygen Concentrations at Different Pressures [a]

Total Pressure (kPa / psia)	**Normoxic Partial Pressure** (kPA-O_2 / psia-O_2)	**Normoxic Concentrations** (percentage of O_2)
25.5 / 3.7	25.53 / 3.70	100
27.6 / 4.0	24.97 / 3.62	90.5
34.5 / 5.0	23.80 / 3.45	69.0
41.4 / 6.0	23.18 / 3.36	56.0
48.3 / 7.0	22.70 / 3.29	47.0
55.2 / 8.0	22.36 / 3.24	40.0
62.1 / 9.0	22.08 / 3.20	35.5
69 / 10.0	21.87 / 3.17	31.7
101.4 / 14.7	21.25 / 3.08	21.0

[a] All measurements are taken at sea level.

Since lowering oxygen partial pressure reduces flammability concerns, a higher total habitat pressure with less concentrated oxygen would be safer. A total habitat atmospheric pressure of 68.9 kPa (10.0 psia) might satisfy both flammability and crew health requirements. Skylab demonstrated that crewmembers and selected materials could function well at 34.5 kPa (5.0 psia).

Crewmember mobility, especially glove dexterity, is improved if the pressure of the EVA system stays low. Low suit pressure also reduces overall suit structural weight. To reduce a crewmember's prebreathe time before an EVA, the cabin pressure should remain as low as possible. The higher the pressure differential between the EVA suit and the spacecraft environment, the greater the risk of DCS.

Shuttle EVA experience reveals that routine EVA operations can be conducted from a 70.3 kPa (10.2 psia) cabin, with a 29.6 kPa (4.3 psia) space suit after a minimum 40-minute prebreathe. This model presents an acceptable bends risk ratio (R) of approximately 1.65.

Skylab EVAs were conducted with a 34.5 kPa (5.0 psia) cabin environment (70% O_2/30% N_2), a 26.2 kPa (3.75 psia) space suit, and no prebreathe period. This model presented a very low bends risk ratio (R) of 0.4. We strongly recommend this second, much safer Skylab approach.

For additional background information, trade-off considerations, and references, refer to Appendix A.

11.5 CO_2, TRACE GAS, AND HUMIDITY LIMITS

Crew comfort and health also depend on the proper mix of atmospheric gases and humidity. CO_2 partial pressure maximum limits for space habitat atmospheres are:

- 400 N/m^2 (3.0 mm Hg) maximum for normal operations;
- 1013 N/m^2 (7.6 mm Hg) maximum 90 days for degraded operations; and
- 1600 N/m^2 (12.0 mm Hg) maximum 28 days for emergency operations.

Dewpoint (humidity) maximum levels for habitat atmospheres are as follows:

- 278-289 K (40–60 °F) maximum for normal operations;
- 274-294 K (35–70 °F) maximum 90 days for degraded operations; and
- 274 - 294 K (35–70 °F) maximum 28 days for emergency operations.

A wide assortment of trace gases can be found in space habitat atmospheres, each of which is assigned a spacecraft maximum allowable concentration (SMAC)—typically in concentrations of parts per million (ppm) or parts per billion (ppb).

11.6 MATERIALS SELECTION

The flammability triangle of fuel, oxygen, and ignition source must be broken. Atmospheric pressure and composition determine material safety. For example, exceeding a 4% hydrogen concentration or a 30% oxygen concentration greatly increases ignition probability and decreases the list of safe material selections. Habitat construction materials must be selected based on their performance during flammability tests at different oxygen concentration levels. Also, materials must be able to withstand the total habitat pressure recommended above. If the pressure is increased, the materials' strength must increase accordingly.

11.7 THERMAL SYSTEMS

The cabin heating, circulation, and cooling systems must closely control air temperature, velocity, pressure, and humidity to maintain crew comfort. The comfort zone, which is defined as that range of environmental conditions in which humans can achieve thermal comfort, is affected by work rate, clothing, and state of acclimatization. Discomfort will be more of a problem as mission length increases, since a thermal system will have to maintain comfort in support of a wide range of activities likely during a long-duration mission, from long periods of relative inactivity to vigorous activities such as exercise and EVA. Under microgravity conditions, sweat does not drip from the body but tends to sheet on the skin and form ringlets around the neck. The thermal system must provide adequate cooling and air circulation to keep perspiration from exercise and strenuous work to a manageable level. Normal atmospheric parameters for thermal comfort are:

- 12.8 °C (55 °F) for crew workloads of 1000 British thermal units (Btu) per hour;
- 21.1–26.7 °C (70–80 °F) when workloads are at a minimal 300–600 Btu per hour; and
- Approximately 50% humidity.

Human Performance in Hot Environments

Performing heavy work elevates skin temperature, followed by an elevation of body core temperature. The body attempts to dissipate heat through vasodilatation and sweating, but this may not completely compensate for the heat load on the body. As the core temperature continues to rise, the heart rate increases and eventually may reach 140 beats per minute or more. If the body continues to overheat, the crewmember may suffer from heat exhaustion, which is characterized by hypertension, difficulty with breathing (dyspnea), confusion, and fainting. A person who is performing moderate or heavy work will develop higher core temperatures before developing heat exhaustion. Occasionally, people who are working hard in the heat experience almost none of the above symptoms and suddenly faint or, in some rare instances, go directly into heat stroke.

The principal effect of microgravity on heat transfer is the loss of natural convection (i.e., warmer air will not naturally rise in microgravity). Therefore, fans or blowers are required to remove heat from around objects and to maintain thermal comfort.

Human Performance in Cold Environments

During cold stress, the body rapidly reduces peripheral circulation in an attempt to conserve core heat. As the core and skin temperatures continue to drop, the person begins to shiver and feels continually uncomfortable. Eventually, shivering may become violent and uncontrollable. If the core continues to lose heat, shivering eventually lessens and stops altogether. At this point, complete loss of thermoregulation is imminent. Death may not follow quickly, however. The core temperature can be drastically reduced—to 26 °C (78.6 °F) or lower—and the body may still survive. When the core is cooled to such an extreme level, death can occur when attempts are made to rewarm the body, for these attempts often cause cardiac fibrillation. A hypothermia victim will become critical when the core temperature drops to about 35 °C (95 °F).

Although future mission concepts do not include cryogenic hibernation for the crew, refrigerated storage of deceased crewmembers may need to be considered.

Special Ventilation and Metabolic Heat Removal Design Considerations

The ventilation requirements of any habitable space element cannot be based on ground-based systems due to an absence of convective airflow.

The amount of air required in any region of a cabin depends on the number of crewmembers present and on their work activity. The recommended amount of cabin air for adults engaged in moderate physical activity ranges from 2.4 to 14.2 liters/second (5 to 30 ft^3/minute) per person, with approximately two-thirds of this being fresh, revitalized air. In a fan-ventilated pressurized suit, the flow rate must be maintained at 6 ft^3/minute. Special consideration should be given to the following areas:

- **Exercise station**: This area should have adjustable airflow controls and added ventilation to relieve sweating during exercise. Individual airflow units with air temperature control would help crewmembers match the airflow to their activity. The direction of airflow should not blow sweat into other station areas, particularly eating or sleeping stations, and should blow over the entire body, not just one part of the body.
- **Sleeping station**: Sleeping stations are usually rather small. Individually adjustable airflow controls would maximize comfort.
- **Galley**: Airflow should not blow loose food around, but should be sufficient to keep food odors from accumulating inside the module.
- **Ventilator intakes**: Ventilation system intakes should be accessible by crewmembers for recovery of lost objects. Airflow in the vicinity of the inlets should not exceed 0.2 m/second (40 ft/minute). The ventilation rates used in the cabin should be sufficient to control local air contamination by body products or from noxious substances in the compartment. The cabin ventilation airflow should be sufficient to dilute contaminants and divert them from crewmembers.

Thermal Monitoring and Control Design Requirements

- **Thermal environment monitoring**: Cabin temperature and relative humidity should be monitored using an automated system. The number, type, and location of temperature sensors and the frequency of monitoring should ensure representative cabin temperature measurements and stable atmospheric control.
- Visual and audible alarms should be initiated automatically if thermal parameters exceed the limits given in Table 11.4.
- **Adjustment of thermal environment by crewmembers**: Crewmembers shall be provided with controls that allow them to modify temperatures, humidity, and ventilation rates inside the space module within the ranges for these parameters as specified in Table 11.3.
- **Compartment controls**: Temperature and ventilation shall be maintained in each of the private crew quarters, the personal hygiene area, and the waste management compartment, and shall be controlled in each of these areas within the range of parameters as specified in Table 11.4.

Table 11.4: Atmosphere Thermal Comfort Requirements [a]

Parameter	Operational		28-Day Emergency	
Temperature [b]	65–80 °F	(292–300 K)	60–85 °F	(289–303 K)
Dew point [c]	40–60 °F	(278–289 K)	35–70 °F	(274–294 K)
Ventilation	15–40 ft/min	(0.08–0.20 m/sec)	10–200 ft/min	(0.05–1.0 m/sec)

[a] Source: MSIS Figure 5.8.3.1-1.[8]

[b] In the operational mode, temperature will be selectable ±2 °F (±256.5 K) throughout the range.

[c] Relative humidity shall be within the range of 25 to 75%.

- **Portable fans**: If activity stations are isolated from the module air circulation systems, auxiliary airflow and/or portable fans shall be provided.
- **Exercise station control**: Each exercise station shall be provided with means for sweat removal.

11.8 TOXICOLOGY AND CONTAMINATION LIMITS

Current limits for gaseous contaminants are obtained from SMAC specifications. Future ultra-long-duration missions may maintain the same SMACs, or may be modified if prolonged exposure becomes a concern.

Normal atmosphere scrubbing, sensing, and off-nominal cleanup provisions are required. Limits and metabolic generation rates are cited in several internal documents. According to these internal standards, airborne microbes must be monitored and limited to 1000 colony-forming units per cubic meter. Airborne particulates must be limited to an average of 100,000 particles per ft^3 with a peak of less than 2 million particles per ft^3 for sizes ranging from 0.5 microns to 100 microns.

11.9 REFERENCES

[1] Eckart P. *The Lunar Base Handbook*. Space Technology Series of NASA and U.S. Air Force. 1998.

[2] Webb P, editor. Report No. NASA-SP-3006, *Bioastronautics Data Book.* Washington, DC: National Aeronautics and Space Administration. 1964.

[3] Larson W and Pranke L, editors. *Human Spaceflight: Mission Analysis and Design*. New York: McGraw Hill. 2001.

[4] Baranek L and Ver I, editors. *Noise and Vibration Control Engineering: Principles and Applications*. 2nd Edition. New York: John Wiley and Sons, Inc. 1992.

[5] Crocker M. *Handbook of Acoustics.* John Wiley and Sons, Inc. 1998.

[6] Bies D and Hansen C. *Engineering Noise Control, Theory and Practice.* E and FN Spon. 1988.

[7] Report No. 98-126, “Criteria for a Recommended Standard, Occupational Noise Exposure.” DHHS (NIOSH), Revised Criteria. 1998.

[8] NASA-STD-3000. *Man-Systems Integration Standards*. Revision B. Houston, TX: Johnson Space Center. July 1995.

12 INFORMATION TECHNOLOGY INTERFACES

Much crew work in future exploration missions undoubtedly will be conducted with the support of intelligent systems at intravehicular workstations. On planetary surfaces, crewmembers may conduct some tasks with the help of robotic assistants or intelligent tools designed to amplify human abilities. If we use the present state-of-the-art to extrapolate what technologies might be available, we can envision that the crew and artificial systems (e.g., automation, intelligent assistants, and ambulatory robots) will collaborate seamlessly to fulfill the exploration goals.

12.1 KEY CONCEPTS

During the design of every spacecraft system, the engineer is confronted with important decisions as to the degree of automation the system will possess and what interfaces crewmembers will use to monitor or control that system as needed. Such decisions must emphasize collaboration between human and machine by capitalizing on the unique capabilities of both the human user and the intelligent system.

- **Technology-driven design**: Design and development of new systems based on the availability of a new technology or capability.
- **Human-centered design**: Design and development of new systems based on the human user's needs.
- **Intelligent systems**: Artificial systems designed to replicate or augment a specific aspect of human intelligence (e.g., expert systems).
- **Workstation**: The well-equipped location(s) where a crewmember performs a particular kind of work or a specific task. Workstation components include hardware, software, and information technology.
- **Information technology**: A broad domain encompassing multiple areas, such as robotics, automation, vehicle health management, human-centered computing, and intelligent systems—all of which supply important infrastructure for mission and spacecraft design.

In the following sections, we will consider how to balance the unique but complementary capabilities of human and machine, so that introducing new technologies into a mission produces the maximum benefit. In addition, two papers (one by Rudisill[3] and one by Stilwell[4]), cited in References, provide detailed information on concerns and lessons to be learned.

12.2 DESIGN CONSIDERATIONS

The reality of future exploration missions is that crewmembers will be completely isolated from society, support from Earth, and terrestrial resources for years at a time. This means that the crewmembers' needs must be supplied solely by onboard or surface systems.

> ***From the very beginning of mission planning and spacecraft design, the paramount consideration must be the capabilities, limitations, and needs of the crew.***

To date, engineers have exclusively used a technology-driven design (TDD) approach for providing the crew with new or improved interfaces or workstations. In the following paragraphs, we will consider why this approach does not produce optimal results and how to shift the perspective of the design process to a human-centered design.

Technology-Driven Design

This approach begins when a designer recognizes the value-added potential of a particular technology. What characterizes TDD is the way the design is carried out. It begins with a technical concept, proceeds through prototype development and testing, and concludes with production and delivery to the human user. However, too often the result is a procrustean design that tries to conform the user to the technology.

Automation provides many examples of how TDD may not work well with, or may exclude entirely, the human component, resulting in an inadequate or unsafe system. We must better understand the strengths and deficiencies of humans in an automated environment. Automated systems born from the TDD process tend to place the human operator either in an occasional monitoring role or completely out of the loop. When an anomaly does occur, the human operator can take control by overriding the automated system, but may be hesitant to do so—

even with compelling evidence of the anomaly—because doing so would require the operator to override the system without fully understanding how the situation occurred or knowing what effects human-directed changes will have on the system.

Commercial aircraft are so automated that flying from point A to point B requires the human pilot only to enter the destination and minimal flight parameters into a flight system. Many accidents occur because pilots place too little or too much confidence in automation. When trouble arises, the pilot may merely assume that the monitoring instruments have failed. Alternatively, since instruments often do not directly reveal the nature of a problem, the pilot has no indication what to do or what will happen if control is not taken. The Federal Aviation Administration's Aviation Safety Reporting System permits the categorization of a large dataset of aircraft accidents and incidents; this analysis attributes approximately 70% of accidents and incidents to human error.

Flight deck automation, like the technology-driven model of automation in general, usually provides an either/or situation where (1) the pilot must take complete control of the aircraft or (2) the automated system maintains complete control. The goal of TDD is not to optimally balance operator workload with automated systems, but is rather to replace human effort and attention completely. This is often called "strong-but-silent" automation.

Human-Centered Design

Human-centered design (HCD), by contrast, revolves around human users. The focus shifts to user capabilities and needs, user tasks, and the most effective way to complete those tasks. HCD facilitates human abilities to do difficult tasks and expands human capabilities. It yields new technologies and methods for reducing workload, thereby increasing human performance, giving users greater flexibility, and allowing the users the ability to respond more quickly.

12.3 INTELLIGENT SYSTEMS

Recent history is replete with many examples of new technologies that are intended to improve human performance, but that had unintended consequences or failed when applied. New technology advances may actually add new burdens to operators or create new types of errors that are more insidious than errors caused by prior technologies. Systems sometimes become so complex that even expert users may not recall how to complete infrequent, but essential, tasks and are not aware of all the features or capabilities. If the new technology is not intuitive, it may actually increase a crewmember's workload during a crisis beyond human capacity. Certainly, this unintended outcome is not acceptable; but it can be improved by a shift in the design process that favors intelligent systems.

The real need is not to transfer every bit of data to the crewmember, but rather to create intelligent systems that can separate the truly critical results from oceans of irrelevant information.

Intelligent systems and interfaces treat both human and system as a vast and closely intertwined network of interacting and interdependent control loops. By building more cooperative human-machine interfaces, designers capitalize on the unique and complementary capabilities of each. Such systems should allow the user to work smarter. Poetically, we speak of the "deep symbiosis between man and machine," in which complex real-time decisions are made to maintain system viability and "homeostasis" in the demanding spaceflight environment. Table 12.1 lists the defining characteristics of such intelligent systems and interfaces.

In this paradigm, the intelligence and quality of the interface permits a very small crew with above-average intelligence and skills to accomplish what legions normally could not accomplish.

The key to the success of intelligent systems and interfaces is to involve humans appropriately, and to do so unobtrusively and efficiently. The spacecraft then becomes an extension of the human being.

Table 12.1: Defining Characteristics of Intelligent Systems and Interfaces

Defining Characteristics
Users can easily monitor a fully autonomous system during nominal operations.
Human skill and reasoning can supersede or completely replace autonomous functions during anomalies.
System automation reduces demands on crew but still permits user interaction with system.
System augments human sensory systems, mapping critical new data in an intuitive fashion.
System compensates for natural limitations on human sensory bandwidth by processing and filtering data before displaying data points that require crew intervention.
Interfaces are very fluid and respond to changing conditions, allowing system to act as a crew multiplier when needed.

12.4 WORKSTATIONS

Beyond the systems and interfaces that support vehicle or habitat operation, crewmembers also require well-designed work areas. The traditional workstation makes sense when work is physically confined to a particular location. For example, a blood chemistry analyzer will still have a fixed port for sample delivery, and a glove box will still require that a crewmember work in a particular location. The concept of a workstation will change drastically in the not-too-distant future, however, where body-worn computers and head-mounted displays will likely be the standard interface for spacecraft systems. As the crew and spacecraft systems journey farther from Earth and become more autonomous, crewmembers must access information quickly and easily and, wherever they are in the spacecraft, take control of situations. Such an interface can only be satisfied by a body-worn system.

Body-Worn Systems

Body-worn systems provide a significant advantage over the bulky, wired systems of today. So if crewmembers must retire to a small radiation shelter, they will still have access to all spacecraft data and controls. Control may be exerted by a combination of body-worn mouse, voice, and gesture-based interfaces. Displays can be made to appear in front of the crewmember at a comfortable viewing distance and individually customized for the task. Head movements can be used to expand the display and control area. Such a system would allow spacecraft systems to be packaged in the densest way possible and to obviate extensive panel space. It is also very likely that such a system would contribute greatly to uniformity of design in displays and controls, thus increasing the productivity of individual crewmembers. Ready access to decision-support and procedural information that is tailored to each individual's role in a group task will significantly influence how work is done in space.

12.5 DESIGN CONSIDERATIONS

A number of guidelines (e.g., MSIS[2], Section 9.0, Workstations) have been developed for building crew workstations and interfaces, but most of these guidelines are too detailed for the scope of this document. Instead, the more interesting and important guidelines are provided below. Although many of these may seem like common sense, they are often unintentionally violated.

- **Tasks must be divided between the crew and spacecraft systems in a way that maximizes the skills and abilities of each**. As the situation changes, it makes sense for the workload to be dynamically assigned to the party most able to handle the task at that time. As part of the HCD process, human factors engineers often use task analysis as a formal method for determining how to divide work, but this process often looks at tasks statically. New methods may need to be developed to deal with the dynamic allocation of tasks in the complex interplay of events that may occur in space.

- To the greatest extent practical, crew interfaces should be standardized and consistent throughout spacecraft system design.

Architecture

- Workstation illumination (fixed, portable, or supplementary) should be suited to the task, be adjustable, and uniformly cover the work area. Reflections and other stimuli that can interfere with vision should be avoided.

- Workstation architecture should consider operator needs and capabilities, including physical dimensions, viewing angles, and distances (Chapter 8, Anthropometry and Biomechanics). Workstations must accommodate the S-shaped, bent-knee posture of microgravity and the erect posture of a planetary environment.
- Ventilation should be consistent with NHB 8060.1[5], flow rate and direction should be adjustable.
- Workstation restraints—e.g., foot and waist restraints, tethers, and handholds—should be adjustable, comfortable, and easy to engage and disengage. They should also provide stability.
- A maintenance facility workstation should provide conditioned/converted power, spare parts, supplies, repair and diagnostic equipment, data links, and a glove box or another contained location for servicing and repairing components. It should also allow access to computer-based maintenance procedures, diagnostics, and interfaces to troubleshooting and built-in test equipment. Ideally, maintenance interfaces should use the same body-worn interface available for other spacecraft control systems.

Controls

The MSIS[2] outlines the advantages and disadvantages of different controls and supplies detailed guidelines for multiple types of hardware controls. Detailed design guidance for multiple types of computer input devices (e.g., keyboard, joystick, light pen, mouse, trackball, stylus and grid, touch display, and bar code reader) are also given in this standard. Below, we include select guidelines for ungloved operations:

- Use shape-coding or shape-separation for blind operation of controls.
- Label emergency or critical controls.
- Protect controls from accidental actuation (by location, orientation, recessing, shielding, cover guards, interlocks, resistance, locks, or “dead-man” switch operation).
- Ensure protective gear does not interfere with normal operations.
- Consider language-based voice communication (for both input and output) for natural communication between crew and machines. New signal processing techniques show great promise for removing ambient noise from voice recognition systems, which is currently the greatest limitation of such systems.

Displays

Displays are the primary method of providing the crew with information about systems, processes, and the vehicle or habitat. Although information is mainly conveyed to the crew visually via meters, indicators, signals, flags, and graphics-capable monitors, displays can also be auditory. A particular concern is the display of crew caution and warning information. The following represents top-level guidance for display design; detailed design guidance for visual, auditory, and caution and warning displays is provided in MSIS[2], Section 9.4.

- In the absence of a direct crew request, display only the information required to perform the task at hand. Do not make the displayed information overly complex, but provide a simple, direct means to access more detailed information.
- If a fixed display is needed, display surfaces should enhance readability, taking into consideration such factors as user height, orientation, viewing distance, glare and reflectance, brightness, contrast, ambient light, and vibration and acceleration state.
- The source of an alarm must be easily determined. Crewmembers should be allowed to view the alarm history, and the right information and decision support should be provided to allow them to make decisions appropriately and rapidly in an emergency.

Display/Control Integration

- All controls should be operable by a pressure-suited crewmember.
- Group functionally related displays and controls should provide clear and readable labels and a common interface across functionally similar displays and controls. Controls should be arranged by sequence of use or by logical flow.
- Controls and displays for maintenance tasks should not be visible during normal operations, but should be readily accessible during maintenance.

- Emergency displays and controls should be located so they can be easily seen and reached. Emergency information on displays should be conspicuous.

User/Computer Interaction

Overall, computers should aid users by providing the required information in an appropriate format. Detailed design guidance is provided in MSIS[2], Section 9.6.

- Visual consistency should be provided across screens. Rapid and predictable feedback should be given for all user actions.
- Intuitive (i.e., easy-to-learn, easy-to-use) actions or commands that do not require significant memorization should be designed.
- Escape, cancel, and abort functions for all user actions should be allowed.
- All information that the user requires to perform the task should be provided. Do not display extraneous information, but allow easy and direct access to more detailed information.
- Make consequences of user actions across displays consistent. Provide distinctive and meaningful abbreviations and acronyms.
- Prototype displays, and allow users to review them and provide feedback.
- Design the interaction so the crewmember can concentrate on the task, not the system.

12.6 INFORMATION TECHNOLOGY

Information technology (IT) is a broad domain encompassing multiple areas; e.g., robotics, automation, vehicle health management, human-centered computing, and intelligent systems. Undoubtedly, future exploration crews will have access to IT-based systems, and much of the exploration work will be conducted using such technologies.

> ***IT infrastructure can enable exploration missions, increasing safety, efficiency, and performance while decreasing cost.***

These benefits will only be accrued to the extent that advanced IT-based systems work collaboratively and effectively with human team members. To do so requires careful mission and system design.

Broadly defined, IT includes:

- **Automated or robotic assembly**: IT will enable the construction of structures—such as transit vehicles, habitats, and observatories—in a 0g environment or on a planetary surface. The human crew will be involved with construction operations at both low levels (e.g., via teleoperation of robotic manipulators) and high levels (e.g., by commands to an autonomous system).
- **Autonomous science**: Since science provides the primary underlying purpose for exploration, some science will be conducted autonomously. Humans and IT systems may forge "collaborative" teams, with autonomous intelligent systems extending a crew's reach and visibility. In advanced IT systems, the level of scientist/system interaction will change, with the crew providing high-level direction and the automated systems making basic decisions, planning, executing the plan, and carrying out much of the data collection and analysis.
- **Automated operations**: IT will enable the automated control of complex systems that support a human crew—such as environmental control, life support, and in-situ resource production—without regular direct human control, using existing industrial automation and process control technologies. Such automation will make complex decisions with limited or no human interaction, perhaps operating for long periods locally (e.g., on the Mars surface) with little or no direction from the crew or Earth-based mission controllers.
- **Human amplification**: The fundamental human capabilities of the crew will be "amplified" or enhanced through IT. For example, in advanced fighter aircraft, automated flight control systems enhance a pilot's manual control of the vehicle. This capability could be extended to areas such as hazard identification

and avoidance. IT systems may be used to amplify human design capabilities with collaborative design tools. Finally, IT may amplify human physical capabilities (e.g., strength) and sensory powers (e.g., extended vision and enhanced touch).

12.7 REFERENCES

[1] Hine B and Clancy D. "The Role of Information Technology in Human Space Exploration." NASA Ames Research Center. 2001. Internal document, unavailable. Contact author for information.

[2] NASA-STD-3000. *Man-Systems Integration Standards*. Revision B. Houston, TX: Johnson Space Center. July 1995.

[3] Rudisill M. "Crew/Automation Interaction in Space Transportation Systems: Lessons Learned from the Glass Cockpit" in *Proceedings of the Human Space Transportation and Exploration Workshop*, Galveston, TX. 2000.

[4] Stilwell DJ. "The View from Earth Versus the View from Mars" presented at *Human Factors and Ergonomics Society Annual Meeting*, Houston, TX. September 1999. Santa Monica, CA: Human Factors and Ergonomics Society.

[5] NASA-NHB-8060.1. *Flammability, Odor, Offgassing, and Compatibility Requirements and Test Procedures for Materials in Environments That Support Combustion*. Revision C. Washington, DC: National Aeronautics and Space Administration. April 1, 1991.

13 WORK INTERFACES AND TOOLS

When designing a mission, the overall goal is to minimize the amount of resources needed to maintain systems. Standardization of interfaces, minimization of actuation loads, adequate access clearances, and appropriate body restraints are typical means of accomplishing work with the least amount of overhead and the best chance of success. Wherever possible, existing designs, standards, and inventory should be used to minimize cost.

Tools in many forms aid humans with their work. In additional to traditional hand tools, the basic spacecraft, information devices, and robotics can be considered to be tools as well.

Good tool design should include low mass, high strength, minimal input loads, torques, and cycles; ambidexterity; ease of repair and cleaning; thermally and electrically insulated handles; and restraint attachment features.

By limiting the quantity and complexity of tools and vehicle interfaces, training time and personnel are also minimized.

13.1 TOOLS AND AIDS

The types of aids to be considered for interior or exterior work include:

- Devices for self rescue and incapacitated rescue that use power and gas sources that are common to EVA suits and detachable elements;
- Free-flight units, such as manned maneuvering units for translation and EVA work;
- Fixed and portable lighting;
- A range of digital still and video cameras designed to work in different lighting situations, such as low light, IR, and UV;
- Body restraints and safety and equipment tethers;
- Heavy equipment carriers, such as sleds, wagons, wheelbarrows, and rover trailers;
- Secure restraint without relying on manual transport;
- Power and manual hand tools, with gripping aids, wrist straps, and ambidextrous features;
- Batteries and chargers;
- Detectors for chemicals, fluids, gases, and leaks;
- Multi-meter diagnostic tools;
- A wide range of geological tools that can support mining and science operations;
- Meteorological and navigation aids, such as barometers, compasses, and binoculars;
- Recreation items and exercise equipment;
- Markers, flags, trail-blaze paint, and rock cairns;
- Walking aids, such as poles;
- In-situ resource utilization devices, such as sandbags;
- Shelters, tents, and caches; and
- Repair tools, such as welders and gas and fluid patches.

The mass, volume, and specific selection of manifested tools depends on the tasks envisioned. For future planning based on past history, microgravity work involving extensive assembly and maintenance could require up to 498.96 kg (1100 lbs) and 0.84 m^3 (30 ft^3) of stowage space for tools and containers. For missions primarily focused on planetary science, even more tools may be needed.

The vehicle and science interfaces to be considered for interior or exterior work may include the following. In addition to the specific considerations listed for each item, all interfaces must address clearance parameters.

- **Handrails**: Cross-sections, spacing, loads, color, labels, and mandatory locations.
- **Foot restraint attachments**: Loads, labels, and criteria for necessity.
- **Tether points**: Dimensions, loads, and criteria for necessity.
- **Electrical and fluid connectors**: Type, sizes, labels, and self alignment.
- **Electrical and fluid connectors caps/covers**: Labels, lanyards, self venting, and dust-/UV-proof.
- **Electrical and fluid lines**: Free length, strain relief, bend radius, stiffness, high flexibility or dual wound to cancel line memory, restraints/spacing, labels, spacing, vent before fluid line mate/de-mate, and trip-proof line runs.
- **Mechanical restraints**: Hard dock, soft dock, alignment aids, latches, bolt heads, self locking, captive, tethered, locking pins, maximum/minimum torque limits with and without restraint, long-life temporary restraints, interior/exterior Velcro, contingency release, labels, etc.
- **Labels and location codes**: Colors, contrast, fonts, sizes, content, and stowage containers.
- **Designs to avoid**: Zippers, lock wires, snaps, and exposed external Velcro.

13.2 DESIGN CONSIDERATIONS FOR EVA

Interfaces unique to EVA should consider additional environmental and human factors constraints. Externally mounted displays must be designed to withstand bright solar lighting, vacuum pressures, and extreme hot and cold temperatures. Hands-free controls that rely on voice actuation, eye tracking, or whole arm/hand tracking are a desired alternative to fatiguing and imprecise gloved-finger controls. If interfaces internal to the space suit are devised, they must be safe for a 100% oxygen atmosphere and fit within the extremely limited free volume of the garment or helmet.

14 PAYLOAD ACCOMMODATIONS

14.1 PLANT AND ANIMAL FACTORS

Animals

The inclusion of animals—primarily as laboratory specimens—in a spacecraft environment poses several challenges. Since animals contribute to the consumption of life support resources and the production of metabolic wastes, they must be factored into the sizing of the life support system. The rate at which an animal may tax a life support system varies widely and can fluctuate, depending on the species and reproduction and mortality. Moreover, waste system maintenance and collection considerations are not insignificant concerns, especially in the microgravity environment.

During missions such as a mature planetary base, animals could be included as a source of food for the crew. These animals would likely be marine life, such as fish or shrimp, which could be more easily contained and transported than typical livestock.

Plants/Biomass Production

An evolved Mars base will probably use higher plants to provide full water regeneration, atmospheric revitalization, and a significant portion of crew food. Such a biomass subsystem could provide the primary air revitalization and water recovery functions, eliminating the need for a duplicate mechanical processing subsystem. More specifically, the plants consume atmospheric CO_2 to produce biomass and oxygen through photosynthesis, thus fulfilling the primary air revitalization task. Furthermore, plants filter organic compounds from slightly processed gray water (water that has been used by humans for showering, laundry, and similar cleaning, but does not contain human waste) and urine mixed with the hydroponic solution, returning transpirate to the water subsystem for final filtering. In the process of fully revitalizing the atmosphere, crops also provide at least half (by mass) of crew diet.[1] When the biomass subsystem produces sufficient oxygen beyond the crew's metabolic requirements, the waste subsystem may oxidize solid wastes.

Biomass subsystem hardware includes a plant chamber and supporting equipment. Plants grown within the plant chamber consume CO_2 from human metabolic activities and other sources. In return, the plant chamber provides edible biomass for the food subsystem, oxygen for the air subsystem, and clean transpirate for the water subsystem. An oxygen scrubber concentrates oxygen from the plant chamber, passing it to the crew cabin. To control the atmospheric temperature and humidity, an anti-microbial condensing heat exchanger dehumidifies the cabin atmosphere. Condensate passes either to the water subsystem for final processing or to the nutrient solution tank, where it is recycled. Recycling excess condensate within the biomass subsystem reduces the overall load on the water subsystem and helps dilute incoming gray water that is sent from the water subsystem. In this arrangement, the biomass subsystem provides both primary air revitalization and water purification functions. Inedible biomass passes to the waste subsystem.

Staple crops that supply mainly carbohydrates—such as sweet potatoes, wheat, and white potatoes—more efficiently generate edible dietary mass on a per-photon, per-volume, and per-time basis than other crops. Crops that supply protein and fat (e.g., peanuts and soybeans) are relatively inefficient at generating edible dietary mass. Furthermore, while some salad crops are fairly efficient, the dietary intake from these crops is typically low. Salad crops are assumed to be cabbage, carrot, chard, fresh herbs, lettuce, onion, spinach, and tomato.[2] Thus, for flight systems that allow or require resupply, it would be most expedient to grow the crew's dietary carbohydrate and some salad crops while providing protein and fat by resupply from Earth.

Under the NASA Advanced Life Support Straw Man concept,[3] the biomass subsystem uses artificial lighting to grow crops. The lighting photoperiod, photosynthetic photon flux levels, and biomass production module environmental conditions are set to maximize crop productivity as a function of time. Alternative models consider using natural lighting for biomass production, but the available natural light available during some mission profiles, such as a Mars mission, may be insufficient to grow most crops.

Partial Pressures of Carbon Dioxide and Oxygen

To promote crop productivity, the nominal atmospheric composition for biomass modules should maintain the CO_2 partial pressure at 0.12 kPa (0.02 psi) and the oxygen partial pressure at 17.27 kPa (2.50 psi). This latter value for oxygen provides sufficient oxygen partial pressure within the biomass modules to support crew accessibility.[4] This minimum oxygen partial pressure allows for reasonably timed crew acclimation, except for the case of maximum oxygen uptake, such as takes place during hard work.[5] Remaining biomass production module atmospheric constituents are water vapor and an inert gas, such as nitrogen.

Minimum Growing Area

- **Total closure**: The minimum growth area in which to achieve total closure depends on available lighting; but based on tests using the Biomass Production Chamber, a locker-sized plant growth chamber and support system for flight experiments, using moderately high irradiance, we typically estimate that 40 to 50 m^2 (430.4 to 538 ft^2) of growing area (continuously planted and harvested) would provide the daily caloric needs, as well as the oxygen and any "waste" carbon oxidation back to CO_2 for one human. Results from the Russian Bios-3 studies using higher irradiance came out with a area of about 40 m^2 (430.4 ft^2). Bugbee and Salisbury estimated that this area could be reduced to less than 20 m^2 (215.2 ft^2) using wheat and the very high irradiance that wheat can tolerate. However, these estimates do not account for a complete diet (i.e., all the minerals and micronutrients).

- **Fifty-percent closure**: This would be half of the of the typical estimate provided above (i.e., half of 50 m^2 is 25 m^2), except if you consider biomass subsystem variations where oxygen is not used for recycling the waste biomass. For example, 20 to 25 m^2 (215.2 to 269 ft^2) could provide half of the dietary food and all of the oxygen if you only stabilize or throw out the inedible biomass. The plants would still have sufficient CO_2 from crewmembers, who would get the remainder of their food from stowage. This model does not necessarily preclude recycling nutrients, which can be processed relatively rapidly by bioreactors before significant biomass oxidation occurs.

Power Requirements

- **Total closure**: A high irradiance of 1000 μmol m^{-2} s^{-1} is equivalent to approximately 200 W m^{-2} of irradiance. Assuming a lamp efficiency of approximately 20%—including electrical conversion, reflector efficiency, and crop interception—this would indicate that the subsystem requires 1 kW to provide high lighting for each square meter of crop-growing area. Thus, for 40 to 50 m^2 (430.4 to 538 ft^2), this would come to 40 to 50 kW of electrical power for lighting. As a rough estimate, this number could be doubled for cooling, water pumps, fans, and other support equipment for a total of approximately 100 kW per person for total closure. This estimate would change significantly if direct, natural lighting can be provided through the use of solar collectors, greenhouses, or some other system.

- **Fifty-percent closure**: The above estimate can be halved to 50 kW per person.

- **Salad machine**: A vegetable production unit that will augment the food system and would be important for long-duration missions. The estimated power requirements will depend on the size of the system and the light intensity. Using a lower light intensity, the current thinking is that a 5 m^2 (53.8 ft^2) system might be sustained with 5 kW and a 10 m^2 (107.6 ft^2) system would require 10 kW.

Carbon Dioxide Levels

- **Ambient**: The optimum CO_2 level for most C3 plants (which includes more than 95% of all plant species and encompasses all of the crops included in the ALS model) typically ranges from 1000 to 2000 ppm at 1 atm pressure (101 kPa). On a partial pressure basis, this would come to a partial CO_2 level of 0.1 to 0.2 kPa.

- **Minimum tolerance**: Acceptable growth can be sustained at 400 ppm (0.04 kPa), which is perhaps 75% of that obtained at 1000 ppm. Growth drops off linearly when the CO_2 drops below this level. Some C4 plants (e.g., corn, sorghum, and sugar cane) can sustain good growth well below this level, perhaps down to 150 ppm.

- **Maximum tolerance**: Some plant species show drops in yield (10 to 25%) at 5000 ppm (0.5 kPa), while other plants show no effects. Yield for susceptible plant species drops even more at 10,000 ppm (1.0 kPa). There are also some peculiar effects on transpiration rates at these super-elevated levels, but these effects vary by species. CO_2 levels should be kept below 5000 ppm (0.5 kPa), assuming we select crops that might be more tolerant of these levels.

Oxygen Levels

- **Ambient**: If the CO_2 level is elevated to 1000 ppm, a 21% (21 kPa) normal ambient is probably the safest way to ensure crop health. Dropping oxygen to 10% (10 kPa) or even 5% (5 kPa) should not affect photosynthesis, but it could affect shoot-tissue respiration during dark cycles and root respiration at any time of day. Since the dissolved oxygen concentration (DO) is a linear function of the oxygen partial pressure above the fluid (in this case, the nutrient solution), and hydroponic growers usually like to keep the DO above 2 to 3 ppm, at least above 5% (5 kPa) will be required. Normal saturated DO below 21% is approximately 8 to 9 ppm.

- **Minimum tolerance**: The minimum oxygen level for healthy crop growth is 5% (5 kPa).
- **Maximum tolerance**: The maximum oxygen level for healthy crop growth is 25% (25 kPa). CO_2 levels should be maintained at 1000 ppm, or this 25% oxygen level will depress photosynthetic rates of C3 crops. Also, fire safety becomes a concern at this level.

Lighting

- **Ambient**: The optimal lighting range for relatively high crop productivity is 600 to 800 μmol m^{-2} s^{-1}.
- **Minimum tolerance**: Lighting requirements vary by crops, but some crops will continue to produce under lighting conditions as low as 150 μmol m^{-2} s^{-1}.
- **Maximum tolerance**: Grasses, such as wheat and rice, can tolerate up to 2000 μmol m^{-2} s^{-1}. Broad leaf crops can only tolerate up to 1000 μmol m^{-2} s^{-1}.

Maintenance Issues

- **Air Quality**: Volatile organics, especially ethylene gas, should be kept below 50 ppb.
- **Watering systems**: Although some types of bacteria are beneficial to plants and can provide plants with essential nutrients through symbiosis, it is important to monitor the nutrient solutions and plant-growth substrates for plant pathogens. Effective countermeasures for pathogen control are also essential.
- **Human access and automation**: While automation may well address much of the burden of biomass cultivation, hands-on human involvement will be necessary throughout the growth cycle. Besides correction of automation failures, the active handling and caring for plants can provide considerable psychological benefits. Assuming that human access is worthwhile, a low-pressure greenhouse, with the volume pressurized to 5 psi, should be entered by a crewmember who is wearing a mask that delivers 100% oxygen. While this low pressure will impact greenhouse structural strength and mass, it also will eliminate the time, risk, awkwardness, and fatigue of wearing a pressurized EVA suit even as it provides normal greenhouse support. The benefits and costs of this approach have yet to be adequately confirmed, however.
- **Planetary contamination**: Providing direct access to the greenhouse by shirtsleeved, oxygen-masked crewmembers will simplify the operations necessary to minimize the risks of forward and backward biological contamination. Direct linkage of the habitat to the greenhouse is recommended.

14.2 REFERENCES

1. Drysdale, A. E. and Hanford, A. J. Advanced Life Support Research and Technology Development Metric Document. 1999. Internal document. Available to JSC users only.
2. Baseline Crops for Advanced Life Support Program. Behrend and Henninger, Lyndon B. Johnson Space Center, Houston, TX. 1998. JSC internal document. Available to JSC users only.
3. Advanced Life Support Systems Integration, Modeling, and Analysis Reference Missions Document, page 24, Lyndon B. Johnson Space Center, Houston, TX. JSC internal document. Available to JSC users only.
4. ALS Program Requirements and Design Considerations Document, Lange, K. E., and Lin, C. H. Lyndon B. Johnson Space Center, Houston, TX. 1998. JSC internal document. Available to JSC users only.
5. *Space Physiology and Medicine, Third Edition*. Nicogossian, A, Huntoon C, and Pool S, editors. Chapter 5, "Spacecraft Life Support Systems." Philadelphia: Lea and Febiger, 1993.
6. Bubgee, B.G. and F.B. Salisbury. 1988. *Exploring the limits of crop productivity. Photosynthetic* efficiency of wheat in high irradiance environments. *Plant Physiol.* 88:869-878.

15 PLANNING FOR HUMAN OPERATIONS

15.1 TRAINING

Crew and ground-team training are essential to properly operate vehicle, payloads, and medical and logistics systems. Preflight training priorities must place a strong focus on crewmember safety. For short-duration missions, mission success training and detailed choreography are essential. Long-duration flights rely more heavily on basic skills, in-situ, just-in-time, and proficiency training. In all cases, clear, concise, and validated procedures are necessary. Except for a limited number of emergency procedures, all procedures should rely on readily accessible hardware with electronic displays, such as palmtop computers or head-mounted displays. This allows the same hardware that is used to guide in-situ training to be used during actual performance, and it also permits decision support to be seamlessly integrated into the system.

Ground-based facilities and personnel are a major influence on human mission costs. Adequately simulating tasks in advance of mission launch often requires multi-part task training facilities to reproduce all of the skills needed. Savings can be leveraged by gracefully evolving development test equipment and software into crew training hardware. Consolidation and co-location of training facilities, personnel, and equipment is another means of achieving cost efficiency. Designs should assume the need for low-maintenance, long-life, hands-off hardware turnaround, simple upgrades, and off-the-shelf components. Operations support facilities that would benefit a mission include:

- Computer simulations and system and environment models;
- Mock-ups for interiors and exteriors of habitats, airlocks, and rovers;
- A planetary surface simulator;
- An unloading system for microgravity and hypogravity;
- Vacuum chambers (crewless, crewed, environmental, dust-rated, and glove boxes);
- A neutral buoyancy laboratory;
- A self-taught training media for ground support and crew;
- Scale models; and
- Body and hand scanners.

15.2 EMERGENCY RESPONSE PROVISIONS

Provisions and design considerations for emergency responses are addressed in Chapter 3 on Vehicle Design, Section 3.4, and the psychosocial aspects of the emergency response are addressed in Chapter 7 on Psychosocial Interaction, Section 7.3.

15.3 ALLOCATION OF CREW TIME

Planning for the on- and off-duty time of crewmembers, as well as for scheduling plans, details, and constraints, are discussed in detail in internal documents from the JSC Mission Operations Directorate. These constraints were derived from both internal NASA Crew Procedures Management Plan and flight experience. Some attention is given to the allocation of crew time in Chapter 7 on Psychosocial Interaction, Section 7.1.

15.4 REFERENCES

[1] "Operations Concept Definition for the Human Exploration of Mars." Lyndon B. Johnson Space Center. 2000. JSC internal document. Available to JSC users only.

[2] Appendix K of the Space Shuttle Crew Procedures Management Plan. Lyndon B. Johnson Space Center. January 1992. JSC internal document. Available to JSC users only.

APPENDIX A: ATMOSPHERIC PRESSURE

A-1: BACKGROUND

A number of factors and parameters must be considered when selecting an atmosphere (e.g., an acceptable oxygen level and pressure regime) for a cabin or a space suit. The most important consideration is maintaining the crew's health. Other significant factors include operations and logistics, science activities, engineering trade-offs, and cost and safety. The atmosphere selected must ultimately be a trade-off or a compromise among all of the above-mentioned factors—with a close regard for the crew safety, comfort, and performance capabilities.

A primary purpose for the human presence in space exploration is to provide a base for doing scientific research, both in the vehicle habitat and in extensive and routine EVA. Because of the importance, extent, and expense of EVA, it is vital to maximize crew productivity during EVA. Selection of the atmospheric pressure level and composition has direct critical effects on technology and engineering requirements of the EVA systems, but has only moderate effects on engineering requirements of the life support and thermal control systems of the spacecraft cabin and habitat elements.

A-2: HISTORICAL PERSPECTIVE

A brief historical summary of space suit and habitat atmospheres is presented in Table A.1. As seen in this table, extensive experience has been gained with both low-pressure and sea-level environments.

Present space vehicles operate at standard sea-level atmospheric pressure, with the Shuttle Orbiter reducing the cabin pressure to 70.3 kPa (10.2 psia) prior to EVA operations. The ISS also operates at a nominal sea-level pressure to maintain compatibility with the Shuttle Orbiter and the Russian Soyuz vehicles, as well as to maintain a "control" atmospheric environment in which to conduct material and biological experiments in the microgravity environment. Unlike the Shuttle Orbiter, the ISS accommodates EVA operations without decreasing habitat pressure, but it requires a rigorous prebreathe protocol coupled with use of an airlock.

In previous space programs, habitat pressures have ranged from 34.5 kPa (5.0 psia) to the current 101.4 kPa (14.7 psia), while corresponding space suit system pressures to support these space missions have ranged from 26.2 kPa (3.8 psia) to 40.0 kPa (5.8 psia), as used by the Russians with their Orlan EVA suit for support of previous *Mir* operations and today for ISS support. It should be noted that to eliminate extensive overhead prebreathe operations, NASA has developed prototype advanced space suits that will operate at 57.2 kPa (8.3 psia).

For short-duration missions of 2 weeks or less, 100% oxygen atmospheres at pressures up to 34.5 kPa (5.0 psia) have been used (e.g., Mercury, Gemini, Apollo). Skylab also used a 34.5 kPa (5.0 psia) pressure regime, but had a mixed atmosphere of 70% oxygen and 30% nitrogen. The longest Skylab mission lasted 84 days.

Russian spacecraft (e.g., *Salyut,* Soyuz, *Mir*) environments have used mixed oxygen-nitrogen atmospheres—all at sea-level pressures. For EVA operations, this environment can present a higher risk level of crewmembers developing DCS ("bends") unless some element of compromise is established between the amount of prebreathe time at 100% oxygen and the space suit operating pressure, both of which are contingent upon vehicle cabin or habitat pressure. In the case of Russian EVA operations and based on extensive ground-based altitude chamber testing of over 500 subject runs, Russian EVA operations are conducted with a suit pressure of 40 kPa (5.8 psia) and only 40 to 60 minutes of 100% oxygen prebreathe time. Although this poses a slightly higher "bends ratio" risk—i.e., the operational values for the decompression ratio—ground-based test results, coupled with extensive EVA operational experience, make this a manageable and acceptable risk.

The bends ratio has historically ranged from zero to 1.84 and is driven by cabin atmosphere levels (based on the concentration of oxygen and pressure regime), prebreathe times, and the corresponding operational pressure level of a space suit. All space suit systems to date have used 100% oxygen atmospheres that range in pressure from 26.2 kPa (3.8 psia) to 40.0 kPa (5.8 psia).

It should be noted that adjustments to vehicle cabin or habitat pressures and subsequent prebreathing operations consume crewmember time, impact requirements for support equipment, and correspondingly affect overall mission overhead and productivity. Therefore, it is highly desirable and perhaps even mandatory to minimize or eliminate these operational requirements in future space missions where EVA may be a frequent or a routine function.

The ability of crewmembers to move quickly and efficiently among the vehicle cabin, habitat, and space suit atmosphere environments is important for crew safety, productivity, and overall mission success.

A-3: SELECTION FACTORS AND PARAMETERS

The following subsections are presented in the form of short synopses or vignettes of the various attributes, consideration factors, parameters, and constraints that influence the design and selection of cabin, habitat, and space suit atmospheres.

A-4: HUMAN PHYSIOLOGY

Hypoxia

For crew well-being, the most significant component in the atmosphere is oxygen. The partial pressure of oxygen at sea level on Earth is 21.0 kPa (3.06 psia). As the atmosphere is breathed, its components are diluted in the lungs by the addition of CO_2 and water vapor so that at the alveoli, where oxygen transfer to the blood takes place, oxygen partial pressure is 13.8 kPa (2.01 psia). The lower limit of oxygen concentration is bounded by the physiologic impact of hypoxia. Although ambient oxygen pressure and alveolar oxygen pressure decrease with increased altitude, the human body, through the process of acclimatization, can adapt (within limits) to a hypoxic environment and increase the lung's alveolar oxygen pressure.

A pressure of 25.8 kPa (3.75 psia) with 100% oxygen is required to maintain the lung alveolar pressure for the human body's blood oxygen saturation to be equivalent to sea level. A sea-level equivalent atmosphere can be achieved between 25.8 kPa (3.75 psia) and 101.2 kPa (14.7 psia) without seriously affecting the body's physiological responses by altering oxygen and nitrogen concentrations.

For total cabin pressures above 25.8 kPa (3.75 psia), the oxygen partial pressure can be controlled between 17.9 kPa (2.6 psia) and 34.5 kPa (5.0 psia) in order to vary the oxygen percent by volume in the atmosphere. Skylab crews could go from a ground-based sea-level launch environment to the 34.5 kPa (5.0 psia, with 70% oxygen and 30% nitrogen) environment of the Skylab cabin and be unable to tell the difference as far as energy expenditure and alertness were concerned. Skylab crews operated at this low pressure and atmosphere composition with only the following subjective notes or observations:

- The lack of convection resulted in a warm feeling, because the rate of heat rejection was reduced;
- The reduced water boiling point caused a cold feeling after showering due to rapid evaporation of water;
- Sweat rapidly evaporated during exercise, which helped body cooling; and
- Lower air density reduced voice projection and made whistling difficult.

Although oxygen pressures that are significantly below sea-level equivalent values induce hypoxia, an operational method for reducing the potential impacts of this effect during a long-duration mission would be to naturally acclimatize the crew to lower physiologically acceptable oxygen pressure levels. Prolonged exposure to low oxygen levels in the hypoxia zone requires acclimatization that can be part of normal adaptations required for long-duration spaceflights.

Oxygen Toxicity

The upper limit of oxygen acceptability is bounded by central nervous system toxicity above approximately 2.5 ATM (36.8 psia). For oxygen pressures from about 2.5 to 0.5 ATM (7.35 psia), pulmonary oxygen is limiting. At oxygen pressures below 0.5 ATM (7.35 psia), the limitation is uncertain, but there could be long-term limitations relating to a reduced circulating blood mass. Symptoms of oxygen toxicity appear to depend on both the oxygen partial pressure and the time of exposure. This potential condition would favor lower oxygen concentration levels without placing the crew in a hypoxia zone. Oxygen concentration is also critical to the materials selected for use inside the cabin, habitat, and space suit environments. As oxygen concentration increases, many materials become more flammable. Given concerns for the oxygen toxicity factor and the flammability factor, lower oxygen pressure regimes would be the better choice.

Table A.1. Historical Space Program Habitat and Spacesuit Atmospheres

		Habitat		Spacesuit [a]	Decompression		
Program	**Crew stay in Habitat (Days)**	**Total Pressure (kPa/psia)**	**Per-cent O_2**	**Total Pressure (kPa/psia)**	**O_2 Pre-breathe (Minutes)**	**Bends Ratio (R = ppN_2/Suit Pressure)[b]**	**Rationale for Habitat Atmosphere Selection**
Mercury	< 2	34.5/5.0	100	—	—	—	Low vehicle mass; reliability; adequate cooling; physiological compatibility for short missions.
Gemini	12	34.5/5.0	100	26.2/3.8	—	0	See Mercury above.
Apollo	12	34.5/5.0	100	26.2/3.8	—	0	See Mercury above.
Skylab	84	34.5/5.0	70	26.2/3.8	—	0.4	Long-duration crew stays necessitated reduced oxygen pressure for physiological reasons. Nitrogen selected as diluent due to some evidence that it may be physiologically beneficial as opposed to other potential diluents.
Shuttle Normal	10	101.4/14.7	21	29.6/4.3	240 (contingency)	2.7 reduced to 1.7 by contingency EVA prebreathe	Low development cost.
Shuttle EVA Preparation	1	70.3/10.2	28-31	29.6/4.3	40	1.77 reduced to 1.65 by pre-breathe before EVA	Increased crew productivity during EVA preparation.
Russian spacecraft	366	101.4/14.7	21	40.0/5.8	40-60		Assumed low technology development requirements.

[a] All space suits contain 100% oxygen atmospheres.

[b] Based on a controlling tissue compartment with a half time for inert gas elimination of 360 minutes.

Decompression Sickness

Also known as altitude decompression sickness (ADS), DCS results from the presence of nitrogen bubbles in the body after a reduction in ambient pressure. For example, if no preventive actions are taken, a change from a sea-level cabin pressure to a lower space suit pressure is a potential source of ADS. Protective measures involve reducing body tissue nitrogen content by partial equilibrium of the body to a breathing medium of 100% oxygen or an atmosphere containing a reduced partial pressure of nitrogen. A reduction of atmospheric pressure with dissolved diluent gas (nitrogen) in the body results in the creation of gas bubbles in body tissues. Current U.S. and Russian spacecrafts have atmospheres that are very much like that at sea level. This is a conservative atmosphere that ensures the well-being of the crew, minimizes flammability concerns, and allows concurrent microgravity adaptation without the masking effect of physiologic acclimatization or adaptation that might be imposed by a less benign atmosphere. Although a normoxic sea-level pressure is an attractive atmosphere for any mission, a number of alternative "operationally friendly" and physiologically safe atmospheres can be proposed for future long-term space missions that would help lower the risk of ADS. It should be noted that the task of the physiologist or physician who is involved in considerations of atmosphere selection is not to assure that the selected conditions are equal to Earth normal values, but to ensure that the atmosphere is physiologically acceptable. Physiologically acceptable approaches—which maximize engineering, cost, and safety factors—are strongly encouraged.

A-5: OPERATIONS AND LOGISTICS

EVA Prebreathe Time

EVA appears to be the chief source of ADS because of the sustained activity and the duration of exposure. Current U.S. space suit systems, used for Space Shuttle and ISS missions, operate at 29.6 kPa (4.3 psia) after a 4-hour, 100% oxygen prebreathe time or a 24-hour protocol involving a staged cabin decompression from 101.4 kPa (14.7 psia) to 70.3 kPa (10.2 psia) and a 40-minute oxygen prebreathe. The Russian EVA space suit system operates at a nominal pressure of 40.0 kPa (5.8 psia) from a 101.4 kPa (14.7 psia) cabin environment after a prebreathe time of between 30 and 40 minutes. Russian investigators have studied and verified long-staged pressure exposures through extensive ground-based chamber test activities, but they have not required or used long pressure-reduced stages to allow lower suit pressures while in flight. While both the U.S. and Russian prebreathe procedures would appear to involve some risk of ADS, there have been no reports of ADS during EVA operations in either the U.S. or Russian space programs.

EVA Crew Performance

High crew productivity is essential to IVAs and EVAs, and probably is even more essential for longer space missions and future planetary surface exploration. Specifically, EVA crew time spent prebreathing oxygen prior to decompression is basically unproductive, but may have a corresponding positive influence on productivity during the EVA if it allows a lower-pressure, more mobile space suit and glove system that induces less fatigue in EVA crewmembers. Many EVA tasks and operations that involve high-dexterity and/or high-mobility performance capabilities (especially those tasks and operations involved with future planetary surface operations) may be more difficult to achieve in a high-pressure space suit system (5.8 to 8.3 psia range), but they may be relatively easier to achieve in a lower-pressure space suit system (3.8 to 4.3 psia range).

Crew Movements Between Habitat Elements

If a habitat contains separate elements at different atmospheric pressures or compositions, airlocks would be required. Prebreathing would also be necessary to change locations within the habitat, if the pressure difference was great enough. Airlocks between habitat elements would also endanger crews by adding to the time required for crewmembers to move from one habitat element to another during emergencies (e.g., solar flares). Therefore, it is recommended that one common atmosphere be used as often as possible. However, there is a safety benefit in being able to close off areas of the habitat during a depressurization or other emergencies.

Transfer Between Lander and Habitat

Crew transfer between a lander and a surface habitat may involve decompression. If crew transfer involves wearing an EVA suit, the differences between pressure in the space suit and the lander will determine the time spent preparing for decompression. Common pressures between the lander cabin and surface habitat could eliminate decompression preparation time, but only if a pressurized rover is used instead of an EVA transfer.

Habitat Noise Level

The noise level in the habitat will be affected by atmospheric pressure. Lower pressures are expected to require higher volumetric-flow rates of air through thermal control and life support subsystems, leading to increased fan and air noise. As noted earlier, noise levels have been a serious problem in spaceflight—a problem that has yet to have been solved. Aside from the degradation of crew productivity due to constant irritation and sleep disruption, since acoustic noise can greatly harm verbal communication, it is a major safety hazard, particularly in emergencies.

Crew Verbal Communication

Cabin and habitat atmospheric pressure and composition may also affect face-to-face crew communications. Atmosphere diluents such as helium, which have a much lower density than the density of nitrogen, increase the frequency of the voice and, at high helium concentrations, may result in decreased intelligibility. Another potential diluent gas, argon, has been suggested as a replacement candidate for helium to alleviate voice communications problems. However, since argon is twice as soluble as nitrogen, the use of argon poses corresponding problems related to ADS and may seriously impact EVA-related operations.

Pressures lower than about 69.0 kPa (10.0 psia) interfere directly with sound transmission and will degrade a crewmember's ability to understand speech. This was shown by measurements of speech intelligibility during ground-based testing for the Skylab Program in a 34.5 kPa (5.0 psia) pressure chamber with ambient noise sources. Speech intelligibility of the Skylab on-orbit crewmembers may also have been affected by facial distortions that were caused by the microgravity environment and the lower pressure. Misinterpretation of oral statements caused by facial feature distortion associated with microgravity environments has been reported as being annoying or upsetting some crewmembers.

Logistics

Atmospheric pressure and composition affect the supply and resupply of gases. Oxygen and diluent gas must be carried in quantities sufficient to make up for structural leakage, airlock losses, and contingency decompressions. Since a higher pressure (whether in the habitat or in space suits) increases the rate of leakage, lower internal pressures would result in lower initial supply or resupply requirements. Other ways to reduce gas losses include increasing the efficiency of airlock gas recovery; reducing overall cabin, habitat, and space suit leakage sources; and producing gases in situ whenever possible. Suitable logistic countermeasures for the loss of a gas supply should be determined for future long-term space missions and planetary surface exploration where return and/or resupply may not be possible.

Flammability

In general, spacecraft-related fires will be more easily contained and extinguished in atmospheres that have lower oxygen concentrations. Higher habitat pressures, coupled with lower cooling air velocities, may reduce the rate of combustion by lowering oxygen concentration and rate of supply of oxygen to a fire in an enclosed space (e.g., as an electronics cabinet).

NASA materials flammability requirements are contained in NHB-8060.1.[4] The basic requirement is that materials are nonflammable or self-extinguishing when exposed to a standard ignition source in an upward flame propagation test 1.[4] Materials that fail this requirement must be restricted such that they are nonflammable or non-propagating in the "as-used" condition. Flammable materials may be acceptable if they are located inside a fireproof container that has no internal ignition sources that can lead to fire propagation. The acceptability of such a configuration can be frequently determined by analysis, but a standard container flammability test (e.g., tests 8 and 9[4]) is conducted when analysis is inconclusive.

When assessing the flammability of spacecraft materials, ignition sources are assumed. The absence of ignition sources is not a justification for acceptance of flammable materials, although it may be used in conjunction with other acceptance rationale. This philosophy was implemented in the aftermath of the Apollo 204 fire and has been the basis for material acceptance for all subsequent U.S. crewed spaceflight programs since. The effect of these requirements is to ensure that all major-use materials are nonflammable or self-extinguishing. Flammable materials are restricted to minor use and are separated from each other such that they are non-propagating in the "as-used" configuration. The following are some general considerations concerning materials selection and atmosphere compositions regarding the management of flammability requirements:

- Materials flammability is strongly dependent on oxygen percentage by volume and weakly dependent on oxygen partial pressure;
- At constant oxygen partial pressure, materials flammability decreases with increasing total pressure;
- These same considerations apply to fire extinguishment; and
- Materials flammability testing in a 1g environment is considered a conservative approach for determining flammability concerns in microgravity environments.

NASA has extensive experience in control of materials flammability in a 30% oxygen, 70.3-kPa (10.2-psia) atmosphere based on Space Shuttle flight operations. Although roughly 85% of materials are flammable in the Space Shuttle environment, sufficient nonflammable materials are available to allow a choice of nonflammable materials for almost all applications. From a strict flammability standpoint, the 70.3-kPa (10.2-psia), 30%-oxygen environment would be the recommended atmosphere for future long-term space missions. Cost impacts would have to be traded against increased materials cost for consideration of higher percentage oxygen, lower pressure atmosphere regimes.

A-6: LABORATORY SCIENCE

Life Sciences (Animal and Plant Experiments)

Laboratory users must conduct additional preflight testing and verification on their hardware if mission designers choose a lower-than-sea-level pressure for the cabin or habitat. The additional testing and verification will be generated by the need for data on science packaging characteristics related to both total pressure and oxygen concentration (e.g., material off-gassing, flammability, and air cooling). Also, ground-based reference (control baseline) experiments should be performed at conditions similar to the actual spaceflight atmosphere conditions to reduce the number of experimental variables. Ground-based experiments in high-altitude (3000 m/10,000 ft) cities might be used as analogs for spaceflight conditions at pressures as low as 70.3 kPa (10.2 psia).

Experimental animal parameters that are known to be affected by habitat pressure and/or composition include but may not be limited to:

- Antibody production (guinea pig);
- Susceptibility to viral infection (mice);
- Recovery time from infection (mice); and
- Gas exchange (chicken eggs).

Plant parameters that are known to be affected by habitat pressure and/or composition include but may not be limited to:

- Photosynthesis (wheat, rice, soybean);
- Water loss by transpiration; and
- Production of toxic gases.

If a space-based or a planetary surface-based habitat is used to generate life science data under atmospheric conditions that differ significantly from Earth sea level, additional ground-based life science research would be required to establish a suitable control database. Development of instruments to measure experimental variables may also be affected by different atmospheric conditions.

Materials Sciences

Materials science experiments may be influenced by cabin or habitat atmospheric pressure and/or oxygen concentration levels. Affected parameters may include but are not limited to:

- Use of negative pressure as a method of material containment;
- Solubility and/or chemical composition;
- Acoustics;

- Combustion and chemical reactions; and
- Heat transfer through surrounding air.

Use of Off-the-shelf Equipment

The use of off-the-shelf equipment will be inhibited by increasingly stringent flight requirements at either lower atmospheric pressures and/or higher oxygen concentrations.

A-7: HABITATION SYSTEMS

Air Cooling

The performance of liquid coolant loops in the thermal control system is not affected by total cabin or habitat atmospheric pressure. To provide required air cooling to the crew and heat-generating equipment in the cabin and habitat elements, a thermal control system has to flow a certain rate of air mass through the elements, independent of cabin or habitat pressure. As the total pressure and air density decreases, the required volumetric flow rate of the air-cooling subsystem increases. A similarity analysis shows that the blower power requirement of the air-cooling subsystem is inversely proportional to the square of the total cabin or habitat pressure. For example, it normally takes 250 to 500 W to provide air cooling in an ISS-sized habitat module at 101.3 kPa (14.7 psia). The blower power requirement will be doubled to 500 to 1,000 W at 70.3 kPa (10.2 psia) and quadrupled to 1.0 to 2.0 kW at 50.6 kPa (7.35 psia). In short, although the thermal control system does not impose a lower limit on the range of the cabin or habitat pressure, the power penalty incurred to the air-cooling subsystem practically limits the total pressure to 50.6 kPa (7.35 psia) or higher.

Use of Off-the-shelf Equipment

In addition to the previous comments (see “Laboratory Science”) regarding the use of off-the-shelf equipment, the following specific parameters are anticipated to be directly affected:

- Materials selection (off-gassing, oxidation/corrosion, flammability);
- Air cooling of equipment (velocity and density);
- Sound levels (noise production from fans and sound transmission);
- Certification and verification (preflight testing at operational conditions); and
- Commonality with other space program equipment (equipment design).

A-8: LIFE SUPPORT

Plant Growth

Plant growth for life support and/or food production may be affected by habitat atmospheric pressure and composition in several ways. Photosynthesis, transpiration, and the release of toxic gases all vary in relation to pressure, oxygen concentration, or CO_2 concentration. The CO_2 concentration affects plant growth, with enriched CO_2/low-oxygen concentration atmospheres producing higher photosynthesis rates. Wheat germination and early growth under atmospheric pressures as low as about 6.0 kPa (0.87 psia) have been shown to be possible. Under these conditions, seedling characteristics—e.g., leaf size and chlorophyll content—were significantly lower than those of control seedlings grown under Earth atmospheric conditions. Germination rate was also significantly lower except when the atmosphere was composed of 99.1%oxygen. Oxygen is required for wheat germination and growth during its pre-photosynthetic phase. Moreover, microorganism activity, ecology, and population dynamics may be affected by habitat atmospheric pressure and composition. Bioengineering of plant-growth characteristics should be considered to accommodate appropriate atmospheric pressures and concentrations that will be suitable to future space missions.

Animal Growth

Although not fully understood or investigated to any certain conclusion, food-crop animal growth may also be affected by habitat atmospheric pressure and/or composition. Known effects on laboratory animals were identified previously in this document under “Life Sciences (Animal and Plant Experimentation).”

Rehumidification

Life-support subsystem heat exchangers that will remove atmospheric humidity will tend to over-condense the humidity at atmospheric pressures substantially lower than 70.3 kPa (10.2 psia). An additional non-condensing heat exchanger or water spray rehumidifier may be required for low habitat pressures. Heat exchangers that are designed specifically for planetary surface habitats will not necessarily have this tendency.

Thermal Control

In addition to comments regarding air cooling (see "Habitation Systems"), a cooling fan's power and, potentially, its size must be increased at reduced atmospheric pressures to maintain equal mass-flow rates. The mass and volume of air-cooling components—e.g., fans, ducts, and filters—are increased in size at reduced atmospheric pressures to maintain equal pressure drop with the increased volumetric flow rate. In general, a thermal control system would not have to physically change greatly if the cabin or habitat could afford the extra power for lower atmospheric pressures.

A-9: HEALTH CARE

Habitat atmospheric pressure and composition may affect the health care system hardware and operations. Health care systems measure or monitor physiologic variables associated with work capacity, lung function, blood chemistry, tissue oxygenation, immune system function, and other physiologic functions that are likely affected by atmospheric pressure and composition. The exact nature of these effects, including the effects of long-duration exposure to atmospheres that differ greatly from sea level, is not totally understood and may be a confounding factor in medical treatment and diagnosis. Examples of parameters that might affect long-term health, ability to perform, or survival of the crew are changes in pressure, dust or particulate matter, temperature, water vapor, and concentrations of oxygen, CO_2, and inert gas. These effects, which could be acute or chronic, could occur when a crewmember moves from one mission task to another or from one mission environment to another.

Medical care will include rescue and resuscitation of crewmembers, delivering oxygen therapy and ventilation support, providing fluid therapy, performing emergency surgery, and offering intensive care and hyperbaric treatment. In other than standard sea-level environments, some medical diagnostic or therapy equipment may not function properly. Much research also needs to be performed to differentiate normal physiologic adaptation to an abnormal environment from pathophysiology.

A-10: CREW ACCOMMODATIONS

Consumables Packaging

The design of packaging for crew consumables, such as food, is affected by the difference between Earth sea-level pressure and cabin or habitat pressure. If a sea-level facility packages consumables for launch, trapped air will exert pressure on the packaging materials when exposed to a lower habitat pressure. Some foods can be vacuum-packed, thereby preventing this effect; but other foods, such as bread, cannot be vacuum-packed without destroying palatability. Frozen foods are also packaged with an air-filled space. Earth-based food packaging for habitat pressures that are much lower than sea level could require construction of specialized food production and packaging facilities on Earth, which would be pressurized to match the mission's habitat pressure. Foods would then be produced, packaged, transported, and stored for use at the same ambient pressure. Such a food preparation facility would be expensive to construct and operate, however.

Food Cooking Time

Lower habitat pressure reduces the boiling point of water and food substances. Reduced pressure impacts food recipes and increases cooking times. The relationship of cooking time to temperature is food-dependent. When cooking in-situ produced food, the crew time required to produce the food will increase with lower habitat pressures, thus potentially affecting IVA crew productivity. Using a pressure cooker for some foods can reduce preparation times.

Generally, prepared food items are heated below the boiling point of water and served around 60 °C (140 °F) to deter the growth of microorganisms. Food-borne illness, which is caused by microorganisms, is the chief concern for the health and safety of the crew. All microorganisms are killed by heat if the temperature is high enough and applied for a sufficient time. The relationship of destruction time to temperature is microorganism-dependent. Destruction temperature ranges from 60 °C (140 °F) for vegetative bacteria to 121.1 °C (250 °F) for heat-resistant, spore-forming bacteria.

A-11: STRUCTURES AND MECHANISMS

Pressure Shell Mass

Cabin and habitat atmospheric pressure and composition may affect structures and mechanisms subsystem hardware and operations in several ways. Pressure vessel design may be more severe for higher pressure regimes; and seals around hatches and penetrations will be subject to higher loads and will require closer design tolerances to reduce leakage. In this case, higher internal atmospheric pressure requires more exacting design and tolerance factors. Pressure vessel mass may be affected by internal pressure in some other cases. The requirements are related to internal atmospheric pressure; but other considerations, such as launch and landing loads, may also drive the thickness. When internal pressure becomes a pressure wall driver, increased pressure will result in a higher structural mass. On the other hand, use of cabin or habitat internal atmospheric pressure as a means of structurally stiffening for launch and landing may be beneficial in terms of overall mass savings. In this case, higher internal pressure may produce additional stiffening and produce a mass savings. Habitat elements at different pressures would require airlocks between elements, which would result in an increased amount of structure, mass, and system complexity.

A-12: EVA ACCOMMODATIONS

Airlock Gas Recovery

Habitat atmospheric pressure and composition may affect EVA accommodations subsystem hardware and operations. Airlock gas losses during depressurization will not be affected by habitat pressure, since the final pressure before evacuation depends on the depressurization pump technology and not on initial pressure. During normal pressure operations, the airlock and other habitable volumes will leak less gas to the outside environment at lower pressures. Airlock pump mass, volume, and power are not significantly impacted by initial airlock pressure. The airlock pump design is driven by the final pressure before evacuation. Power expended during the initial stages of depressurization is very low compared to power expended when the airlock pressure reaches low values such as 3.4 to 6.9 kPa (0.5 to 1.0 psia).

Space Suit System Mass and Mobility

A major issue that strongly affects the overall weight, design, and mobility functions of future space suit systems is the pressure level and atmospheric composition chosen for operational use. From both test and functional experience, EVA crew task productivity has been shown to be related to space suit operational pressure levels. This is especially noticeable by suited subjects with pressurized gloves, who experience corresponding levels of reduced mobility and increased hand fatigue. Higher suit pressure also tends to drive the requirement for increased structural thickness and associated hardware weight increases. The most straightforward method of increasing crewmember productivity and decreasing fatigue is to lower suit pressure. From an EVA standpoint, suit pressure should be selected from a range of 26.2 to 29.7 kPa (3.8 to 4.3 psia). Within this range, current space suit technology yields excellent body and hand mobility and dexterity capabilities, and it also enables a high degree of productivity. Within this operational pressure range, the atmosphere will also provide good breathing for performing various work loads and will be suitable for ventilation and cooling purposes.

A-13: REFERENCES

[1] Conkin J. Report No. NASA-TM-2000-210188, “The Mars Project: Avoiding Decompression Sickness On A Distant Planet.” National Space Biomedical Research Institute. May 2000.

[2] Waligora J, Horrigan D, and Nicogossian A. “The Physiology of Spacecraft and Space Suit Atmosphere Selection,” *Acta Astronautica*, 23:171–177. 1991.

[3] Hills B. “Compatible atmospheres for a space suit, space station, and shuttle based on physiological principles.” *Aviation, Space, and Environmental Medicine*. November 1985.

[4] NHB-8060.1. “Flammability, Odor, Off-gassing, and Compatibility Requirements and Test Procedures for Materials in Environments that Support Combustion.” Revision C. Washington, D.C.: National Aeronautics and Space Administration. April 1, 1991.

APPENDIX B: WASTE

The following tables contain provide detailed information on various waste components.

Table B.1: Waste Components

Component	Kg/Person/Day	Lbs/Person/Day
Human waste (dry weight)		
Feces	0.03	0.07
Urine	0.06	0.13
Shower/hand wash [a-c]	0.01	0.02
Sweat	0.02	0.04
Total	0.12	0.26
Inedible plant biomass (dry weight)		
Protein	0.25	0.56
Carbohydrate	0.29	0.64
Lipids	0.07	0.16
Fiber	1.09	2.41
Lignin	0.11	0.24
Total [h]	1.82	4.01
Trash		
Hygiene		
Clothes and towels	0.0007	0.0015
Toilet paper [d]	0.0230	0.0507
Pads and tampons [d]	0.0035	0.0077
Menstrual solids [d]	0.0004	0.0009
Paper [d]	0.0650	0.1433
Subtotal	**0.0926**	**0.2041**
Packaging material [i]		
Snack packaging	0.060	0.132
Food containers [e]	0.470	1.036
Plastic bags [e]	0.060	0.132
Food remains [f]	0.100	0.220
Frozen	0.050	0.110
Refrigerated	0.020	0.044
Ambient	0.410	0.904
Beverage [j]	0.128	0.232
Straws	0.020	0.044
Subtotal	**1.318**	**2.906**
Paper		
Wipes	0.140	0.309
Tissues	0.020	0.044
Facial tissues	0.030	0.066

Component	Kg/Person/Day	Lbs/Person/Day
Waste	0.004	0.009
Subtotal	**0.194**	**0.428**
Tape		
Masking	0.002	0.004
Conduit	0.004	0.009
Duct	0.035	0.077
Subtotal	**0.041**	**0.090**
Filters		
Air	0.0244	0.0540
Pre-filters	0.0300	0.0660
Subtotal	**0.0544**	**0.1200**
Miscellaneous		
Teflon	0.0110	0.0240
PVC	0.0005	0.0010
Subtotal	**0.0115**	**0.0250**
Total	**1.7115**	**3.7731**

[a] Shower/hand wash soap = 10 g/person/day.

[b] Clothes wash = 25 g/person/day.

[c] Hygiene latent water (0.43 kg/person/day), food preparation latent water (0.03 kg/person/day), and laundry latent water (0.06 kg/person/day).

[d] Cellulosic.

[e] Polyethylene.

[f] Twenty-five percent protein, 51% carbohydrate, 8% lipid, and 16% fiber.

[g] High-efficiency particle accumulators.

[h] Derived from Hanford (2002).

[i] Derived from Grounds(1991).

[j] Derived from Grounds (1991b).

[k] NASA (1998).

[l] ISS air filters (2.15 kg), 29 total.

Table B.2: Inedible Biomass Calculation for a 20-Day Diet Using All Available Crops [a]

Crop	**Average Consumption** (kg/person/day)	Harvest Index	**Inedible Biomass** (kg/person/day)
Soybean	0.086	0.37	0.146
Wheat	0.24	0.4	0.360
White potato	0.2	0.7	0.086
Sweet potato	0.2	0.7	0.086
Rice	0.029	0.4	0.044
Peanut	0.013	0.27	0.035
Tomato	0.22	0.48	0.238
Carrot	0.041	0.9	0.005

Crop	**Average Consumption** (kg/person/day)	Harvest Index	**Inedible Biomass** (kg/person/day)
Cabbage	0.0038	0.9	0.000
Lettuce	0.024	0.95	0.001
Dry bean	0.013	0.37	0.022
Celery	0.013	0.7	0.006
Green onion	0.048	0.5	0.048
Strawberry	0.016	0.4	0.024
Peppers	0.049	0.4	0.074
Pea	0.0075	0.37	0.013
Mushroom	0.0011	0.5	0.001
Snap bean	0.01	0.37	0.017
Spinach	0.04	0.8	0.010
Crop subtotal	1.2544	n/a	1.215
Resupplied food	0.37	n/a	0.037
Total	1.62	n/a	1.25

NOTE: Inedible biomass ratio = 0.77.

[a] Crops for 20-day diet chosen by NASA's Advanced Life Support Program.

Table B.3: Inedible Biomass Calculation for a 20-Day Diet Using Carbohydrate Crops [a]

Crop	**Average Consumption** (kg/person/day)	Harvest Index	**Inedible Biomass** (kg/person/day)
Soybean	0	0.37	0.000
Wheat	0.22	0.4	0.330
White potato	0.17	0.7	0.073
Sweet potato	0.18	0.7	0.077
Rice	0	0.4	0.000
Peanut	0	0.27	0.000
Tomato	0.21	0.48	0.228
Carrot	0.04	0.9	0.004
Cabbage	0.0025	0.9	0.000
Lettuce	0.021	0.95	0.001
Dry bean	0.013	0.37	0.022
Celery	0.0075	0.7	0.003
Green onion	0.034	0.5	0.034
Strawberry	0	0.4	0.000
Peppers	0.031	0.4	0.047
Pea	0.0038	0.37	0.006
Mushroom	0.0013	0.5	0.001
Snap bean	0.01	0.37	0.017
Spinach	0.04	0.8	0.010

Crop	Average Consumption (kg/person/day)	Harvest Index	Inedible Biomass (kg/person/day)
Crop subtotal	0.9841	n/a	0.854
Resupplied food	0.5	n/a	0.05
Total	1.48	n/a	0.90

NOTE: Inedible biomass ratio = 0.61.

[a] Crops for 20-day diet selected by NASA's Advanced Life Support Program.

B.4: REFERENCES

1 Hanford A. "Advanced Life Support Baseline Values and Assumptions Document." NASA Johnson Space Center, Houston, TX. May 2002. JSC Internal document. Available to JSC users only.

2 Grounds P. "STS-35 Trash Evaluation Report." NASA TM SP4-91-041. March 1991.

3 Grounds P. "Beverage Pouches." NASA TM SP4-91-081. June 1991.

4 "ECLSS Architecture Description Document." Vol. 2, Book 2, Revision A. 1998. JSC internal document. Available to JSC users only.

APPENDIX C: SENSORY ADAPTATION

C-1: VESTIBULAR SYSTEM

Two effects of spaceflight on the human vestibular system may impair crew performance: (1) spatial disorientation and (2) SAS. Both spatial disorientation and SAS likely stem from a conflict between vestibular and other sensory input, such as vision, when compared to expectations of a 1g environment. Although approximately 50% of spaceflight crewmembers experience these symptoms, individual susceptibility cannot be reliably predicted. Symptoms, which are more pronounced during the first 2 to 4 days of microgravity exposure, typically dissipate over time. Effects also become progressively less pronounced in individuals with more space experience.

Serious readaptation symptoms occur after return to Earth from a long period in microgravity. The symptoms become more severe the longer an individual stays in microgravity. Russian cosmonauts who spent about a year in the microgravity environment were barely able to move upon return to Earth. Even with much shorter stays in microgravity, the return to the terrestrial gravitational environment is often difficult. A quick motion of the head, for example, can induce all the symptoms of SMS, including vomiting.

Crewmembers will likely experience adaptation symptoms when first entering a reduced-gravity environment on a planetary surface. The brief trip to the Moon caused few adverse effects in the adaptation to 1/6g, but there is no information on the effects that may occur when a crew spends 6 to 8 months in microgravity and then transitions to the 0.38g of Mars. A change from 6 months of 0g to 0.38g might be worse than a return to 1g. It seems unlikely, but we don't know. Based on our experience with 0g to 1g transitions, we might hypothesize that the crew would be able to do very little surface exploration and science during the first month of a Mars stay because of their physical condition. During the first month on Mars, crewmembers may spend much of their time, when not occupied with mission-critical tasks, undergoing a slow and gentle process of rehabilitation. Also, the precise effect of multiple gravity transitions—from 1g to the microgravity of LEO, then acceleration to an orbit around Mars, and finally from Mars orbit to 0.38g—is also not known.

Spatial disorientation is exhibited primarily as postural and movement illusions (e.g., induced perception of tumbling or spinning, vertigo, and dizziness), and can occur when the eyes are open or closed. SAS symptoms, which are similar to Earth-based motion sickness, can vary from individual to individual, and can range from stomach "awareness" or nausea to repeated episodes of vomiting, and may be accompanied by pallor and sweating. As with similar conditions on Earth, crewmembers can maintain a basic level of performance with SAS symptoms, but it is advisable to allow an adaptation period after major gravity transitions. Some crewmembers who exhibit severe symptoms show significant performance decrements, other crewmembers show less severe performance decrements. These effects may become particularly serious during emergencies.

It is difficult to design countermeasures for this problem, and anti-motion sickness drugs (typically a scopolamine/dexedrine combination) do not totally prevent symptoms. Restricting head movements helps, and prior flight experience also reduces symptoms. Biofeedback can both prevent and reduce symptoms to some extent.

C-2: VISION

Little is known about the effects of microgravity on the human vision system, especially during long-duration, exploration missions. Most data are anecdotal evidence.

The most important effects on vision are derived from acceleration and vibration. Because acceleration effects depend on the direction of force vector, high accelerations can render visual displays useless. Vibration-related visual effects range from minimal to severe, with severity dependent on the frequency and amplitude of vibration. With severe vibration, vision can be seriously affected, decreasing visual display and instrument readability and degrading overall performance. Visual displays and instruments that will be used during high vibration periods (e.g., launch, reentry) should be designed to account for this reduced readability (e.g., character size and contrast; sufficient illumination for photopic vision).

In the space environment, differences in light transmission and reflectance reduce visual perceptual cues. Understandably, this is especially pronounced during an EVA. Rapidly changing brightness levels over a broad intensity range, high contrasts (caused by reduced light scattering in the absence of an atmosphere), and rapid brightness drop-off combine to significantly reduce visual cues and may affect crew performance.

Anecdotal reports from crewmembers aside, there is no substantive objective evidence to verify that normal vision alters in microgravity. Therefore, vision under nominal conditions in space should be considered reliable—at least across the mission durations experienced thus far.

Display Design Considerations

High accelerations can render visual displays useless. Vibration-caused visual effects may be minimal to severe, depending on the frequency and amplitude of a vibration. Severe vibration can impair display and instrument readability and make visual performance difficult or impossible. Visual displays and instruments used during high-vibration occurrences (e.g., launch or reentry) should be designed to increase readability—e.g., by increasing character size and contrast. For additional information on display design considerations, see Chapter 8 on Crew Accommodations, section 8.3.

C-3: HEARING

There is no evidence that human hearing is altered in microgravity. However, noise and vibration in space caused by fans that circulate the internal air and cool equipment is a problem. Even low-level noise can interfere with normal communications and increase fatigue through sleep disturbance and sensory irritation. Extreme noise and extended noise exposure can cause pain and permanent hearing loss.

Design Considerations

Sound-dampening, vibration-absorbing materials can greatly reduce noise and vibration within a spacecraft or habitat. These materials should be incorporated into payload racks and fan housings, as well as around other high-noise and vibration machinery. Special care should be used when selecting materials to enclose crew sleep areas. For additional information on noise considerations, see Chapter 11 on Crew Environment, section 11.2.

C-4: SMELL AND TASTE

Microgravity causes a head-ward shift in body fluids and nasal congestion, thereby reducing smell and taste. Crewmembers regularly increase the seasoning in their food because of this decrease in taste. Fortunately, humans do not strongly rely on the sense of smell for information.

The internal atmosphere of a spacecraft in microgravity contains a higher number of particulate and microbial contaminants because particles do not settle out. These contaminants can cause odors and disease during a long-duration mission. Microbial contaminants will cause sickness if not properly managed.

Design Considerations

- **Food**: Prepackaged food must be highly acceptable by crewmembers to ensure that they maintain an appropriate caloric intake. The inclusion of condiments and seasonings in the food system allows crewmembers to adjust food according to personal taste. See Chapter 9 on crew accommodations for more information on food system considerations.

- **Smell**: It will be important to keep surfaces clean during long-duration missions. Surfaces in the galley and personal hygiene areas should be constructed of mold- and bacterial-growth-resistant materials. Stowage should include a selection of low-fume, nontoxic cleaning products. The air system must be designed to filter and circulate the atmosphere throughout the vehicle.

The vehicle must also be equipped with multiple sensors for detecting smoke as well as chemical, gas, and biological leaks. Since the crewmembers' sense of smell will be diminished and cannot be relied on to sense slight changes in atmospheric odors, sensors must detect spills and leaks before they become health hazards. See Chapter 11 on Crew Environment, section 11.8 for more information.

APPENDIX D: CREW RESOURCE MODEL

D-1: ABOUT THE MODEL

This resource model considers system-level components only and **excludes** the mass and volume of several common components of the habitat architecture and life support system, including:

- Potable and hygiene water, because the quantity needed depends on onboard reserves and the reclamation system used;
- The structural and integration hardware needed to install or attach crew accommodations (e.g., lockers, racks, dividers, etc.);
- Spares or replacement parts, because the quantities needed are based on system reliability; and
- Contingency supplies, because the quantities needed require separate analysis of potential failures

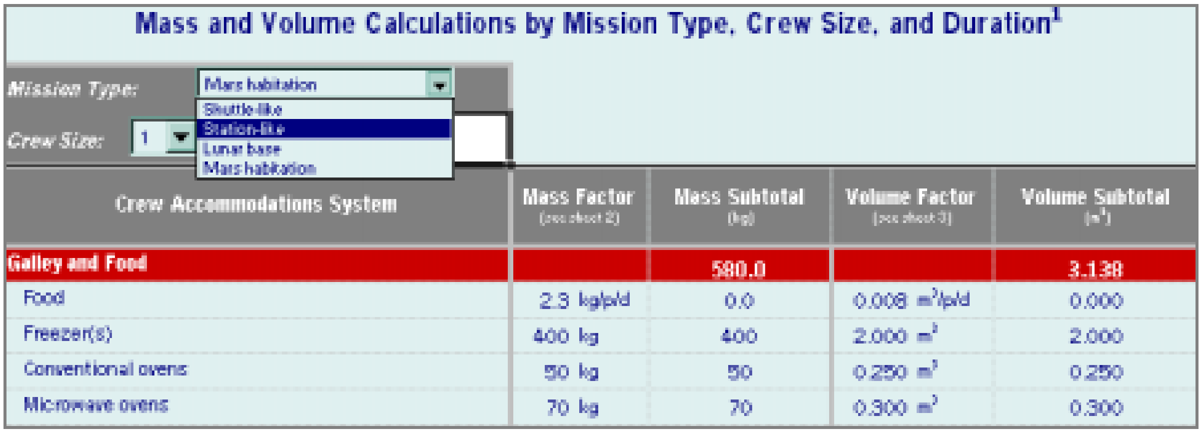
The suggested mass and volume factors used in this resource model are estimates based on historical data, with some educated guesses that assume new technologies with more efficient designs will be available.

The Excel file includes a number of spreadsheets that permit you to make basic calculations and compare crew accommodations for at least four types of mission scenarios. Mass and volume factors for each mission scenario are provided for 11 accommodations systems (see Tables D.1 and D.2 at the end of this appendix or the spreadsheet for the actual values). While these factors are educated or best guesses, they should be changed to accommodate the particular parameters of each unique mission design. The calculations spreadsheet allows you to enter the basic parameters (type, crew size, and duration) of a mission design and produces total mass and volume amounts. The system subtotals spreadsheet summarizes the calculated data by system, in both table and graphic format, for easy comparison to other designs.

D-2: INSTRUCTIONS

Open the file "model_v5.xls." The tabs along the bottom of the Excel spreadsheet will provide you with all of the values and functions required to make calculations and comparisons.

1 **Enter parameters**: Click on the spreadsheet called "Calculations" to enter the parameters of the mission (Figure D-1). In the upper left corner of this sheet are three cells or menus that allow you to enter your particular parameters.



Mass and Volume Calculations by Mission Type, Crew Size, and Duration[1]

Mission Type: Mars habitation

Crew Size: 1

Crew Accommodations System	Mass Factor (see sheet 2)	Mass Subtotal (kg)	Volume Factor (see sheet 3)	Volume Subtotal (m^3)
Galley and Food		580.0		3.138
Food	2.3 kg/p/d	0.0	0.008 m^3/p/d	0.000
Freezer(s)	400 kg	400	2.000 m^3	2.000
Conventional ovens	50 kg	50	0.250 m^3	0.250
Microwave ovens	70 kg	70	0.300 m^3	0.300

Figure D-1: Entering Parameters into the Calculation Spreadsheet

2 **Mission Type**: Select one of the four mission types that most nearly approximates your mission design. (You can alter the actual mass or volume factors to further tailor the resource model to your design.)

- *Shuttle-like mission*: Generally a short, 14- to 21-day mission with little need for self-sufficiency.

- *Station-like mission*: Approximately 90 days or more in duration, an ISS-like mission can take advantage of Earth resupply and proximity but could benefit from some self-sufficiency.
- *Lunar base*: Expected to be about 180 to 365 days; a mission where moderate self-sufficiency is needed.
- *Mars habitation module*: Occupied for an extended period of time—6 to 8 months in transit or up to about 700 days on the surface—and requiring considerable self-sufficiency.

3 **Crew size**: Select a value (up to 10) from the pull-down menu.

4 **Duration**: Enter the mission duration in days. Upon hitting return, the spreadsheet automatically calculates the mass and volume of crew accommodations and totals the items. The factors used for calculation and their units are both shown. Some items in the model are affected by duration and number of crew, and some are not. For example, if you select "Mars habitation" for the mission type, a crew size of six, and type in "600", you have indicated that you are interested in a surface habitat model rather than a transit habitat one.

5 **Review results**: By selecting the "Systems Subtotals" tab, you can view the distribution of masses and volumes. This is NOT the final step of the model. As with any model, you must look carefully at the data and decide whether it truly fits your design.

6 **Tailoring the model**: Based on the particular needs of your mission design, you may want to modify values or add or remove elements from the model. The model should not be slavishly applied, but it should be modified to tailor it to your specific mission application. If a particular element does not apply to a particular mission, it should be allocated zero resources in the model. If you need more of something, you'll need to increase the value in the appropriate table of factors. On the following pages, the tables of mass and volume factors used in the model are provided.

D-3: REFERENCES

[1] Stilwell, D., Boutros, R., and J. Connolly. Chapter 18, "Crew Accommodations," in *Human Spaceflight Mission Analysis and Design*. New York: McGraw Hill Companies. 1999.

Table D.1: Mass Factors for Crew Accommodations in Various Mission Types [3]

Factors given are for hypothetical Shuttle-like, station-like, lunar base, and Mars habitation missions, showing how the model might be customized for different scenarios. The notation "kg/p/d" indicates kilograms/person/day.

Crew Accommodations System	Mass Factors					Assumptions and Notes
	Shuttle-like	Station-like	Lunar base	Mars habitat	Units	
Galley and Food System						
Food	2.3	2.3	2.3	2.3	kg/p/d	Minimum is 1.8 kg/p/d (current Shuttle allowance)
Freezer(s)			100	400	kg	Empty freezer (no food mass included)
Conventional ovens	50	50	50	50	kg	
Microwave ovens	70	70	70	70	kg	Assumes two ovens
Cleaning supplies	0.25	0.25	0.25	0.25	kg/d	Includes solvents and supplies for cleaning galley and ovens
Sink and spigot	15	15	15	15	kg	For food rehydration and drinking water
Dishwasher			40	40	kg	
Cooking/eating supplies	0.5	0.5	2	5	kg/p	
Waste Collection System						
System	45	45	45	90	kg	Assumes one toilet for each mission except Mars (two toilets)
Supplies	0.05	0.05	0.05	0.05	kg/p/d	
Contingency collection mittens/bags	0.23	0.23	0.23	0.23	kg/p/d	
Personal Hygiene						
Shower	0	75	75	75	kg	
Handwash/mouthwash faucet	8	8	8	8	kg	
Personal hygiene kit	1.8	1.8	1.8	1.8	kg/p	

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[3] See References.

Crew Accommodations System	Mass Factors					Assumptions and Notes
	Shuttle-like	Station-like	Lunar base	Mars habitat	Units	
Hygiene supplies	0.075	0.075	0.075	0.075	kg/p/d	Consumables
***Clothing*[4]**						
Clothing	69	214	69	99	kg/p	Assumes 2.3 kg/p for pme complete change of clothes
Washing machine	0	0	100	100	kg	
Clothes dryer	0	0	60	60	kg	
Recreational Equipment						
Personal stowage	10	25	25	50	kg/p	
Housekeeping						
Vacuum	13	13	13	13	kg	Prime and two spares
Disposable wipes for housecleaning	0.15	0.30			kg/p/d	
Trash compactor/trash lock	0	150	150	150	kg	
Trash bags	0.05	0.05	0.05	0.05	kg/p/d	
Operational Supplies and Restraints						
Operational supplies	10	20	20	20	kg/p	Includes diskettes, Ziplocs, and tape
Restraints	25	83	50	100	kg	
Maintenance						Assumes all repairs in habitable areas
Hand tools and accessories	100	200	200	300	kg	

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[4] This is an important trade to consider for long-duration mission because it involves supplying complete sets of clothes for the duration of the mission versus using a clothes-cleaning system. By default, this model assumes that a washer/dryer system is not appropriate for Shuttle- or ISS-like missions and that the clothing mass for lunar/Mars missions includes cleaning and reuse of clothing. Generally, the following rule of thumb applies: If the mass (washer + dryer + cleaning supplies) < mass of clothing (duration*crew size*0.46 kg/p/d), a cleaning system should be considered to lower clothing mass. The mass factor 0.46 kg/p/d assumes 2.3 kg for one change of clothes and a clothing change every 5 days.

Crew Accommodations System	Mass Factors					Assumptions and Notes
	Shuttle-like	Station-like	Lunar base	Mars habitat	Units	
Spare parts and consumables					-	Assumes no spare parts or consumables for maintenance
Test equipment	50	100	300	500	kg	Includes oscilloscopes, gauges, etc.
Other tools and equipment	50	50	600	1000	kg	Includes fixtures, large machine tools, glove boxes, etc.
Photography						Assumes an all-digital approach
Equipment	120	120	120	120	kg	Includes still and video cameras, lenses, etc. but no film
Sleep Accommodations						
Sleep provisions	9.00	9.00	9.00	9.00	kg/p	Includes sleep restraints only
Crew Health Care						
Exercise equipment	145	145	145	145	kg	Assumes two devices for aerobic exercise
Medical/surgical/dental suite	15	250	500	1000	kg	
Medical/surgical/dental consumables		125	250	500	kg	

Table D.2: Volume Factors for Crew Accommodations in Various Mission Types[5]

Factors given are for hypothetical Shuttle-like, station-like, lunar base, and Mars habitation missions, showing how the model might be customized for different scenarios. The notation "kg/p/d" indicates kilograms/person/day.

Crew Accommodations System	**Volume Factors**					**Assumptions and Notes**
	Shuttle-like	Station-like	Lunar base	Mars habitat	Units	
Galley and Food System						
Food	0.0080	0.0080	0.0080	0.0080	m^3/p/d	
Freezer(s)	0	0	0.50	2.00	m^3	
Conventional ovens	0.25	0.25	0.25	0.25	m^3	
Microwave ovens	0.30	0.30	0.30	0.30	m^3	Assumes two ovens
Cleaning supplies	0.0018	0.0018	0.0018	0.0018	m^3/d	Includes solvents and supplies for cleaning galley and ovens
Sink and spigot	0.0135	0.0135	0.0135	0.0135	m^3	For food rehydration and drinking water
Dishwasher	0	0	0.56	0.56	m^3	
Cooking/eating supplies	0.0014	0.0014	0.0056	0.014	m^3/p	
Waste Collection System						
System	2.18	2.18	2.15	4.36	m^3	Assumes one toilet for each mission except Mars (two toilets)
Supplies	0.0013	0.0013	0.0013	0.0013	m^3/p/d	
Contingency collection mittens/bags	0.0008	0.0003	0.0008	0.0008	m^3/p/d	
Personal Hygiene						
Shower	0	1.41	1.41	1.14	m^3	
Handwash/mouthwash faucet	0.01	0.001	0.01	0.01	m^3	

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[5] From: Chapter 18, "Crew Accommodations," in *Human Spaceflight Mission Analysis and Design*. Stilwell, D., Boutros, R., and J. Connolly. New York: McGraw Hill Companies. 1999.

Crew Accommodations System	Volume Factors					Assumptions and Notes
	Shuttle-like	Station-like	Lunar base	Mars habitat	Units	
Personal hygiene kit	0.005	0.005	0.005	0.005	m^3/p	
Hygiene supplies	0.0015	0.0015	0.0015	0.0015	$m^3/p/d$	Consumables
***Clothing*[6]**						
Clothing	0.224	0.720	0.224	0.336	m^3/p	Assumes 0.008m^3/p for one complete change of clothes
Washing machine	0	0	0.75	0.75	m^3	
Clothes dryer	0	0	0.75	0.75	m^3	
Recreational Equipment						
Personal stowage	0.19	0.38	0.38	0.75	m^3	
Housekeeping						
Vacuum	0.07	0.07	0.07	0.07	m^3	Prime and two spares
Disposable wipes for housecleaning	0.001	0.002	0	0	$m^3/p/d$	
Trash compactor/trash lock	0	0.3	0.3	0.3	m^3	
Trash bags	0.001	0.001	0.001	0.001	$m^3/p/d$	
Operational Supplies						
Operational supplies	0.001	0.002	0.002	0.002	m^3/p	Includes diskettes, Ziplocs, and tape
Restraints	0.135	0.54	0.27	0.54	m^3/kg	
Maintenance						Assumes all repairs in habitable areas
Hand tools and accessories	0.33	0.66	0.66	1.00	m^3	

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[6] This is an important trade to consider for long-duration mission because it involves supplying complete sets of clothes for the duration of the mission versus using a clothes cleaning system. By default, this model assumes that a washer/dryer system is not appropriate for Shuttle- or ISS-like missions and that the clothing volume for lunar/Mars missions includes a cleaning system and reuse of clothing. Generally, the volume factor assumes 0.008 m^3/p for one change of clothes and a clothing change every 5 days.

Crew Accommodations System	Volume Factors					Assumptions and Notes
	Shuttle-like	Station-like	Lunar base	Mars habitat	Units	
Spare parts and consumables					-	Assumes no spare parts or consumables for maintenance
Test equipment	0.15	0.3	0.9	1.50	m^3	Includes oscilloscopes, gauges, etc.
Other tools and equipment	0.25	0.25	3.00	5.00	m^3	Includes fixtures, large machine tools, glove boxes, etc.
Photography						Assumes an all-digital approach
Equipment	0.50	0.50	0.50	0.50	m^3	Includes still and video cameras, lenses, etc. but no film
Sleep Accommodations						Does not include recommended 1.5 m^3/p for sleeping
Sleep provisions	0.10	0.10	0.10	0.10	m^3/p	Includes sleep restraints only (suitable for short duration)
Crew Health Care						
Exercise equipment	0.19	0.19	0.19	0.19	m^3	Assumes two devices for aerobic exercise
Medical/surgical/dental suite	0.25	1.00	2.00	4.00	m^3	
Medical/surgical/dental consumables		0.64	1.30	2.50	m^3	