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ACRONYMS & ABBREVIATIONS

°C	degrees Centigrade
µg	microgram
ALS	Advanced Life Support
CFU	colony forming unit
CO_2	carbon dioxide
CTSD	Crew and Thermal Systems Division
d	day
EMU	extravehicular mobility unit
EPA	Environmental Protection Agency
EVA	extravehicular activity
g	gram
Gr-Eq	gray equivalent
ISM	integrated system management
ISS	International Space Station
JSC	Johnson Space Center
K	Kelvin
kJ	kilojoule
kPa	kilopascal
L	liter
LSS	life support system
m/s	meters per second
m^3	cubic meters
MCL	maximum contamination level
mEq/L	milliequivalents per liter
mg	milligram
MJ	megajoule
mL	milliliter
N_2	nitrogen
NASA	National Aeronautics and Space Administration
NRC	National Research Council
n/a	not applicable
n/d	not detectable
NE	niacin equivalents
O_2	oxygen
p_x	partial pressure of gaseous constituent “x”
PFU	phage forming unit
pH	potential of hydrogen
psia	pounds (force) per square inch, absolute
RDA	Recommended Dietary Allowance
RE	retinol equivalents
SMAC	Spacecraft Maximum Allowable Concentration
Sv	sievert
TBD	to be determined
TE	α-tocopherol equivalents
y	year

ACRONYMS & ABBREVIATIONS

PREFACE

This Advanced Life Support (ALS) Requirements Document is intended to outline the requirements that ALS Element leads and hardware developers must meet as they develop system and subsystem designs and prototypes. For mission planners and developers of systems outside of ALS, it can be thought of as an interface document. Since there still is much to learn about future human space missions, these requirements are subject to change. Where there is a great deal of uncertainty in data to use for design, the ALS Project has chosen to document that type of information in the ALS Baseline Values and Assumptions Document. It is expected that some "baseline values" from the ALS Baseline Values and Assumptions Document will in time make their way into this Requirements Document. An additional source of mission specific assumptions is the ALS Reference Missions Document. When particular missions are selected, either for flight or ground test programs, many of these assumptions, or similar values, will become additional requirements.

1. INTRODUCTION

1.1 PURPOSE

This document provides high-level performance requirements for the development of advanced regenerative life support systems. Such systems are enabling for long-duration human space travel and planetary exploration.

1.2 SCOPE

This document defines high-level performance requirements for an advanced life support system (LSS) based on the functional decomposition in Section 4.1.2. Because system management is important to life support system design, high-level requirements are also defined for an advanced integrated system management (ISM) system. System design considerations and candidate advanced mission architecture designs are presented in the Advanced Life Support Baseline Values and Assumptions Document, JSC-47804, and the Advanced Life Support Systems Integration, Modeling, and Analysis Reference Missions Document, JSC-39502, respectively.

1.3 ADVANCED LIFE SUPPORT PROJECT

The chief goal of the ALS Project, as stated in its Project Plan (NASA, 2002), is to

> *"provide life support self-sufficiency for human beings to carry out research and exploration productively in space for benefits on Earth and to open the door for extended on-orbit stays and planetary exploration."*

For long-duration space missions, both inside and outside of low Earth orbit, life support systems will require not only a high degree of closure of the oxygen and water regeneration loops, but they must also begin to close the food loop. Closure is driven by high costs associated with the launch and storage of consumables. For lunar or planetary bases, greater autonomy of the life support system will also reduce the dependency on resupply missions, thereby increasing safety and reducing cost.

By contrast with past and current spacecraft life-support systems, advanced life support systems will include food production, and will utilize biological processes in addition to physicochemical processes. Solid waste processing will recover valuable chemicals from food-production and human wastes. In-situ resources, where available, may also replenish life support consumables.

Two primary objectives of the Advanced Life Support Project, with corresponding supporting objectives (NASA, 2002), are to:

- Provide Advanced Life Support technologies that significantly reduce life cycle costs, improve operational performance, promote self-sufficiency, and minimize expenditure of resources for long-duration missions.

Supporting Objectives:

- Fully close air and water loops in a manner that eliminates expendables.
- Develop and integrate resource recycling/processing and contaminant control systems that increase the level of self-sufficiency.
- Optimize food closure loop, with concomitant air and water revitalization, based on the growth of crop plants or other photosynthetic organisms.
- Provide efficient, reliable active thermal control (heat acquisition, transport, and rejection).
- Develop fully regenerative integrated systems technologies that provide air, water, food, and resource recovery from wastes.

- Resolve issues of microgravity performance through space flight research and evaluation.

  Supporting Objectives:

  - Develop predictive models of liquid and liquid/gas behavior and interactions in microgravity that can be used as a basis for design of new life support hardware for microgravity applications.
  - Achieve equivalent productivity, control and predictability of bioregenerative life support components in microgravity as on Earth and characterize performance of bioregenerative systems at Lunar and Martian gravity (i.e., 1/6g and 1/3g, respectively).
  - Demonstrate microgravity performance of gravity-sensitive life support hardware components and subsystems (e.g., membrane behavior, microbe performance, crop nutrient delivery systems).

The development of advanced regenerative life support systems is critical to meeting the National Aeronautics and Space Administration (NASA) Agency's plans for human missions to planetary and other bodies of the solar system starting as early as the second decade of the 21st century (NASA, 1998).

1.4 MISSIONS

Human space missions beyond the International Space Station (ISS) have yet to be fully defined. However, on-going advanced studies continue to consider some possible missions. JSC-39502 details, from a life support perspective, several possible missions. Such missions, then, are the ultimate context for the material that follows.

2. DOCUMENTS

2.1 APPLICABLE DOCUMENTS

The following specifications and standards form a part of this specification to the extent specified in Sections 3-5 of this document. In some cases, these specifications and standards have been developed for current and near-term missions, such as ISS or other low-Earth orbit operations, and will likely undergo changes as more information is obtained, and as future missions become more clearly defined. Current specifications appear, in some cases, to be overly restrictive for the development of advanced life support systems. These specifications are noted and discussed in the appropriate sections. In the event of a conflict between the contents of this document and the documents referenced herein, the current or advanced-mission-specific version of the referenced documents shall take precedence.

JSC-28354 June 1998	Human Rating Requirements
JSC-26882 January 1996	Space Flight Health Requirements Document
NASA-STD-3000 Rev. B July 1995	Man-Systems Integration Standards
NASA-STD-6001 February 1998	Flammability, Odor, Offgassing, and Compatibility Requirements and Test Procedures for Materials in Environments that Support Combustion
JSC-28038 December 1996	Nutritional Requirements for International Space Station Missions Up to 360 Days
JSC-20584 June 1999	Spacecraft Maximum Allowable Concentrations for Airborne Contaminants
SSP-50260	International Space Station Medical Operations Requirements Document
SSP-41000	System Specification For The International Space Station

2.2 REFERENCE DOCUMENTS

The following specifications, standards, and technical documents are referenced as sources of information for specific requirements in Sections 3 to 5 of this document. In the event of a conflict between the contents of this document and the documents referenced herein, the current or advanced-mission-specific version of the referenced documents shall take precedence.

JSC-38715 CTSD-ADV-290 Rev. B August 1997	Advanced Technology Spacesuit Technical Requirements Document
NASA-CP-2499 1988	Airborne Particulate Matter in Spacecraft
NASA-TM-4755 JPLD-13832 May 1996	Advanced Environmental Monitoring and Control Program Development Requirements
NASA-TM-108497 August 1995	Trace Chemical Contaminant Generation Rates for Spacecraft Contamination Control System Design
SSP 41000E July 1996	System Specification for the International Space Station
NCRP 132 2000	Radiation Protection Guidance for Activities in Low-Earth Orbit
SSP-41162R March 2000.	Segment Specification for the United States On-Orbit

2.3 ADVANCED LIFE SUPPORT DESIGN DOCUMENTS

The following technical documents are sources of information for advanced life support research. They do not provide requirements, but rather working values for analysis and design.

JSC-47804 May 2002	Advanced Life Support Baseline Values and Assumptions Document
JSC-39502 November 2001	Advanced Life Support Systems Integration, Modeling, and Analysis Reference Missions Document

3. HIGH-LEVEL REQUIREMENTS AND STANDARDS

The applicable documents referenced in Section 2.1 contain high-level requirements and standards that drive or define functional requirements for the LSS and the ISM system. The most relevant of these requirements and standards are included or mentioned in this section to facilitate traceability of lower-level requirements. The original source of each requirement is indicated. Some requirements are taken directly from the indicated document while others have been modified or rewritten, focusing more on life support issues.

3.1 HUMAN-RATING REQUIREMENTS

The following requirements come from or are derived from JSC-28354.

3.1.1 General Requirements

3.1.1.1 Design for Human Space Flight

Requirement: Equipment for human-rated vehicles shall be designed, built, inspected, tested and certified specifically addressing requirements for human rating. [Based on JSC-28354]

> ***Rationale:*** *"Human beings place very specific and severe design requirements on spacecraft built to carry them. Different factors and environments can either singularly or in combination pose serious hazards to crews in the hostile expanse of space. All aspects of a vehicle design, therefore, should reflect the primary concern of a human-rated spacecraft to carry human beings safely to and from their intended destination."*
>
> *"While some spacecraft equipment may trace ancestry to hardware designed for applications other than a human-rated vehicle, the redesigned or modified systems shall meet the same standards as equipment specifically designed for a human-rated vehicle. In situations where it is not feasible, either technically or economically, for the redesigned or modified equipment to meet standards for human-rated vehicles then other approaches should be used rather than introducing equipment into a human-rated vehicle that may be inappropriate for the task." [JSC-28354]*

3.1.1.2 Aerospace Design Standards

Requirement: The vehicle design, manufacture, and test shall comply with current applicable aerospace design standards. Where alternative approaches are employed, verification shall be provided that the alternative approaches meet or exceed the performance of accepted approaches [Based on JSC-28354].

> ***Rationale:*** *"Aerospace design practices are the product of a long and costly evolution. Many failures and lost lives have been incurred in accumulating the combined knowledge base now available to the designer. This knowledge is captured in a variety of certification requirements documents, "lessons learned" documents such as JSCM 8080.5, military standards, and other technical publications. This data base contains thousands of valid requirements and is too extensive and detailed to capture in a set of top level requirements, but the documents listed in the bibliography provide the major sources for this information."*

> *"It is essential that the intent of the detailed design requirements and practices specified in these documents be incorporated in the design of human-rated spacecraft. The direct applicability of these documents varies, but as a minimum the practices listed in JSCM 8080.5 should be applied to human-rated spacecraft. Alternative approaches to these practices must demonstrate that they are as effective as the accepted methods." [JSC-28354]*

3.1.1.3 Crew Habitability

Requirement: The vehicle crew habitability and life support systems shall comply with all current applicable standards for crew habitability and life support systems design [Based on JSC-28354].

> ***Rationale:*** *Through many heritage missions, including many successes and some failures, NASA has developed significant expertise designing and mounting human spaceflights. Current requirements incorporate both sound engineering judgment augmented by sober experience.*
>
> ***Note:*** *Current applicable crew habitability and life support systems requirements are listed in NASA-STD-3000.*

3.1.1.4 Flight Test

Requirement: A successful, comprehensive flight test program shall be completed to validate analytical models, verify the safe flight envelope, and provide a performance database prior to the first operational flight with humans on board. (Here an operational flight is one in which the specific purpose of the flight is not to test the vehicle itself.) [Based on JSC-28354].

> ***Rationale:*** *"No aerospace vehicle can be certified on the basis of analysis alone. Flight experience has shown that many critical design parameters are highly design-specific and require a careful flight test program to verify. Virtually all flight programs have shown important areas where flight experience did not match predictions."*
>
> *"Whenever possible, the flight test program should be conducted across the entire mission profile. This is generally possible for vehicles with discrete mission profiles of manageable duration such as the Earth-to-orbit and crew return vehicles. These vehicles can usually be operated through several complete ascent and/or descent profiles and should give good confidence in the suitability of the design for the planned mission."*
>
> *"In the case of a [Space] Station or beyond-Earth-orbit vehicle, flight test across the entire mission profile may not be feasible, either due to the excessive amount of time required to cover the planned mission duration, or the lack of suitable conditions to test, as in the case of planetary landing vehicles. In these cases a series of individual stand-alone tests under actual or high fidelity-simulated conditions is required. Backed with extensive analyses and simulation, these test results are used to verify vehicle performance across the integrated mission profile. The cardinal rule should be that all aspects of the mission that can be flight-tested, should be flight-tested." [JSC-28354]*

Requirement: Equipment that is immediately life-critical must be designed to allow operators to initiate nominal life support functions, such as cabin atmospheric revitalization and temperature control, from outside the vehicle.

> ***Rationale:*** *The crew may be incapacitated and unable to do so themselves.*

3.1.2 Safety and Reliability Requirements

3.1.2.1 Crew Survival

Requirement: A human spaceflight 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, where appropriate, including mission success, abort, safe haven, and crew escape. [Based on JSC-28354].

> ***Rationale:*** *Crew survival is specifically addressed in this requirement and is best described in terms of a reliability requirement for the space flight program. The requirement must address all aspects of a space flight program, including vehicle design, operations, logistics, maintenance, and training. This reliability requirement must also address all missions and flights planned for the life of the program, not just a single vehicle for a single mission. Therefore, the requirement should account for cumulative risk exposure during the life of a program, and address specific reliability requirements inherent in the different missions." [JSC-28354]*

3.1.2.2 Contingency

Requirement: Life support equipment and commodity stores shall be sized to support any mission-specific safe haven requirements and/or pre-defined abort-scenario capabilities. [Based on JSC-28354]

3.1.2.3 Failure Tolerance

Requirement: 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 the purposes of this requirement, maintenance can be considered as the third leg of redundancy so long as mission operations and logistics resupply permit it. [JSC-28354].

> ***Rationale:*** *"System design for reliability is a definitive element of spacecraft design. Aerospace hardware is designed for inherent reliability at the component level, but the architecture of the vehicle systems must also protect against random failures and minimize the probability of loss of mission, vehicle, or crew. In systems with relatively short periods of operation or where dynamic flight modes (such as powered ascent) are involved, installed redundancy is the principal means of assuring the system's reliability. In vehicles with longer missions and more time for recovering from failures, maintenance and logistics resupply are the keys."*
>
> *"Fault tolerance is a term frequently used to describe minimum acceptable redundancy, but it may also be used to describe systems that are able to cross-link functions to compensate for failures. It is highly desirable that vehicle performance degrade gracefully when experiencing multiple failures. Where possible this should include cross-linking functions to compensate for failures."*
>
> *"For ascent and descent vehicles, the time constraints of the dynamic flight modes preclude the opportunity to utilize in-flight maintenance and system reconfiguration to recover from failures. Therefore, two-fault tolerance is a critical element in ensuring adequate vehicle reliability and should be incorporated whenever possible. When two-fault tolerance is either impractical or may have a negative impact on overall vehicle*

reliability, single fault tolerance will be provided wherein no single-failure will result in the loss of the crew.

"For long duration missions such as on [International Space] Station or a beyond-Earth-orbit vehicle, fault tolerance is not sufficient. For these missions, multiple failures are expected, and the response must include maintenance and system reconfiguration to restore the failed functions. In the case of the [International Space] Station, the maintenance capability and associated logistics inventory need only support critical systems until the arrival of the next resupply vessel. This is likely to be a period of a few weeks to a month or two.

"In the case of beyond-Earth-orbit vehicles, it is unlikely that resupply vehicles can supplement the resources aboard the vehicle unless that capability was planned for in advance via pre-positioned spares. Therefore, safe operation of the vehicle requires that sufficient reliability be achieved through a combination of reliable hardware design, installed redundancy, and logistics capability to support maintenance." [JSC-28354]

3.1.2.4 Reliability Verification

Requirement: Vehicle reliability shall be verified primarily by test supported by analysis at the integrated system level prior to the first flight with human beings on board. Flight-based analysis and system health monitoring will verify reliability and readiness for each subsequent flight. [JSC-28354].

3.1.2.5 Software Reliability

Requirement: The performance and reliability of all critical software shall be tested on a flight equivalent avionics testbed across the entire flight envelope. Independent Verification and Validation methods shall be used to confirm the integrity of the software testing process. [JSC-28354].

Rationale: *"Software has become a key component in the reliability of today's aerospace vehicles and as such all critical software must be tested to the same levels of quality as the hardware systems. Critical software is any software component whose failure or unanticipated performance could lead to the loss of the vehicle or crew. This includes the flight software as well as ground software that can affect flight safety."*

"Critical software must be tested across the entire flight envelope as well as mission functions and transitions. The testing facility must use a flight-equivalent avionics testbed operating in a real-time, closed-loop test environment. Ground software must be tested on the computer platforms that will be used to support actual flights."

"The software industry has also evolved to the use of Independent Verification and Validation as a key method of assuring software safety. This requires the use of an independent organization to assure that the software requirements are consistent and complete, the scope of the test matrix covers all requirements, and that all discrepancies in the test results are resolved before flight." [JSC-28354]

3.1.3 Human-in-the-Loop Requirements

3.1.3.1 Crew Role and Insight

Requirement: 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. [JSC-28354].

Requirement: The flight crew shall be capable of taking manual control of the vehicle during all phases of flight. [Based on JSC-28354].

> ***Rationale:*** *"The use of automation in aerospace vehicles is continually increasing. Correct implementation of automation has greatly improved human operator efficiencies by performing many time-consuming tasks such as system-monitoring functions, fault diagnosis, navigation, and precision flight path management. A prime example of the results of these efforts is in the reduction of the flight crew size on modern airliners from three to two. Building a fully automated vehicle that precludes the human-in-the-loop, while technically feasible, currently requires a significant reduction in real-time decision-making capability over that available utilizing the human-in-the-loop since the cognitive ability of the human brain has yet to be approached in machine-based decision-making."*
>
> *"The database of successful autonomous vehicles designed to perform complex space missions is small. Industry experience does not support placing humans on board without the capability to intervene in the case of malfunction or other unanticipated events. History has shown that the overall contribution of the flight crew increases mission reliability since in addition to being available to respond to hardware failures and unanticipated natural events, a human can overcome many latent errors in hardware and software design given the opportunity and proper attention is paid to the human-machine interface. The contribution of the flight crew is maximized when it is provided with the proper insight, intervention capability, control over vehicle automation, authority to enable irreversible actions, and autonomy from the ground."*
>
> ***"Insight:*** *Insight is the ability to determine where the vehicle is, its condition, and what it is doing. Insight helps to build situational awareness."*
>
> *"Good situational awareness greatly improves the performance of the human operator and enhances the mission. Poor situational awareness does exactly the opposite. The technology of displays and controls design has made tremendous progress in recent years, and the state of the art should be applied to the human interface to minimize crew workload and errors. It is crucial to use a team of human factors engineers with cockpit design experience, vehicle engineers, and crew members to develop the appropriate displays for each task to be performed during each phase of flight."*
>
> ***"Intervention/Override Capability:*** *This refers to the ability of crew to assert control over all vehicle functions in nominal and off-nominal situations."*
>
> *"The presence of the flight crew and the provision for them to interact with the vehicle enables a wide variety of control functions. The use of fly-by-wire systems and hierarchical architecture for automation provide the technical means for the human to intervene at multiple levels within the navigation and control loop. This allows the crew to intervene for nominal and off-nominal situations and is absolutely required for any critical phase of flight. The design goal shall be to allow the human operator to bypass higher-level software and automation and exert maximum feasible control without adversely impacting vehicle performance or system reliability. Override includes actions ranging from simply pushing an "emergency button" to hands-on control of the vehicle. …"*

> ***"Control over vehicle automation:*** *This is the active role of the crew in the decision process."*
>
> *"Automation of a process is only as good as the hardware/software developed for the task and can not take all eventualities into consideration. This requires the crew to be able to either inhibit, modify, consent, or initiate automated sequences."*
>
> ***"Authority to enable irreversible actions:*** *This is the mandatory crew role in enabling safety-critical irreversible actions."*
>
> *"Any safety-critical irreversible action, such as deorbit burn, rendezvous, or docking, must be enabled by the crew. The cognitive ability of the crew is essential to make the judgment call as to whether or not to proceed with the these critical events. A crew member on board the vehicle, with good insight into the state of the vehicle and an understanding of external factors supplied via vehicle sensors, personal observation, and ground control, is in the best position to weigh all the options and decide whether or not to proceed with a safety-critical irreversible action."*
>
> ***"Autonomy from the ground:*** *This is the ability of the crew to make decisions when input from the ground is unavailable, incomplete, or the situation is time-critical."*
>
> *"All critical phases of flight must provide human operator insight, intervention capability, and control over vehicle automation if there are people on board or when operating in close proximity to another manned vehicle (e.g., ISS). To operate a spacecraft without crew autonomy capability requires large investments in facilities, personnel training/certification, and provisions for guaranteed continuous communications. Time delay in receiving information from the vehicle, processing it, acting on it, and transmitting appropriate commands back to the vehicle make ground control-only architecture impractical. On the other hand, to implement the computational power and insight of ground controllers on board the vehicle required to safely accomplish a human mission would be prohibitive. Therefore, while the crew needs to be able to make decisions and select alternatives rapidly, or when ground control is unavailable, there are many functions that enhance safety and mission success that are more appropriate for ground control to accomplish." [JSC-28354]*

3.1.3.2 Task Analysis

Requirement: Equipment display and control designs shall be based on a detailed function and task analysis. [Based on JSC-28354].

Requirement: The mission design, including task design and scheduling, shall not adversely impact the ability of the crew to operate the vehicle. [JSC-28354].

> ***Rationale:*** *"The unique elements of the space mission and the variability of human response to the space environment must be accounted for in the mission design. Since the human must be prepared to intervene in the loop at any time, the mission design must not adversely impact his/her ability to function in that capacity. Mission design must explicitly address such factors as crew rest, space adaptation, and deconditioning for all flight crew."*
>
> *"Guidelines exist which provide the required information to ensure mission success by providing a comprehensive health care program throughout all mission phases to optimize crew health and performance, and to prevent negative short and long term health consequences." [JSC-28354]*

3.2 SPACE-FLIGHT HEALTH REQUIREMENTS

3.2.1 Environmental Health

Requirement: An environment suitable for human habitation shall be provided and maintained within all pressurized elements designated for crew access according to current applicable specifications and standards for respirable atmosphere, drinking water, contact surface cleanliness, lighting, noise and vibration exposure, radiation exposure, hygiene, habitability, and acceleration.

3.2.1.1 Water Quality

Requirement: Water provided for crew use and consumption shall meet current established water quality requirements, including those for microbial control. [Based on JSC-26882].

> ***Note:*** *Current water quality standards may be found in SSP-41000 and SSP-50260.*

3.2.1.2 Water System Decontamination

Requirement: Capabilities shall be provided for in-flight decontamination of water processing and storage systems. [JSC-26882].

3.2.2 Air Quality

Requirement: Any internal atmosphere intended for crew respiration shall meet the current respirable atmosphere and air quality requirements. Internal atmosphere for crew respiration also shall meet current requirements for microbial control and trace contaminants. [Based on JSC-26882]

> ***Note:*** *Current air quality standards may be found in JSC-20584. See also the Appendix.*

3.2.2.1 Offgas Testing

Requirement: All materials and hardware capable of contributing to contamination of respirable air in a spacecraft shall be offgas tested and certified safe according to current applicable procedures. [Based on JSC-26882].

> ***Note:*** *Current offgas testing standards may be found in NASA-STD-6001.*

3.2.2.2 Air System Decontamination

Requirement: The toxic hazard potential of all payload and utility chemicals, which could contaminate the respirable atmosphere during a mission, shall be evaluated. Hazard information on potential air contaminants shall be readily available to the crew and Flight Surgeon, throughout the mission to support decontamination operations. [Based on JSC-26882].

3.2.3 Microbiology

Requirement: Human-inhabited space environments, including spacecraft, spacesuits, and permanent space-based facilities, shall be kept microbiologically safe according to current standards for air, water, food, surface, and biological specimens.

> ***Note:*** *Current standards may be found in NASA-STD-3000.*

3.2.3.1 Microbiology Identification and Characterization

Requirement: The capability to identify, and characterize etiologic agents of infectious diseases shall be provided as stipulated by the flight surgeon. [JSC-26882].

3.2.3.2 Microbiology Decontamination

Requirement: Capabilities shall be provided for in-flight microbial decontamination of surfaces and biological hazards as stipulated by the flight surgeon. [JSC-26882].

3.2.4 Ionizing Radiation

a. **Requirement:** Flight crew ionizing radiation exposure shall be kept as low as is reasonably achievable.

> ***Rationale:*** *It is permissible for each flight crewmember to be exposed to a limited dosage of ionizing radiation within his or her lifetime. So, lower exposure during any mission will prolong careers of flight crewmembers, providing NASA with the benefits associated with low turnover of mission-critical personnel.*

b. **Requirement:** Flight crew ionizing radiation exposure shall not exceed current applicable standards.

> ***Note:*** *Current applicable radiation exposure limits may be found in NCRP No. 132.*

3.2.5 Non-ionizing Radiation

Requirement: Exposure to non-ionizing radiation, including radio frequency, electromagnetic fields, optical laser radiation, and incoherent ultraviolet optical radiation, shall not exceed current applicable standards.

> ***Note:*** *Current standards are published in NASA-STD-3000.*

3.2.6 Habitability

Requirement: Spacecraft design and mission planning shall consider issues of habitability according to current applicable standards.

> ***Note:*** *Depending on mission duration and architecture, the following habitability issues may require attention: human factors and ergonomics, adequate work and living volumes, odor and particulate control, social, entertainment, and recreational provisions, sleep space and privacy, personal hygiene provisions, exterior viewing opportunities, temperature control, noise control, color, and lighting. See JSC-26882.*

3.2.6.1 Noise Exposure

Requirement: In-flight noise exposure shall meet current applicable standards in all volumes inhabited by crewmembers.

> ***Note:*** *Current noise exposure standards may be found in NASA-STD-3000.*

3.2.7 Human Oxygen Requirements

Requirement: Oxygen shall be sufficient to support a crew participating in mild to strenuous activities. Variations in metabolic oxygen uptake per crewmember are tabulated for extreme and nominal cases in Table 3-1.

Table 3-1. Table of Oxygen Requirements

Category	Metabolic Load [kJ/(person•day)]	Oxygen Requirements: [kg/(person•day)]
Low Activity Metabolic Load *	10,965	0.78
Nominal Activity Metabolic Load **	11,820	0.84
High Activity Metabolic Load *	13,498	0.96
5th Percentile Nominal Female	7,590	0.52
95th Percentile Nominal Male	15,570	1.11

- ***Notes:***
- ** From Space Station Freedom Program via C. H. Lin (NASA/JSC), personal communication.*
- *** From the Baseline Values and Assumptions Document, JSC-47804.*
- *The assumed conversion factor from liters of O_2 to calories is 4.8 cal/L here. A pressure of 101.325 kPa and a temperature of 0 °C are the standard conditions.*

3.3 HUMAN WATER REQUIREMENTS

Requirement: The potable water supplied for the crew to drink shall be at least 2.0 L/person•day (~8 cups/person•day). Hygiene water shall be supplied according to current applicable requirements.

> ***Note:*** *Current values for basic personal hygiene based on NASA-STD-3000 are listed in Table 3-2.*

Table 3-2. Hygiene water requirements

Mode	Hygiene Water [kg/person*day]
Operational	2.84 - 5.16
90-day Degraded	2.84
Emergency	2.84

3.4 HUMAN NUTRITIONAL REQUIREMENTS

Diets for past U.S. space missions have been based largely on conventional criteria, such as the Recommended Dietary Allowances (RDAs) published by the National Research Council (NRC) (NRC, 1989). The RDAs also serve as a reasonable starting point for the development of nutritional requirements for extended duration space missions, although physiological studies on the long-term effects of microgravity will likely result in modifications of these requirements (Lane and Rambaut, 1994). Modified nutritional requirements have been developed for International Space Station missions of 120-360 days (Lane, *et al.*, 1996). These requirements are given below. The requirements listed are divided into two main categories: 1) specific nutrients required (on a per-day basis), and 2) the requirement to monitor nutrient intake.

3.4.1 Metabolic Energy Intake

Requirement: Intake of metabolic energy shall be sufficient to maintain body weight, body composition, and the level of activity required for the extensive activities planned for future human spaceflight crewmembers. Metabolic energy requirements will be defined on an individual basis as calculated using the following equations [JSC-28038]: [1]

men:

(18-30 yrs): 1.7 (64.02W+2841) = kJ/day required
(30-60 yrs): 1.7 (48.53W+3678) = kJ/day required

women:

(18-30 yrs): 1.6 (61.50W+2075) = kJ/day required
(30-60 yrs): 1.6 (36.40W+3469) = kJ/day required

Where W = mass in kg.

Note that these equations account for moderate levels of activity. An additional 2.09 MJ/day (500 kcal/day) will be supplied to the diet during the period where end of mission countermeasures are being conducted.

Based on previous space missions, it is recommended that an additional 2.09 MJ/day (500 kcal/day) be supplied to crewmembers on days of extravehicular activity (EVA); the extra metabolic energy should be of similar nutrient composition as the rest of the diet.

3.4.2 Nutrient Requirements

The daily diet will supply the basic nutritional requirements as specified below. Mass size should be taken into account in individual calculations, since the following requirements assume a 70-kg person.

3.4.2.1 Protein

Requirement: Intake of protein shall provide 12-15 percent of total metabolic energy consumed. [JSC-28038].

> ***Rationale:*** *This should be provided from both animal and plant sources, in a 60:40 ratio. This ratio will facilitate meeting other nutrient requirements while ensuring an adequate intake of all essential amino acids. It is important to provide protein in the amounts specified, as higher or lower intakes may exacerbate space-induced musculoskeletal changes.*

---

[1] Or:

men:	women:
(18-30 yrs): 1.7 (15.3W+679) = kcal/day required	(18-30 yrs): 1.6 (14.7W+496) = kcal/day required
(30-60 yrs): 1.7 (11.6W+879) = kcal/day required	(30-60 yrs): 1.6 (8.7W+829) = kcal/day required

Where W = mass in kg.

3.4.2.2 Carbohydrate

Requirement: Carbohydrates shall provide 50 to 55 percent of daily metabolic energy intake. [JSC-28038].

> ***Rationale:*** *This should be provided primarily in the form of complex carbohydrates (i.e., starches) such as cereal products - flour, bread, rice, and corn. Less than 10 percent of total carbohydrate intake should be provided as simple sugars (e.g., sucrose and other sweeteners). Ten to twenty-five grams per day of total dietary fiber should be provided, in both soluble and insoluble forms. This will help maintain gastrointestinal function and decrease the incidence of constipation.*

3.4.2.3 Fat

Requirement: Thirty to thirty-five percent of dietary metabolic energy shall be provided as fat, with a distribution among polyunsaturated : monounsaturated : saturated of 1:1.5-2:1. [JSC-28038].

> ***Rationale:*** *This is designed to increase the palatability and metabolic energy density of the diet while simultaneously reducing the health risks associated with a high-fat intake.*

3.4.2.4 Fluid

a. **Requirement:** Intake of fluid shall be 239.0-358.5 mL per MJ (1.0-1.5 mL/kcal) of metabolic energy consumed (at least 2,000 mL per day). [JSC-28038].

b. **Requirement:** Intake of fluid shall be at least 2,000 mL per day. [JSC-28038].

> ***Rationale:*** *It is imperative for the health of the crew that fluid intake be maintained to reduce the incidence of kidney stones and to prevent dehydration.*

3.4.2.5 Fat-Soluble and Water-Soluble Vitamins

Requirement: Daily intake of fat-soluble and water-soluble vitamins shall be per the quantities listed in Table 3-3. [JSC-28038].

Table 3-3. Daily Allowances for Fat-Soluble and Water-Soluble Vitamins

Fat-Soluble Vitamins	
Vitamin A	1000 RE [1]/d
Vitamin D	10 μg/d [2]
Vitamin E	20 TE [3]/d
Vitamin K	80 μg/d [4]

Water-Soluble Vitamins	
Vitamin C	100 mg/d
Vitamin B12	2.0 μg/d
Vitamin B6	2.0 mg/d
Vitamin B1 - Thiamine	1.5 mg/d
Vitamin B2 - Riboflavin	2.0 mg/d
Vitamin B9 - Folate	400 μg/d
Vitamin B3 - Niacin	20 NE [5]/d
Biotin	100 μg/d
Vitamin B5 - Pantothenic Acid	5 mg/d

1. *RE = retinol equivalents; 1 RE = 1 μg retinol or 6 μg B-carotene. The unit "RE" is sometimes recorded as "μg RE." Though redundant, this terminology is accepted because it serves as a reminder to the scaling of the defined unit.*
2. *This is designed to augment calcium and bone retention in light of decreased exposure to ultraviolet light (and thus, decreased endogenous production*
3. *TE = α-tocopherol equivalents; 1 TE = 1 mg d-α-tocopherol. The unit "TE" is sometimes recorded as "mg TE." Though redundant, this terminology is accepted because it serves as a reminder to the scaling of the defined unit.*
4. *Meeting this requirement is important because of the role of Vitamin K in calcium and bone metabolism and due to the uncertainty of production of Vitamin K in the gastrointestinal tract in humans exposed to microgravity, the Vitamin K requirement shall be provided as Vitamin K-1 (phylloquinone), which is obtained primarily from plant sources*
5. *NE = niacin equivalents; 1 NE = 1 mg niacin or 60 mg dietary tryptophan. The unit "NE" is sometimes recorded as "mg NE." Though redundant, this terminology is accepted because it serves as a reminder to the scaling of the defined unit.*

3.4.2.6 Minerals and Trace Elements

Requirement: Daily intake of minerals and trace elements shall be per the quantities listed in Table 3-4. [JSC-28038].

Table 3-4. Daily Allowances for Minerals and Trace Elements

Minerals	
Calcium	1000-1200 mg/d
Phosphorus	< 1.5 times Calcium
Magnesium	350 mg/day
Sodium	1500-3500 mg/d
Potassium	3500 mg/d

Trace Elements	
Iron	< 10 mg/d
Copper	1.5-3.0 mg/d
Manganese	2-5 mg/d
Fluoride	4.0 mg/d
Zinc	15 mg/d
Selenium	70 μg/d
Iodine	150 μg/d
Chromium	100-200 μg/d

- ***Rationale:*** *Iron intake is based on space-induced changes in iron storage, and is designed to prevent iron overload, a situation that may lead to oxidative tissue damage*

3.4.2.7 Nutrition Delivery Approaches

a. **Requirement:** Metabolic nutrients shall be provided in standard foods. [JSC-28038].

> ***Rationale:*** *These foods provide other non-nutritive substances, such as fiber and carotenoids, as well as a sense of palatability and psychological well being that will be critical during long missions. Standard foods, which provide many vitamins and minerals, will counter some of the physiological changes associated with space flight.*

b. **Requirement:** Vitamin or mineral supplements shall be used as a countermeasure only when the nutrient content of standard foods does not meet the requirements [JSC-28038].

> ***Rationale:*** *Many nutrients, when provided as supplements or pills, are not metabolized by the body as when contained in foods. Supplements, then, can increase the risk of certain diseases.*

c. **Requirement:** Food shall not be used past its freshness date.

> ***Rationale:*** *Not only is food past its freshness date possibly hazardous to crew health, but nutritional value and acceptability also degrades with time. Thus, the crew may eat their fill of food past its freshness date and not receive adequate nutrition.*

3.5 HUMAN RADIATION PROTECTION REQUIREMENTS

Requirement: Radiation exposure shall be limited according to current applicable standards. [NCRP-132]

> ***Note:*** *The current standard is NCRP-132. Current values from NCRP-132 are presented in Table 3-5 and Table 3-6.*

Table 3-5. Recommended Organ Dose-Equivalent Limits for All Ages

Time Period	Blood Forming Organs * [Gy-Eq]	Lens of the Eye [Gy-Eq]	Skin [Gy-Eq]
Career	See Below	4.0	6.0
1 y	0.50	2.0	3.0
30 d	0.25	1.0	1.5

Note: ** This term has been used to denote the dose at a depth of 0.05 m.*

Source: *NCRP No. 132*

Table 3-6. Recommended 10 year Career Limits Based on Three Percent Excess Risk of Cancer Mortality

Age [y]	Female [Sv]	Male [Sv]
25	1.0	1.5
35	1.75	2.5
45	2.5	3.25
55	3.0	4.0

Source: *NCRP No. 132*

3.6 MATERIALS REQUIREMENTS

Requirement: Materials used in areas of human habitation shall meet current applicable materials testing requirements for flammability, off-gassing, and fluid compatibility. [NASA-STD-6001]

> ***Note:*** *The applicable material test depends upon the environment to which the material is exposed. Applicable environments are habitable environments, liquid oxygen and gaseous oxygen systems, breathing gases and reactive fluids.*

> ***Note:*** *The current materials testing requirements are presented in NASA-STD-6001.*

3.7 AIR QUALITY STANDARDS

Spacecraft maximum allowable concentrations have been defined by NASA for a wide variety of potential atmospheric contaminants. Current values defined in terms of length of the exposure period are given below. For advanced life support, contaminant generation arising from plant growth and waste processing will have to be considered, along with potential new contaminants. For example, Wheeler, et al. (1996), report ethylene generation by plants of 0.04-0.06 mL/m^2(growth area)-day (equivalent to 0.05-0.075 mg/m^2-day) based on highest plant production rates.

It is permissible for subsystems that use or process habitat air to impose separate, and possibly more stringent, air quality requirements. (See, for example, Tibbits (1996)).

> ***Note:*** *Current Spacecraft Maximum Airborne Concentrations are listed in JSC-20584. These values are reproduced in the Appendix.*

3.8 WATER QUALITY STANDARDS

Current NASA potable and hygiene water requirements are given below. It is permissible, based on alternate microbial control methods, or studies of long-term exposure to specific LSS-generated water contaminants, to modify these requirements. The use of separate potable and hygiene water supplies, or the use of a single (potable) water supply for both potable and hygiene purposes, as in the planned ISS, is an issue that should be resolved by trade studies and optimization.

It is permissible for individual subsystems that use or process water to impose separate and possibly more stringent water quality requirements.

Requirement: Water quality shall meet current water quality standards. [SSP-41000; SSP-50260]

Note: Current water quality standards are listed in SSP-41000 for the United States on Orbit Segment and the International Space Station Medical Operations Requirements [SSP 50260] for the Russian Segment. These are reproduced in Table 3-7.

Table 3-7 Potable Water Quality Requirements

Parameter	Units	Russian Standard	USOS Standard	Most Stringent Standard [2]
Physical				
Total Solids	mg/L	100	100	100
Color True	degree	20	n/a	20
Taste	grade	2	n/a	2
Odor	grade	2	n/a	2
Particulates, maximum size	µm		40	40
pH		5.5 to 9.0	4.5 to 8.5	4.5 to 9.0
Turbidity	mg/L NTU	1.5	 1	1.5
Dissolved Gas, free at 37 °C	mg/L		n/d (1)	n/d (1)
Free Gas; standard pressure and temperature	mg/L		n/d (1)	n/d (1)
Inorganic Constituents				
Ammonia	mg/L	2	0.5	0.5
Arsenic	mg/L	0.01	0.01	0.01
Barium	mg/L	1	1.0	1
Cadmium	mg/L	0.005	0.005	0.005
Calcium	mg/L	100	30	30
Chlorine, including Chlorides	mg/L	250	200	200
Chromium	mg/L	0.1	0.05	0.05
Copper	mg/L	1	1.0	1
Fluoride	mg/L	1.5		1.5
Iodine, including Organic Iodine	mg/L	0.05	15	0.05
Iron	mg/L	0.3	0.3	0.3
Lead	mg/L	0.05	0.05	0.05
Magnesium	mg/L	50	50	50
Manganese	mg/L	0.05	0.05	0.05
Mercury	mg/L	0.002	0.002	0.002
Nickel	mg/L	0.1	0.05	0.05
Nitrate	mg/L	10	10	10
Potassium	mg/L		340	340
Selenium	mg/L	0.01	0.01	0.01
Silver	mg/L	0.5	0.05	0.05
Sulfate	mg/L	250	250	250
Sulfide	mg/L		0.05	0.05
Zinc	mg/L	5	5	5
Total hardness	mEq/L	7		7

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[2] Unless otherwise noted, this is the maximum allowable contamination level.

Parameter	Units	Russian Standard	USOS Standard	Most Stringent Standard
Bactericide				
Potable				
Residual Iodine, minimum	mg/L		1	1
Residual Iodine, maximum	mg/L		4	4
Crew Consumption – Residual Iodine	mg/L		<TBD	
Aesthetics				
Cations	mg/L		30	30
Anions	mg/L		30	30
Carbon Dioxide	mg/L		15	15
Microbial				
Bacteria:				
Total Count	CFU/mL	100		
Bacteria/Fungi	CFU /100 mL		100	100
Total Coliform	CFU /100 mL	<1	n/d	n/d
Virus	PFU /100 mL	<1	n/d	n/d
Organic Parameters (2)				
Total Acids	μg/L		500	500
Cyanide	μg/L	200	200	200
Ethylene glycol	mg/L	12		12
Phenol	mg/L	1		1
Volatile Organics			<EPA MCL (4)	
Semi-Volatile Organics			<EPA MCL	
Total Alcohols	μg/l		500	
Total Organic Carbon	μg/l	20,000	500	500
Uncharacterized Total Organic Carbon (3)			For Reference only	

Notes:

(1) No detectable gas using a volumetric gas versus fluid measurement system; excludes carbon dioxide used for aesthetic purposes.

(2) Each parameter/constituent Maximum Contamination Level must be considered individually and independently of others.

(3) Uncharacterized total organic carbon equals total organic carbon minus the sum of analyzed organic constituents expressed in equivalent total organic carbon.

(4) Environmental Protection Agency (EPA) Maximum Contamination Level (MCL)

3.9 FOOD QUALITY STANDARDS

Requirement: Microbiological organism limits for food packaging areas and food products shall observe the standards listed in Table 3-8 and Table 3-9. [JSC-28038].

Table 3-8. Food Packaging Area Microbiological Limits

Area/Item	Microorganism Tolerances	
Food Production & Packaging Area	Samples Collected	Limits (CFU)
Surfaces	3 surfaces sampled per day	≤ 3 CFU/cm^2
Packaging Film	Before use	≤ 3 CFU/cm^2
Food Processing Equipment	2 pieces sampled per day	≤ 3 CFU/cm^2
Air	1 sample of 320 liters	< 0.353 CFU/L$_{air}$

Table 3-9. Food Microbiological Limits

Food Product	Factor	Limits
Non-thermostabilized	Total aerobic count	< 20,000 CFU/g
	Coliform	< 10 CFU/g
	Coagulase positive	0 CFU/g
	Staphylococci Salmonella	0 CFU/25 g
	Yeasts and Molds	< 50 CFU/g
	Escherichia coli	0 CFU/10 g
	Bacillus cereus	< 10 CFU/g
Commercial sterile products (thermostabilized and irradiated)		100% inspection for package integrity
	Sporogenic mesophilic bacilli	< 10 CFU/g
	Mesophilic anaerobes	0 CFU/5 g
	Yeasts, fungi (in items with pH<4.2)	0 CFU/2 g

4. LIFE SUPPORT SYSTEM REQUIREMENTS

4.1 SYSTEM DEFINITION

4.1.1 Ground Rules and Assumptions

Life support systems for planetary and lunar exploration missions will be required for a variety of vehicles and surface habitats. A distinguishing feature of these applications is the length of time that the life support system must support the crew without resupply. Figure 4-1 provides examples of life support system applications ranging from short duration flights to permanent surface habitats.

Short Duration (hours to days)
- lander
- ascent vehicle
- orbit transfer vehicle
- lunar transit vehicle
- pressurized surface rover

Long Duration (months to years)
- Mars transit vehicle
- Mars base
- lunar base

Permanent (many years)
- Mars settlement
- lunar settlement

Figure 4-1. Examples of potential life support system applications in interplanetary and lunar exploration missions.

The functional decomposition and resulting requirements in this document are aimed at long-duration and permanent applications where regenerative life support technologies will have the greatest impact and use. Nevertheless, many of the functions and requirements are sufficiently general as to be applicable to any life support system.

The following assumptions were made in the functional decomposition process:

Assumption: The cabin atmosphere will contain an inert gas component. It is permissible for the inert gas component to be a single species, such as nitrogen, or a mixture of species, such as nitrogen/argon or nitrogen/helium.

> ***Rationale:*** *This assumption is based on flammability and health considerations.*

Assumption: Food will be produced to meet some portion of the crew's nutritional requirements, if only for occasional fresh vegetables.

Assumption: Oxygen and water will be regenerated when the life support system is functioning normally.

Assumption: Monitoring of various physical parameters for life support commodities and wastes within the vehicle will likely be essential to any viable control scheme. However, here monitoring, and its associated accuracy, is specified indirectly. Monitoring is only necessary to support control functions that maintain the life support system parameters within the stipulated bounds. Monitoring, especially its associated accuracy, is mission and vehicle dependent.

These assumptions are based on generally accepted concepts of advanced life support, and provide some bounds on potential system functions.

4.1.2 Functional Decomposition

A high-level functional decomposition of an advanced LSS is shown in Table 4-1. Some lower-level functions in this table may not be applicable to all missions or system designs. This functional decomposition forms the basis for the definition of requirements in Section 4.2. Further functional decomposition would require additional assumptions about system design and technologies.

Table 4-1. Life Support System Functional Decomposition

Function
Maintain Environment
Atmosphere design
Control atmosphere total pressure
Prevent overpressurization and/or underpressurization
Equalize atmosphere pressure
Control metabolically inert gas partial pressure
Add metabolically inert gas to atmosphere
Control oxygen partial pressure
Add oxygen to atmosphere
Control atmospheric temperature
Remove or add sensible heat
Control atmospheric humidity
Remove or add moisture
Control uniformity of atmospheric composition
Ventilation velocities in the crew habitable volume
Exchange atmosphere between modules
Control partial pressures of atmospheric contaminants
Remove gaseous atmospheric contaminants
Control airborne particulates
Remove airborne particulates
Control microbes
Remove airborne microbes
Remove surface microbes
Contain liquids in microgravity
Respond to Emergencies
Respond to rapid decompression
Detect rapid decompression
Recover from rapid decompression
Respond to fire
Detect fire
Isolate fire
Suppress fire
Recover from fire
Respond to hazardous atmosphere
Detect hazardous atmosphere
Recover from hazardous atmosphere

Table 4-1. Life Support System Functional Decomposition - Continued

Function

- Grow Plants
  - Produce biomass
  - Isolate biomass production chamber and internal environmental conditions
  - Isolate crop species
  - Define plant growth zones
    - *Aerial zone*
    - *Root zone*
  - Use resources
    - *Use carbon dioxide*
    - *Use wastewater*
    - *Use other wastes*
  - Provide resources from biomass production
    - *Provide edible biomass*
    - *Provide inedible biomass*
    - *Provide oxygen*
    - *Provide water*
    - *Provide used nutrient solution*
    - *Provide thermal energy*
  - Process harvested biomass
  - Store edible biomass
- Provide Resources
  - Provide inert gas
    - *Supply inert gas*
    - *Store inert gas*
    - *Accept external inert gas*
  - Provide oxygen
    - *Supply oxygen*
    - *Store oxygen*
    - *Regenerate oxygen*
    - *Accept external oxygen*
  - Provide water
    - *Supply water*
    - *Store water*
    - *Regenerate water*
    - *Accept external water*
  - Provide food
    - *Store food and food ingredients*
    - *Regenerate food and food ingredients*
    - *Process food and food ingredients*
    - *Accept external food and food ingredients*
  - Manage gaseous wastes
    - *Accept gaseous wastes*
    - *Transport gaseous wastes*
    - *Store gaseous wastes*
    - *Process gaseous wastes*
    - *Dispose of excess gaseous wastes*

Table 4-1. Life Support System Functional Decomposition - Continued

Function
Manage wastewater
Accept wastewater
Transport wastewater
Store wastewater
Process wastewater
Dispose of excess wastewater
Manage solid and concentrated liquid wastes
Accept solid and concentrated liquid wastes
Transport solid and concentrated liquid wastes
Store solid and concentrated liquid wastes
Process solid and concentrated liquid wastes
Dispose of solid and concentrated liquid wastes
Maintain Thermal Conditioning
Accept thermal energy
Accept thermal energy from atmosphere
Accept thermal energy from equipment
Accept thermal energy from liquid systems
Transport thermal energy
Transport excess thermal energy to cooling external interface
Transport thermal energy for reuse within vehicle
Release thermal energy
Reject (dispose of) excess thermal energy
Reuse thermal energy
Cool equipment and maintain surface touch temperatures
Transport equipment thermal energy loads
Maintain equipment touch temperatures
Prevent water condensation
Support Extravehicular Activities
Support extravehicular mobility unit servicing and checkout
Support desorption of inert gas from body tissues
Support depressurizaton for egress
Support repressurization for ingress
Support contaminant detection and decontamination

4.1.3 Interfaces

4.1.3.1 External Interfaces

External interfaces for an advanced LSS are shown schematically in Figure 4-2. Because regenerative life support technologies generally require more power than nonregenerative technologies, advanced life support systems can place significantly greater heat loads on the thermal control system than current and past life support systems. Interfaces between the LSS and Cooling arise from air processing, water processing, solid waste processing and food production and processing.

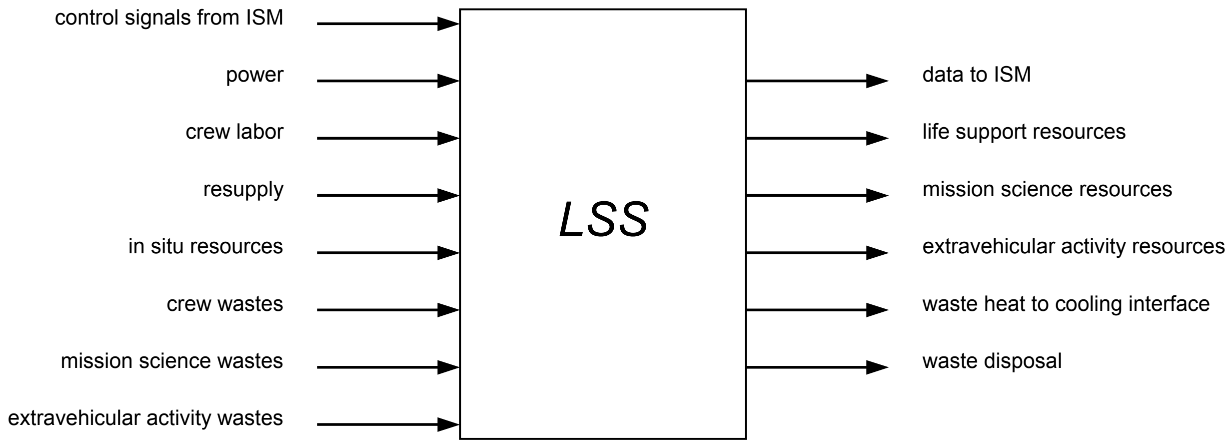

Figure 4-2. Life Support System interfaces. Some interfaces are mission/design dependent.

4.1.3.2 Internal Interfaces

Internal interfaces depend on system design and chosen technologies. This is particularly true with multifunctional bioregenerative technologies, such as plant growth systems, which can provide food production, air revitalization, water purification, and some waste processing. In general, internal interfaces include material (gas, liquid and solid) interfaces between processors and between processors and storage systems. The result of these internal interfaces will be additional requirements governing the supply and distribution of resources and wastes.

4.2 PERFORMANCE REQUIREMENTS

Requirements are defined below for the LSS functions listed in Section 4.1.2.

4.2.1 Maintain Environment

Requirement: The life support system shall maintain an environment in the crew habitat that is adequate to support and maintain crew health, well being, and comfort, and that is adequate to support and maintain satisfactory equipment operation.

4.2.1.1 Atmosphere Design

a. **Requirement:** The nominal design crew-cabin total atmospheric pressure shall be maintained within the range of 48 to 103 kPa (7.0-14.9 psia) with 21-50% oxygen by volume.

> ***Note:*** *It is permissible for actual missions to use more restricted ranges.*

b. **Requirement:** The nominal oxygen partial pressure in the crew cabin shall be maintained within the range of 18 to 23 kPa.

> ***Rationale:*** *Several considerations influenced this decision. Extravehicular activities shall have little or no prebreathe. The ratio of nitrogen pressure, or other inert gas, in the cabin to the total extravehicular mobility unit pressure is defined as R. From statistically*

designed experiments, values of R equal to 1.2 or less have almost no incidence of decompression sickness. When R is approximately 1.2 for cabin pressures of 50.3 kPa (7.3 psia), oxygen composes 35-36% of the atmosphere. Because oxygen levels greater than 35-36% increase flammability significantly, this atmospheric environment allow extravehicular activities with very limited prebreathe at extravehicular mobility unit pressures of 25.9 kPa (3.75 psia) while allowing some nonflammable materials for cabin fabrication.

Acceptable materials, from a fire safety perspective, are reduced by 85% as atmospheric oxygen increases from 21% to 30%, and materials become extremely limited and expensive above 30% oxygen. Therefore it is recommended that total atmospheric pressures below 70.3 kPa (10.2 psia) be reserved for missions whose success depends on frequent extravehicular activities with low suit pressures. Approved materials for atmospheres up to 70% oxygen exist, but these materials are mostly metals. Further, such materials are not effective radiation shields due to their low hydrogen content.

Note: *Highly enriched-oxygen atmospheres are not likely to be compatible with long-term LSS plans. For example, growing food is likely to generate flammable materials. Heating food in an enriched-oxygen, low-pressure environment would not only present a fire hazard but would also present heat transfer challenges compared to traditional food preparation techniques. Further, without adequate oxygen barrier packaging, and enriched-oxygen environment may encourage oxidation of the food resulting in off-flavors and colors.*

Cabin atmosphere design considerations

Rationale and notes:

Respirable atmosphere requirements are governed foremost by the following health and safety constraints (NASA-STD-3000, 1995):

There must be sufficient total pressure to prevent the vaporization of body fluids.

There must be free oxygen at sufficient partial pressure for adequate respiration.

Oxygen partial pressure must not be so great as to induce oxygen toxicity.

For long duration (in excess of two weeks), some physiologically inert gas must be provided to prevent atelactasis.

All other atmospheric constituents must be physiologically inert or of low enough concentration to preclude toxic effects.

The breathing atmosphere composition should have minimal flame propagation/explosive hazard.

Within these constraints, there are many considerations that enter into the optimal selection of atmospheric conditions. In a previous study directed at planetary surface habits and extravehicular mobility units (JSC-25003, 1991), 33 different considerations were reviewed that influence the selection atmospheric pressure and composition (N_2 and O_2 partial pressures). Some of the more important of these considerations are listed in Table 4-2, along with a description of the underlying issues. Also included are considerations influencing the selection of the maximum CO_2 partial pressure.

Table 4-2. Considerations Influencing the Selection of ALS Atmospheric Conditions*

Consideration	Issues
crew performance	• crew acclimation required for p_{O2} < 21 kPa • sufficiently low p_{O2} (p_{O2} < 18.3 kPa for nonacclimated individuals) results in hypoxia, with reduced night vision and reduced crew performance (NASA-STD-3000, 1995) • p_{CO2} > 1000 Pa results in physiological changes; p_{CO2} > 3000 Pa results in outwardly apparent physiological and mental changes (NASA-STD-3000, 1995) • 180-day SMAC for CO_2 has been set at 13,000 mg/m^3 (equivalent to 710 Pa) (James and Coleman, 1993)
materials flammability	• flammability increases with increasing vol% O_2
EVA prebreathe time	• prebreathe time decreases as the partial pressure of diluent gas (N_2) in the habitat decreases • prebreathing can be eliminated when partial pressure of diluent gas exceeds the suit pressure by a "bends" ratio, *R*, of 1.2 or less (Shuttle EVA suits operate at 29.6 kPa (*R* = 2.7 at *P* = 101.4 kPa; *R* = 1.6 at *P* = 70.3 kPa)
plant growth	• decreasing p_{O2} increases net photosynthesis (CO_2 uptake) and decreases dark respiration (Corey, et al., 1996) • for C_3 plants such as wheat, soybean, and lettuce, photosynthesis increases sharply with increasing p_{CO2} below about 70 Pa, and becomes CO_2 saturated at a p_{CO2} of 120-150 Pa (Wheeler, et al., 1996; Grodzinski et al., 1996) • transpiration of water decreases with increasing p_{CO2} and increasing humidity (Bubenheim, 1991; Grodzinski et al., 1996)
equipment performance	• power requirements for blowers increase with decreasing *P* to provide the same mass flow for air cooling and other air processing applications • efficiency of physicochemical CO_2 removal systems decreases with decreasing p_{CO2}; current systems are designed for a nominal p_{CO2} of 400 Pa
leakage to space	• gas leakage to space decreases with decreasing *P*
habitat structure	• required pressure strength of module shell decreases with decreasing *P* (potential mass savings may not be realized if structural mass is dictated by launch/landing stresses or radiation shielding)

*P = total pressure; p_{O2} = oxygen partial pressure; p_{CO2} = carbon dioxide partial pressure.

For advanced life support, the range of allowable habitat total pressure and O_2 partial pressure is bounded mainly by hypoxia and flammability considerations as indicated in Figure 4-3. The upper curve in this figure defines the normoxic equivalent O_2 partial pressure as a function of total pressure.[3] The normoxic equivalent O_2 partial pressure results in an alveolar O_2 partial

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[3] The equivalent O_2 partial pressure corresponding to a given alveolar O_2 partial pressure and total pressure was calculated using the following equation, with p_{H2OI} = 1.23 kPa, p_{H2OA} = 6.27 kPa, p_{CO2A} = 5.33 kPa, and RQ = 0.87:

pressure of 13.87 kPa, equivalent to that in a person living at sea level. As the total pressure is reduced, inhaled oxygen is diluted to a greater extent by carbon dioxide and water vapor added in the lung; a higher inspiratory (ambient) O_2 partial pressure is therefore required to maintain the same O_2 partial pressure in the alveoli, the site of oxygen transfer to the blood. The lower curve in Figure 4-3 defines the equivalent ambient O_2 partial pressure resulting in an alveolar O_2 partial pressure of 10.34 kPa, equivalent to that in a person living at an altitude of about 1,830 m. According to Waligora, et al. (1994), that alveolar O_2 partial pressure is the minimum for which, "in time, acclimation can be nearly complete (with the exception of maximum oxygen uptake during hard work)".

Additional bounds are imposed by limits on the volume percentage of oxygen in the atmosphere. These limits correspond to the Earth ambient value of 20.7%, and the assumed maximum allowable value of 50%, based on flammability considerations. The result is an allowable range (envelope) of total pressure and O_2 partial pressure defined by the region bounded by heavy lines in Figure 4-3. In Figure 4-4, lines defining the decompression sickness ratios, R, where $R = p_{N2}/P_{suit}$, for an extravehicular mobility (EMU) operating at 25.9 kPa (3.75 psia) are superposed on the ALS operating envelope. Figure 4-5 presents the same material for an EMU operating at 29.6 kPa (4.3 psia).

Potential ranges of respirable atmosphere conditions for advanced life support are shown in Table 4-3. Ranges specified for total pressure, O_2 partial pressure, and CO_2 partial pressure reflect overall bounds on these parameters. (It is permissible for mission specific requirements to be more restrictive.) Lower bounds on the total pressure and O_2 partial pressure are those from the envelope in Figure 4-3. Upper bounds on these parameters are from NASA-STD-3000 (1995), and allow some positive deviation when the parameters are nominally set at sea-level values. The remaining conditions are also based largely on NASA-STD-3000, except for the CO_2 partial pressure. A potential range of CO_2 partial pressure is specified between the Earth ambient value and the 180-day Spacecraft Maximum Allowable Concentration (SMAC) value. The upper bound on ventilation has been increased to provide a mass flow at 59.2 kPa total pressure equivalent to the NASA-STD-3000 upper bound at 101.3 kPa. Nominal values of the habitat total pressure, O_2 partial pressure, and CO_2 partial pressure for a given mission must be determined by optimization based on considerations such as those in Table 4-2.

$$p_{O2I} = \frac{\left(P - p_{H2OI}\right)\left(p_{O2A} + \dfrac{p_{CO2A}}{RQ}\right)}{\left[P - p_{H2OA} - p_{CO2A}\left(1 - \dfrac{1}{RQ}\right)\right]}$$

where

P	= total (barometric) pressure	p_{H2OA}	= alveolar H_2O partial pressure
p_{O2I}	= inspiratory (ambient) O_2 partial pressure	p_{CO2A}	= alveolar CO_2 partial pressure
p_{H2OI}	= inspiratory (ambient) H_2O partial pressure	RQ	= respiratory quotient
p_{O2A}	= alveolar O_2 partial pressure		

This equation can be derived from the "alveolar equation" found in standard textbooks on respiratory physiology (see, for example, Slonim and Chapin, 1967).

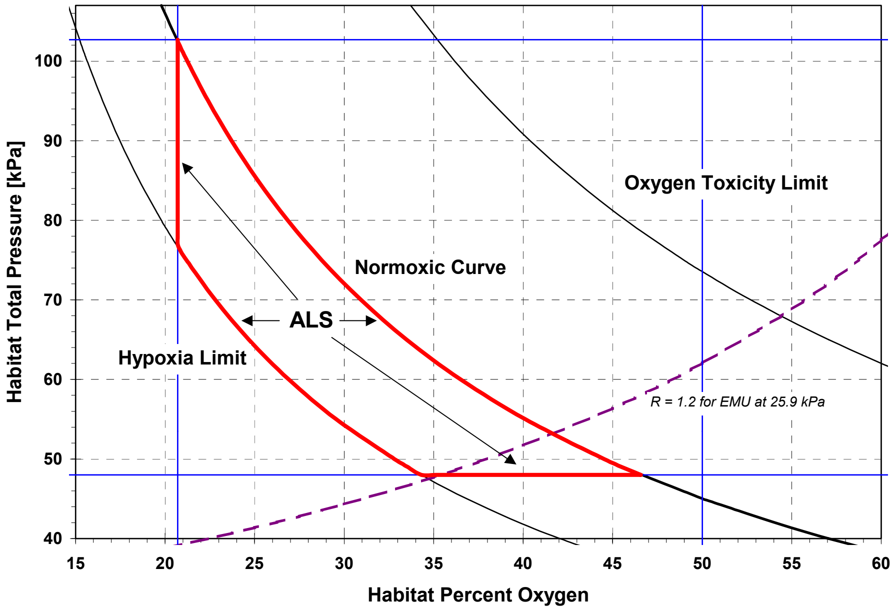

Figure 4-3. Bounds on habitat total pressure and oxygen partial pressure for advanced life support systems.

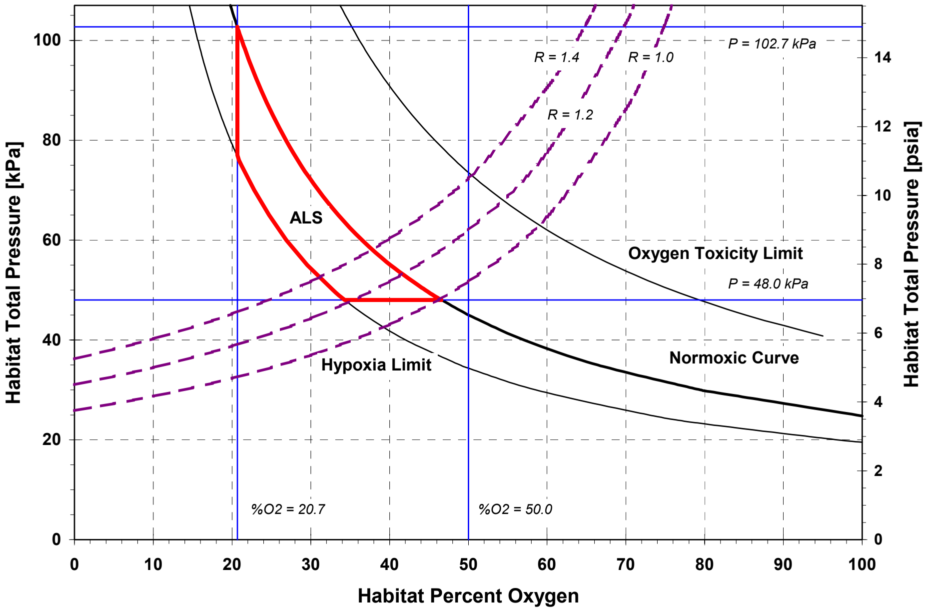

Figure 4-4. Superposition of decompression sickness potential ratios, R, on the advanced life support system operating envelope for an extravehicular mobility unit operating at 25.9 kPa (3.75 psia).

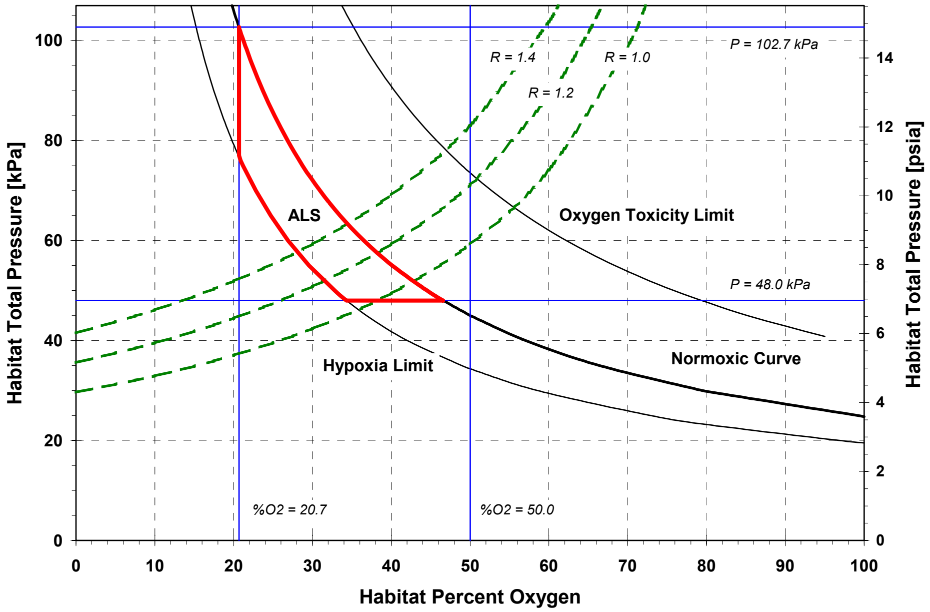

Figure 4-5. Superposition of decompression sickness potential ratios, R, on the advanced life support system operating envelope for an extravehicular mobility unit operating at 29.6 kPa (4.3 psia).

Table 4-3. Potential Range of Nominal ALS Atmospheric Conditions

Parameter	Potential Range
Total Pressure, kPa	48.0-102.7
O_2 Partial Pressure, kPa	18.0-23.1
CO_2 Partial Pressure, Pa	31-710
Diluent Gas	N_2, N_2/Ar or other inert gas mixture
Temperature, K	291.5-299.8
Dew Point, K	277.6-288.7
Relative Humidity, %	25-70
Ventilation, m/sec	0.076-0.347
Particulates (> 0.5 µm), particles/m^3	≤ 3,500,000
Microorganisms, CFU/m^3 (a)	≤ 500
Trace Contaminants, mg/m^3	≤ SMAC (b)

Notes:
(a) CFU = Colony Forming Units
(b) SMAC = Spacecraft Maximum Allowable Concentration

4.2.1.2 Control Atmosphere Total Pressure

Requirement: The total atmospheric pressure in the crew cabin shall be maintained in accordance with current applicable standards.

> ***Note:*** *Atmospheric pressure conditions for advanced missions have not been established, and may be mission dependent. Current NASA-STD-3000 respirable atmosphere requirements for operational, degraded, and emergency modes are reproduced in Table 4-4.*

Table 4-4. NASA-STD-3000 Respirable Atmosphere Requirements

Parameter	Operational	90-Day Degraded	28-Day Emergency
Total Pressure, kPa	100.0-102.7	100.0-102.7	100.0-102.7
O_2 Partial Pressure, kPa	19.5-23.1	16.5-23.8	15.9-23.8
Diluent Gas	N_2	N_2	N_2
Temperature, K	291.5-299.8	291.5-299.8	288.7-302.6
Dew Point, K	277.6-288.7	274.8-294.3	274.8-294.3
Relative Humidity, %	25-70	25-75	25-75
Ventilation, m/sec	0.076-0.203	0.051-0.508	0.051-1.016
Particulates > 0.5 μm, particles/m^3	$\leq$ 3,500,000	TBD	TBD
Microorganisms, CFU/m^3	$\leq$ 500	$\leq$ 750	$\leq$ 1000

Ref**:** Figure 5.1.3.1-1, NASA-STD-3000-I-B, 1995. Values converted from customary units.
CFU = Colony Forming Units.

4.2.1.2.1 Prevent Overpressurization and/or Underpressurization

Requirement: The internal-to-external differential pressure in each module shall not exceed the maximum structural design loading for the module under static or dynamic pressures.

4.2.1.2.2 Equalize Atmosphere Pressure

Requirement: The capability to equalize the pressure differential between adjacent, isolated pressure volumes at opposite ends of the pressure control range to less than a difference of 0.07 kPa within 180 seconds shall be provided.

> ***Note:*** *This specification is equivalent to the ISS requirement.*

4.2.1.2.3 Add Metabolically Inert Gas to Atmosphere

a. **Requirement:** Gaseous metabolically inert gas, such as nitrogen, shall be added to the cabin atmosphere as needed during normal operations.

b. **Requirement:** Gaseous metabolically inert gas, such as nitrogen, shall be added to the cabin as needed to restore the atmosphere following decompression.

> ***Note:*** *This requirement is not applicable for vehicles using a cabin atmosphere comprised solely of oxygen.*

4.2.1.3 Control Oxygen Partial Pressure

Requirement: The atmospheric oxygen partial pressure in the crew cabin shall be maintained in accordance with current applicable standards.

> ***Note:*** *Oxygen partial pressure conditions for advanced missions have not been established, and may be mission dependent. Current NASA-STD-3000 requirements are reproduced in Table 4-4.*

4.2.1.3.1 Add Oxygen to Atmosphere

a. **Requirement:** Gaseous oxygen shall be added to the cabin atmosphere as needed during normal operations.

b. **Requirement:** Gaseous oxygen shall be added to the cabin to restore the atmosphere following decompression.

4.2.1.4 Control Atmospheric Temperature

a. **Requirement:** The atmospheric temperature in the crew cabin shall be maintained in accordance with current applicable standards.

> ***Note:*** *Current NASA-STD-3000 requirements are reproduced in Table 4-4.*

b. **Requirement:** The atmospheric temperature in the crew cabin shall be crew selectable within the acceptable operational range.

c. **Requirement:** The atmospheric temperature in the crew cabin shall be within 1.1 Kelvin of the selected temperature at steady state regardless of crew activities.

4.2.1.4.1 Remove or Add Sensible Heat

Requirement: Sensible heat shall be removed from and/or added to the cabin atmosphere as needed during normal operations.

4.2.1.5 Control Atmospheric Humidity

a. **Requirement:** The atmospheric relative humidity in the crew cabin shall be maintained in accordance with current applicable standards.

b. **Requirement:** The atmospheric dew point in the crew cabin shall be maintained in accordance with current applicable standards.

> ***Note:*** *Current NASA-STD-3000 requirements are reproduced in Table 4-4.*
>
> ***Rationale:*** *Both (a) and (b) are required for different reasons: (a) for crew comfort and (b) for prevention of condensation.*
>
> ***Note:*** *Cabin atmospheric relative humidity and dew point are not independent quantities, but rather different assessments of the moisture in the cabin atmosphere. This understanding, however, does not waive either (a) or (b). Rather, both (a) and (b) must be satisfied.*

4.2.1.5.1 Remove or Add Moisture

Requirement: Moisture shall be removed from and/or added to the cabin atmosphere as needed during normal operations.

4.2.1.6 Control Uniformity of Atmospheric Composition

a. **Requirement:** Atmospheric composition within the crew cabin shall be maintained within the specified ranges throughout the cabin volume.

b. **Requirement:** Atmospheric composition shall be sufficiently uniform across each independently controlled habitat volume so that variations are not noticeable to the crew.

> ***Note:*** *Crewmembers should be able to work anywhere within the crew cabin and expect that atmospheric parameters, such as composition and temperature, are each within the accepted control tolerance of the set point. Or, crewmembers should be able to move freely from one station in the cabin to another without resetting the atmosphere to assure personal comfort.*

4.2.1.6.1 Ventilation Velocities in the Crew Habitable Volume

Requirement: Atmospheric velocities in the crew habitable volume shall not exceed a velocity of 0.203 m/s for nominal operational situations.

> ***Note:*** *Higher ventilation rates may be required at reduced atmospheric pressure. Current NASA-STD-3000 requirements are reproduced in Table 4-4.*

4.2.1.6.2 Exchange Atmosphere between Modules

Requirement: Atmosphere exchange between adjacent, non-isolated pressurized volumes shall be provided to maintain sufficiently uniform conditions for atmosphere composition control when atmospheric constituents are controlled by centralized systems.

4.2.1.7 Control Partial Pressures of Atmospheric Contaminants

Requirement: The partial pressures of contaminants, such as carbon dioxide and other trace contaminants, in the cabin atmosphere shall be maintained at or below current applicable Spacecraft Maximum Allowable Concentration limits for various exposure periods.

> ***Note:*** *Current Spacecraft Maximum Allowable Concentrations are specified in JSC-20584.*
>
> ***Note:*** *Partial pressure conditions for carbon dioxide or other trace contaminants found on advanced missions have not been established, and may be mission dependent. Current SMACs, from JSC-20584, are reproduced in the Appendix.*

4.2.1.7.1 Remove Gaseous Atmospheric Contaminants

Requirement: Atmospheric contaminants, such as carbon dioxide and other trace contaminants, shall be removed from the cabin atmosphere as needed.

4.2.1.8 Control Airborne Particulates

Requirement: The concentration of airborne particulates in the cabin atmosphere shall be maintained in accordance with current applicable standards.

> ***Note:*** *Current NASA-STD-3000 requirements are reproduced in Table 4-4. See also NASA-CP-2499.*

4.2.1.8.1 Remove Airborne Particulates

Requirement: Airborne particulates shall be removed from the cabin atmosphere as needed.

4.2.1.9 Control Microbes

Requirement: The concentration of microbes within the cabin, whether airborne or on a surface, shall be controlled in accordance with current applicable standards.

> ***Note:*** *Current NASA-STD-3000 requirements are reproduced in Table 4-4.*

4.2.1.9.1 Remove Airborne Microbes

Requirement: Airborne microbes shall be removed from the cabin atmosphere as needed.

> ***Note:*** *The current applicable standards for airborne microbes for ISS may be found in SSP 41162R.*

4.2.1.9.2 Remove Surface Microbes

Requirement: Surface microbes shall be removed from cabin surfaces as needed.

> ***Note:*** *The current applicable standards for surface microbes for ISS may be found in SSP 41162R.*

4.2.1.10 Contain Liquids in Microgravity

Requirement: In general, free, uncontained liquids are not permitted within pressurized spaces of a vehicle in microgravity; all liquids shall be contained within equipment or volumes that are specifically designed to handle those liquids for all vehicles operating in microgravity.

> ***Rationale:*** *Free, unconstrained liquids have been known to flow into equipment, electronics, or even onto or into crewmembers in a microgravity environment, causing unforeseen hazards. Even water, an essential for human life, may be hazardous to the crew and vehicle while unconstrained in the cabin. Thus, liquids must be contained.*

4.2.2 Respond to Emergencies

Requirement: The life support system shall respond to emergency events to protect the crew, vehicle, and equipment.

4.2.2.1 Respond to Rapid Decompression

Requirement: A capability to detect and recover from rapid decompression events shall be provided.

4.2.2.1.1 Detect Rapid Decompression

Requirement: A rapid decompression event shall be detected independent of active crew observation or monitoring prior to the cabin total pressure decreasing by 3.4 % based on a hole size of 1.3 cm to 5.1 cm diameter.

> ***Note:*** *This specification value is equivalent to the ISS requirement.*

4.2.2.1.2 Recover from rapid decompression

Requirement: The capability to recover from a rapid decompression event shall be provided.

4.2.2.2 Respond to Fire

Requirement: The capability to detect, suppress, and recover from fire events shall be provided.

4.2.2.2.1 Detect Fire

Requirement: Fire events shall be detected in selected enclosed locations and in the open cabin volume independent of active crew observation or monitoring.

4.2.2.2.2 Isolate Fire

Requirement: Fire events shall be isolated in the affected location.

4.2.2.2.3 Suppress Fire

Requirement: The capability to suppress a fire event shall be provided.

4.2.2.2.4 Recover from Fire

Requirement: Following a fire, the atmospheric combustion products shall be removed and the habitable environment shall be restored.

4.2.2.3 Respond to Hazardous Atmosphere

Requirement: The capability to detect and recover from a hazardous atmosphere shall be provided.

4.2.2.3.1 Detect Hazardous Atmosphere

a. **Requirement:** Potentially hazardous gaseous, vapor, aerosol and particulate atmospheric contaminants shall be detected independent of active crew observation and monitoring before they reach hazardous concentrations within the crew cabin.

b. **Requirement:** Potential atmospheric hazards shall be assessed for each mission and vehicle.

4.2.2.3.2 Recover from Hazardous Atmosphere

Requirement: The capability to recover from a hazardous atmosphere shall be provided.

> ***Note:*** *Some permissible recovery options include complete replacement of cabin atmosphere, increasing the capacity of the existing contaminant removal system, and/or activation of a secondary contaminant removal system. It is permissible for each option to also be coupled with an emergency source of breathing air for the crew. Alternately, it is permissible to move the crew to a cabin volume that is not contaminated.*

4.2.3 Grow Plants

This section contains high-level requirements for growing higher plants as part of an advanced bioregenerative life support system. Necessary resources for plant growth, such as lighting, diurnal cycle, and atmospheric temperature, vary from one species to another, so the requirements here focus on general facilities within biomass production chambers and interfaces between the biomass production chambers and other life support subsystems.

> ***Note:*** *While many advanced life support system configurations include biomass production in some capacity, it is permissible for some advanced missions to forgo such systems for some or all of the mission vehicles. In such situations, the requirements in this section are not applicable. Thus, the requirements here assume plants are an integral part of the life support system.*

4.2.3.1 Produce Biomass

a. **Requirement:** Specialized growth chambers, called biomass production chambers, shall produce biomass by raising higher plants and/or other organisms.

b. **Requirement:** The biomass production chambers shall produce edible biomass.

> ***Note:*** *It is permissible to use edible biomass for food or for producing food.*

c. **Requirement:** It is permissible for the biomass production chambers to produce inedible biomass.

> ***Note:*** *Inedible biomass is a natural consequence of growing plants. Such material, however, contains resources that may be reclaimed for use by the life support system.*

4.2.3.2 Isolate Biomass Production Chamber and Internal Environmental Conditions

a. **Requirement:** When crewmembers are present within a biomass production chamber, all requirements elsewhere in this document also apply to the biomass production chamber to assure crew safety and health.

> ***Note:*** *The above applies for mission designs that require crew interaction within the biomass production chambers.*

b. **Requirement:** When crewmembers are excluded from entering the biomass production chamber during normal operations, it is permissible for internal chamber environmental conditions to deviate from the requirements applicable to human-inhabited volumes. However, if crewmembers ever do enter the biomass production chambers, then the current environment must abide by all applicable requirements elsewhere in this document to assure crew safety and health.

> ***Note:*** *This configuration requires almost wholly autonomous operation within the biomass production chamber, including planting, plant growth support, and harvesting.*

b1. **Requirement:** If crewmembers enter the biomass production chambers without any protective equipment to guard against atmospheric conditions that will not support human metabolic needs as described above, then the current biomass production chamber environment must abide by all applicable atmospheric requirements elsewhere in this document to assure crew safety and health while any crewmember occupies the biomass production chambers.

b2. **Requirement:** If crewmembers enter the biomass production chambers with protective equipment to guard against atmospheric conditions that will not support human metabolic needs, then the current biomass production chamber environment is not restricted by the atmospheric requirements to support human beings listed elsewhere in this document.

> ***Note:*** *Either (b1) or (b2) applies, depending on the life support system architecture and frequency with which the crew is expected to enter the biomass production chamber. In the default case, where provisions are not provided to support (b2), then (b1) applies.*

4.2.3.3 Isolate Crop Species

Requirement: Where species-to-species isolation is required, it is permissible for environmental conditions, including air and growing media/nutrient solution temperatures, atmospheric composition, and lighting to be controlled independently from similar conditions for other species.

> ***Note:*** *The actual extent of isolation depends on the specific species-to-species interaction that shall be suppressed and the overall mission design.*

4.2.3.4 Define Plant Growth Zones

a. **Requirement:** Each individual crop shall have a distinct aerial environment and a distinct root zone environment.

> ***Note:*** *"Distinct" implies that the aerial and root zone environments are readily identifiable, so as to apply the requirements below, not that they be separated by a physical barrier.*

b. **Requirement:** It is permissible to isolate the aerial and root zone environments from each other.

> ***Note:*** *Ideally, such isolation is unnecessary. In reality, isolation may improve overall system robustness and reliability or provide a necessary buffer between crop species environments that are incompatible with each other.*

4.2.3.4.1 Aerial Zone

a. **Requirement:** The volume and height available for each crop species shall be adequate to accommodate the full plant shoot growth for that species.

b. **Requirement:** The atmospheric temperature control shall accommodate different settings for day and night cycles.

c. **Requirement:** The constituent composition within the aerial zone environment shall be maintained to support healthy growth for each crop species within the biomass production chambers according to current applicable standards.

> ***Note:*** *Important aerial zone environment constituents include plant metabolic gases, such as carbon dioxide and oxygen, relative humidity, and prompt removal of gas-phase toxins, such as ethylene.*

4.2.3.4.2 Root Zone

a. **Requirement:** The volume and depth available for each crop species shall be adequate to accommodate the full plant root zone for that species.

b. **Requirement:** The root zone environment, including temperature and composition, shall accommodate different settings and constituents as required by the species supported according to current applicable standards.

4.2.3.5 Use Resources

Requirement: The biomass production chambers shall use resources recovered from elsewhere in the vehicle.

4.2.3.5.1 Use Carbon Dioxide

Requirement: The biomass production chambers shall use carbon dioxide collected within the crew cabin to support plant photosynthesis.

4.2.3.5.2 Use Wastewater

Requirement: It is permissible for the biomass production chambers to use reclaimed or raw wastewater, including processed or raw urine, according to the applicable interface specifications and current safety requirements.

> ***Note:*** *The technical implementation of using wastewater within the biomass production chambers depends upon assuring crew safety first, and that safety may not be assured in general by this approach. However, because natural processes with plants perform this function in nature, wastewater usage by plants should not be dismissed without further consideration.*

4.2.3.5.3 Use Other Wastes

Requirement: The biomass production chambers shall use reclaimed or raw wastes other than wastewater according to the applicable interface specifications and current safety requirements.

***Note:** The technical implementation of using other wastes besides wastewater within the biomass production chambers depends upon assuring crew safety first, and that safety may not be assured in general by this approach. However, because natural processes with plants perform this function in nature, waste usage by plants should not be dismissed without further consideration.*

4.2.3.6 Provide Resources from Biomass Production

Requirement: The biomass production chambers shall provide life support commodities to be transferred within the life support system according to the applicable interface specifications.

4.2.3.6.1 Provide Edible Biomass

Requirement: The biomass production chambers shall provide edible biomass for use as food and/or food ingredients according to applicable interface specifications.

4.2.3.6.2 Provide Inedible Biomass

Requirement: It is permissible for the biomass production chambers to generate inedible biomass as a waste according to applicable interface specifications.

***Note:** Inedible biomass is a natural by-product of producing edible biomass.*

4.2.3.6.3 Provide Oxygen

Requirement: The biomass production chambers shall provide excess oxygen for use as a gas product according to applicable interface specifications.

4.2.3.6.4 Provide Water

Requirement: The biomass production chambers shall provide excess transpirate as a clean water product or a wastewater according to applicable interface specifications.

***Note:** To maintain the overall mass balance within the biomass production chambers, any transpirate removed must be replaced by an equal mass of water, which could include wastewater.*

4.2.3.6.5 Provide Used Nutrient Solution

Requirement: The biomass production chambers shall provide used nutrient solution as a wastewater according to applicable interface specifications.

4.2.3.6.6 Provide Thermal Energy

Requirement: The biomass production chambers shall provide excess thermal energy as waste heat according to applicable interface specifications.

***Note:** It is permissible to transfer this waste thermal energy to another process within the vehicle, such as waste dryer, or to the cooling external interface for rejection from the vehicle.*

4.2.3.7 Process Harvested Biomass

Requirement: Biomass grown in the biomass production chambers shall be processed following harvest to segregate edible biomass from inedible biomass.

4.2.3.8 Store Edible Biomass

Requirement: Edible biomass shall be stored until it is transferred for use as food or further processing into food ingredients according to the applicable interface specifications.

4.2.4 Provide Resources

This section contains high-level requirements to provide resources for atmosphere maintenance, crew consumption, crew hygiene, mission science, thermal control and extravehicular activities. When the life support system is fully defined, it is permissible to add additional requirements to provide internal resources necessary for system operation, such as water and nutrients for plant growth.

Requirement: The life support system shall provide gases, water and food as needed for atmosphere maintenance, crew consumption, crew hygiene, mission science, thermal control and extravehicular activities.

4.2.4.1 Provide Inert Gas

a. **Requirement:** An inert gas, such as nitrogen, shall be provided to make up for atmospheric leakage.

b. **Requirement:** An inert gas, such as nitrogen, shall be provided to make up for airlock losses.

c. **Requirement:** An inert gas, such as nitrogen, shall be provided to repressurize the cabin in the event of loss of atmosphere.

> ***Note:*** *Inert gas may be required for other uses.*

4.2.4.1.1 Supply Inert Gas

Requirement: An inert gas, such as nitrogen, shall be supplied to points of use in accordance with applicable interface specifications for gas temperature, pressure and flow rate.

4.2.4.1.2 Store Inert Gas

Requirement: Storage of an inert gas, such as nitrogen, shall be provided with a minimum capacity to meet usage and contingency needs, including cabin repressurization.

4.2.4.1.3 Accept External Inert Gas

Requirement: Resupplied inert gas, such as nitrogen, shall be accepted in accordance with applicable interface specifications. It is permissible to obtain resupply gas from in situ resources.

4.2.4.2 Provide Oxygen

a. **Requirement:** Oxygen shall be provided to support human metabolic needs.

b. **Requirement:** Oxygen shall be provided to support animal metabolic needs.

c. **Requirement:** Oxygen shall be provided to recharge extravehicular mobility units to support nominal human metabolic needs during extravehicular activities.

d. **Requirement:** Oxygen shall be provided to make up for atmospheric leakage.

e. **Requirement:** Oxygen shall be provided to make up for airlock losses.

f. **Requirement:** Oxygen shall be provided to repressurize the cabin in the event of loss of atmosphere.

g. **Requirement:** Supplies of portable and umbilical emergency breathing oxygen shall be provided.

> ***Note:*** *Oxygen may be required for other uses.*

4.2.4.2.1 Supply Oxygen

Requirement: Oxygen shall be supplied to points of use in accordance with applicable interface specifications for gas temperature, pressure and flow rate.

4.2.4.2.2 Store Oxygen

Requirement: Storage of oxygen or oxygen generating resources shall be provided with a minimum capacity to meet usage and contingency needs, including cabin repressurization.

4.2.4.2.3 Regenerate Oxygen

Requirement: It is permissible to regenerate oxygen.

4.2.4.2.4 Accept External Oxygen

Requirement: Resupplied oxygen shall be accepted in accordance with applicable interface specifications. It is permissible to obtain resupply oxygen from in situ resources.

4.2.4.3 Provide Water

a. **Requirement:** Potable water shall be provided for drinking and food preparation in accordance with current potable water quality standards.

b. **Requirement:** Potable water shall be provided for oral hygiene, EVA needs and mission science needs according to the mission architecture.

c. **Requirement:** Water shall be provided for personal hygiene, laundry and dishwashing in accordance with the mission architecture and current hygiene water quality standards.

d. **Requirement:** Water shall be provided for other needs with a minimum of hygiene quality according to the mission architecture and current applicable water quality standards.

> ***Note:*** *Water may be required for other uses.*

4.2.4.3.1 Supply Water

Requirement: Water shall be supplied to points of use in accordance with applicable interface specifications for water temperature, pressure, flow rate and quality.

4.2.4.3.2 Store Water

a. **Requirement:** At minimum capacity, stored water shall meet peak usage demands during normal operations.

b. **Requirement:** Stored potable water shall provide sufficient capacity to meet mission-specific contingency needs.

4.2.4.3.3 Regenerate Water

Requirement: It is permissible to regenerate potable and/or hygiene water.

4.2.4.3.4 Accept External Water

Requirement: Resupplied water shall be accepted in accordance with applicable interface specifications. It is permissible to obtain resupply water from in situ resources.

4.2.4.4 Provide Food

a. **Requirement:** Food shall be provided for crew consumption in accordance with current nutritional requirements.

> ***Note:*** *Current nutritional requirements may be found in JSC 28038. As more data is collected, the nutritional requirements for longer duration missions (>360 days) will be established.*
>
> ***Note:*** *Dietary requirements may be met through a combination of in-situ food production, re-supplied foods and pre-supplied foods, and dietary supplements.*

b. **Requirement:** The food shall be safe in accordance with current food safety standards.

c. **Requirement:** The diet shall meet food-related psychological needs of the crew by accommodating some individual food choice for meals and snacks and both individual and group dining formats.

d. **Requirement:** The diet shall be organoleptically acceptable.

4.2.4.4.1 Store Food and Food Ingredients

Requirement: Storage of food and food ingredients shall be provided with a minimum capacity to meet usage and contingency needs.

> ***Note:*** *During normal operation, it is permissible to consume some food or food ingredients immediately after harvest and/or production, eliminating the need to store them.*

4.2.4.4.2 Regenerate Food and Food Ingredients

Requirement: It is permissible to regenerate food and food ingredients.

4.2.4.4.3 Process Food and Food Ingredients

Requirement: Raw food materials and ingredients shall be processed into appropriate ready-to-eat foods and food ingredients according to the mission architecture.

4.2.4.4.4 Accept External Food and Food Ingredients

Requirement: Resupplied food and food ingredients shall be accepted in accordance with applicable interface specifications.

4.2.5 Manage Wastes

This section contains requirements to manage wastes for resource recovery, during transport, storage, or disposal. When the life support system is fully defined, it is permissible to write additional requirements to manage internal wastes and processing byproducts from system operation, such as hydrogen and methane.

Requirement: The life support system shall accept and process gaseous, liquid and solid wastes for resource recovery, transport, storage, and/or disposal.

4.2.5.1 Manage Gaseous Wastes

Requirement: Gaseous Wastes shall be managed for resource recovery, storage or disposal.

4.2.5.1.1 Accept Gaseous Wastes

Requirement: Gaseous wastes shall be accepted from points of collection in accordance with applicable interface specifications.

4.2.5.1.2 Transport Gaseous Wastes

Requirement: It is permissible to transport gaseous wastes between points of collection, storage facilities, and/or processing equipment in accordance with applicable interface specifications.

> ***Rationale:*** *It is permissible for gaseous waste collection, processing, and storage to be located apart from each other. Even if co-location is possible, safety considerations or overall system efficiency may advise locating some activities well away from other activities.*

4.2.5.1.3 Store Gaseous Wastes

Requirement: Storage for gaseous wastes shall provide the minimum capacity necessary to meet peak and contingency storage needs.

> ***Note:*** *Contingencies include temporary loss of downstream processing capability.*

4.2.5.1.4 Process Gaseous Wastes

Requirement: It is permissible to process gaseous wastes to recover useful products.

4.2.5.1.5 Dispose of Excess Gaseous Wastes

Requirement: Excess gaseous wastes shall be disposed.

4.2.5.2 Manage Wastewater

Requirement: Wastewater shall be managed for resource recovery, storage, and/or disposal.

> ***Note:*** *It is permissible for wastewater streams to include humidity condensate, plant transpirate, urine, urine flush water, shower wastewater, handwash wastewater, dish washing wastewater, food processing, preparation, and cleaning wastewater, solid waste processor wastewater, mission science wastewater, and/or other sources.*
>
> ***Note:*** *Wastewater quantities from many sources are mission and design dependent. Current wastewater models are presented in JSC-47804.*

4.2.5.2.1 Accept Wastewater

Requirement: Wastewater shall be accepted from points of collection in accordance with applicable interface specifications.

4.2.5.2.2 Transport Wastewater

Requirement: It is permissible to transport wastewater between points of collection, storage facilities, and/or processing equipment in accordance with applicable interface specifications.

> ***Rationale:*** *It is permissible for wastewater collection, processing, and storage to be located apart from each other. Even if co-location is possible, safety considerations or overall system efficiency may advise locating some activities well away from other activities.*

4.2.5.2.3 Store Wastewater

Requirement: Storage for wastewater shall provide the minimum capacity necessary to meet peak and contingency storage needs.

> ***Note:*** *Contingencies include temporary loss of downstream processing capability.*

4.2.5.2.4 Process Wastewater

Requirement: It is permissible to process wastewater to recover potable or hygiene water and produce a concentrated waste.

> ***Note:*** *It is permissible for urine processing to include chemical stabilization as well as water recovery.*

4.2.5.2.5 Dispose of Excess Wastewater

Requirement: Excess wastewater shall be disposed.

> ***Note:*** *Disposal may include jettisoning the waste to the local environment and/or transfer to a returning vehicle. Implementation of this requirement is mission dependent.*

4.2.5.3 Manage Solid and Concentrated Liquid Wastes

Requirement: Solid and concentrated liquid wastes shall be managed for resource recovery, storage, and/or disposal.

> ***Note:*** *It is permissible for solid and concentrated liquid wastes to include human wastes, such as feces, urine brine, vomitus, and menses, uneaten food, trash, such as paper, plastic, foil, and other items, wastewater processor brine, food processing waste, crop production waste, air processor residuals, medical wastes, discarded clothing, mission science wastes, maintenance wastes, and/or other sources.*
>
> ***Note:*** *Solid and concentrated liquid waste quantities from many sources are mission and design dependent. Current waste models are presented in JSC-47804.*

4.2.5.3.1 Accept Solid and Concentrated Liquid Wastes

Requirement: Solid and concentrated liquid wastes shall be accepted from points of collection in accordance with applicable interface specifications.

> ***Note:*** *Waste collection facilities, such as the commode and urinal, are considered part of "Crew Systems". The life support system accepts wastes from these external facilities.*

4.2.5.3.2 Transport Solid and Concentrated Liquid Wastes

Requirement: It is permissible to transport solid and concentrated liquid wastes between points of collection, storage facilities, and/or processing equipment in accordance with applicable interface specifications.

> ***Rationale:*** *It is permissible for solid and concentrated liquid waste collection, processing, and storage to be located apart from each other. Even if co-location is possible, safety considerations or overall system efficiency may advise locating some activities well away from other activities.*

4.2.5.3.3 Store Solid and Concentrated Liquid Wastes

a. **Requirement:** Temporary storage of unprocessed solid and concentrated liquid wastes shall provide the minimum capacity necessary to meet peak and contingency storage needs.

> ***Note:*** *Contingencies include temporary loss of downstream processing capability.*

b. **Requirement:** Long-term storage for residuals and non-recovered wastes shall be provided.

> ***Note:*** *Residuals are defined as wastes from which no further useful resources can be recovered. It is permissible for non-recovered wastes to contain useful resources. Non-recovered wastes will not be processed to recover resources.*

4.2.5.3.4 Process Solid and Concentrated Liquid Wastes

Requirement: It is permissible to process solid and concentrated liquid wastes to recover useful products.

> ***Note:*** *It is permissible for useful products to include nitrogen, methane, hydrogen, nutrients, carbon dioxide, oxygen, and/or water. Specific resources recovered will depend on the mission and life support system architecture.*

4.2.5.3.5 Dispose of Solid and Concentrated Liquid Wastes

Requirement: Non-recovered wastes and process residuals shall be disposed of safely in accordance with current safety and environmental guidelines and mission protocols.

> ***Note:*** *it is permissible for disposal to include jettisoning to the environment and transfer to a returning vehicle. This requirement is mission dependent.*

4.2.6 Maintain Thermal Conditioning

High-level requirements are defined below for controlling thermal loads.

Requirement: The life support system shall maintain thermal conditioning of the vehicle so as to ensure crew health and comfort and to ensure that all systems can be maintained within their operating temperature envelopes.

4.2.6.1 Accept Thermal Energy

Requirement: Excess thermal energy shall be accepted from internal sources in accordance with applicable interface specifications.

> ***Note:*** *The total collected thermal energy is the sum of waste thermal energy from equipment, waste thermal energy from experiments, human metabolic thermal energy, and the gain or loss of thermal energy through the vehicle wall (spacecraft/habitat heat leakage).*
>
> ***Note:*** *It is permissible for interface specifications to include coolant flow rate, pressure, and temperature.*

4.2.6.1.1 Accept Thermal Energy from Atmosphere

Requirement: Excess thermal energy shall be accepted from the spacecraft/habitat atmosphere.

4.2.6.1.2 Accept Thermal Energy from Equipment

Requirement: Excess thermal energy shall be collected from equipment.

> ***Note:** Appropriate thermal energy acceptance interfaces from equipment may include heat exchangers, cold plates, or other designated thermal energy transfer equipment.*

4.2.6.1.3 Accept Thermal Energy from Liquid Systems

Requirement: Excess thermal energy shall be accepted from internal sources of liquids that require cooling according to interface specifications.

> ***Note:** This requirement could apply to internal equipment cooling loops.*

4.2.6.2 Transport Thermal Energy

Requirement: Accepted thermal energy shall be transported from thermal energy acquisition sites to other sites for reuse or rejection.

4.2.6.2.1 Transport Excess Thermal Energy to Cooling External Interface

Requirement: Accepted excess thermal energy shall be transported from thermal energy acquisition sites to the cooling external interface.

4.2.6.2.2 Transport Thermal Energy for Reuse Within the Vehicle

Requirement: Accepted thermal energy shall be transported, as specified by interface requirements, to provide thermal energy inputs for other vehicle processes and equipment.

4.2.6.3 Release Thermal Energy

Requirement: Thermal energy shall be transferred from the thermal energy transport equipment.

4.2.6.3.1 Reject (Dispose of) Excess Thermal Energy

Requirement: Excess thermal energy shall be transferred to the cooling external interface.

> ***Note:** The cooling external interface shall reject the excess thermal energy to the environment.*

4.2.6.3.2 Reuse Thermal Energy

Requirement**:** It is permissible to transfer thermal energy to other vehicle processes and equipment, as specified by mission interface requirements.

> ***Note:** It is permissible for various processes to reuse waste thermal energy. For example, a convective dryer might use the hot air stream from lightbox cooling rather than passing air over resistive heaters.*

4.2.6.4 Cool Equipment and Maintain Surface Touch Temperature

Requirement: Powered and/or activated equipment inside the vehicle shall maintain itself within its temperature envelope.

4.2.6.4.1 Transport Equipment Thermal Energy Loads

Requirement: Powered and/or activated equipment inside the vehicle shall transport its waste thermal energy load to applicable interface locations for removal according to applicable interface specifications and current safety requirements.

4.2.6.4.2 Maintain Equipment Touch Temperatures

Requirement: Powered and/or activated equipment inside the vehicle shall maintain its surface temperature at or below the specified surface temperature, often called a touch temperature, to safeguard crewmembers from burn and fire hazards.

4.2.6.4.3 Prevent Water Condensation

Requirement: Condensation of moisture on to structures within the pressurized crew cabin shall not be permitted unless the surfaces on to which the water condenses are specifically designed for such action.

> ***Note:*** *While active heating generally represents inefficiency for a human-tended vehicle, active resistive heating elements are effective for maintaining cabin wall temperatures above the cabin dew point. Free moisture in a microgravity environment may jeopardize safety of an entire vehicle and its crew if the water contacts equipment and electronics in unforeseen modes. Even under partial gravity, liquid water may behave in an unpredictable manner and again endanger the vehicle and its crew if allowed to develop at any location within the cabin. At the very least, liquid water on structure often supports corrosion of metallic materials.*

4.2.7 Support Extravehicular Activities

Requirement: The life support system shall support EVA operations.

4.2.7.1 Support Extravehicular Mobility Unit Servicing and Checkout

a. **Requirement:** Life support commodities shall be provided for EMU servicing.

> ***Note:*** *It is permissible for commodities provided for EMU servicing to include oxygen, potable water, and/or food.*

b. **Requirement:** Removal of EMU wastes following an EVA shall be accommodated.

> ***Note:*** *Actual waste products are EMU design dependent, but they may include human urine, other wastewater, feces, and/or carbon dioxide.*

c. **Requirement:** Cleaning and drying of the EMU shall be supported.

> ***Note:*** *Cleaning and drying of the EMU may place loads on cabin life support equipment in the form of airborne, water-borne, or solid by-products.*

4.2.7.2 Support Desorption of Inert Gas from Body Tissues

a. **Requirement:** Pre-breathe protocols, if required, shall be supported.

> ***Note:*** *It is permissible for pre-breathe protocols to include a reduced-pressure campout and an in-suit prebreathe of pure oxygen.*

b. **Requirement:** An in-suit purge using pure oxygen to remove atmospheric inert gas, as appropriate for the mission and EMU design, shall be supported prior to EVA operation.

> ***Note:*** *The ISS requirement specifies a minimum of 12 minutes for the in-suit purge operation.*

4.2.7.3 Support Depressurization for Egress

a. **Requirement:** Depressurization of the airlock for a crewmember from the cabin atmospheric pressure to the external pressure shall be supported at a nominal rate of 0.34 kPa per second.

> ***Rationale:*** *Ear discomfort limits govern the practical rate of airlock pressure change.*

b. **Requirement:** Airlock atmospheric gases shall be recovered during depressurization under normal, non-emergency, EVA operations according to applicable interface specifications.

4.2.7.4 Support Repressurization for Ingress

Requirement: Repressurization of the airlock for a crewmember from the external ambient pressure to the cabin atmospheric pressure shall be supported at a nominal rate of 0.34 kPa per second.

> ***Rationale:*** *Ear discomfort limits govern the practical rate of airlock pressure change.*

4.2.7.5 Support Contaminant Detection and Decontamination

Requirement: Contaminant detection and decontamination of the crew and EVA equipment shall be supported following an EVA.

5. INTEGRATED SYSTEM MANAGEMENT SYSTEM REQUIREMENTS

5.1 SYSTEM DEFINITION

5.1.1 Groundrules and Assumptions

5.1.2 Functional Decomposition

A high-level functional decomposition of an advanced ISM system is shown in Table 5-1. Some lower-level functions in this table may not be applicable to all missions or system designs. This functional decomposition forms the basis for the definition of requirements in Section 5.2. Further functional decomposition would require additional assumptions about system design and technologies.

Table 5-1. Integrated System Management Functional Decomposition

Function
Provide integrated monitoring and control
Provide planning
Provide caution and warning capability

5.1.3 Interfaces

5.1.3.1 External Interfaces

External interfaces for an advanced ISM system are shown schematically in Figure 5-1.

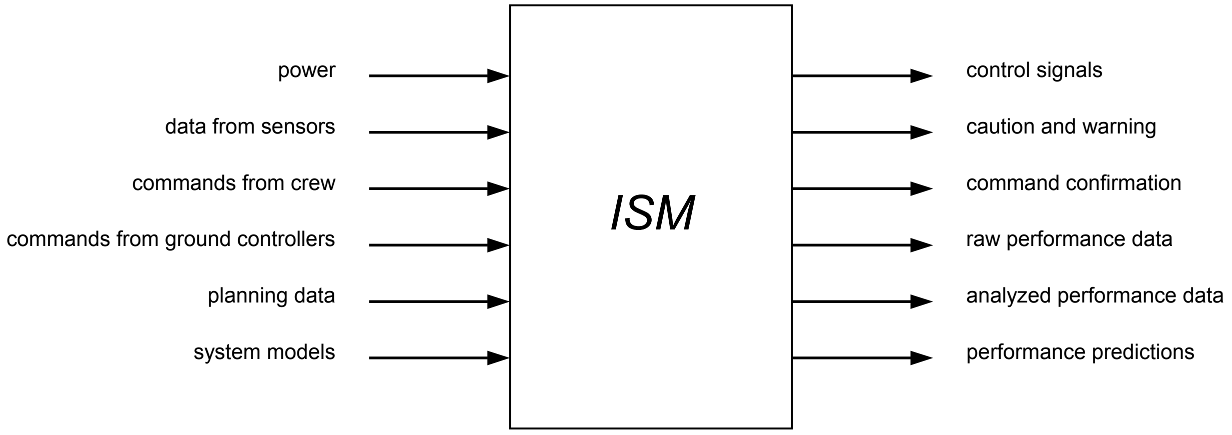

Figure 5-1. Integrated System Management System interfaces.

5.1.3.2 Internal Interfaces

Internal interfaces are highly dependent on system design and chosen technologies. This is particularly true with multifunctional bioregenerative technologies, such as plant growth systems, which can provide food production, air revitalization and water purification. In general, internal interfaces will include material (gas, liquid and solid) interfaces between processors and between processors and storage systems. The result of these internal interfaces will be additional requirements governing the supply and distribution of resources and wastes.

5.2 PERFORMANCE REQUIREMENTS

High-level requirements are defined below for ISM functions listed in Table 5-1. The terms “control” and “automation” are used in these requirements as defined below:

> ***Notes:***
>
> ***Control*** *is taken here to include monitoring and control functions carried out by computer controlled machines as substitutes for crew cognitive labor, including the functions from sensing through making decisions to actuation at both the subsystem and system levels. Control is taken here to include both traditional control and monitoring of systems, which provide crew visibility into sensor and effector status and which provides command control of equipment and systems, and automated control which integrates mission operations planning, crew and automated procedures, and system level configuration control with traditional control and monitoring.*
>
> ***Automation*** *is taken here to include mobility and manipulation functions carried out by computer-controlled machines as substitutes for crew manual labor, such as mechanization, materials handling, telerobotics and robotics systems, but not monitoring and control of life support subsystems, or of a life support integrated system.*

5.2.1 Provide Integrated Monitoring and Control

a. **Requirement:** The ISM system shall monitor life support subsystems, critical parameters and variables.

b. **Requirement:** The ISM system shall interface with and provide supervisory control of life support subsystem controllers.

c. **Requirement:** The ISM system shall be able to detect and on-line diagnose multiple system faults, including those in the ISM system itself.

d. **Requirement:** The ISM system shall provide robust control and be able to achieve the desired operating conditions of the LSS despite multiple, known, non-critical faults.

e. **Requirement:** The ISM system shall be able to achieve satisfactory operating conditions of the LSS after a critical fault.

f. **Requirement:** The ISM system operation shall be able to be overridden by the local and remote operators at any chosen level of shared or traded automatic control (adjustable autonomy).

g. **Requirement:** The ISM system shall be able to show the operator, either continuously or on demand, the control systems current assessment of the LSS's state in the context of the mission.

h. **Requirement:** The ISM system shall be able to resolve multiple feasible goals and tasks of the operators simultaneously.

i. **Requirement:** The ISM system shall be able to support the operator in obtaining broader comprehension of the LSS and its historical, current and predicted state.

k. **Requirement:** The ISM system shall provide sensor and system data on demand.

5.2.2 Provide Planning

a. **Requirement:** The ISM system shall provide for planning/re-planning of operations.

b. **Requirement:** The ISM system shall be able to advise the crew on resolving unplanned situations by reasoning with a model based on structure and function of the life support system, or by allowing and taking feedback from crew operators.

b1. **Requirement:** Every system, subsystem or component shall be delivered with a mathematical model and with a computer model for building an integrated system model.

5.2.3 Provide Caution and Warning Capability

Requirement: The ISM system shall provide caution and warning capability.

5.3 CANDIDATE ARCHITECTURE REQUIREMENTS

A life support system imposes a load on the human crew, in terms of cognitive and manual labor for operations and maintenance of the systems and equipment. Operations include control and monitoring of life support parameters, as well as the planning, scheduling and procedural aspects of using and maintaining the systems, subsystems and equipment, including logistics, resupply, consumables, maintenance (planned and unplanned), fault detection, isolation and recovery, many of which are interdependent. Because of this, crew time requirements are an essential element of the design. Because mission science and technology objectives place priority demands on crew time, minimizing, or better, optimizing, involvement of the crew in life support operations is critical.

In order to provide an integrated approach to managing the operations of the various life support systems, optimized with respect to interaction between crew and computer controlled machines, the ISM must incorporate several "levels" of functionality in a robust, efficient, easily configurable manner. Due to the constraint on crew resources, it is imperative that the ISM not require constant or even intermittent crew vigilance and interaction during nominal operations. Because of this, it is also imperative that the ISM provide a concise, easily understood presentation of any off-nominal situations that do require crew intervention, including what options are available to the crew. Controls of the various life support systems will vary due to interdependencies between systems (e.g. O_2 control may change due to waste management demands) and due to operational and procedural activities (e.g. light control may vary due to plant germination requirements; O_2 control may vary due to impending crew ingress into the biomass production chambers). These interdependencies drive the ISM requirements for an integrated layered approach to control of the life support systems.

The ISM subsystem shall provide three primary levels of control in an integrated, robust fashion. These three layers are:

The planning level, which integrates mission goals with crew time and system procedures and which provides automatic replanning capability to accommodate changes caused by internal and external system events.

The procedural level, which provides conditional, sequenced control of subsystems and equipment based upon events generated by the control level. The procedural level operates autonomously after activation by the planning level.

The control level which interfaces with equipment to control and monitor subsystem activity. The control level operates autonomously after activation by the procedural level. The control level includes sensing and actuation.

5.3.1 The Planning Level

a. **Requirement:** The Planning Level of the ISM shall determine which procedures are necessary to achieve a specified goal, when the procedures must be executed, and what events and conditions must be monitored to verify status, success and failure.

b. **Requirement:** The Planning Level of the ISM shall be capable of executing these procedures automatically.

c. **Requirement:** The Planning Level of the ISM shall function in a safe, robust manner, and provide crew and ground visibility into plan status and execution.

d. **Requirement:** For certain defined critical activities and events the ISM shall require crew interaction before proceeding with plan execution.

e. **Requirement:** The Planning Level of the ISM shall determine precondition and postcondition checks for the procedures, including but not limited to crew availability, equipment status and availability, current configurations, planned configurations, pass/fail criteria, resource status and availability, inventory availability, potential conflicts with other plans and procedures, etc.

f. **Requirement:** The Planning Level of the ISM shall be capable of scheduling activities and procedures based upon constraints of crew time, available resources and system dependencies.

g. **Requirement:** The Planning Level of the ISM shall monitor critical parameters and events generated by the Procedural and Control levels to verify the plan is executing successfully.

h. **Requirement:** The Planning Level of the ISM shall be capable of modifying the plan based upon those monitored parameters and events.

i. **Requirement:** The Planning Level of the ISM shall be capable of modifying the plan based upon crew input.

j. **Requirement:** The Planning Level of the ISM shall be capable of replanning based upon unsuccessful execution of the plan.

k. **Requirement:** The Planning Level of the ISM shall support traded control, where the mix of autonomy and manual control is adjustable by the crew.

5.3.2 The Procedural Level

a. **Requirement:** The Procedural Level of the ISM shall be capable of executing multiple procedures as activated by the Planning Level.

b. **Requirement:** The Procedural Level of the ISM shall monitor critical parameters and events generated by the Control level to verify the procedures are executing successfully.

c. **Requirement:** The procedures shall be capable of conditionally responding to monitored parameters and events, including activation of other procedures.

d. **Requirement:** The Procedural Level of the ISM shall be capable of retrying unsuccessful procedures in a controlled fashion.

e. **Requirement:** The Procedural Level of the ISM shall be capable of configuring the Control Level to ensure execution of the procedures.

f. **Requirement:** The Procedural Level of the ISM shall function in a safe, robust manner, and provide crew and ground visibility into procedure status and execution. For certain defined critical activities and events the ISM shall require crew interaction before proceeding with procedure execution.

g. **Requirement:** The Procedural Level of the ISM shall provide status and event notification to the Planning Level.

h. **Requirement:** The Procedural Level of the ISM shall support traded control, where the mix of autonomy and manual control is adjustable by the crew.

5.3.3 The Control Level

a. **Requirement:** The Control Level of the ISM shall be capable of controlling and monitoring multiple systems, subsystem and equipment parameters and alarms as configured by the Planning Level.

b. **Requirement:** The Control Level of the ISM shall be capable of providing event notification to the Procedural Level and the Planning Level, where events are defined as significant changes in data and status (e.g. red-line temperature alarm, change in rate above a certain percent, valve position change, etc.). Events shall be definable, configurable and modifiable in real time.

c. **Requirement:** The Control Level of the ISM shall monitor critical parameters and events generated by the equipment and subsystems to verify successful operation.

d. **Requirement:** The Control Level of the ISM shall be capable of conditionally responding to monitored parameters and events, to maintain system, subsystem and equipment parameters to within defined limits.

e. **Requirement:** The Control Level of the ISM shall be capable of configuring the equipment, equipment parameters and alarms in response to procedure execution by the Procedural Level.

f. **Requirement:** The Control Level of the ISM shall function in a safe, robust manner, and provide crew and ground visibility into system, subsystem and equipment status, control and health. For certain defined critical commands, the ISM shall require crew interaction before configuration changes.

g. **Requirement:** The Control Level of the ISM shall provide status, event and alarm notification to the Planning Level.

h. **Requirement:** The Control Level of the ISM shall support traded control, where the mix of autonomy and manual control is adjustable by the crew.

6. REFERENCES

ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers), 1989 ASHRAE Handbook. Fundamentals. I-P Edition, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, GA, 1989.

Bubenheim, D. L., Plants for Water Recycling, Oxygen Regeneration and Food Production, *Waste Management & Research*, 9, 435-443 (1991).

Corey, K. A., M. E. Bates and S. L. Adams, Carbon Dioxide Exchange of Lettuce Plants under Hypobaric Conditions, *Adv. Space Res.*, 18(1/2), 301-308 (1996).

D684-10508-1-1, International Space Station Program. Environmental Control and Life Support (ECLS) Architecture Description Document. Vol. 1. ECLS Requirements and Rationale. Book 1. Control Atmospheric Pressure. Rev. A, Boeing, May 1996.

D684-10508-1-2, International Space Station Program. Environmental Control and Life Support (ECLS) Architecture Description Document. Vol. 1. ECLS Requirements and Rationale. Book 2. Condition Atmosphere. Rev. A, Boeing, May 1996.

D684-10508-1-3, International Space Station Program. Environmental Control and Life Support (ECLS) Architecture Description Document. Vol. 1. ECLS Requirements and Rationale. Book 3. Respond to Emergency Conditions. Rev. A, Boeing, May 1996.

D684-10508-1-4, International Space Station Program. Environmental Control and Life Support (ECLS) Architecture Description Document. Vol. 1. ECLS Requirements and Rationale. Book 4. Control Internal Carbon Dioxide and Contaminants. Rev. A, Boeing, May 1996.

D684-10508-1-5, International Space Station Program. Environmental Control and Life Support (ECLS) Architecture Description Document. Vol. 1. ECLS Requirements and Rationale. Book 5. Provide Water. Rev. A, Boeing, May 1996.

D684-10508-2-1, International Space Station Program. Environmental Control and Life Support (ECLS) Architecture Description Document. Vol. 2. ECLS Architecture. Book 1. Station ECLS Architecture Overview. Rev. A, Boeing, May 1996.

D684-10508-2-3, International Space Station Program. Environmental Control and Life Support (ECLS) Architecture Description Document. Vol. 2. ECLS Architecture. Book 3. Russian Segment ECLS Architecture. Rev. A, Boeing, May 1996.

Ewert, M. K., P. A. Petete and J. Dzenitis, Active Thermal Control Systems for Lunar and Martian Exploration, Paper No. 901243, 20th International Conference on Environmental Systems, Society of Automotive Engineers, Warrendale, PA, 1990.

Ewert, M. K., Investigation of Lunar Base Thermal Control System Options, Paper No. 932112, 23rd International Conference on Environmental Systems, Society of Automotive Engineers, Warrendale, PA, 1993.

Grodzinski, B., L. Woodrow, E. D. Leonardos, M. Dixon and M. J. Tsujita, Plant Responses to Short- and Long-Term Exposures to High Carbon Dioxide Levels in Closed Environments, *Adv. Space Res.*, 18(4/5), 203-211 (1996).

Hanford, A. J., and M. K. Ewert, Advanced Active Thermal Control Systems Architecture Study, NASA TM-104822, NASA Johnson Space Center, Houston, TX, October 1996.

Hoff, J. E., J. M. Howe and C. A. Mitchell, Nutritional and Cultural Aspects of Plant Species Selection for a Controlled Ecological Life Support System, NASA-CR-166324, Purdue University, West Lafayette, IN, March 1982.

Hoffman, S. J., compiler, and D. I. Kaplan, editor, Mars Reference Mission, NASA Special Publication 6107, NASA Johnson Space Center, Houston, TX, January 1997.

James, J. T., and M. E. Coleman, Toxicology of Airborne Gaseous and Particulate Contaminants in Space Habitats, in *Space Biology and Medicine. Vol. II. Life Support and Habitability*, F. M. Sulzman and A. M. Genin, editors, American Institute of Aeronautics and Astronautics, Washington, DC, 1993.

James, J. T., Spacecraft Maximum Allowable Concentrations for Airborne Contaminants, JSC-20584, NASA Johnson Space Center, Houston, TX, February 1995.

Jan, D., P. Seshan, G. Ganapathi, G. Schmidt and C. Doarn, Advanced Environmental Monitoring and Control Program: Technology Development Requirements, NASA-TM-4755, JPLD-13832, Jet Propulsion Laboratory, Pasadena, CA, May 1996.

JSC-20584, Spacecraft Maximum Allowable Concentrations For Airborne Contaminants, Toxicology Group Medical Operations Branch Medical Sciences Division Space And Life Sciences Directorate, National Aeronautics And Space Administration Lyndon B. Johnson Space Center Houston, Texas, June 1999.

JSC-25003, Internal Atmosphere Pressure and Composition for Planet Surface Habitats and Extravehicular Mobility Units, LESC-29278, NASA Johnson Space Center, Houston, TX, March 1991.

http://www-sn.jsc.nasa.gov/explore/Data/Lib/DOCS/EIC017.HTML

JSC-25736, Final Report on NASA Workshop on Resource Recovery from Wastes Generated in Lunar/Mars Controlled Ecological Life Support Systems (CELSS), CTSD-ADV-035, NASA Johnson Space Center, August 1992.

JSC-31000, Space Station Projects Description and Requirements Document. Vol. 3. Projects Design and Development Requirements. Rev. H, Space Station Projects Office, NASA Johnson Space Center, Houston, TX, November 1992.

Lane, H. W., Metabolic Energy Requirements for Space Flight, in *Space Biology and Medicine. Vol. II. Life Support and Habitability*, F. M. Sulzman and A. M. Genin, editors, American Institute of Aeronautics and Astronautics, Washington, DC, 1993.

Lane, H. W., and P. C. Rambaut, Nutrition, in *Space Physiology and Medicine*, 3rd ed., A. E. Nicogossian, C. L. Huntoon, and S. L. Pool, editors, Lea & Febiger, Malvern, PA, 1994.

Lane, H. W., C. T. Bourland, D. Pierson, E. Grigorov, A. Agureev and V. Dobrovolsky, Nutritional Requirements for International Space Station: Missions Up to 360 Days, JSC 28038, NASA Johnson Space Center, Houston, TX, December 1996.

Leach, C. S., J. I. Leonard, P. C. Rambaut and P. C. Johnson, *J. Appl. Physiol.*, 45(3), 430-436 (1978).

Lide, D. R., editor, *CRC Handbook of Chemistry and Physics*, 76th ed., CRC Press, Boca Raton, FL, 1995.

Liu, B. Y. H., K. L. Rubow, P. H. McMurry, T. J. Kotz and D. Russo, Airborne Particulate Matter and Spacecraft Internal Environments, Paper No. 911476, 21st International Conference on Environmental Systems, Society of Automotive Engineers, Warrendale, PA, 1991.

McBarron, J. W., C. E. Whitsett, G. I. Severin and I. P. Abramov, Individual Systems for Crewmember Life Support and Extravehicular Activity, in *Space Biology and Medicine. Vol. II. Life Support and Habitability*, F. M. Sulzman and A. M. Genin, editors, American Institute of Aeronautics and Astronautics, Washington, DC, 1993.

McLean, J. A., and G. Tobin, *Animal and Human Calorimetry*, Cambridge University Press, Cambridge, UK, 1987.

Mitchell, K. L, Technical Assessment of Mir-1 Life Support Hardware for the International Space Station, NASA Marshall Space Flight Center, AL, 1993.

NASA, Advanced Life Support Project Plan, JSC-39168 (CTSD-ADV-348, Revision C), National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, Houston, Texas, February 2002.

http://advlifesupport.jsc.nasa.gov/

NASA, NASA Strategic Plan, NASA Policy Directive (NPD)-1000.1, NASA Headquarters, Washington, DC, 1998.

NASA-STD-3000, Space Station Freedom Man-Systems Integration Standards, Vol. IV, Rev. A, NASA Johnson Space Center, Houston, TX, June 1991.

NASA-STD-3000, Man-Systems Integration Standards, Vol. I, Rev. B., NASA Johnson Space Center, Houston, TX, July 1995.

NCRP, Radiation Protection Guidance for Activities in Low-Earth Orbit, Report 132, National Council on Radiation Protection and Measurements, 2000.

NRC (National Research Council), *Recommended Dietary Allowances*, 10th ed., National Academy Press, Washington, DC, 1989.

Perry, J. L., Trace Chemical Contaminant Generation Rates for Spacecraft Contamination Control System Design, NASA-TM-108497, NASA Marshall Space Flight Center, AL, August, 1995.

Slonim, N. B., and J. L. Chapin, *Respiratory Physiology*, C. V. Mosby Co., St. Louis, MO, 1967.

Smith, R. E., and G. S. West, Space and Planetary Environment Criteria Guidelines for Use in Space Vehicle Development, 1982 Revision, Vol. 1, NASA TM-82478, 1983.

SSP-30000, Space Station Program Definition and Requirements: Section 3: Space Station Systems Requirements, Rev. L, Space Station Freedom Program Office, NASA, Reston, VA, August 1992.

SSP-30262, Environmental Control and Life Support System Architectural Control Document, PDR Draft, NASA Marshall Space Flight Center, AL, April, 1990.

SSP-30262, Environmental Control and Life Support System Architectural Control Document, Rev. D, Space Station Freedom Program Office, NASA, Reston, VA, July 1991.

SSP-41000AG, System Specification For The International Space Station, Boeing Defense and Space Group, Missiles and Space Division, Houston, TX, March 29,2002.

SSP-41162R, Segment Specification for the United States On-Orbit, Boeing Defense and Space Group, Missiles and Space Division, Houston, TX, March 15, 2000.

SSP-50260 International Space Station Medical Operations Requirements Documents (MORT), Rev A, NASA International Space Station Program, Johnson Space Center, Houston, TX, May 2000.

Tibbitts, T. W., Injuries to Plants from Controlled Environment Contaminants, *Adv. Space Res.*, 18(4/5), 197-201 (1996).

Waligora, J. M., M. R. Powell, and R. L. Sauer, Spacecraft Life-Support Systems, in *Space Physiology and Medicine*, 3rd ed., A. E. Nicogossian, C. L. Huntoon, and S. L. Pool, editors, Lea & Febiger, Malvern, PA, 1994.

Wheeler, R. M., C. L. Mackowiak, G. W. Stutte, J. C. Sager, N. C., Yorio, L. M. Ruffe, R. E., Fortson, T. W. Dreschel, W. M. Knott and K. A. Corey, NASA's Biomass Production Chamber: A Testbed for Bioregenerative Life Support Studies, *Adv. Space Res.*, 18(4/5), 215-224 (1996).

Wheeler, R. M., B. V. Peterson, J. C. Sager and W. M. Knott, Ethylene Production by Plants in a Closed Environment, *Adv. Space Res.*, 18(4/5), 193-196 (1996).

WHO (World Health Organization), Energy and Protein Requirements. Report of a Joint FAO/WHO/UNU Expert Consultation. Technical Report Series 724, World Health Organization, Geneva, 1985. (Reproduced in NRC (1989)).

Wieland, P. O., Designing for Human Presence in Space: An Introduction to Environmental Control and Life Support Systems, NASA RP-1324, NASA Marshall Space Flight Center, AL, 1994.

APPENDIX: TABLES FOR SPACECRAFT MAXIMUM AIRBORNE CONTAMINANT (SMAC) LOADINGS

Spacecraft Maximum Allowable Concentrations

Chemical Name **Potential Exposure Duration**

	1 hr		24 hr		7 d		30 d		180 d		
Acetaldehyde	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: Ethanal	12	22	6	10	2	4	2	4	2	4	carcinogen
Synonyms:	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 75-07-0	mucosa irritation		mucosa irritation		mucosa irritation		mucosa irritation		mucosa irritation		
Year SMAC reviewed 1992											

	1 hr		24 hr		7 d		30 d		180 d		
Acetone	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: 2-Propanone	500	1200	200	500	22	52	22	52	22	52	
Synonyms:	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 67-64-1	CNS depression		CNS depression		CNS depression		CNS depression		CNS depression		
Year SMAC reviewed: 1994											

	1 hr		24 hr		7 d		30 d		180 d		
Acrolein	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: 2-Propenal	0.075	0.2	0.035	0.08	0.015	0.03	0.015	0.03	0.015	0.03	Ceiling Values
Synonyms: Propenal	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 107-02-08	mucosa irritation		mucosa irritation		mucosa irritation		mucosa irritation		mucosa irritation		
Year SMAC reviewed: 1992											

C3-C8 Aliphatic	1 hr		24 hr		7 d		30 d		180 d		
Saturated Aldehydes	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Names: propanal-octanal	50	125-250	50	125-250	6	15-30	1.5	4-8	1.5	4-8	ranges due to
Synonyms:	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		MW differences
CAS #: various	mucosa irritation		mucosa irritation		mucosa irritation		hepatotoxicity		hepatotoxicity		
Year SMAC reviewed: 1998					hepatotoxicity						

	1 hr		24 hr		7 d		30 d		180 d		
Ammonia	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: same as above	30	20	20	14	10	7	10	7	10	7	Ceiling values
Synonyms:	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 7664-41-7	mucosa irritation		mucosa irritation		mucosa irritation		mucosa irritation		mucosa irritation		
Year SMAC reviewed: 1991											

	1 hr		24 hr		7 d		30 d		180 d		
Benzene	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: same as above	10	35	3	10	0.5	1.5	0.1	0.3	0.07	0.2	leukemogen
Synonyms:	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 71-43-2	immunotoxicity		immunotoxicity		immunotoxicity		immunotoxicity		immunotoxicity		
Year SMAC reviewed: 1993											

	1 hr		24 hr		7 d		30 d		180 d		
Bromotrifluoromethane	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: same as above	3500	21000	3500	21000	1800	11000	1800	11000	1800	11000	
Synonyms: Halon 1301	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 75-63-8	Heart arrhythmia		Heart arrhythmia		CNS depression		CNS depression		CNS depression		
Year SMAC reviewed: 1993											

	1 hr		24 hr		7 d		30 d		180 d		
1-Butanol	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: same as above	50	150	25	80	25	80	25	80	12	40	
Synonyms:	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 71-36-3	CNS depression				Systemic injury		Systemic injury		Systemic injury		
Year SMAC reviewed: 1994	Eye irritation		Eye irritation		Eye irritation		Eye irritation				

	1 hr		24 hr		7 d		30 d		180 d		
tert-Butanol	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: 2-methyl-2-propanol	50	150	50	150	50	150	50	150	40	120	
Synonyms: 2-methyl-2-propanol	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 75-65-0	CNS depression		CNS depression		CNS depression		CNS depression		CNS depression		
Year SMAC reviewed: 1995							Nephrotoxicity		Nephrotoxicity		
									U. Bladder injury		

	1 hr		24 hr		7 d		30 d		180 d		
Carbon Dioxide	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: same as above	13000	23000	13000	23000	7000	13000	7000	13000	7000	13000	
Synonyms:	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 124-38-9	CNS hyperventil'n		CNS hyperventil'n		CNS hyperventil'n		CNS hyperventil'n		CNS hyperventil'n		
Year SMAC reviewed: 1992	CNS visual		CNS visual								

	1 hr		24 hr		7 d		30 d		180 d		
Carbon Monoxide	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: same as above	55	63	20	23	10	11	10	11	10	11	Carboxyhemoglobin target
Synonyms:	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 630-08-0	CNS depression		CNS depression		CNS depression		CNS depression		CNS depression		
Year SMAC reviewed: 1991	Heart arrhythmia		Heart arrhythmia		Heart arrhythmia		Heart arrhythmia		Heart arrhythmia		

	1 hr		24 hr		7 d		30 d		180 d		
Chloroform	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: Trichloromethane	2	10	2	10	2	10	1	5	1	5	
Synonyms: Trichloromethane	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 67-66-3	CNS depression		CNS depression		CNS depression		CNS depression		CNS depression		
Year SMAC reviewed: 1999	Hepatotoxicity		Hepatotoxicity		Hepatotoxicity		Hepatotoxicity		Hepatotoxicity		
	Nephrotoxicity		Nephrotoxicity		Nephrotoxicity		Nephrotoxicity		Nephrotoxicity		

	1 hr		24 hr		7 d		30 d		180 d		
Decamethylcyclopentasiloxane	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: same as above	N.S.		N.S.		7	100	5	75	1	15	documented as a Polydimethyl-cyclosiloxane
Synonyms:	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 541-02-6					RspSys Injury		RspSys Injury		RspSys Injury		
Year SMAC reviewed: 1998					Gonad toxicity		Gonad toxicity		Gonad toxicity		
Diacetone alcohol	1 hr		24 hr		7 d		30 d		180 d		
IUPAC Name: 4-hydroxy-4methyl-	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
2-pentanone or 2-methyl-2-	50	250	50	250	20	100	6	30	4	20	
pentanol-4-one	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 123-42-2	CNS depression		CNS depression		CNS depression		CNS depression		CNS depression		
Year SMAC reviewed: 1995	Mucosa irritation		Mucosa irritation		Mucosa irritation		Mucosa irritation		hepatomegaly		
	1 hr		24 hr		7 d		30 d		180 d		
Dichloroacetylene	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: Dichloroethyne	0.6	2.4	0.04	0.16	0.03	0.12	0.025	0.1	0.015	0.06	
Synonyms:	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 7572-29-4	CNS depression		CNS depression		CNS depression		CNS depression		CNS depression		
Year SMAC reviewed: 1992	nephrotoxicity		nephrotoxicity		nephrotoxicity		nephrotoxicity		nephrotoxicity		
	hepatotoxicity		hepatotoxicity		hepatotoxicity		hepatotoxicity		hepatotoxicity		
	1 hr		24 hr		7 d		30 d		180 d		
1,2-Dichloroethane	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: same as above	0.4	2	0.4	2	0.4	2	0.4	2	0.2	1	carcinogen; impairs defenses against bacteria
Synonyms: Ethylene dichloride	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 107-06-2	GI toxicity		GI toxicity		GI toxicity		GI toxicity		various cancers		
Year SMAC reviewed: 1992	immunotoxicity		immunotoxicity		immunotoxicity		immunotoxicity				

	1 hr		24 hr		7 d		30 d		180 d		
Ethanol	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: same as above	2000	4000	2000	4000	1000	2000	1000	2000	1000	2000	Skin "flushing" is
Synonyms: Ethyl alcohol	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		a cardiovascular effect.
CAS #: 64-17-5	mucosal irritation		mucosal irritation		mucosal irritation		mucosal irritation		mucosal irritation		
Year SMAC reviewed: 1994	Eye irritation		Eye irritation		Eye irritation		Eye irritation				
	skin flushing		skin flushing		skin flushing		skin flushing		skin flushing		
					hepatotoxicity		hepatotoxicity		hepatotoxicity		

	1 hr		24 hr		7 d		30 d		180 d		
2-Ethoxyethanol	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: same as above	10	40	10	40	0.8	3	0.5	2	0.07	0.3	
Synonyms: ethyl cellosolve	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 110-80-5	hematotoxicity		hematotoxicity		hematotoxicity		hematotoxicity		hematotoxicity		
Year SMAC reviewed: 1992	mucosa irritation		mucosa irritation								

	1 hr		24 hr		7 d		30 d		180 d		
Ethylbenzene	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: same as above	180	800	60	250	30	130	30	130	12	50	
Synonyms:	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 100-41-4	CNS depression		CNS depression		Testes necrosis		Testes necrosis		Testes necrosis		
Year SMAC reviewed: 1993	mucosa irritation		mucosa irritation		mucosa irritation		mucosa irritation				

	1 hr		24 hr		7 d		30 d		180 d		
Ethylene glycol	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: 1,2-ethanediol	25	60	25	60	5	13	5	13	5	13	
Synonyms:	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 107-21-1			CNS depression		CNS depression		CNS depression		CNS depression		
Year SMAC reviewed: 1993	mucosal irritation		mucosal irritation		mucosal irritation		mucosal irritation		mucosal irritation		
					nephrotoxicity		nephrotoxicity		nephrotoxicity		

	1 hr		24 hr		7 d		30 d		180 d		
Formaldehyde	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: methanal	0.4	0.5	0.1	0.12	0.04	0.05	0.04	0.05	0.04	0.05	Ceiling values, carcinogen
Synonyms:	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 50-00-0	mucosa irritation		mucosa irritation		mucosa irritation		mucosa irritation		mucosa irritation		
Year SMAC reviewed: 1991											

	1 hr		24 hr		7 d		30 d		180 d		
Freon 11	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: trichlorofluoromethane	140	790	140	790	140	790	140	790	140	790	
	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 75-69-6	heart arrhythmia		heart arrhythmia		heart arrhythmia		heart arrhythmia		heart arrhythmia		
Year SMAC reviewed: 1998											

	1 hr		24 hr		7 d		30 d		180 d		
Freon 113	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: 1,1,2-trichloro-1,2,2-trifluoro-ethane	50	400	50	400	50	400	50	400	50	400	
	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 76-13-1	heart arrhythmia		heart arrhythmia		heart arrhythmia		heart arrhythmia		heart arrhythmia		
Year SMAC reviewed: 1991											

Freon 12
IUPAC Name: dichlorodifluoro-methane
CAS #: 75-71-8
Year SMAC reviewed: 1998

1 hr		24 hr		7 d		30 d		180 d	
ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)
540	2600	95	470	95	470	95	470	95	470
organ / effect		organ / effect		organ / effect		organ / effect		organ / effect	
heart tachycardia		heart arrhythmia		heart arrhythmia		heart arrhythmia		heart arrhythmia	

Remarks:

Freon 21
IUPAC Name: dichlorofluoro-methane
CAS #: 75-43-4
Year SMAC reviewed: 1998

1 hr		24 hr		7 d		30 d		180 d	
ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)
50	210	50	210	15	63	12	50	2	8
organ / effect		organ / effect		organ / effect		organ / effect		organ / effect	
heart tachycardia		heart tachycardia		hepatotoxicity		hepatotoxicity		hepatotoxicity	

Remarks:

Freon 22
IUPAC Name: chlorodifluoro-methane
CAS #: 75-45-6
Year SMAC reviewed: 1998

1 hr		24 hr		7 d		30 d		180 d	
ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)
1000	35000	1000	35000	1000	35000	1000	35000	1000	35000
organ / effect		organ / effect		organ / effect		organ / effect		organ / effect	
heart arrhythmia		heart arrhythmia		heart arrhythmia		heart arrhythmia		heart arrhythmia	
CNS depression		CNS depression		CNS depression		CNS depression		CNS depression	

Remarks:

	1 hr		24 hr		7 d		30 d		180 d		
Furan	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: 1,4-epoxy-	4	11	0.36	1	0.025	0.07	0.025	0.07	0.025	0.07	
1,3-butadiene	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 110-00-9	hepatotoxicity		hepatotoxicity		liver cancer		liver cancer		liver cancer		
Year SMAC reviewed: 1998											

	1 hr		24 hr		7 d		30 d		180 d		
Glutaraldehyde	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: 1,5-pentanedial	0.12	0.5	0.04	0.08	0.006	0.025	0.003	0.012	0.0006	0.002	
Synonyms: 1,5-pentanedial	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 111-308	Mucosa irritation		Mucosa irritation		RspSys lesions		RspSys lesions		RspSys lesions		
Year SMAC reviewed: 1993	CNS headache		CNS headache								

	1 hr		24 hr		7 d		30 d		180 d		
Hexamethylcyclotrisiloxane	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: same as above	N.S.		N.S.		10	90	5	45	1	9	documented as a Polydimethyl-cyclosiloxane
Synonyms:	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 541-05-9					CNS depression		CNS depression		RspSys injury		
Year SMAC reviewed: 1998					RspSys injury		RspSys injury				

	1 hr		24 hr		7 d		30 d		180 d		
Hydrazine	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: same as above	4	5	0.3	0.4	0.04	0.05	0.02	0.03	0.004	0.005	carcinogen
Synonyms: diamine	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 302-01-2	death		hepatotoxicity		hepatotoxicity		hepatotoxicity		hepatotoxicity		
Year SMAC reviewed: 1993							liver hyperplasia		nose cancer		
							nose cancer				

	1 hr		24 hr		7 d		30 d		180 d		
Hydrogen	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: same as above	4100	340	4100	340	4100	340	4100	340	4100	340	ceiling levels are 10% of the lower explosive limit.
Synonyms:	<u>organ / effect</u>		<u>organ / effect</u>		<u>organ / effect</u>		<u>organ / effect</u>		<u>organ / effect</u>		
CAS #: 1333-74-0	explosion		explosion		explosion		explosion		explosion		
Year SMAC reviewed: 1990											

	1 hr		24 hr		7 d		30 d		180 d		
Hydrogen Chloride	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: same as above	5	8	2	3	1	1.5	1	1.5	1	1.5	
Synonyms: Hydrochloric acid	<u>organ / effect</u>		<u>organ / effect</u>		<u>organ / effect</u>		<u>organ / effect</u>		<u>organ / effect</u>		
CAS #: 7647-01-1	eye irritation		eye irritation		eye irritation		eye irritation		eye irritation		
Year SMAC reviewed: 1998	Mucosa irritation		Mucosa irritation		Mucosa irritation		Mucosa irritation		Mucosa irritation		

	1 hr		24 hr		7 d		30 d		180 d		
Hydrogen cyanide	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: same as above	8	9	4	4.5	1	1.1	1	1.1	1	1.1	
Hydrocyanic acid	<u>organ / effect</u>		<u>organ / effect</u>		<u>organ / effect</u>		<u>organ / effect</u>		<u>organ / effect</u>		
CAS #: 74-90-8	CNS depression		CNS depression		CNS depression		CNS depression		CNS depression		
Year SMAC reviewed: 1998	CNS headache		CNS headache		CNS headache		CNS headache		CNS headache		
	CNS nausea		CNS nausea		CNS nausea		CNS nausea		CNS nausea		

	1 hr		24 hr		7 d		30 d		180 d		
Indole	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: 2,3-benzopyrrole	1	5	0.3	1.5	0.05	0.25	0.05	0.25	0.05	0.25	Normal turnover of indole was used to establish a lower bound of 0.05 ppm
Synonyms:	<u>organ / effect</u>		<u>organ / effect</u>		<u>organ / effect</u>		<u>organ / effect</u>		<u>organ / effect</u>		
CAS #: 120-72-9	CNS nausea		CNS nausea		CNS nausea		CNS nausea		CNS nausea		
Year SMAC reviewed: 1992	hemotoxicity		hemotoxicity		hemotoxicity		hemotoxicity		hemotoxicity		

	1 hr		24 hr		7 d		30 d		180 d		
Isoprene	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: see synonyms	50	140	25	70	2	6	2	6	1	3	
Synonyms: 2-methyl-1,3-butadiene	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 78-79-5					anemia		anemia		CNS neurotoxicity		
Year SMAC reviewed: 1998	Mucosa irritation		Mucosa irritation		Mucosa irritation		Mucosa irritation		lung injury		
									anemia		

	1 hr		24 hr		7 d		30 d		180 d		
Mercury	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: same as above	0.01	0.1	0.002	0.02	0.001	0.01	0.001	0.01	0.001	0.01	
Synonyms: Quicksilver	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 7439-97-6	lung irritation		lung irritation		CNS neurotoxicity		CNS neurotoxicity		CNS neurotoxicity		
Year SMAC reviewed: 1992					nephrotoxicity		nephrotoxicity		nephrotoxicity		

	1 hr		24 hr		7 d		30 d		180 d		
Methane	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: same as above	5300	3800	5300	3800	5300	3800	5300	3800	5300	3800	Ceiling values are 10% above the lower explosive limit. Methane is a non-toxic simple asphyxiant
Synonyms: Natural gas	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 74-82-8	Explosion		Explosion		Explosion		Explosion		Explosion		
Year SMAC reviewed: 1990											

	1 hr		24 hr		7 d		30 d		180 d		
Methanol	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: same as above	30	40	10	13	7	9	7	9	7	9	
Synonyms: carbinol; wood alcohol	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 67-56-1	visual		visual		visual		visual		visual		
Year SMAC reviewed: 1992	disturbances		disturbances		disturbances		disturbances		disturbances		

	1 hr		24 hr		7 d		30 d		180 d		
Methyl Ethyl Ketone	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: 2-Butanone	50	150	50	150	10	30	10	30	10	30	Ceiling values
Synonyms: 2-Butanone	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 78-93-3	Mucosa irritation		Mucosa irritation		Mucosa irritation		Mucosa irritation		Mucosa irritation		
Year SMAC reviewed: 1992											

	1 hr		24 hr		7 d		30 d		180 d		
Methyl Hydrazine	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: 1-Methyl Hydrazine	0.002	0.004	0.002	0.004	0.002	0.004	0.002	0.004	0.002	0.004	Carcinogen
Synonyms: Monomethyl-Hydrazine	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 60-34-4	Nose leisons		Nose leisons		Nose leisons		Nose leisons		Nose leisons		
Year SMAC reviewed: 1991											

4-Methyl-2-pentanone	1 hr		24 hr		7 d		30 d		180 d		
IUPAC Name: same as above	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
Synonyms: methylisobutylketone	35	140	35	140	35	140	35	140	35	140	
MIBK	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 108-10-1	CNS depression		CNS depression		CNS depression		CNS depression		CNS depression		
Year SMAC reviewed: 1994	Mucosa irritation		Mucosa irritation		Mucosa irritation		Mucosa irritation		Mucosa irritation		

	1 hr		24 hr		7 d		30 d		180 d		
Methylene chloride	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: dichloromethane	100	350	35	120	15	50	5	20	3	10	CO formation
Synonyms: dichloromethane	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		carcinogen
CAS #: 75-09-2	CNS depression		CNS depression		CNS depression		hepatotoxicity		hepatotoxicity		
Year SMAC reviewed: 1992											

	1 hr		24 hr		7 d		30 d		180 d		
Nitromethane	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: same as above	25	65	15	40	7	18	7	18	5	13	
Synonyms:	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 75-52-5	Anemia		Anemia		Anemia		Anemia		Anemia		
Year SMAC reviewed: 1992											

	1 hr		24 hr		7 d		30 d		180 d		
Octamethylcyclotetrasiloxane	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: same as above	N.S.		N.S.		23	280	5	60	1	12	documented as Polydimethyl-cyclosiloxane
Synonyms:	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 556-67-2					CNS depression RspSys injury Gonad Toxicity		RspSys injury Gonad Toxicity		RspSys injury Gonad Toxicity		
Year SMAC reviewed: 1998											

	1 hr		24 hr		7 d		30 d		180 d		
Octamethyltrisiloxane	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: same as above	400	4000	200	2000	100	1000	20	200	4	40	based on structure activity relationships
Synonyms: MDM	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 107-51-7	death		death		hepatotoxicity nephrotoxicity death		hepatotoxicity nephrotoxicity		hepatotoxicity nephrotoxicity		
Year SMAC reviewed: 1992											

Perfluoropropane & other	1 hr		24 hr		7 d		30 d		180 d		
aliphatic perfluoroalkanes	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	Remarks:
IUPAC Name: Octafluoropropane	11000	85000	11000	85000	11000	85000	11000	85000	11000	85000	This group SMAC is not applicable to Perfluoro-cycloalkanes
Synonyms: Octafluoropropane	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
CAS #: 76-19-7	CNS symptoms		CNS symptoms		CNS symptoms		CNS symptoms		CNS symptoms		
Year SMAC reviewed: 1998											

	1 hr		24 hr		7 d		30 d		180 d		
	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm (mg/m^3)		
2-Propanol	400	1000	100	240	60	150	60	150	60	150	Remarks:
IUPAC Name: same as above	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
Synonyms: Isopropanol	CNS depression		CNS depression		CNS depression		CNS depression		CNS depression		
CAS #: 67-63-0	Mucosa irritation		Mucosa irritation		Mucosa irritation		Mucosa irritation		Mucosa irritation		
Year SMAC reviewed: 1992			hepatotoxicity		hepatotoxicity		PNS decr.				
							cond'n velocity				

	1 hr		24 hr		7 d		30 d		180 d	
Toluene	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)
IUPAC Name: same as above	16	60	16	60	16	60	16	60	16	60
Synonyms: methyl benzene	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect	
CAS #: 108-88-3	CNS depression		CNS depression		CNS depression		CNS depression		CNS depression	
Year SMAC reviewed: 1992					Mucosa irritation		Mucosa irritation		Mucosa irritation	

	1 hr		24 hr		7 d		30 d		180 d	
Trichloroethylene	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)
IUPAC Name: same as above										
Synonyms:	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect	
CAS #: 79-01-6										
Year SMAC reviewed:										

Trimethylsilanol	1 hr		24 hr		7 d		30 d		180 d		
IUPAC Name: same as above	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	
Synonyms: trimethylhydroxy-silane	150	550	20	74	10	37	10	37	10	37	Remarks:
CAS #: 1066-40-6	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		
Year SMAC reviewed: 1991	CNS depression		CNS depression		CNS depression		CNS depression		CNS depression		

Vinyl chloride	1 hr		24 hr		7 d		30 d		180 d		
IUPAC Name: chloroethene	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	
Synonyms: chloroethene, chloroethylene	130	330	30	77	1	2.6	1	2.6	1	2.6	Remarks:
CAS #: 75-01-4	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		carcinogen
Year SMAC reviewed: 1992	CNS depression CNS headache hepatotoxicity		CNS depression CNS headache hepatotoxicity		testis necrosis hepatotoxicity		testis necrosis hepatotoxicity		testis necrosis liver cancer		

Xylene	1 hr		24 hr		7 d		30 d		180 d		
IUPAC Name: 1,3 or	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	ppm	(mg/m^3)	
1,4-dimethylbenzene	100	430	100	430	50	220	50	220	50	220	Remarks:
Synonyms: xylol	organ / effect		organ / effect		organ / effect		organ / effect		organ / effect		applies to each individual xylene isomer & mixtures of xylene isomers
CAS #: 1330207	CNS depression		CNS depression								
Year SMAC reviewed: 1992	Mucosa irritation		Mucosa irritation		Mucosa irritation		Mucosa irritation		Mucosa irritation		

Abbreviations:

CNS - central nervous system
GI - gastrointestinal system
MW - molecular weight
NRC - national research council
N.S. - not set

PNS - peripheral nervous system
RBC - red blood cells
RspSys - respiratory system