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Life Support
Baseline Values and Assumptions Document

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June 1999			JSC 39317	A. Drysdale, A. Hanford
May 2002			JSC 47804	A. Hanford
August 2004			NASA CR-2004-208941	A. Hanford
April 2006			NASA CR-2006-213693	A. Hanford
October 2008	Rev. A		Update Reflecting Constellation Program Requirements Refinement	B. Duffield
February 2010	Rev. B		Update Reflecting Constellation Program & LAT2 High Mobility Scenario	B. Duffield
2015	NASA TP		Removed restricted Constellation information to create a publicly releasable version	Anderson, Ewert, Wagner, Keener
January 2018	NASA TP REV 1		Error corrections, minor updates	Anderson, Ewert, Keener
February 2022	NASA TP REV 2		Updated “Infrastructure Costs and Equivalencies” with new habitat design information. Rewrote the “Metabolic Analysis Programs” section. Updated the values for exploration metabolic loads and the logistic and waste loads. Added a new section called “System Reliability Impacts and Analysis.” Significantly updated the “In-Situ Resource Utilization section”. General error corrections and minor updates throughout.	Chen, Powell, Ewert

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1 INTRODUCTION

The Life Support Baseline Values and Assumptions Document (BVAD) provides analysts, modelers, and other life support researchers with a common set of values and assumptions which can be used as a baseline in their studies. This baseline, in turn, provides a common point of origin from which many studies in the community may depart, making research results easier to compare and providing researchers with reasonable values to assume for areas outside their experience. With the ability to accurately compare different technologies' performance for the same function, managers will be able to make better decisions regarding technology development.

1.1 PURPOSE AND PROCESS

The BVAD identifies specific physical quantities that define life support systems from an analysis and modeling perspective. For each physical quantity so identified, the BVAD provides a nominal or baseline value and often provides a range of possible or observed values. Finally, the BVAD documents each entry with a description of the quantity's use, value selection rationale, and appropriate references. The baseline values listed in the BVAD are designed to provide defaults for those quantities within each study that are not of particular interest for that study and may be adequately described by default values.

Some life support assumptions are well bounded. For example, the direct solar irradiation for vehicles orbiting around Earth's Moon varies between 1,323 Watts per square meter W/m² and 1,414 W/m² with a mean value of 1,367 W/m² (K&K, 1998). Accordingly, the solar constant at the Moon naturally varies by 91 W/m² (6.7 %). Williams (1997) lists a mean value of 1,380 W/m² for the solar constant at the Moon. While any value from 1,323 W/m² to 1,414 W/m² may be selected for the solar constant in a study sited in Lunar orbit, a mean value of 1,370 W/m² may be defined in the BVAD as the baseline solar flux at the Moon. Consequently, all life support studies would use a consistent value of 1,370 W/m² unless they were specifically exploring the effect of varying the solar constant. Many life support assumptions are similarly well bounded. Others, such as the growth rate for plants, are not well bounded. For these types of values, reasonable upper and lower values are given, although other values showing a greater range could be used. Without an agreement, each researcher will generally select his/her baseline values using whatever sources are available and/or deemed most accurate. While values from one researcher to the next may be similar, variations in input values lead to further variations in results when one compares studies from multiple sources. As such, it is more difficult to assess the significance of variations in results between studies from different sources without conducting additional analyses to bring the multiple studies to a similar baseline.

The BVAD does not attempt to be the wholly definitive source of all baseline values important to life support systems analysis. Rather, this document has attempted, through the efforts of many, to consolidate widely distributed data into a single entity and in doing so also tries to maintain this data as up-to-date as possible. There are, however, other reference documents which may take precedence over the BVAD due to seniority as well as breadth. In particular, the NASA Spaceflight Human-System Standard, also known as NASA-STD-3001, and Human Integration Design Handbook (HIDH) are both exhaustive knowledge bases. NASA-STD-3001 Vol. 1 sets crew health standard and describes the physiologic parameters of the human body, whereas NASA-STD-3001 Vol. 2 focuses on human-system interfaces where the system may be the habitat and/or environment. The HIDH is a compendium of human space flight history, lessons learned, and design information that provides guidance for the development of crewed space systems and operations which relate to crew health, habitability, and human factors standards. Due to the nature of the content within the BVAD, NASA-STD-3001, and HIDH, much overlap will occur. In which case, NASA-STD-3001 and/or derivatives of HIDH tailored to specific programs take precedence as the definitive requirements document. However, due to the nature of this document, the BVAD, in its attempt to consolidate the data from many sources, may deviate from the requirements of NASA-STD-3001. Depending on program or contractual requirements the NASA-STD-3001 may in cases take precedence over the BVAD. However, it should be noted that the BVAD may at times have newer information since it is trying to be as up-to-date as possible. As an example, new human metabolic profiles have recently been developed for new programs, which are not currently publish in NASA-STD-3001 due to the novelty of this data. The BVAD also tries to fill gaps in the data when these may be present through its incorporation of many other documents. This document serves as a common point of origin for studies and may guide its users towards the more complete, original data sources.

Values for this document are taken from a variety of sources. Many researchers from the modeling and analysis community, in addition to the authors, helped to prepare the manuscript as it evolved over many years. As part of the process of assigning values to each of the life support quantities, the writers evaluated and debated entries to produce a set of mutually agreeable values with corresponding limits. Comments from all readers are welcomed and encouraged. To allow the BVAD to maintain its utility as a store of modeling and analysis information, the BVAD must be a living document that is updated as necessary to reflect new technology and/or scientific discoveries.

The BVAD has been developed under the auspices of several NASA life support technology development programs in its history and is currently maintained by the Design and Analysis Branch of the Crew and Thermal Systems Division at the NASA Johnson Space Center in support of the NASA ECLSS community. Please send comments to:

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1.2 ADVANTAGES

Aside from the advantages listed above, the BVAD provides several additional benefits:

The BVAD allows the life support analysis community to carefully review and evaluate input study assumptions. Such review will lead to greater confidence in and understanding of the studies' results.

Each study can now benefit from the “best” available input values and assumptions by drawing upon information collected by a group of researchers instead of a single researcher. Further, such values reflect the combined expertise of the group as a whole rather than one individual.

The BVAD process identifies those quantities that are not well-defined by current information. Such quantities are primary candidates for parametric studies to determine their importance on modeling and analysis results. Further, this approach identifies values that may require additional experimental input to adequately quantify.

The BVAD allows researchers from multiple sites to efficiently and quickly compare results from multiple studies. Because each study uses the same baseline, the variations between studies arise from differences in models or the parameters varied rather than a complex combined effect that includes variations in the assumed baseline.

The BVAD will allow any researcher to conduct a follow-on study or replicate previous work because assumptions from each study will be clearly available and carefully recorded. Further, researchers can reference the BVAD for their baseline parameter values except those that are unique to their specific study.

1.3 ACKNOWLEDGEMENTS

Many researchers have contributed information or insights to this document over the years. Thus, the BVAD authors would like to specifically acknowledge the following individuals for their contributions: James E. Alleman, PhD, Molly S. Anderson, Susan D. Baggerman, Daniel J. Barta, PhD, Scott Bell, David Bergeron, Charles Bourland, PhD, Cheryl B. Brown, Juan M. Castillo, Robert L. Cataldo, James Cavazzoni, PhD, Joe P. Chambliss, Bruce Conger, Nicholas Coppa, PhD, Katherine R. Daues, Grace Douglas, PhD, Alan E. Drysdale, PhD, Bruce E. Duffield, John W. Fisher, Guy Fogleman, PhD, Melanie French, Steve J. French, PhD, James R. Geffre, Anthony J. Hanford, PhD, Donald L. Henninger, PhD, John A. Hogan, PhD, Jean B. Hunter, PhD, Frank F. Jeng, Harry Jones, PhD, Jitendra Joshi, PhD, John F. Keener, John M. Keller, PhD, Kevin E. Lange, PhD, Wen-Ching Lee, Julie A. Levri, Sabrina Maxwell, Dean Muirhead, PhD, Seza Orcun, PhD, Michele Perchonok, PhD, Alan T. Perka, Jay L. Perry, Karen D. Pickering, PhD, Luis F. Rodriguez, PhD, Stephanie Roohi, Michael Rouen, Kathy Ruminsky, James Russell, PhD, John Sager, PhD, Laura A. Shaw, David A. Vaccari, PhD, Jennifer Villarreal, Yael Vodovotz, PhD, Sandra Wagner, Kanapathipi Wignarajah, PhD, Chantel Whatley, Raymond Wheeler, PhD, Kristina R. Wines, Jannivine Yeh.

2 APPROACH

The assumptions here arise from various sources and they are organized into sets of similar data. These assumptions relate to the scenarios, the mission infrastructure, and the various life support subsystems. References are documented where possible to provide traceability.

2.1 DEVELOPMENT

The baseline values and assumptions are based on experience in developing models of life support systems. The various contributors to the BVAD have focused on quantitative aspects of their areas of expertise allowing comparison with other life support system models or other scenarios. Nominal values as well as upper and lower limits are often given as recommended values. In some cases, the upper and lower limits are definite values set by scientific principles, while in other cases they are representative values that will not often be exceeded in a real system.

2.2 CONTEXT

This document does not assume and is not particular to a specific mission but does focus on near-term and far-term exploration missions of importance to NASA. In some cases, the data may be applicable to only certain missions. Life support focused reference mission documents (the most recent published by the former Exploration Life Support project in 2008) may be referred to for more details of potential mission scenarios.

2.3 LIFE SUPPORT SUBSYSTEMS

A vehicle's life support system is made of several different subsystems performing different functions. Hanford (2000) provides a generic description of life support subsystems as well as subsystem and interface relationships for a life support system. This approach originally mirrored the organization for the Advanced Life Support (ALS) Program (Berry, *et al*. 1994). This classification initially arose from a Systems Modeling and Analysis Project [1] workshop in the fall of 1999. The Exploration Life Support (ELS) project followed ALS and more recently life support technology development has been conducted under Next Generation Life Support and Advanced Exploration Systems within NASA. System classification can vary depending on a specific project's work breakdown structure, so a representative grouping commonly used in the NASA life support community has been adopted for this BVAD. Basic descriptions of the subsystems and their interfaces are given in Table 2-1 and in Table 2-2. Information within the BVAD will be organized according to this structure.

As noted above, many formats to describe life support systems exist. Here Air, Waste, and Water are classified as systems or subsystems, while Habitation, Crew [2], Environmental Monitoring and Control (EMC), Extravehicular Activity (EVA) Support, Food, In-Situ Resource Utilization (ISRU), Power, Propulsion, Radiation Protection, Thermal and Medical Systems are external life support interfaces. The interfaces listed in the last column for each subsystem or interface are generally inclusive, attempting to account for all possible interactions, even if some of those interactions are highly unlikely. Figure 2-1 provides a graphical depiction of the information in Table 2-2.

Please note that within this document the subsystem names, such as "Air Subsystem" and "Water Subsystem," are proper names. However, the generic terms "system" and "subsystem" are often used interchangeably in the text within this document to refer to similar suites of equipment, depending on the scope of the project or analysis, as systems can be defined at many levels. This relaxed approach with respect to nomenclature reflects the constantly changing perspective that both researchers and analysts use while considering many different technologies or groups of technologies. In reality, most life support equipment is constructed from several lower-level components and also fits within a higher-level assembly. Thus, the terms "system" and "subsystem" vary according to the current discussion and often differ for other studies.

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[1] Systems Modeling and Analysis Project is the previous name for the Systems Integration, Modeling, and Analysis element.

[2] Though the presence of the crew alone justifies the inclusion of the life support subsystems, the crewmembers are external to the life support equipment and thus are listed as an interface here.

Table 2-1 Life Support Subsystem Descriptions and Interfaces

Subsystem	Description	Life Support System Interfaces
Air	The Air Subsystem maintains the vehicle cabin atmospheric pressure and quality. Functional areas include atmospheric gas storage, supply, and air circulation including positive and negative pressure control; carbon dioxide partial pressure control; moisture removal (often in cooperation with a Thermal Interface condensing heat exchanger); trace chemical contaminant control; particulate matter control; resource recovery, storage, and recycling; and supporting infrastructure. The air system often includes many components for emergency scenarios. These emergency systems need to provide similar functions as the nominal systems, but very different technologies may be used for the specific contingency scenarios.	Habitation, Waste, Water, EMC, Crew, EVA Support, ISRU, Power, Thermal, Propulsion
Waste	The Waste Subsystem collects waste products from packaging materials, human wastes, or process wastes. Depending on mission needs the wastes can be minimally processed to reduce storage size and control odor, can be rendered biologically inactive or can be recycled into commodities useful for accomplishing mission goals.	Air, Habitation, Water, EMC, Crew, EVA Support, Food, Power, Radiation Protection, Thermal, Propulsion
Water	The Water Subsystem collects wastewater from all possible sources, recovers and transports potable water, and stores and provides that water at the appropriate purity and at the appropriate level of biological activity, for crew and external users, for consumption, hygiene, for use as a process reactant or for meal cleanup and housekeeping.	Air, Habitation, Waste, EMC, Crew, EVA Support, Food, ISRU, Power, Radiation Protection, Thermal, Propulsion

Table 2-2 Life Support Interfaces Descriptions and Interfaces

Life Support Interfaces	Description	Life Support System Interfaces
Crew	The Crew Interface interacts with all life support subsystems and interfaces. It accounts for all metabolic inputs and outputs from crew members. Historically, and likely in the near-term (until other animals or plants are included in the mission in large scales), crewmembers are the foremost consumers of life support commodities and the primary producers of waste products.	All
Environmental Monitoring and Control	The Environmental Monitoring and Control (EMC) Interface provides information on the chemical and biological status of the crew habitat. This includes trace and major constituent composition of air and water, smoke detection, and microbial content of air, water, and surfaces. The information is used to control proper functioning of the life support system, as well as indicate off-nominal events.	All
Extravehicular Activity Support	The Extravehicular Activity (EVA) Support Interface provides life support consumables for all suited activities, including oxygen, water, and food, as well as carbon dioxide and waste removal. Suits may be employed for launch, entry and abort (in case of cabin depressurization); nominal or contingency EVA in a weightless environment; emergency return from a human mission beyond low-Earth orbit; and surface EVA operations on the Moon and Mars.	Air, Habitation, Waste, Water, EMC, Crew, Food, Power, Thermal
Food	The Food Interface provides the crew with prepackaged food products or commodities requiring some level of preparation or processing, and includes the stowage systems necessary for these items. If an advanced life support system were to include a Biomass Subsystem, the Food System would also receive harvested agricultural products and process them into an edible form.	Air, Habitation, Waste, Water, EMC, Crew, EVA Support, Power
Habitation	The Habitation Interface is responsible for crew accommodations and human engineering. The packaging and preparation and storage of crew supplies includes the galley layout and food supplies, clothing management systems, fire suppressant, gas masks, hygiene stations and supplies, housekeeping and related supplies, and other functions related to configurable crew living. This technology area is responsible for implementing the hardware resulting from human factors requirements.	Air, Waste, Water, EMC, Crew, EVA Support, Food, Power, Radiation Protection, Thermal
In-Situ Resource Utilization	The In-Situ Resource Utilization Interface provides life support commodities such as gases, water and regolith from local planetary materials for use throughout the life support system.	Air, Water, EMC, Crew, Power, Radiation Protection
Medical Systems	Under nominal conditions medical systems would generally have an inconsequential impact on the life support systems, but if an event should occur causes illness or injury, the impacts on the Life Support System could be drastic. This includes medical and metabolic monitoring of the crew during EVAs. Gases may be required for hyperbaric treatment, respiratory therapy, or to provide oxygen for certain medical procedures while controlling flammability risks in the cabin. Additional water may be required, and waste could be generated that might not be allowed to be stored, processed, or recycled like waste from nominal activities.	Air, Water, Waste
Power	The Power Interface provides the necessary energy to support all equipment and functions within the life support system. It may also provide resources like fuel cell product water to the life support system.	All
Propulsion	The Propulsion Interface may provide resources such as oxygen and cooling evaporant to the life support system and thermal control system	Air, Water, EMC, Waste, EVA Support, Thermal

Table 2-2 Life Support Interfaces Descriptions and Interfaces (concluded)

Life Support Interfaces	Description	Life Support System Interfaces
Radiation Protection	The Radiation Protection Interface includes systems design to provide the crew protection from environmental radiation. The life support system could provide some useful contribution to radiation protection, especially in the form of water or waste products. The Radiation Protection Interface also provides sensors and other predictive measures for solar particle events, so the crew might seek shelter from such an event.	Habitation, Waste, Water, Crew, Food, ISRU, Power
Thermal	The Thermal Interface is responsible for maintaining cabin temperature and humidity (unless controlled jointly with other atmosphere revitalization processes) within appropriate bounds and for collection and removal of the collected waste heat from crew, equipment, and the pressurized volume to the external environment. Note: Equipment to remove thermal loads from the cabin atmosphere normally provides sufficient air circulation. Thermal Interface work is conducted under the Thermal Control System Development for Exploration Project.	Air, Habitation, Waste, Water, EMC, Crew, EVA Support, Food, Power

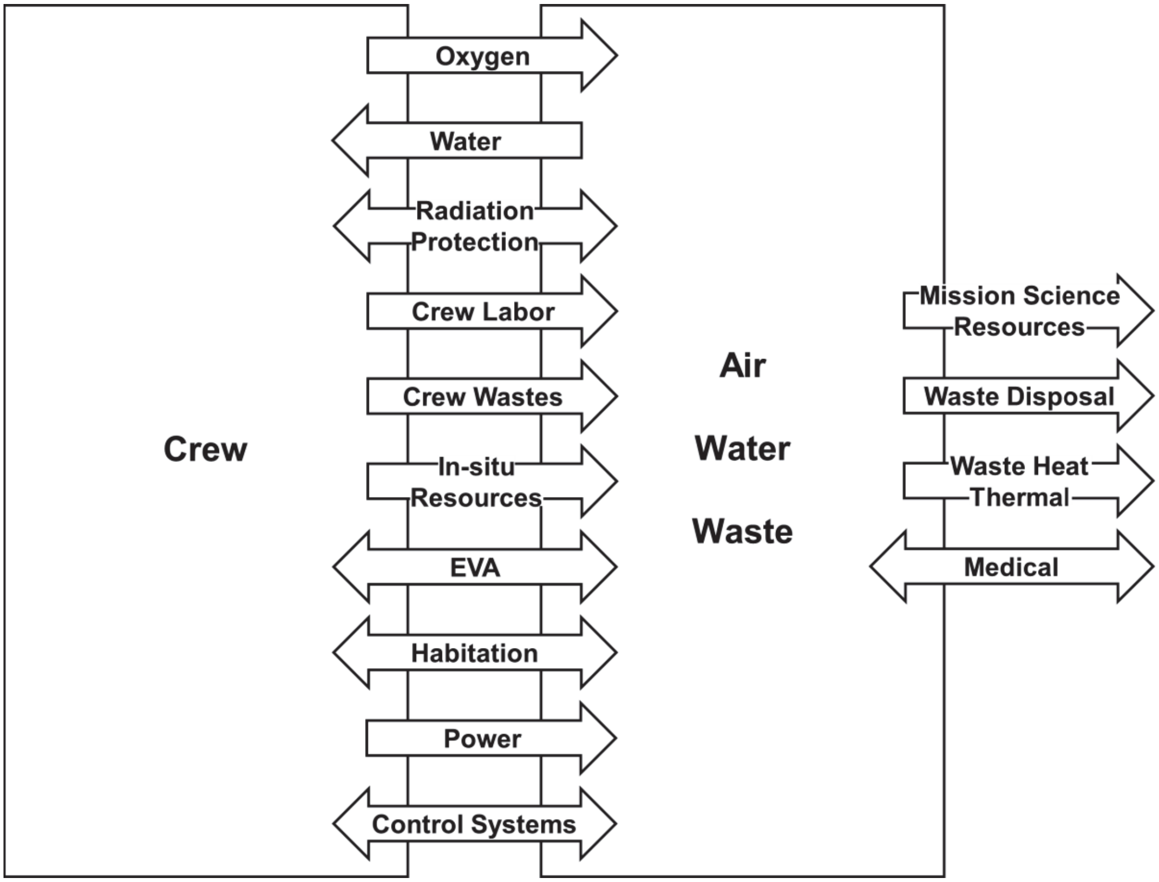

Figure 2-1 Life Support System interfaces.

2.4 DEFINITIONS

2.4.1 MODELING

Modeling is analogous to a system that mimics the behavior of some real system. Within ELS, mathematical models are used to predict or simulate, control, design, optimize, or facilitate an understanding of a life support system, a component, or a subsystem. Models might be quite simple, a calculation of overall masses, for example, or quite complex, involving gas exchange at molecular levels. This document includes and supports both types of models.

2.4.2 INFRASTRUCTURE

Infrastructure is everything necessary to operate the life support equipment that is not otherwise specifically defined elsewhere as a component of the life support system. For an overall life support system analysis, the system includes the life support equipment. Necessary infrastructure, then, may include all necessary supplies and equipment for electrical power generation or a pressurized cabin in which the equipment operates. Some infrastructure, though vital to overall system success, may have a small or negligible impact on a study's primary focus. For example, data and communications infrastructure generally have little impact on the equivalent system mass of a life support system and can thus be safely neglected in this case[3]. Table 2-1 and Table 2-2 identify the most common and significant interactions between life support subsystems and other spacecraft systems outside of the life support system. Section 3.2 discusses and lists infrastructure cost factors for overall life support system analyses, while Table 2-2 provides additional information about commodity demands to and from the life support interfaces.

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[3] While the life support system requires displays, the mass of these items are small relative to the overall system mass.

2.4.3 EQUIVALENT SYSTEM MASS

Although there are many possible ways to assess progress toward goals for the Life Support System, one of the key parameters used is a metric based on Equivalent System Mass (ESM).

2.4.3.1 *EQUIVALENT SYSTEM MASS EXAMPLE*

Equivalent system mass (ESM) is a technique by which several physical quantities describing a system or subsystem may be reduced to a single physical parameter – "mass" – using the equation below where M is the mass of the system, V is the volume of the system, V_{eq} is the volume equivalency factor, C is the system cooling requirement, C_{eq} is the cooling equivalency factor, P and P_{eq} are the power and power equivalency factor, respectively, D is the number of mission days, and CT and CT_{eq} are the crew time and crew time efficiency factor, respectively.[4] For example, say a power generator solely supplies a water purification system, then the mass required for the water purification system is the mass of the system itself plus the mass of the power system. In reality, for a space vehicle, the power system supplies power for several different functions, not just water purification. A power equivalency factor is defined to indicate how much of the total power being generated can be attributed to water purification and how much supports other needs. This power equivalency factor allows the fraction of the power dedicated to water purification to be separated and grouped with the water purifier. Equivalency factors for the volume, power, cooling, and crew time requirements can be found in section 3.2 below.

$$ESM = M + \left(V \times V_{eq}\right) + \left(P \times P_{eq}\right) + \left(C \times C_{eq}\right) + \left(CT \times D \times CT_{eq}\right) \qquad \text{Equation 2-1}$$

2.4.3.2 *EQUIVALENT SYSTEM MASS DESCRIPTION*

Conversion of quantities like power, volume, thermal load, and crewtime to equivalent masses is accomplished by determining appropriate mass penalties or conversion factors to convert the non-mass physical inputs to an equivalent mass. For systems that require power, the Power Interface can yield an appropriate power-mass penalty by dividing the average power plant output by the total mass of the generating power plant. Thus, for a nuclear power plant on an independent lander that delivers an average of 100 kW_e of electrical power and has an overall mass of 8,708 kg (Mason, *et al.*, 1992) [5] the power-mass penalty is 87.1 kg/kW-electric W_e. This power-mass penalty effectively assigns a fraction of the Power Interface mass to a power-using subsystem in place of that subsystem's power requirement. This would include the impact to thermal loads for cooling the power generation and power used to heat the cabin habitability volume. In like manner, mass penalties to account for heat rejection and volume within a pressurized shell are defined. A crewtime mass penalty is also defined below. The definition of equivalent mass for a system is the sum of the equipment and consumable commodity mass plus the power, volume, thermal control, and crewtime requirements converted to mass by using equivalency factors. Please see ESM GD (2003) for additional information on ESM.

2.4.4 UNITS AND VALUES

All numerical assumptions are given using the Système Internationale d'Unités (SI). This approach is consistent with NASA Policy Directive 7120.4E (NPD 7140.4E, 2017). A list of SI units for physical quantities of interest is provided in the Appendices. Some values are also presented in comparable English units.

Generally, lower, nominal, and upper values are provided. Unless stated otherwise, the numbers are intended to represent average values under nominal conditions for different design cases. Short-term fluctuations are not considered, nor are emergency or contingency situations except as explicitly noted. Values not listed per capita assume a crew of four, unless otherwise stated.

2.5 MISSION DURATION

Duration of space exploration missions with a crew may vary from a few hours up to decades when considering historical experience and planned and possible mission concepts to explore the Moon, Mars, and beyond. To provide

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[4] An ESM evaluation is similar in form to computing a project's net present value in that if future value, interest rate and/or annuitized value can be converted into present value then two projects can be compared by like units since all the numbers used have been converted to present value. Thus, ESM is a method for ranking a system or subsystem concept relative to other concepts.

[5] The actual mass quoted here has been adjusted slightly to account for some differences between the work listed in the reference and the desired system.

guidance on common mission duration characteristics, Table 2-3 through Table 2-7 provide a series of classifications for mission durations with a corresponding listing, in qualitative terms, of likely approaches for life support functions. Two or more approaches for life support functions may exist because the design ultimately is influenced by numerous architectural decisions and mission constraints. Table 2-3 provides an overall summary, while Table 2-4 through Table 2-7 provides details of life support functions as well as qualitative examples for each function. For an actual flight program, each life support function, as well as the subsystems comprising the vehicle environmental control and life support subsystem, will have detailed functional specifications assigned. Specific requirements, constraints, and trade-offs for the vehicle may result in selecting a life support system for a future mission that is different from these generalized groupings of functions.

Tables such as Table 2-3 through Table 2-7 may be used in many ways. Of primary importance here are the following two uses.

The first use involves the mission designators listed in Table 2-3. The subsystem and interface descriptions associated with each designator bounds, in a qualitative manner, some approaches to process technologies and architecture that NASA might consider to accomplish a mission of the specific duration. While deviations may exist, the descriptors for each designator provide either common shorthand or at least a common starting point to discuss a mission. For example, a researcher may examine a "short" mission using the first option when more than one option is available.

The second use involves using Table 2-4 through Table 2-7 to categorize life support system architecture regardless of the mission duration. In general, "Option 1" is an open-loop approach, relying strongly on single-use systems and supplies from Earth. Option 2 and 3 will begin to add some reusable components and technologies that can regenerate wastes into useful resources. The later options evolve more and more into complex closed-loop systems intended to be sustainable without resupply from Earth, but at the expense of sending a large and complex life support system.

For an overall example starting with the categories in Table 2-3, Project Mercury used "stored commodities (oxygen in tanks) with consumable waste removal hardware (lithium hydroxide cartridges)" for the air subsystem, "launch-entry suit" for the habitation interface, "waste storage only" for the waste subsystem, "stored (water)" for the water subsystem, "stored food only", for the food interface, "rejection with consumables" for the thermal interface, *etc*. Using Table 2-4, the categorization for Project Mercury might continue by specifying "consumables" for carbon dioxide removal, "stored commodities" for oxygen supply, "none" for carbon dioxide reduction, *etc*. It should be noted that for another mission concept, individual options might be "physicochemical hardware and regenerable consumables" for carbon dioxide removal, "stored commodities" for oxygen supply, "none" for carbon dioxide reduction.

Table 2-3 Overall Description of Mission Duration and Life Support System Functionality

Designator	Duration	Air Subsystem	Habitation Interface	Waste Subsystem	Water Subsystem	Food External Interface	Thermal External Interface
Opt 1: Very Short	~30 hours	Stored Commodities w/ Consumable Waste Removal Hardware	Launch-Entry Suit w/ Wipes Only	Waste Storage Only; Minimal Restrictions on Inputs	Stored / Consumables	Stored Food Only	Rejection w/ Consumables
Opt 2: Short	~20 days	Stored Commodities w/ Consumable Waste Removal Hardware	Launch-Entry Suit +/- Other Clothing w/ Wipes & Bags for Toilet	Waste Storage Only; Minimal Restrictions on Inputs	Stored / Consumables	Stored Food Only	Non-Consumable Rejection Supplemented by Consumables
		Regenerable Physicochemical Hardware w/ Consumables & Make Up, If Necessary	Pre-Packaged Clothing; Limited Water for Oral Hygiene; Wipes for Body Hygiene; Dedicated Toilet, Semi-private/temporary sleep areas; Smoke Detection and Fire Suppression	Waste Stabilization w/o Water Recovery; Minimal Restrictions on Inputs; Source Separation			
Opt 3: Medium	~20 weeks	Regenerable Physicochemical Hardware w/ Consumables & Make Up, If Necessary	Pre-Packaged Clothing; Limited Water for Oral Hygiene; Wipes for Body Hygiene; Dedicated Toilet, Private Sleep Areas, Temporary Radiation Storm Shelter; Smoke Detection and Fire Suppression	Waste Stabilization w/o Water Recovery; Minimal Restrictions on Inputs; Source Separation. 25% logistics carrier waste reuse	Stored / Consumables	Stored Food Only	Non-Consumable Rejection Supplemented by Consumables
					Recovery / Reuse of Some Waste Water w/ Other Waste Water Stored; Make Up from Stores; Consumables Supplied		Non-Consumable Rejection

Table 2-3 Overall Description of Mission Duration and Life Support System Functionality (continued)

Designator	Duration	Air Subsystem	Habitation Interface	Waste Subsystem	Water Subsystem	Food External Interface	Thermal External Interface
Opt 4: Long	~10-20 months	Physicochemical Hardware & Regenerable Consumables w/ Negligible Bioregeneration & In-Situ Oxygen, If Necessary & Available	Limited Clothing Laundry; Water for Oral & Body Hygiene; Dedicated Toilet, Private Sleep Areas, Dedicated Radiation Storm Shelter	Waste Stabilization w/ Water Recovery; Wet Wastes Accepted w/ Others Stored 50% logistics carrier waste reuse. 50% Waste processing residuals used for shielding or converted to methane propulsion for station keeping	Recovery / Reuse of Some or All Wastewater w/ Any Other Waste Water Stored w/o Brine Recovery, If Produced; Consumables Supplied	Stored Food w/ Fresh Vegetable Production Unit	Non-Consumable Rejection Supplemented by Consumables
		Physicochemical Hardware & Regenerable Consumables w/ Minor Bioregeneration & In-Situ Oxygen, f Necessary & Available			Recovery / Reuse of All Wastewater w/ Brine Recovery, If Produced; Consumables Supplied; ISRU Make Up Possible	15 % Bioregeneration w/ Stored Food	Non-Consumable Rejection

Table 2-3 Overall Description of Mission Duration and Life Support System Functionality (continued)

Designator	Duration	Air Subsystem	Habitation Interface	Waste Subsystem	Water Subsystem	Food External Interface	Thermal External Interface
Opt 5: Very Long	~10 years	Physicochemical Hardware & Regenerable Consumables w/ Minor Bioregeneration & In-Situ Oxygen, If Necessary & Available	Clothing Laundry; Free Water for Oral & Body Hygiene; Dedicated Toilet Private Sleep Areas, Dedicated Radiation Storm Shelter	Waste Stabilization w/ Water Recovery; Wet Wastes Accepted w/ Others Stored >75% logistics carrier waste reuse. >75% Waste processing residuals used for shielding. Production of methane (combined with ISRU) or oxygen/water	Recovery / Reuse of All Wastewater w/ Brine Recovery, If Produced; Consumables Supplied; ISRU Make Up Possible	Stored Food w/ Fresh Vegetable Production Unit	Non-Consumable Rejection
		Significant Bioregeneration w/ Physicochemical Hardware & In-Situ or Regenerable Consumables; Wastes Vented or Stored		Reclamation of Life Support Commodities w/ Consumables, Mineralization, & Storage	Recovery / Reuse of All Wastewater w/ Brine Recovery, If Produced; ISRU Make Up & Consumable Manufacture	15 % Bioregeneration w/ Stored Food	

Table 2-3 Overall Description of Mission Duration and Life Support System Functionality (concluded)

Designator	Duration	Air Subsystem	Habitation Interface	Waste Subsystem	Water Subsystem	Food External Interface	Thermal External Interface
Opt 6: Multi-Generational	~2-10 decades	Integrated Bioregeneration w/ In-Situ Commodities for Minimal Losses & Some Hardware Manufacturing	Clothing Laundry; Unlimited Water for Oral & Body Hygiene; Dedicated Toilet	Reclamation of Life Support Commodities w/ Consumables, Mineralization, & Storage	Recovery / Reuse of All Wastewater w/ Brine Recovery, If Produced; ISRU Make Up & Consumable Manufacture	50 % Bioregeneration w/ Stored Food	Non-Consumable Rejection
				Reclamation of Life Support Commodities w/ Mineralization, & Storage w/o Consumables		75 % Bioregeneration w/ Stored Food	
		Integrated Bioregeneration w/ In-Situ Commodities for Minimal Losses & All Hardware Manufacturing	Clothing Laundry; Unlimited Water for Oral & Body Hygiene; Dedicated Toilet; Clothing Manufactured Locally		Recovery / Reuse of All Wastewater w/ Brine Recovery, If Produced; ISRU Make Up & All Hardware Manufacture	Essentially Complete Bioregeneration w/ Protein from Plant Products	
				Reclamation of All Commodities w/ Mineralization w/o Consumables w/o Permanent Storage (No Waste)		Complete Bioregeneration w/ Protein from Animal Products	
Opt 7: "Permanent"	~1 × 109 years	Integrated Bioregeneration w/ In-Situ Commodities for Minimal Losses & All Hardware Manufacturing	Clothing Laundry; Unlimited Water for Oral & Body Hygiene; Dedicated Toilet; Clothing Manufactured Locally	Reclamation of All Commodities w/ Mineralization w/o Consumables w/o Permanent Storage (No Waste)	Recovery / Reuse of All Wastewater w/ Brine Recovery, If Produced; ISRU Make Up & All Hardware Manufacture	Complete Bioregeneration w/ Protein from Animal Products	Non-Consumable Rejection

Table 2-4 Functionality and Possible Options for the Air Subsystem

	Air Subsystem	Air Subsystem: Carbon Dioxide Removal	Air Subsystem: Oxygen Supply	Air Subsystem: Carbon Dioxide Reduction	Air Subsystem: Trace Contaminant Control	Air Subsystem: Pressure Control	Air Subsystem: In-Situ Resource Utilization	Air Subsystem: Sparing
Opt 1	Stored Commodities w/ Consumable Waste Removal Hardware	Consumables	Stored Commodities / Consumables	None	None	Stored	None	None
Opt 2	Regenerable Physicochemical Hardware w/ Consumables & Make Up, If Necessary	Physicochemical Hardware & Regenerable Consumables	Physicochemical Hardware & Regenerable Consumables	Physicochemical Hardware & Regenerable Consumables; Waste Gases Vented	Consumables & Venting Wastes, If Necessary	Consumable Chemical Generation or Stored Gases	Provide Oxygen	Logistics Supply
Opt 3	Physicochemical Hardware & Regenerable Consumables w/ Negligible Bioregeneration & In-Situ Oxygen, If Necessary & Available	Physicochemical Hardware & Regenerable Consumables w/ Minor Bioregeneration	Physicochemical Hardware & Regenerable Consumables w/ Minor Bioregeneration	Physicochemical Hardware & Regenerable Consumables; Wastes Vented or Stored	Regenerable Hardware, Venting Wastes, If Necessary, w/o Consumables	Completely Regenerable Generation	Provide Diluent Gas	Logistics Supply w/ Limited Remanufacturing
Opt 4	Physicochemical Hardware & Regenerable Consumables w/ Minor Bioregeneration & In-Situ Oxygen, If Necessary & Available	Significant Bioregeneration w/ Physicochemical Hardware & Regenerable Consumables	Significant Bioregeneration w/ Physicochemical Hardware & Regenerable Consumables	Physicochemical Hardware & Regenerable Consumables; Wastes Vented or Stored; Minor Bioregeneration	Regenerable Hardware w/o Losses or Consumables	Use Local Materials	Provide Oxygen & Diluent Gas	Local Manufacturing; In-Situ Resource Feedstock

Table 2-4 Functionality and Possible Options for the Air Subsystem (concluded)

	Air Subsystem	Air Subsystem: Carbon Dioxide Removal	Air Subsystem: Oxygen Supply	Air Subsystem: Carbon Dioxide Reduction	Air Subsystem: Trace Contaminant Control	Air Subsystem: Pressure Control	Air Subsystem: In-Situ Resource Utilization	Air Subsystem: Sparing
Opt 5	Significant Bioregeneration w/ Physicochemical Hardware & In-Situ or Regenerable Consumables; Wastes Vented or Stored	Integrated Regeneration; Bioregenerative w/ > 50 % Food Closure; Consumables Produced In-Situ	Integrated Regeneration; Bioregenerative w/ > 50 % Food Closure; Consumables Produced In-Situ	Significant Bioregeneration w/ Physicochemical Hardware & Regenerable Consumables; Wastes Vented or Stored	Regenerable Hardware w/o Losses; Local Spares Manufacturing		Provide Oxygen, Diluent Gas, & Other Consumables	Local Manufacturing of All Equipment; In-Situ Resource Feedstock
Opt 6	Integrated Bioregeneration w/ In-Situ Commodities for Minimal Losses & Some Hardware Manufacturing	Integrated Regeneration; Bioregenerative w/ > 75 % Food Closure; Any Spares & Consumables Produced In-Situ	Integrated Regeneration; Bioregenerative w/ > 75 % Food Closure; Any Spares & Consumables Produced In-Situ	Integrated Regeneration; Bioregenerative w/ > 50 % Food Closure; Consumables Produced In-Situ			Provide All Required Consumables	None; No Spares Needed (Fully Reliable w/o Spares)
Opt 7	Integrated Bioregeneration w/ In-Situ Commodities for Minimal Losses & All Hardware Manufacturing			Integrated Regeneration; Bioregenerative w/ > 75 % Food Closure; Any Spares & Consumables Produced In-Situ			Provide All Required Consumables & Spares	

Table 2-5 Functionality and Possible Options for the Habitation Interface

	Habitation Interface	Habitation Interface: Metabolic Waste Collection	Habitation Interface: Oral & Body Hygiene	Habitation Interface: Clothing	Habitation Interface: Sparing
Opt 1	Launch-Entry Suit w/ Wipes Only	MAGs or UCDs	None or Wipes	Launch-Entry Suit Only	None
Opt 2	Launch-Entry Suit +/- Other Clothing w/ Wipes & Bags for Toilet	MAGs or UCDs, Apollo Bags / No Dedicated Hardware	Wipes w/ Limited Water for Oral Hygiene; Toothpaste Restrictions	Launch-Entry Suit w/ Pre-Packaged Clothing	Logistics Supply
Opt 3	Pre-Packaged Clothing; Limited Water for Oral Hygiene; Wipes for Body Hygiene; Dedicated Toilet	Dedicated Toilet w/ Consumables	Limited Water for Oral & Body Hygiene; Cleanser Restrictions	Launch-Entry Suit w/ Pre-Packaged Clothing	Logistics Supply w/ Limited Remanufacturing
Opt 4	Pre-Packaged Clothing; Limited Water for Oral & Body Hygiene; Dedicated Toilet	Dedicated Toilet w/o Consumables or Regenerable Consumables	Free Water for Oral & Body Hygiene; Cleanser Restrictions	Aqueous Laundry w/ Consumable Cleaning Agent; Launch-Entry Suit w/ Pre-Packaged Clothing	Local Manufacturing; In-Situ Resource Feedstock
Opt 5	Clothing Laundry; Unlimited Water for Oral & Body Hygiene; Dedicated Toilet	Toilet & Associated Supplies Manufactured Locally	Free Water for Oral & Body Hygiene; No Cleanser Restrictions	Aqueous Laundry w/ Regenerable Cleaning Agent; Launch-Entry Suit	Local Manufacturing of All Equipment; In-Situ Resource Feedstock
Opt 6	Clothing Laundry; Unlimited Water for Oral & Body Hygiene; Dedicated Toilet; Clothing Manufactured Locally			Clothing Manufactured Locally	None; No Spares Needed (Fully Reliable w/o Spares)

Table 2-6 Functionality and Possible Options for the Waste Subsystem

	Waste Subsystem	**Waste Subsystem: Input Trash Model**	**Waste Subsystem: Volume Reduction**	**Waste Subsystem: Stabilization / Making Safe**	**Waste Subsystem: Containment**	**Waste Subsystem: Resource Recovery**	**Waste Subsystem: Sparing**
Opt 1	Waste Storage Only; Minimal Restrictions on Inputs	Trash, including Expended Clothing & Crew Metabolic Wastes w/o Source Separation	None / Manual / "Footballs"	None	Storage in Vehicle	None	None
Opt 2	Waste Stabilization w/o Water Recovery; Minimal Restrictions on Inputs; Source Separation	Trash, including Expended Clothing & Crew Metabolic Wastes w/ Source Separation	Physical Compaction	Chemical Stabilization (Consumables)	Storage w/ Odor Control; Limited Duration in Vehicle	Water Only	Logistics Supply
Opt 3	Waste Stabilization w/ Water Recovery; Wet Wastes Accepted w/ Others Stored	Trash, Clothing, Crew Metabolic Wastes & Inedible Biomass w/ Source Separation	Melt Compaction	Moisture Removal (Dewatering / Freeze-Drying) w/o Encapsulation	Storage w/ Odor Control; Unlimited Duration in Vehicle	Water & Minerals; < 50 % Food Closure w/ Biomass Production	Logistics Supply w/ Limited Remanufacturing
Opt 4	Reclamation of Life Support Commodities w/ Consumables, Mineralization, & Storage	Trash, Clothing, Crew Metabolic Wastes & Inedible Biomass w/o Source Separation	Partial Mineralization w/ Melt Compaction	Moisture Removal (Dewatering / Freeze-Drying) w/ Encapsulation	Storage w/ Odor Control & Stabilization; Unlimited Duration Outside Vehicle	Water, Minerals, & Some Carbon Dioxide; > 50 % Food Closure w/ Biomass Production	Local Manufacturing; In-Situ Resource Feedstock
Opt 5	Reclamation of Life Support Commodities w/ Mineralization, & Storage w/o Consumables	Trash, Clothing, Crew Metabolic Wastes & Inedible Biomass w/o Source Separation; Expended Hardware w/ Source Separation	Complete Mineralization or Other Complete Volume Reduction	Partial or Complete Mineralization	None; Essentially Complete Reutilization	Water, Minerals, & Full Carbon Dioxide	Local Manufacturing of All Equipment; In-Situ Resource Feedstock
Opt 6	Reclamation of All Commodities w/ Mineralization w/o Consumables w/o Permanent Storage (No Waste)					Water, Minerals, Carbon Dioxide, Paper, Plastics, Organic Feedstocks for Food & Other Materials	None; No Spares Needed (Fully Reliable w/o Spares)

Table 2-7 Functionality and Possible Options for the Water Subsystem

	Water Subsystem	**Water Subsystem: Removal of Organic Compounds**	**Water Subsystem: Removal of Inorganic Compounds**	**Water Subsystem: Removal of Particulates**	**Water Subsystem: Removal of Microbial Organisms**	**Water Subsystem: Polishing**
Opt 1	Stored / Consumables	None / n/a	None / n/a	None / n/a	None / Removable / Consumable Biocide at Launch	None / n/a
Opt 2	Recovery / Reuse of Some Wastewater w/ Other Wastewater Stored; Make Up from Stores; Consumables Supplied	Regenerative Technology w/ Consumables w/o Brine Recovery; If Produced	Regenerative Technology w/ Consumables w/o Brine Recovery; If Produced	Filtration; Consumable Technology	Locally Produced / Regenerable, Low-Toxicity Biocide	Polishing w/ Consumables
Opt 3	Recovery / Reuse of Some or All Wastewater w/ Any Other Waste Water Stored w/o Brine Recovery, If Produced; Consumables Supplied	Regenerative Technology w/ Consumables & Brine Recovery; If Produced	Regenerative Technology w/ Consumables & Brine Recovery; If Produced	Regenerable Filtration or Other Regenerable Technology	Filtration; Consumable Technology	Polishing w/ Regenerable Technology
Opt 4	Recovery / Reuse of All Wastewater w/ Brine Recovery, If Produced; Consumables Supplied; ISRU Make Up Possible	Regenerative Technology w/ Brine Recovery; If Produced; w/o Consumables or Consumables Produced In-Situ	Regenerative Technology w/ Brine Recovery; If Produced; w/o Consumables or Consumables Produced In-Situ		Regenerable Filtration or Other Regenerable Technology	
Opt 5	Recovery / Reuse of All Wastewater w/ Brine Recovery, If Produced; ISRU Make Up & Consumable Manufacture					
Opt 6	Recovery / Reuse of All Wastewater w/ Brine Recovery, If Produced; ISRU Make Up & All Hardware Manufacture					

2.6 APPLICABLE DOCUMENTS

The BVAD is intended to provide values for analysis and modeling tasks to study human spaceflight and not to design a specific mission, vehicle or technology. Analysis and modeling are charged with examining both off-nominal and diverse technology options. As a result, many studies may consider situations that differ from the accepted bounds listed in the various documents containing requirements. However, when applicable, the BVAD is intended to capture the individual extremes for inputs that are appropriate for human space flight. Further, while the nominal values throughout this document should be consistent with one another, off-nominal values may not be consistent with other values within this document. Thus, the user should independently verify the validity of using off-nominal values.

As noted, the BVAD attempts to provide inputs for all quantities of importance for studies associated with life support systems. However, as research constantly changes, many studies will require inputs for quantities not listed here. In such situations, analysts should use whatever values are appropriate and available and so note and reference those values in their reports or documentation. Further, analysts are asked to report such omissions to the document authors and provide whatever information could be used to determine values for such omitted quantities.

The life support community has used other documents in parallel with the BVAD to document requirements or assumptions for specific missions, tailored specifically for life support system relevant content. The most recent versions of the documents are listed below. For the reference missions document especially, previous editions of the document are not necessarily wrong, but rather describe different kinds of missions that NASA has considered at one time.

ELS RD (2008) "Exploration Life Support Requirements Document", National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, Houston, Texas.

RMD (2008) "Advanced Life Support Systems Integration, Modeling, and Analysis Reference Missions Document," JSC-64109, Revision A, Duffield, BE Editor, National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, Houston, Texas, November.

HIDH (2014) "Human Integration Design Handbook". NASA/SP-2010-3407/REV1, National Aeronautics and Space Administration, Mary W. Jackson NASA Headquarters, Washington, DC. Approved 06-05-2014.

HIDP (2014) "Human Integration Design Processes", NASA/TP-2014-218556, Boyer, J, National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, Houston, Texas.

Parameters that are non-negotiable, for whatever reason, were documented within the ELS RD (2008) prior to the end of that project. Some of the assumptions documented in the BVAD may in time become requirements while others will be uncertain until the National Aeronautics and Space Administration (NASA) embarks on a specific mission. Some possible future missions are documented in the RMD (2008) as well as more recent reports. Background information on the rationale for human-system standards is provided in the HIDH (2014). Design processes, methodologies, and best practices that NASA uses to meet human systems and rating requirements during the development of crewed space systems/operations are described in the HIDP (2014). These documents can be used as companions to the BVAD to develop consistent mission scenarios for life support system concepts.

3 OVERALL ASSUMPTIONS

3.1 MISSIONS

The mission affects analyses and models by changing the weighting of the various pieces of the system in terms of time dependent items, equipment design, and infrastructure cost. It can also require different contingency planning for a mission with a short-term abort option (e.g., low-Earth orbit or Lunar missions) versus one without such an option (e.g., Martian missions).

3.1.1 TYPICAL VALUES FOR EXPLORATION MISSIONS

Many of the missions supported here are outlined in the Exploration Life Support Reference Missions Document (RMD, 2008). Assumptions are given in Table 3-1 for mission parameters associated with missions described within the RMD (2008).

The given volume assumptions in Table 3-1 describe unobstructed or free volume per crewmember [6] and are specified in terms of 'tolerable', 'performance', and 'optimal' for the listed mission segment. For purposes here, performance should be viewed as nominal. The underlying Lunar mission is taken from RMD (2008) which is based on the long-duration Lunar Outpost mission outlined in the Exploration Systems Architecture Study (ESAS) (2005) and LAT2 (2007) study. For either Moon or Mars missions, the duration values represent the complete time the crew occupies the indicated vehicle. Thus, for a transit vehicle, this is the sum for both the outbound and return trips. As a final note, each mission's architectural configuration may send more than one crew member in sequence to use a specific surface habitat. The values in Table 3-1 represent durations for just a single crew member's visit to a surface habitat.

Power levels in a spacecraft or habitat depend on its size and functions. Some minimum or "keep alive" level of power is required in any human mission to assure crew survival and higher levels will be required for comfort and mission objectives. Table 3-2 contains representative power requirements by system for the International Space Station (ISS) (Pritchett, 2014). The data is nominal stage operations with no robotic or EVA operation being performed. No visiting vehicles are attached, and values are the average power for each system over a one day period at the output of the direct-current-to-direct-current conversion units (DDCUs). The data is for 0° solar beta angle and the power for some systems will vary with solar beta angle.

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[6] These values are also called net habitable volume, which is the remaining pressurized cabin volume after accounting for losses due to equipment, stowage, trash, and other items that decrease volume (Ramsey, 2002).

Table 3-1 Mission Assumptions

		Assumptions		
Parameter	**Units**	**Lower**	**Nominal**	**Upper**
Crew Size	CM	4 (1)	4 (1)	6 (1, 2)
Destination: Moon				
Volume: [7]		***Tolerable***	***Performance***	***Optimal***
Transit Vehicle [8]	m^3/CM	2.76 (3)	3.54 (3)	4.25 (3)
Crew Lander [9]	m^3/CM	1.27 (3)	3.54 (3)	4.39 (3)
Surface Habitat [10]	m^3/CM	4.8 [11](4)	37 [12](4)	39-50 [13](4)
Duration: [14]		***Minimum***	***Nominal***	***Maximum***
Transit Vehicle [8]	d	12 (1)	18	21.1
Crew Lander [9]	d	5 (1)	7	8 (1)
Surface Habitat [10]	d	8 (1)	210	210 (1)
Destination: Mars				
Volume: [7]		***Tolerable***	***Performance***	***Optimal***
Transit Vehicle [15]	m^3/CM	5.10 (3)	9.91 (3)	18.41 (3)
Crew Lander [16], 7 days	m^3/CM	1.13 (3)	3.54 (3)	4.25 (3)
Crew Lander [16], 30 days	m^3/CM	2.27 (3)	4.25 (3)	10.62 (3)
Surface Habitat [17]	m^3/CM	5.10 (3)	9.91 (3)	18.41 (3)
Duration: [14]		***Minimum***	***Nominal***	***Maximum***
Transit Vehicle [15]	d	220 (2)	360 (2)	360 (2)
Crew Lander [16]	d	7 (2)	7 (2)	30 (2)
Surface Habitat [17]	d	540 (2)	600 (2)	619 (2)

References

(1) ESAS (2005)
(2) Hoffman & Kaplan (1997)
(3) Ramsey (2002)
(4) LAT2 (2007)

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[7] The volume here specifically is unobstructed or free volume within the crew cabin.

[8] In ESAS (2005) and/or RMD (2008), this vehicle is the “Crew Exploration Vehicle.”

[9] In ESAS (2005) and/or RMD (2008), this vehicle is the “Lunar Surface Access Module.”

[10] In ESAS (2005) and/or RMD (2008), this vehicle is the “Lunar Outpost.”

[11] LAT2 mobile-hab design

[12] LAT2 mini-hab design

[13] LAT2 monolithic-hab design

[14] This mission would have an immediate abort-to-orbit option, although not necessarily an immediate return option. Values represent total time the vehicle is occupied by the crew throughout the mission.

[15] In Hoffman and Kaplan (1997) and/or RMD (2001), this vehicle is the “Mars Transit Vehicle.”

[16] In Hoffman and Kaplan (1997) and/or RMD (2001), this vehicle is the “Mars Descent / Ascent Lander.”

[17] In Hoffman and Kaplan (1997) and/or RMD (2001), this vehicle is the “Surface Habitat Lander.”

Table 3-2 Typical System Power Requirements based on International Space Station

System	Avg. Power (kW)
Command & Data Handling (C&DH)	4.08
Crew Health Care System (CHeCS)	0.11
Communication & Tracking Systems (CTS)	2.90
Environmental Control & Life Support Systems (ECLSS)	5.31
Electrical Power Systems (EPS)	2.02
European Space Agency (ESA)	2.04
Extravehicular Activity (EVA)	0.00
Flight Crew Equipment System (FCES)	1.07
Functional Cargo Block (FGB)	1.80
Guidance, Navigation, & Control (GN&C)	0.62
Japanese Experiment Module (JEM)	5.35
Mechanical (MECH)	0.19
Multi-Purpose Logistics Module (MPLM)	0.56
Mobile Servicing System (MSS)	1.20
Payload	up to 30
Service Module (SM)	3.64
Structure (STRUC)	0.00
Thermal Control System (TCS)	8.72

3.1.2 ASTEROID MISSIONS

Asteroid missions have been suggested to robotically capture and then redirect a small asteroid into a stable Lunar orbit, where astronauts can safely visit and study it. This mission is expected to be accomplished with the Orion exploration vehicle with EVAs utilizing the Portable Life Support Subsystem (PLSS) conduced from Orion. Other supporting elements could be added to enhance mission capabilities later (Gates 2014). The vehicle assumptions for human exploration are not unique for this mission but use the expected capabilities of the Orion vehicle.

3.2 INFRASTRUCTURE COSTS AND EQUIVALENCIES

Infrastructure "costs" (mass, volume, power, thermal control, and crewtime, for example), are key factors in overall system analysis. They conceptually apportion a fraction of the infrastructure mass to hardware components of the life support system (see section 2.2). Appropriate infrastructure "costs" or "equivalencies" for two possible near-term exploration objectives, Luna and Mars, are provided in Table 3-3 and Table 3-4. The listed "costs" or "penalties" for volume account for primary structure only, including micrometeoroid and orbital debris protection, and radiation protection for the crew, if necessary. Table 3-12 provides information on secondary structure, including the racks and conditioned volumes such as refrigerated spaces. The nominal values listed in Table 3-3 and Table 3-4 correspond to current technologies with few improvements or synergistic advantages. Less conservative values, with comments on applicability, are presented in Table 3-7, Table 3-16, and Table 3-19.

Infrastructure "costs" vary according to the external mission environment, the technologies used, the mission duration, and sometimes other factors. For example, a power system using solar photovoltaic generation to provide electrical power for a transit vehicle has different energy storage requirements than a comparable system with the same architecture for an equatorial Lunar base. Likewise, the thermal environment of interplanetary space differs from the thermal environment of the Lunar or Martian surface. The tables here include values for surface locales indicative of equatorial sites. Studies at polar sites may use very different values, especially for thermal control (see RMD (2008) for polar site values).

Table 3-3 and Table 3-4 provide two volume cost factors. The first entry, for shielded volume, reflects pressurized primary structure with sufficient radiation protection to provide a safe environment for the crew. The second entry, for unshielded volume, models pressurized primary structure without any radiation protection other than what the pressure shell may provide. The crew will spend limited time within pressurized volume without radiation protection. Thus, the former value applies to technologies and equipment that are susceptible to environmental radiation or require significant crew interaction while the latter may be used for technologies and equipment that are insensitive to interplanetary radiation and require little crew interaction. The fourth entry is for thermal control. These values are combined here for convenience.

Table 3-5 provides additional infrastructure costs associated with in-space missions. In-space refers to space habitats, typically orbital stations, which can support a crew for extended periods of time. These types of space habitats typically lack major propulsion or landing systems. However, a Mars transit vehicle may have similar characteristics since it would also house crew members for months to years. The table values are based on vendor concepts for the Lunar Gateway through NASA's Next Space Technologies for Exploration Partnerships (NextSTEP) program. The tabulated infrastructure volume costs in Table 3-5 are the average for the two categorical concepts that were proposed by vendors: (1) hard-shell in-space habitats, shown under the nominal column, and (2) inflatable in-space habitats, shown under the lower column. Power and thermal control costs are averages over all vendor concepts, shown in the nominal column, as these values are less dependent on hard-shell versus inflatable designs.

Table 3-3 Long-Duration Lunar Mission Infrastructure "Costs"

		Assumptions		
Parameter	**Units**	**Lower**	**Nominal**	**Upper**
Transit				
Shielded Volume	kg/m³	--	80.8 (1)	--
Unshielded Volume	kg/m³	--	45.2 (1)	--
Power	kg/kW_e	--	136 (2)	--
Thermal Control [18]	kg/kW_{th}	45 (3)	55.4 (3)	65 (3)
Crewtime [19]	kg/CM-h	3.64(4)	5.05(4)	
Surface				
Shielded Volume	kg/m³	102.0 (1)	133.1 (1)	137.3 (1)
Unshielded Volume	kg/m³	--	9.16 (1)	13.40 (1)
Power	kg/kW_e	29 (2)	76 (2)	749 (2)
Thermal Control [18]	kg/kW_{th}	97 (3)	102 (3)	246 (3)
Crewtime [19]	kg/CM-h	1.48 (4)	2.10 (4)	

References

(1) See Table 3-7
(2) See Table 3-16
(3) See Table 3-19
(4) See Table 3-30

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[18] Theses thermal control values are the sum of the Internal Thermal Control System and External Thermal Control System Costs for their respective mission type – Lunar transit/surface or Mars transit/surface.

[19] These crewtime values originate from calculations supporting Metric (2005) which assumes different values than those listed for other elements of the infrastructure. However, the values here are of the same order of magnitude so that the crewtime values are of the correct order of magnitude. To be rigorous, crewtime infrastructure values should be computed based upon both the other infrastructure values assumed and the actual life support system configuration. However, when such information is not available, the values here may be used as approximations.

Table 3-4 Mars Mission Infrastructure "Costs"

		Assumptions		
Parameter	**Units**	**Lower**	**Nominal**	**Upper**
Transit				
Shielded Volume	kg/m³	36.1 (1)	79.3 (1)	--
Unshielded Volume	kg/m³	9.4 (1)	38.4 (1)	--
Power [20]	kg/kW_e	--	162	N/A
Thermal Control [18]	kg/kW_{th}	45 (3)	96 (3)	158 (3)
Crewtime [19]	kg/CM-h	0.565 (4)	0.565 (4)	0.728 (4)
Surface				
Shielded Volume	kg/m³	--	170 (5)	
Unshielded Volume	kg/m³	--	9.16 (1)	13.40 (1)
Power	kg/kW_e	54 (2)	87 (2)	338 (2)
Thermal Control [18]	kg/kW_{th}		146 (3)	170 (3)
Crewtime [19]	kg/CM-h	0.506 (4)	0.940 (4)	

References
(1) See Table 3-7
(2) See Table 3-16
(3) See Table 3-19
(4) See Table 3-30
(5) See Table 3-11

Table 3-5 In-Space Mission Infrastructure "Costs" [21]

		Assumptions		
Parameter	**Units**	**Lower**	**Nominal**	**Upper**
Shielded Volume [22]	kg/m³	36(1)	79 (1)	--
Unshielded Volume [23]	kg/m³	9	38	--
Power	kg/kW_e	--	162	--
Thermal Control	kg/kW_{th}	--	180	--
Crewtime	kg/CM-h	--	N/A	--

References
(1) Smitherman and Schnell (2020)

3.2.1 INFRASTRUCTURE COSTS BASED UPON THE EXPLORATION SYSTEMS ARCHITECTURE STUDY

ESAS (2005) and subsequent Constellation Program (CxP) documentation presented fairly detailed descriptions of concepts for a return to the Moon, discussing both a shorter-duration Lunar Sortie and a longer-duration Lunar Outpost. Even though the Constellation Program was discontinued, these studies may be useful for planning future space exploration missions. While the Lunar Sortie approach is nearer term, the Lunar Outpost is more likely to use regenerative life support technologies. RMD (2008) outlines a possible implementation for a Lunar Outpost based upon the documents listed in 3.2.1. The values in Table 3-20 at the end of section 3.2, taken from the RMD (2008), reflect a Lunar Outpost mission. [24] Please note that without reference to the RMD (2008), Table 3-20 is incomplete and the reader is encouraged to consult the original source for a broader understanding. However, for those familiar with the RMD (2008), a brief explanation may suffice. According to ESAS (2005), the Crew Exploration Vehicle primarily uses solar photovoltaic cells for power generation, although after separation of the Command Module (capsule) from the Service Module, all power is provided by batteries. Further, according to ESAS

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[20] The power infrastructure cost assumption for Mars transit assumes the same value as the in-space habitats in Table 3-5 where it is expected that the power technology is translatable among the two vehicle/habitat types.

[21] In-Space refers to space habitats, typically orbital stations, which can support a crew for extended periods of time. These types of space habitats typically lack major propulsion or landing systems. Unless referenced otherwise, the values provided in this table are based on the vendor concepts for a lunar Gateway under the NASA NextSTEP program (2019).

[22] The nominal and lower values for the shielded volume cost correspond to the average of the hard-shell in-space habitats and inflatable in-space habitats, respectively.

[23] The nominal and lower values for the unshielded volume cost correspond to the average of the hard-shell in-space habitats and inflatable in-space habitats, respectively.

[24] Some values in Table 3-6 may also apply to a Lunar Sortie mission.

(2005), the Lunar Surface Access Module uses hydrogen-oxygen fuel cells located on the Descent Stage for primary power generation, so the appropriate power-mass penalty has a fixed contribution from the fuel-cell hardware, 166.2 kg/kW$_e$, and a time-dependent contribution from the reactants consumed, 0.528 kg/kW$_e$h. Following separation of the Ascent Stage from the Descent stage, all power aboard the Lunar Surface Access Module is provided by batteries. The thermal control infrastructure penalties are similar in that the time-independent values of those recommended for life support correspond to radiant rejection before module or stage separation, while the time-dependent components correspond to rejection using consumables after module or stage separation.[25] Because many life support systems function during all mission phases, both the time-independent and time-dependent thermal control penalties apply.[26] Finally, because this mission, as outlined in RMD (2008), must have precise definition for "crewtime" to be calculated there are no corresponding values given for "crewtime".[27]

In 2020, NASA released a catalog containing lander (i.e. surface access module) designs from the Apollo era through the Constellation program (Connolly, 2020). This catalog provides highly detailed designs and descriptions of various landers, which were actually implemented (Apollo Lunar Module G, H, and J Series) as well as exploration concepts for future landers including both NASA and contractor designs, such as the Boeing Lunar Surface Access Module, Massachusetts Institute of Technology Crasher-Bouncer, and Altair Lander to name a few. In many of these designs, a mass breakdown, payload size, pressurized volume, and a wealth of additional information is provided as a reference to the reader. See Connolly (2020) for these details.

Table 3-6 Lunar Outpost Mission Infrastructure Costs

Parameter	Units	Crew Exploration Vehicle	Lunar Surface Access Module	Lunar Outpost
Power				
Power-Mass Penalty	kg/kW$_e$	125.9	166.2	274.1 [28]
Energy-Mass Penalty, Batteries	kg/kW$_e$h	13.0	12.3	undefined
Energy-Mass Penalty, Reactants	kg/kW$_e$h	n/a	0.528	undefined
Thermal Control				
Acquired by Cabin Heat Exchangers & Coldplates	kg/kW$_{th}$	60.11	59.1	--
Thermal Transport	kg/kW$_{th}$	25.9	15.8	--
Rejection by Radiators	kg/kW$_{th}$	12.2	8.5	--
Rejection by Consumables	kg/kW$_{th}$h	10.7	6.7	--
Recommended Values for Life Support Analyses [29]	kg/kW$_{th}$ kg/kW$_{th}$h	50.0 10.7	33.1 6.7	31.6 [30] --
Vehicle Structure				
Volume	kg/m³	133.8	61.7	100.0

3.2.2 *PRESSURIZED VOLUME OR PRIMARY STRUCTURE COSTS*

Pressurized volume houses the crew and crew-accessible systems. Characteristic volume "costs" are presented in Table 3-7. The International Space Station (ISS) common module currently provides pressurized volume in low-Earth orbit. An inflatable module could be used as an alternative. In both cases, the lower value corresponds to primary structure with protection from micrometeoroids and orbital debris. The upper value, if known, also includes some dedicated radiation protection.

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[25] Both the Crew Exploration Vehicle and the Lunar Surface Access Module may use consumables to supplement rejection before separation during particularly hot mission segments, so this direction is an approximation.

[26] Alternately, for life support hardware that is not used following vehicle separation, only the time-independent thermal control penalty applies.

[27] Values from Table 3-30 for the Moon are good approximations in the absence of customized values.

[28] Solar power generation with regenerable fuel cells and cryogenic reactants for energy storage (ESAS, 2005). This value assumes a South-Pole site on the North Rim of Shackleton Crater.

[29] See RMD (2008) for underlying assumptions and details.

[30] For a South Polar site on the North Rim of Shackleton Crater with horizontal radiators with a power-mass penalty of 274.1 kg/kW$_e$.

The aerodynamic crew capsule in Table 3-7 is based on an ellipse sled and designed to aero-capture in the upper atmosphere upon returning to Earth (NASA, 2001a). The second entry reflects the crew cabin structure without radiation shielding while the first entry reflects the crew cabin with sufficient radiation shielding for a Lunar transit mission. Nominally, according to concepts within NASA (2001a), crew vehicles for near-term Lunar missions will aero-capture upon returning to Earth, so the nominal values here include thermal protection for aerodynamic heating.

Table 3-7 Cost of Pressurized Volume

	Assumptions [kg/m^3]		
Technology/Approach	**Lower**	**Nominal**	**Upper**
Low-Earth Orbit			
ISS Module (shell only)	42.9 (5)	66.7 (1)	--
Inflatable Module	19.61 (2)	28.1 (2)	32.4 (2)
Lunar Mission – Transit			
Shielded Aerodynamic Crew Capsule (Ellipse Sled)	--	80.8 (3)	--
Unshielded Aerodynamic Crew Capsule (Ellipse Sled)	--	45.2 (3)	--
Lunar Mission – Surface			
Shielded Inflatable Module	102.0 (4) [31]	133.1 (4) [31]	137.3 (4) [32]
Unshielded Inflatable Module	--	9.16 (2) [33]	13.40 (2)
Martian Mission – Transit			
Shielded Hard-Shell Transit Habitat	--	79 (6)	--
Unshielded Hard-Shell Transit Habitat [34]	--	38	--
Shielded Inflatable Transit Habitat	--	36 (6)	--
Unshielded Inflatable Transit Habitat [35]	--	9	--
Martian Mission – Surface			
Shielded Inflatable Module [36]	--	79 (6)	
Unshielded Inflatable Module	--	9.16 (2)	

References

(1) Hanford (1997)
(2) See Table 3-10
(3) NASA (2001a)
(4) See Table 3-11.
(5) From James Russell, Lockheed
(6) Smitherman and Schnell (2020)

The cost factors listed for inflatable modules, both for the Lunar and Martian missions, assume surface sites. The unshielded value reflects just the primary structure without any radiation protection, presuming that some "to be determined" in-situ resources, such as regolith, a natural cavern, or local atmosphere, will provide the necessary

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[31] Estimate based on primary structure plus shielding mass.

[32] Estimate based on all listed module masses, including avionics and power management and distribution.

[33] Estimate based on primary structure mass only. Habitats sited on a planetary surface might use in-situ resources for radiation shielding and micrometeoroid protection. Additional equipment may be required to construct such shielding, but the associated mass should be considerably less than the corresponding masses from Earth.

[34] The Mars transit vehicle unshield volume costs for hard-shell habitats are based on vendor concepts for a Lunar Gateway through NASA's NextSTEP program (2019). These concepts are extendable to a Mars transit design as shown in Smitherman and Schnell (2020).

[35] The inflatable Mars transit vehicle unshielded volume costs are, similarly to the hard-shell habitats, an extension of the NextSTEP concepts (2019).

[36] These values are derived from hazards associated with interplanetary space transit. Vehicles on the surface of Mars would receive some beneficial shielding from the local Martian environment.

radiation protection. The nominal shielded value assumes sufficient radiation protection for the location assuming the surface locale provides no beneficial protection against radiation, while the upper value for shielded volume also includes avionics and power management and distribution masses. Often, however, this last cost is associated with the Power Interface and, therefore, should not also be assessed against the structure mass.

In recent studies, transit vehicles for Martian missions are generally larger than corresponding vehicles for Lunar missions, so the volume-mass penalties for surface applications are suitable for transit applications. In fact, the radiation protection values for the Martian missions are sized assuming a crew is present during transfer to Mars. Because Mars itself will provide some shielding, the transfer segment is the most severe environment and provides the criteria for sizing radiation protection.

The appropriate volume cost factor generally depends on the sensitivity of specific equipment to the external environment or whether the crew must regularly interact with the equipment. As noted above, in radiation intensive environments anywhere beyond the Van Allen Belts, cost factors for shielded volume should be used whenever equipment is sensitive to radiation or must be frequently accessed by the crew. This value reflects the cost of placing equipment within the primary crew cabin. The cost for unshielded volume applies whenever the technology is not sensitive to radiation but must remain within a pressurized environment. The crew might service such equipment infrequently. Finally, some technologies are located outside the pressurized cabin, such as pressurized control system tanks, water tanks or thermal control heat exchangers. The associated volume cost factor would be much less than the lower value, such as 6-11 kg/m^3 for a minimal structure with micrometeoroids and orbital debris (MMOD) barrier.

Leakage is technology dependent. Life support systems are designed to carry consumables to meet the maximum allowable leakage rate in the design specifications for the spacecraft. In most cases the actual leakage rate is significantly lower than the specification.

3.2.2.1 *MINIMUM NET HABITABLE VOLUME*

The net habitatable volume (NHV), as defined by NASA and outlined in Net Habitable Volume Verification Method (NASA, 2014b), is the volume that the crew and lives and works in. This is differentiated from the pressurized volume which consists of the NHV as well as the systems volume, storage volume, and voids. The minimum NHV was evaluated by Stromgren, et al. (2021) in a new method. Rather than scaling or extrapolating from previous flight vehicles, the minimum NHV was derived from a list of required activities and the associated volume for each activity. They postulated that the longer the mission the greater the NHV should be, up to 180 days, at which point an asymptote was reached, and no additional NHV is needed for longer missions. For this reason, the calculations were performed assuming activities required for long duration space flight including several types of exercise and regenerable ECLSS maintenance.

The net volume required for each task was determined after careful evaluation of previous research, habitat analogs, and subject matter expert input. Given that many activities can be performed in the same volume sequentially, all activities were evaluated for commonalities in volume and hardware uses. The calculations were performed for both 4-person and 6-person crew, with certain activities being scaled per crew member, such as exercise requiring 2 devices for 6 crew and 1 device for 4 crew, while other volumes were not scaled, such as major medical spaces. The final NHV for a 180+ day mission is provided in Table 3-8 below. Stromgren*, et al.* (2021) describes all functions allotted to each functional space.

Table 3-8 Combined Functional Space and Minimum Net Habitable Volume for a 4-person and 6-person Crew[37]

Combined Functional Space	Minimum volume (m^3)	
	4-person Crew	6-person Crew
Exercise: Cycle Ergometer	6.12	12.24
Exercise: Treadmill	3.38	6.76
Exercise: Resistive Device	3.92	7.84
Group Social: Open Area / Mission Planning: Training	18.2	27.30
Group Social: Table / Eating: Table / Mission Planning: Table	10.09	15.14
Human Waste: Waste Collection	2.36	4.72
Human Waste: Cleansing / Hygiene: Cleansing	4.35	8.70
Logistics: Temporary Stowage	6.00	6.00
Maintenance: Computer / EVA: EVA Computer + Data	3.40	3.40
Maintenance / Logistics: Work Surface / EVA: Suit Testing	4.82	4.82
Meal Preparation: Food Prep	4.35	8.70
Meal Preparation: Work Surface	3.30	3.30
Medical: Computer	1.20	1.20
Medical: Medical Care	5.80	5.80
Mission Planning: Computer + Command / Spacecraft Monitoring	3.42	3.42
Private Habitation: Work Surface / Medical – Ambulatory Care	17.40	26.10
Private Habitation: Sleep + Relaxation / Hygiene: Non-Cleansing	13.96	20.94
Waste Management	3.79	3.76
Total Minimum Net Habitable Volume	**115.83**	**170.14**
Minimum Net Habitable Volume per Crew Member	**28.96**	**28.36**

3.2.2.2 *TRANSHAB STRUCTURAL DETAILS*

Currently, the United States uses the ISS common module to provide pressurized volume. Alternately, inflatable modules have been suggested since the Apollo Program. TransHab (Kilbourn, 1998, and NASA, 1999) presented in Table 3-9, is a robust inflatable module proposed for low-Earth orbit trials while attached to ISS. TransHab encloses 329.4 m^3 within a primary shell with an inner surface area of 250.9 m^2. A connecting tunnel provides access to ISS with an additional 12.6 m^3. The values in Table 3-9 include micrometeoroid protection and a storm shelter for radiation protection in low-Earth orbit against solar particle events. Finally, the ISS common module and TransHab are designed using different design philosophies, so a rigorous comparison between the two approaches is not intended. Rather, the values here document both approaches. A proof-of-concept inflatable module has been implemented on the ISS since May 28, 2016 and is called the Bigelow Expandable Activity Module (BEAM). Further details on this module are provided at the end of this section.

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[37] Stromgren *et al.* (2021)

Table 3-9 Masses of Inflatable Shell Components

Item	Mass [kg]	References
Inflatable Shell Assembly, including Liner, Bladder, and Restraint	1,265	Based on TransHab Technology. See Kilbourn (1998), NASA (1999), and Atwell and Badhwar (2000)
Multi-Layer Insulation	235	
Micrometeoroid and Orbital Debris Protection	3,208	
Other (Windows, Deployment and Attachment Systems)	204	
Central Core Structure, including End Cones	1,405	
Water Containment [38] (Enclosing 18.8 m³ and covering 40.1 m²)	142	
Radiation Protection Media (A 0.0574 m thick water shield; areal density 5.7 g/cm^2)	2,304	
Initial Inflation System	502	
Avionics and Power Management and Distribution	1,398	
Total Mass	10,663	

Based on Table 3-9, several cost factors for various configurations of the components presented are possible (See Table 3-10). While each configuration is not independently viable, they provide background for other estimates. The applicable volume is 329.4 m³.

Table 3-10 Estimated Masses and Volume-Mass Penalties for Inflatable Module Configurations

Configuration	Mass [kg]	Volume-Mass Penalty [kg/m³]	Volume-Mass Penalty [m³/kg]
All listed Inflatable Module components listed in Table 3-9	10,663	32.37	0.0309
Previous Option without Avionics and Power Management and Distribution	9,265	28.13	0.0355
Primary Shell and Central Core Only	3,016	9.16	0.1092
Previous Option plus Multi-Layer Insulation and Micrometeoroid and Orbital Debris Protection	6,459	19.61	0.0510
Previous Option plus Initial Inflation System	6,961	21.13	0.0473
Previous Option plus Avionics and Power Management and Distribution	8,359	25.38	0.0394
Avionics and Power Management and Distribution alone	1,398	4.25	0.2358

Table 3-11 contains data relating various proposed shielding materials via an inflatable TransHab structure. The volume is assumed to be 329.4 m^3. The areal density of shielding to protect the crew from environmental radiation, for a Lunar surface mission should be about 15 g/cm^2. For a longer stay such as a Mars mission the assumption is made that the areal density would be 20 g/cm^2. However, there is a complication to this simplistic approach, because secondary particles can be released from the nucleus when struck by heavy and/or high-speed radiation particles, the effectiveness of shield materials varies on a molecular level. Thus, more massive shield materials are more likely to produce more secondary radiation. In general, atoms with lower atomic mass have less nuclear material and thus produce fewer secondary particles than the heavier nuclei. The simple hydrogen nuclei contain only one proton and no neutrons; therefore, they are able to absorb some of the energy of the incoming radiation while producing fewer additional particles.[39] Radiation scientists often use areal density when comparing the shielding needed for various environments:

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[38] The water tank surrounding the crew quarters is actually integrated with the central core structure.

[39] Hydrogen nuclei contain only one proton and thus the nucleus when struck by high speed particles cannot produce multiple secondary radiation from each hydrogen source.

$$\boldsymbol{\chi}(\boldsymbol{areal\ density}) = \boldsymbol{\rho}(\boldsymbol{density}) \times \boldsymbol{th}(\boldsymbol{thickness}) \qquad \text{Equation 3-1}$$

Table 3-11 Estimated Masses for Inflatable Modules

ITEM (BASED ON TRANSHAB ARCHITECTURE)	Mass for Lunar Mission[40] [kg]	Mass for Lunar Mission[41] [kg]	Mass for Martian Mission [42] [kg]
Primary Structure Mass (Core, Shell) (1) [43]	6,961	6,961	6,961
Shielding Mass is 0.163 m of polyethylene around each of 4 CMs covering 2.0 m^2 surface area per CM. (2)	1,200		
Shielding Mass is 0.163 m of polyethylene around the entire shell volume of 329.4 m^3 (2)		34,599	
Shielding Mass is 0.217 m of polyethylene around the entire shell volume of 329.4 m^3 (2)			46,131
Total Mass	8,161	41,560	53,092
Volume-Mass Penalty [kg/m³]	24.8	126.2	170.3
Volume-Mass Penalty [m³/kg]	0.0403	0.00792	0.00587

References

(1) Kilbourn (1998) and NASA (1999)
(2) Duffield (2010)

Note: the surface area is estimated assuming a spherical configuration to relate volume and surface area.

Including the avionics and power management and distribution masses, as listed in Table 3-10, adds an additional 4.24 kg/m³ to the volume-mass penalties listed above. However, these masses are often accounted for in other factors, such as the power-mass penalty. Without radiation shielding or micrometeoroid protection, the primary shell and structure of the inflatable module has a volume-mass penalty of 21.1 kg/m³ or 0.047 m³/kg. This would be an appropriate estimate for a habitat shielded by local resources, whether regolith or in a natural feature such as a lava tube or cavern. The Human Integration Design Handbook (NASA HIDH) (2014) has a more complete description of the radiation environment.

TransHab represents a concept which was pursued by NASA to develop the technology for inflatable habitats. Recently, the technology has been demonstrated on ISS on a small-scale. As a proof-of-concept, the Bigelow Expandable Activity Module (BEAM) was expanded and pressurized on the ISS on May 28, 2016. The BEAM consists of the bulkheads, aluminum structure, and multiple layers of softgoods as MMOD and radiation shielding as well as various sensors to collect habitat data. The purpose of BEAM is is to test and validate the inflatable habitat technology in low-Earth orbit. However, recently, the BEAM has even been utilized as storage space aboard the ISS. Based on the mass (1360 kg) and volume (16 m^3) of the fully inflated habitat, its volume-mass penalty equals 85 kg/m^3 or 0.012 m^3/kg (NASA, 2016; Levy*, et al.*, 2021). This volume-mass penalty is greater than that of the above TransHab estimates. This difference is believed to arise due to the scale of the BEAM versus the conceptual TransHab. The former is significantly larger in size, which results in improved mass efficiencies. This is caused by not only the core masses, which are comprised of the bulkheads and aluminum structure, but also the necessary tanks for inflation and pressurization, which become dead weight after the habitat is expanded.

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[40] areal density= 15 g/cm^2
[41] areal density= 15 g/cm^2
[42] areal density= 20 g/cm^2
[43] See the fifth configuration in Table 3-10.

3.2.3 SECONDARY STRUCTURE COSTS

The values in the previous tables quantify the vehicle's primary structural mass, including the pressure vessel and radiation shielding. However, many systems also require additional secondary structure, such as a payload rack, drawers, or refrigeration. Based on data from the International Space Station Program (Green, *et al.*, 2000), Table 3-12 provides estimates for secondary structure masses. Though somewhat simplistic, the volume, power, and thermal control for equipment housed within or mounted to secondary structure is assumed to be identical to the values for the uninstalled piece of equipment. Assuming a piece of equipment is not mounted directly to the vehicle primary structure; most are mounted to an International Standard Payload Rack. Small items are placed within trays and drawers of a stowage rack, while some foodstuffs and experiments require the chilled climate provided by a refrigerator or freezer. For example, 100 kg of food stored within a refrigerator would incur a secondary mass penalty of 136 kg in addition to any power, thermal control, or volume penalties, while a 100 kg pump mounted to the vehicle floor would have no associated secondary mass, though power, thermal control, and volume to account for primary structure might still apply.

Table 3-12 Secondary Structure Masses

Mounting Configuration	Secondary Structure Mass per Mass of Equipment [$\text{kg}_{\text{Secondary Structure}}$ /$\text{kg}_{\text{Equipment}}$]	Internal Cargo Volume [m^3]
Directly to Primary Structure (No Secondary Structure)	0.00	n/a
Directly to International Standard Payload Rack	0.21	1.57
Within Trays of a Stowage Rack	0.80	0.9
Within Refrigerator/Freezer Rack	1.36	0.614 (1)

References

Information from Green, *et al.* (2000) except as noted.

(1) Toups, *et al.* (2001)

The external volume for an International Standard Payload Rack is 2.00 m^3 (Rodriguez and England, 1998). The Stowage Rack and the Refrigerator/Freezer Rack are derived from the International Standard Payload Rack and have the same external dimensions.

3.2.4 LUNAR MISSIONS

The Artemis plan represents the most recent proposal from NASA to return humans to the moon as well as the establishment of a sustained Lunar presence to support science and technology development for continued exploration. These missions consist of two phases which correspond to the short- and long-term goals of NASA, which are (1) to bring humans back to the Lunar surface and (2) sustain human presence in cislunar space and on the Lunar surface. The details of phases 1 and 2 can be seen in Smith*, et al.* (2021) and NASA (2020a). One part of the Artemis proposal is the development and deployment of an orbiting Lunar outpost called Gateway, which provides the primary components to support early human expedition to the Lunar South Pole as well as continued cislunar presence and a science and technology demonstration testbed. In phase 2, the focus shifts to advancing technologies to allow for sustained missions to the Moon. An additional goal of this phase is the assessment of human exploration systems in preparation for crewed missions to Mars beginning in the 2030s, which include an increasingly closed loop ECLSS as well as in-situ resource utilization (ISRU) development to utilize Lunar/planetary resources. As indicated in Schneider*, et al.* (2020), early Artemis missions will consist of a mostly open loop ECLSS due to the initial short Lunar surface duration missions. However, sustained Lunar and Martian surface missions will require partially-closed ECLSS that are adapted for partial gravity with ECLS oxygen system closure of greater than 75% and average launched food water content of less than 40% being noted as strong drivers towards minimizing overall system mass. These Artemis plans are continuing to evolve as development continues; thus, specific values associated with the life support systems may not be readily available for the time being. However, the referenced papers, including Watson-Morgan*, et al.* (2021), which contains additional details concerning the human landing system as well as possible early and sustained mission durations, provide a good overview of the current state of the Artemis plan. An additional reference document, which provides relevant details of the Artemis missions, as well as future exploration missions, is Coan (2020). This document provides details on the EVA concept of operations for exploration missions including some mission details of the Artemis program, information on the different spacecraft and surface mobility vehicles to be used, and the EVA mission parameters (duration, frequency, and tasks). The reference document not only pertains to the Artemis missions but also includes parameters for exploration missions to Mars as well as small natural bodies, i.e. asteroids. Formerly during the Constellation Program, the Lunar Architecture Team (LAT) conducted various studies of viable mission architectures. The proposals consisted of a series of 32 Lunar missions, starting with a build-up mission which included four 7-day Sorties (Toups and Kennedy, 2008). The missions generally increase in length and complexity as the number of missions in the study increase. The initial Sorties were to carry all logistics, but as the Outpost portion of the proposal is developed, expendables are either sent with the crew, sent via a supply vehicle, used from stores, saved from a previous mission or missions, or recovered from the waste stream. The High Mobility Scenario is much more specific in the missions, the mission deliverables, modular development of habitat, EVAs and rovers, and other exploratory vehicles, than earlier LAT Cycle 2 (LAT2) proposals. Major emphasis for High Mobility Scenario is on mobility for exploration. Surface mobility was identified as a key element to the Constellation program and its endeavors to set up an Outpost (Bagdigian, 2009). Assuming this Lunar exploration architecture, life support resources, such as oxygen, nitrogen, and water, are deployed to various loci on the Lunar or Martian surface. Planning must include delivery of logistical elements from Earth and then distribution of those elements to points of use on the Lunar surface. Things like water and oxygen will need to be transported back to a central location for regeneration or cleanup and then be redistributed to points on the surface where they are needed.

Table 3-13 contains equivalencies based on hardware from the Constellation Program LAT2 study. These are based on designs for the crew exploration vehicle (CEV) which was the predecessor to Orion, a Lunar lander, and hard-shell Lunar outpost. These values may be useful in analysis of different Lunar missions as they are more general in their nature compared to those values in Table 3-14 which are specific to the High Mobility Scenario Outpost.

Table 3-13 Equivalencies Based on Hardware Delineated During the Second Lunar Architecture Study of the Constellation Program

Subsystem	Components	Units	CEV[44]	Lunar Lander	Lunar Outpost
Total Power:		kg/kW$_e$	125.9	67.2	72.1 (day)/ 605.1 (night)
	Power Transport	kg/kW$_e$	91.9	27.6	
	Power Generation	kg/kW$_e$	14.5	11.3	
	Power Storage	kg/kW$_e$	13.0	0.504	
Structures		kg/m^3	101.3 [3]	86.4	25.8
Total Thermal:		kg/kW$_{th}$			48.5
	Coldplates & related articles	kg/kW$_{th}$	50.9	105.3	
	Radiator Rejection	kg/kW$_{th}$	59.7	40.8	
	Evaporative Cooling	kg/kW$_{th}$	110.6	28.42	
	Ascent & Rentry	kg/kW$_{th}$	14.6	11.6	

The High Mobility Scenario Outpost consists of a Pressurized Core Module (PCM), a Pressurized Excursion Module (PEM), and Pressurized Logistics Module (PLM). There are four pressurized Lunar Electric Rovers (LER). The PCM is assumed to house most of the regenerative environmental control and life support system (ECLSS) equipment. Each LER has the critical mass to support two crewmembers by using a portable utility palette (PUP).

In order to calculate equivalent system mass for High Mobility Scenario, equivalencies are given in Table 3-14. A more complete accounting of the equivalencies can be obtained in (Lange, 2009).

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[44] Crew Exploration Vehicle (CEV), a predecessor of Orion

Table 3-14 Calculated Equivalencies for Constellation High Mobility Scenario[45]

Parameter	Value	Units
Outpost Pressurized Core Module (PCM) Pressurized Volume Equivalency		
PCM Pressurized Volume Equivalency, $(E_v)_{PCM}$	49	$\frac{kg}{m^3}$
Outpost Pressurized Logistics Module (PLM) Pressurized Volume Equivalency		
PLM Pressurized Logistics Module (PLM) $(E_v)_{PLM}$	36	$\frac{kg}{m^3}$
LER Pressurized Crew Cab (PCC) Pressurized Volume Equivalency		
PCC Pressurized Volume Equivalency, $(E_V)_{PCC}$	100	$\frac{kg}{m^3}$
Outpost Power Supply Unit (PSU) Power Equivalency		
PSU Illuminated-Only Power Equivalency, $(E_P)_{PSU-I}$	43	$\frac{kg}{kW}$
PSU Continuous-Only Power Equivalency, $(E_P)_{PSU-C}$	362	$\frac{kg}{kW}$
Outpost Fission Surface Power System (FSPS-1) Power Equivalency		
FSPS Continuous Power Equivalency, $(E_P)_{FSPS}$	221	$\frac{kg}{kW}$
LER Battery Power Equivalency (without PUP)		
LER Power Equivalency (LER Batteries Only), $(E_P)_{LER}$	1076[46]	$\frac{kg}{kW}$
Outpost Thermal Equivalency without LERs		
PCM Thermal Equivalency, $(E_T)_{PCM}$	49	$\frac{kg}{kW}$
Outpost Average Thermal Equivalency without LERs	69	$\frac{kg}{kW}$
LER Thermal Equivalency (Ice Block Only; 3 day life)		
LER Thermal Equivalency Based on the Ice Block only	777	$\frac{kg}{kW}$
LER Mobility Equivalency		
LER Mobility Equivalency without PUP, $(E_M)_{LER}$	1.33	$\frac{kg}{kg}$
LER Mobility Equivalency with PUP, $(E_M)_{LER-P}$	1.35	$\frac{kg}{kg}$
LER Mobility Equivalency with PUP and and extra batteries, $(E_M)_{LER-PB}$	1.45	$\frac{kg}{kg}$

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[45] The following equivalencies were calculated by (Lange, 2009)

[46] Modified from the original Lange calculation according to estimates by Patrick George recorded via e-mail December 2009.

3.2.5 POWER COSTS [47]

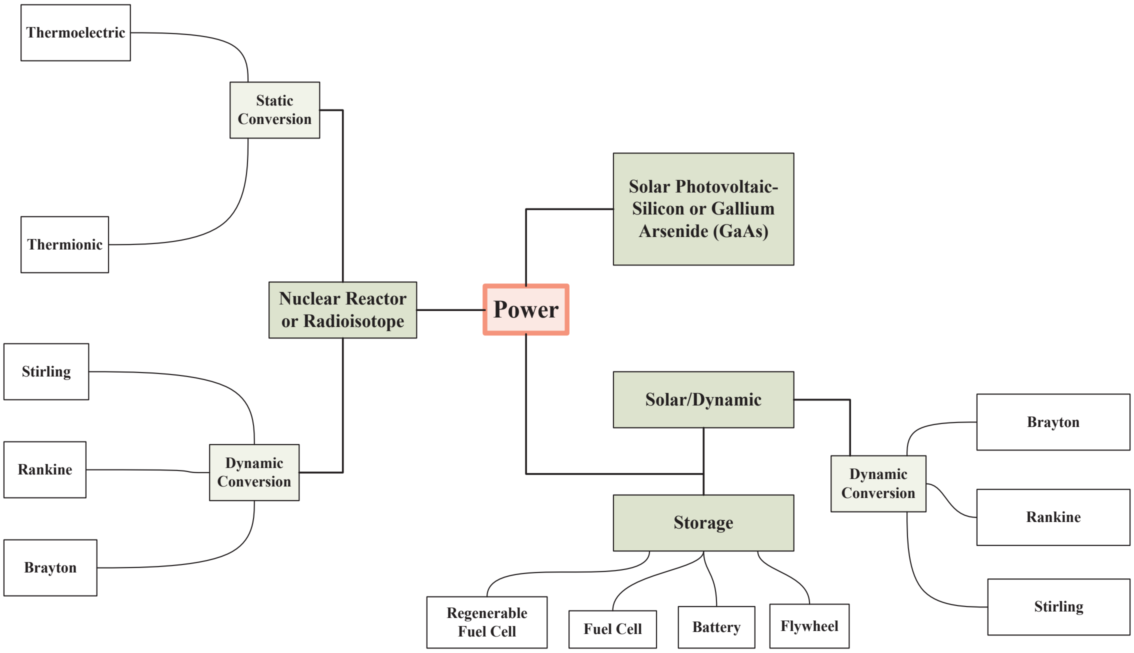

Figure 3-1 Power generation and storage options considered.

Options for power generation, recovery, and storage considered here, and their general inter-relationship, are presented graphically in Figure 3-1. Table 3-16 outlines the power options with data available from the literature. Consideration was given to all the processes listed in Figure 3-1, but the table presents only those technologies with available data. The generalized cycles and processes are briefly discussed in the following paragraphs.

Figure 3-1 lists the solar and nuclear power options considered for near-term human exploration missions. The three cycles presented here are dynamic conversion cycles: the Rankine, Brayton, and Stirling cycles. These cycles are applicable for conversion of heat to current flow whether the heat is generated by an environmental source such as the Sun or possibly heat produced by nuclear fission or radioisotopic decay. Dynamic cycles may emit vibrational loads, but they can be integrated with or into balanced machines. Static cycles, though lacking vibrational emissions, are typically less efficient than their dynamic counterparts. Each cycle has attractive features which tend to manifest at different locations and operating conditions.

The Rankine cycle operates via a working fluid phase change. The working fluid is typically a liquid metal or an organic fluid. At constant pressure, which is typical for this approach, the process offers isothermal heat rejection. Because the heat-rejection-phase of power generation is isothermal, power can be obtained at relatively low operating temperatures and, theoretically, at higher efficiencies than the Brayton cycle. The Rankine cycle uses a liquid, typically a liquid metal, which passes through a heat exchanger to vaporize a working fluid, which then passes through turbo machinery, releasing work, and re-condenses.

Characteristic of the Brayton cycle is a single-phase working fluid which typically requires smaller radiators. The cycle is often used in a turbine to convert heat to current flow by pressurizing the air in a piston, adding fuel, and then igniting the mixture to trigger an expansion cylinder. The expanding gas drives a turbine releasing work.

The Stirling cycle is also single-phase with efficiencies theoretically close to those of the ideal Carnot cycle. The Stirling cycle uses a fixed mass of gas sealed inside the engine. Stirling engines are quiet since there are no explosions or high pressure gas releases. The process is controlled by external heating and cooling of the sealed gas. The major drawback of this cycle is the relatively slow response time of the sealed gas to external heating and cooling. Thus, this cycle tends to favor smaller engines at lower power levels, so if larger amounts of power are needed several smaller reactors operate in parallel which increases overall system mass. A comparison of the Brayton, Rankine and

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[47] The authors wish to thank Robert L. Cataldo of the NASA's Glenn Research Center for his inputs and poignant comments on the makeup and structure of this power section.

Stirling Power Module Characteristics (Frisbee and Hoffman, 1993), based on the SP-100 Nuclear Reactor Proposal for Mars Cargo Missions, is given in Table 3-15.

Table 3-15 Power Module Characteristics for Nuclear Reactor Proposals [48]

		Cycle		
Item	**Units**	**Rankine**	**Stirling**	**Brayton**
Reactor Full Power Projected Operating Life	y	7.4	9.6	7.6
Operating Temperature	K	1,355	1,355	1,355
Average Radiator Temperature	K	788	567	469
Radiator Platform Area	m^2	90	183	531
Radiator Physical Area	m^2	128	282	821
Auxiliary Radiator Area	m^2	25	25	25
Stowed Dimensions				
Length	m	12.2	16.9	28.3
Diameter	m	5.5	5.5	5.5
Number of modules/launches	--	3	2	1
Power Module Masses				
Reactor and Controls	kg	841	841	841
Shield	kg	1,396	1,396	1,396
Primary Heat Transport	kg	895	807	1,104
Power Conversion System	kg	933	6,293	3,302
Heat Rejection & Transport	kg	1,066	420	1,157
Heat Rejection Radiator	kg	1,733	3,078	7,063
Parasitic Load Radiator	kg	140	140	140
Total Module Mass	kg	7,004	12,975	15,003
Module Power and Efficiency				
Thermal Power	kW_{th}	2,356	1,850	2,309
Electric Power, gross	kW_e	578	596	582
System Power	kW_e	6	20	10
Net Power	kW_e	572	576	572
System Efficiency	%	24	31	25
System Power-Mass Penalty [49]	kg/kW_e	12	23	26

Several static conversion approaches exist. Two approaches that are of interest to NASA are thermionic and thermoelectric energy conversion. Several approaches also exist to make use of local insolation. The most prevalent are solar photovoltaic cells and solar dynamic systems, while thermionic Photon Chips™ are a recent development.

Thermionic energy conversion is the direct production of electric power from heat by thermionic electron emission. From a thermodynamic viewpoint, it is the use of electron vapor as the working fluid in a power-producing cycle. A thermionic converter consists of a hot emitter electrode from which electrons are vaporized by thermionic emission and a colder collector electrode into which they are condensed after conduction through the inter-electrode plasma. The resulting current, typically several amperes per square centimeter of emitter surface, delivers electrical power to a load at a typical potential difference of 0.5-1 volt and thermal efficiency of 5–20%, depending on the emitter temperature (1,500–2,000 K) and specific mode of operation.

Thermoelectric systems rely on the Seebeck effect where two dissimilar materials create a voltage at the material interface when exposed to a temperature gradient. Systems relying on thermoelectric conversion tend to have low efficiencies.

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[48] Brayton, Rankine, and Stirling power module characteristics according to Frisbee and Hoffman (1993). The assessments are sized based on the SP-100 nuclear reactor proposal for Mars cargo missions with approximately 600 kW_e of total power capacity. Note that most near-term to mid-term mission scenarios do not require that much power on the surface of Mars.

[49] This quantity is also known in the literature as the “system specific mass.”

Solar photovoltaic (PV) cells have powered NASA probes in the inner Solar System for decades and, more recently, the International Space Station. According to ESAS (2005), solar PV cells are likely to power the Crew Exploration Vehicle. Finally, solar PV cells are being considered for human vehicles on the surface of Mars where temperatures vary from 130 K to 300 K. Cell performance increases with decreasing temperature, with peak efficiencies occurring at 150-200 K according to Landis and Appelbaum (1991). Some materials, such as silicon, increase in performance rapidly in PV cells at the relatively low temperatures found on Mars.

Solar dynamic systems for surface applications concentrate incident solar radiation using a spectral parabolic mirror and achieving high temperatures at a focal point to drive a generator. Local dust is an obstacle to this approach as the dust blocks some of the incident photons preventing them from reaching the collector.

Choices among conversion cycles are quite complex and choices among theoretical advantages sometimes suffer from engineering challenges and do not realize their full potential. Some cycles do offer greater maturity, but none of the cycles have demonstrated long-term reliability in space applications yet. Table 3-16 lists many power system options, and is divided into options by usage locale, power generation source, and vehicle type, with systems for similar vehicles being grouped together. Lee and Duffield (2006) provide additional details for many of the systems presented, and this work should be consulted by readers who desire more than what are given below. Power mass penalties are provided in terms of kg/kW_e for power generation systems that do not use consumables, while energy storage devices with consumables or power generation via consumables are characterized by energy-mass penalties in terms of kg/kW_eh. Several systems below are rated separately for non-consumable power generation technologies and consumable storage technologies, and both factors should be assessed during for impacts on equivalent system mass if power is required when by the system under study when both power systems are in use during the projected mission. A brief discussion and further information on batteries (Table 3-17) and fuel cells (Table 3-18) follow Table 3-16.

Generally, solar power systems grow linearly with power required while nuclear power systems have a high initial mass, especially for shielding. With a nuclear power system, adding small amounts of generating capacity with respect to total power generating capacity adds little to the overall system mass. For example: starting with a 25 kW_e nuclear plant with a mass of 6000 kg, doubling the power output to 50 kW_e increases the overall mass to approximately 8000 kg. Doubling the power output again to 100 kW_e increases the mass to around 11,000 kg (Cataldo, 2006).

Table 3-16 Power Option Summary

System	**kg/kW$_e$**	**kg/kW$_e$h**	**Comments**
Static Conversion Power Options in Low Earth Orbit[50]			
Concentrating Photovoltaic Cells; Solar Photovoltaic Cells w/o Storage (1)	n/a		Commerically available concentrator photovoltaic modules with efficiencies exceeding 30%
Solar Photovoltaic Cells w/ Hydrogen Oxygen Fuel Cell Storage (4, 5, 6)	41	1.1	11% efficient producing 100 kW$_e$; Shuttle technology with a six-day mission or Lunar base solar power plant study.
Solar Photovoltaic Cells w/o Structure w/o Energy Storage Structure (Calculated from 5, 7, 8, 9, 10)	101		10 to 15% efficient producing 28 kW$_e$; Subtracted the mass of the structure batteries and related items.
Solar Photovoltaic Cells w/ Battery Storage (5, 7, 8, 10)	133	20.8	10 to 15% efficient producing 28 kW$_e$; Does not include the main supporting truss (P6); ISS
Solar Photovoltaic Cells w/ Battery Storage (5, 11)	166 [51]	20.8	20% efficient is the goal for thin film solar arrays; 35-40% efficient is the goal for advanced concepts producing 100 kW$_e$; [52] Best specific power to 1991 for earth orbit solar intensity.
Solar Photovoltaic Cells w/o Storage; Includes Support Structure (4, 11)	239		Up to 14% efficient; In sun power only with deployable PV cells
Solar Photovoltaic Cells w/ Battery Storage (4)	476	29	10 to 15% efficient producing 28 kW$_e$; ISS Continuous power with deployable cells.
Solar Photovolatic Cells w/o Storage (12)	37		Estimate of the original ISS arrays producing 84 – 120 kW$_e$. This value considers only the arrays.
Current Technology: Solar Photovolatic Cells w/o Storage (13, 14)	16.25		Estimate of the ISS Roll-Out Solar Array (iROSA) producing 20 kW$_e$. This value considers only the arrays.
Dynamic Conversion Power Options in Low Earth Orbit			
Solar w/ Stirling Dynamic Power Production (6)	405		26% efficient producing 100 kW$_e$

References

(1) Philipps, *et al.* (2015)
(2) Piñero, *et al.* (2002)
(3) Littman (1994)
(4) Hanford and Ewert (1996)
(5) Lee and Duffield (2006)
(6) Eagle Engineering (1988)
(7) Landis, *et al.* (1999)
(8) Eagle-Picher (2003)
(9) ISS (1999)
(10) Patel (2005)
(11) Landis and Appelbaum (1991)
(12) Beauchamp, *et al.* (2015)
(13) NASA (2017a)
(14) Schwanbeck (2019)

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[50] Specific Power is usually given for low Earth orbit conditions. Values at the surface of Mars can be estimated by multiplying by the ratio of Mars solar intensity to low Earth orbit solar intensity according to Landis, *et al.* (1999).

[51] Projected value based on components.

[52] Flight tested system is 15 kg/kW$_e$ (Landis and Appelbaum, 1991). Current system is 7.7 kg/kW$_e$. Combining existing technology with gallium-arsenide, GaAs, at 3.3 kg/kW$_e$, adds to the existing technology specific mass.

Table 3-16 Power Option Summary (continued)

System	kg/kW$_e$	kg/kW$_e$h	Comments
Solar Conversion Power Options for the Surface of the Moon			
Solar Power generation at Lunar Equator w/o Storage (15, 16)	54		n/a efficient; Tracking PV arrays
Solar w/ Stirling Dynamic Power Production (6)	405		26% efficient producing 100 kW$_e$
Solar Power Generation at Lunar Equator w/ Fuel Cell Storage (15, 16)	749	4	n/a efficient; Tracking PV arrays
Deployable Solar Photovoltaic Cells w/o Storage (21)	20 - 25		Based on a deployable solar array, i.e. Vertical Solar Array Technology (VSAT)
Lithium Ion Battery Storage (21)		5.9	Based on commercial Li-ion battery technology including enclosure
Nuclear Conversion Power Options on the Surface of the Moon			
Nuclear w/ Brayton Dynamic Power Production (17)	29		n/a efficient producing 550 kW$_e$
Nuclear w/ Brayton Dynamic Power Production (18)	76		n/a efficient producing 20 kW$_e$
Nuclear refractory reactor w/ Brayton Dynamic Power Production; Moon or Mars (19)	77[53]		23.5% efficient producing 55 kW$_e$; direct high-temperature Brayton
Nuclear refractory reactor w/ Stirling Dynamic Power Production; Moon or Mars (19)	149		23.5% efficient producing 31 kW$_e$; Lithium liquid metal
Nuclear refractory reactor w/ Thermoelectric Power Production; Moon or Mars (19)	349		4.1% efficient producing 16 kWe; Lithium and SiGe
Nuclear Fission w/ Brayton dynamic conversion (20)	125		n/a efficient producing 50 kW$_e$
Nuclear Fission w/ Stirling dynamic conversion (20)	120		50 kW$_e$
Nuclear Fission w/ thermoelectric static conversion (20)	136		50 kW$_e$

References

(6) Eagle Engineering (1988)
(15) Hughes (1995)
(16) Ewert, *et al.* (1996)
(17) Harty and Durand (1993)
(18) Juhasz and Bloomfield (1994)
(19) Mason (2006)
(20) Kerslake (2005)
(21) Cataldo (2021)

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[53] A comparison with a stainless steel reactor resulted in superior performance for the refractory reactor for Brayton, Stirling, and Thermoelectric options (Mason, 2006).

Table 3-16 Power Option Summary (continued)

System	kg/kW	kg/kW_eh	Comments
Solar Conversion Power Options on the Surface of Mars			
Solar Photovoltaics w/o Storage (22)	149		28% efficient; Static solar power at an equatorial site on Mars
Solar Photovoltaic Cells w/ Fuel Cell Storage (23)	178	10	30% efficient; PV cell; Power generated at a Mars equatorial site
Solar Photovoltaic Cells w/ Fuel Cell Storage (23)	228	10	20% efficient; Power generated at an equatorial site on Mars
Solar Photovoltaic Cells w/ Fuel Cell Storage (22)	338	n/a	Static solar power at an equatorial site on Mars
Solar Photovoltaics w/o Storage (25, 26)	10		Based on the Orbital ATK Ultraflex array with usage in space, e.g. Mars Phoenix (2008) and InSight (2018).
Nuclear Conversion Power Options on the Surface of Mars			
Nuclear w/ Static Thermoelectric Power Production (23)	54		Emplaced in excavated hole; Excavation equipment is included
Nuclear w/ Static Thermionic Power Production (3)	55		Producing 75 kW_e; Conceptual design
Nuclear w/ Static Thermoelectric Power Production (23)	75		22% efficient producing 160 kW_e; On a self-deployed cart two kilometers from base.
Nuclear w/ Static Thermoelectric Power Production (3)	87		Producing 100 kW_e; On independent lander
Small Radioisotope Power Systems (24)	88		176 kg power system producing 2 kW_e
Nuclear w/ Stirling Dynamic Power Production (23)	88		Producing 100 kW_e; Conceptual design: Stirling engine with shielding
Nuclear w/ Static Thermionic Power Production (3)	107		Conceptual design producing 25 kW_e
Nuclear w/ Static Thermoelectric Power Production (23)	226		Producing 100 kW_e; On mobile cart; Shielding included
Current Technology: Radioisotope Power System on the Curiosity and Mars 2020 (21)	400		45 kg power system producing 110 W_e
Radioisotope Power System (28)	278		Power production of 0.1 - 0.5 kW_e.
Nuclear Fission Power System (28)	409		Total power production of 1 - 5 kW_e targeting a transit spacecraft. Kilopower concepts family.
Nuclear Fission Surface Power System (28)	260		Total power production of 10 - 50 kW_e targeting a surface habitat.
Nuclear w/ Stirling Dynamic Power Production (28)	200		10 kW_e Stirling system from the kilopower concepts family. ~4 m tall and 2000 kg in mass.

References

(3) Littman (1994)
(21) Cataldo (2020)
(22) NASA (1989)
(23) Cataldo (1998)
(24) Hoang, *et al.* (1988)
(25) Kerslake (2017)
(26) Murphy*, et al.* (2016)
(27) NASA (2017b)
(28) McClure and Poston (2013)

Energy storage devices for spacecraft with human crews come in two common forms, which are batteries, per Table 3-17, and fuel cells, per Table 3-18. The differences between batteries and fuel cell capabilities are not easy to discern. The rate and quantity of a battery discharge cycle is not equivalent to the availability of energy from a fuel cell. After installing a fuel cell's components, a fuel cell will output its full rated power continuously if supplied sufficient reactants. A battery, however, degrades with each discharge cycle and must be replaced more frequently than the components of a comparable fuel cell.

Table 3-17 Characteristics of Advanced Rechargeable Batteries [54]

Battery Technology	Cell Energy Density [W·h/L]	Cell Specific Energy [W·h/kg]	Operating Temperature [°C]	Number of Discharge Cycles in Cell Life [Cycles]	Depth of Discharge per Cycle [%]	Technology Readiness Level
"State of the Art" Nickel-Hydrogen (Ni-H_2)	40 to 50	30 to 40	-5 to 30	60,000	30	9
Lithium-ion with Liquid Electrolyte	200 to 300	100 to 150	-40 to 65	1,500	60	5 to 9
Lithium-Solid Polymer Electrolyte	300 to 450	> 200	0 to 80	1,500	60	3
Lithium-Solid Inorganic Electrolyte	> 300	> 200	0 to 80	> 10,000	60	1 to 2

Table 3-18 Advanced Fuel Cell Systems [55]

Technology	Energy-Mass Penalty [kg/kW$_e$h]	Lifetime	Technology Readiness Level
"State of the Art" Alkaline Fuel Cell	8 [56]	n/a	9
Polymer Electrolyte Membrane	4	n/a	4 to 5
Direct Methanol	4.5 [57]	n/a	2 to 4
Solid Oxide	n/a	n/a	2 to 3 [58]
Regenerative Systems based on Polymer Electrolyte Membrane or Solid Oxide	n/a	n/a	3

3.2.6 THERMAL CONTROL COSTS

Table 3-19 presents options for thermal control "costs" assuming an internal and an external thermal control system. Internal thermal control system masses primarily depend on the overall thermal load. External thermal control "costs" vary according to the magnitude of the thermal load and the ease of rejecting thermal loads from the vehicle and, therefore, depend heavily on both site and vehicle configuration. As shown in Table 3-19, many of the values pertaining to the external thermal control system include only the cost of the radiators without consideration of the flow loop and pump requirements. The cost has been presented as such due to the high dependability of the associated flow loop hardware on the vehicle and habitat design and size, which can greatly affect the extensiveness of the needed plumbing. A few examples of a complete external control system cost have been provided which utilize the cost of the flow loop and cold plates from the NextSTEP concepts (2019) with different radiator options. The values in Table 3-19 are representative of typical external thermal control system "costs" for the conditions listed. Lighter, more cost-effective thermal control options exist, but the values here provide representative or typical values for most design studies. They assume a traditional thermal control system architecture employing both an internal and an external thermal control system.

(1) ***Note: The cost of a complete thermal control system is the sum of the internal thermal control system cost plus the appropriate external thermal control system cost.***

(2) ***Note: The inverse thermal-control-mass penalties, given in kW/kg, may not be summed directly. Rather, only the reciprocal values, given in terms of kg/kW, may be summed directly.***

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[54] See Davis, *et al.* (2005).

[55] Information from Davis, *et al.* (2005) except as noted.

[56] See NASA (2002).

[57] See Larminie and Dicks (2003) for details.

[58] This technology is available commercially, but there has been little testing for aerospace applications.

Table 3-19 Advanced Mission Thermal Control Costs and Equivalencies

Internal Thermal Control System Cost			
Vehicle/Site Independent	**kg/kW**	**kW/kg**	**Comments**
Flow Loop with Heat Acquisition Devices	~25 (1)	~0.040	Half of the heat load is acquired by Coldplates.
Radiators Only			
Transit or Low-Earth Orbit	**kg/kW**	**kW/kg**	**Comments**
Current Technology, Vehicles: Flow-Through Radiators	30.4 (2)	0.0329	Shuttle Technology: Aluminum, Body-Mounted Radiators with Silver Teflon Surface Coating.
Lightweight, Flow-Through Radiators	~20 (4)	~0.05	As above with Composite Radiators.
Flow-Through Radiators with a Supplemental Cooling Subsystem	40.0 (2)	0.0250	"Current Technology, Vehicles," with an additional Flash Evaporator Subsystem.
Lightweight, Flow-Through Radiators with a Supplemental Cooling Subsystem	~30 (4)	~0.033	As above with Composite Radiators
Current Technology, Space Stations: International Space Station [59]	323.9 (2)	0.00309	ISS Technology: Aluminum, Anti-Sun Tracking Radiators with Z-93 Surface Coating.
Surface – Moon	**kg/kW**	**kW/kg**	**Comments**
For an Equatorial Site using Horizontal Radiators with Silver Teflon Coating			
Current Technology: Flow-Through Radiators	221 (1)	0.0045	Aluminum, Surface-Mounted Radiators
Lightweight, Flow-Through Radiators	~190 (4)	~0.0053	As above with Composite Radiators.
Flow-Through Radiators + Solar Vapor Compression Heat Pump (SVCHp)	77 (1)	0.013	Aluminum, Surface-Mounted Radiators with SVCHp
Lightweight, Flow-Through Radiators with Solar Vapor Compression Heat Pump	~72 (4)	~0.014	As above with Composite Radiators.
Surface – Mars	**kg/kW**	**kW/kg**	**Comments**
For an Equatorial Site using Vertical Radiators with Silver Teflon Coating			
Current Technology: Flow-Through Radiators	~145 (3)	~0.0069	Aluminum, Surface-Mounted Radiators
Lightweight, Flow-Through Radiators	~121 (3)	~0.0083	As above with Composite Radiators.
Lunar Orbit - In Space [60]	**kg/kW**	**kW/kg**	**Comments**
Body Mounted Radiators Only	92.6	0.011	Based on NextSTEP concepts
Complete External Thermal Control System Cost			
Current Technology, Vehicles: Shuttle Flow-Through Radiators + Flow Loop and External Cold Plates	71.2	0.014	Estimated from Shuttle body-mounted radiators plus the coolant, cold plates, pumps, and plumbing from NextSTEP.
Body Mounted Radiators + Flow Loop and External Cold Plates	133.4	0.0075	Based on the NextSTEP concepts including coolant, cold plates, pumps, and plumbing

References

(1) Estimated from Hanford and Ewert (1996) and Ewert, *et al.* (1999)

(2) Hanford and Ewert (1996)

(3) Estimated from Hanford and Ewert (1996) and Hanford (1998)

(4) Estimated from technology development efforts circa 2000

Notes

– The cost of a complete thermal control system is the sum of the internal thermal control system cost plus the appropriate external thermal control system cost.

– Inverse values, given here in kW/kg, may not be summed directly.

The values in Table 3-19 come from a variety of sources. The internal thermal control system values are derived from studies of a Lunar base, but they are considered typical of other enclosed cabins. The transit vehicle external thermal control system estimates are based on Shuttle technology. The primary heat rejection technology is radiators while an evaporative device, a flash evaporator, provides supplemental cooling. Transit vehicle external thermal control system estimates are provided both with and without supplemental evaporative cooling devices. Because a vehicle cannot reject heat using radiant transfer while aero-capturing or entering a planetary atmosphere, some other technology, like evaporative cooling, supplements the radiators. Vehicles that do not experience aerodynamic heating may employ an external thermal control system without any evaporative cooling. The external thermal control system value for the International Space Station includes significant penalties for thermal-control-system-specific structure that is not necessary for transit vehicles with their lesser heat loads. See Hanford and Ewert (1996) for a detailed disposition of International Space Station external thermal control system masses.

Options for cooling habitats at a Lunar surface site rely on horizontal radiators. Some options also employ a vapor compression heat pump powered by a dedicated solar PV array. While the heat pump is only available while the Sun is above the local horizon, the radiators alone for this option are sized to reject the design load in the absence of sunlight. All options assume an equatorial site, which is the most severe for the Lunar surface.

Finally, the external thermal control system options for the Martian surface employ only radiators sized for the worst environmental conditions expected at an equatorial site, which is a moderate dust storm, and assume that the environment does not impact the radiator surface properties. Sites in the Martian southern hemisphere can be more severe thermally than equatorial sites.

For each external thermal control system option above, less massive approaches are available with additional mission restrictions. In particular, the options listed with lightweight radiators are conservative approximations and research will reduce equipment masses further than these estimates imply. See Weaver and Westheimer (2002). Thus, the technologies here are generally available but are far from optimal for specific applications.

3.2.7 CREWTIME COSTS

Life support equipment requires crewtime for operations and maintenance. This time can be small for some systems and large for others. Notably for functions related to food – food production, food product preparation, meal preparation, and waste disposal – the crewtime may be very large. The cost of crewtime is derived from the life support system equivalent system mass (ESM) and the crewtime available. Typical equivalencies vary from about 0.1 to 10 crewmember-hours per kg of ESM. Section 3.3.4 provides additional details.

3.2.8 LOCATION FACTORS

Location factors [61] describe the additional resources necessary to move a mass of payload from low-Earth orbit to some location elsewhere in space. The additional resources here refer to propulsion assets such as engines, fuel, tankage, and associated propulsion-related structure. [62] Specifically, a location factor represents the additional mass necessary in low-Earth orbit to push a mass of payload to a particular destination. Location factors allow comparisons between cases where all payloads do not share the same transportation history. In other words, one payload option may stay entirely aboard one vehicle during the entire mission, while another payload option may jettison mass midway through the mission and thus reduce its associated propulsion costs for the remainder of the mission. ESM GD (2003) details the use of location factors within equivalent system mass assessments.

Location factors for two destinations, Moon and Mars, are presented in Table 3-20. Estimates for Mars assume the Mars Dual Lander architecture, while estimates for the Moon are based on the L_1 Gateway architecture. Values for the Moon based on ESAS (2005) are presented in RMD (2008). Both sets of estimates in Table 3-20 assume chemical propulsion and aero-braking when possible. [63]

Transfer Vehicles travel from low-Earth orbit to Lunar or Mars orbit and return to low-Earth orbit. The first estimate is for a round trip to one of the aforementioned bodies, while the second estimate is for payloads that only travel to the celestial body and then remain behind when the Transfer Vehicle returns.

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[59] The value includes significant structures to attach or rotate the thermal radiator clusters.

[60] In Space refers to space habitats, typically orbital stations, which are capable of supporting a crew for extended periods of time. The in space thermal costs are based on vendor concepts for a lunar Gateway through NASA's NextSTEP program (2019).

[61] Some researchers use the term "gear ratio" for "location factor." However, these terms refer to the same concept.

[62] Recall that cabin structure, power, thermal control, and crewtime costs or penalties are already assessed with other factors.

[63] Advanced propulsion concepts may yield much lower location factors in the future, but development of advanced propulsion systems for human space flight currently has high programmatic risks.

Landers travel from low-Earth orbit to either the Lunar or Martian surface and, in some cases, back to orbit. For example, within the Mars Dual Lander architecture there are two landers. The first, the Mars Descent / Ascent Lander, travels to Martian orbit robotically. In orbit, the Mars Transit Vehicle rendezvous with the Mars Descent / Ascent Lander and the crew transfers to the latter vehicle for the trip to the Martian surface. At the end of the surface stay, the Mars Descent / Ascent Lander returns the crew to Martian orbit and the Mars Transit Vehicle for the trip back to Earth. The second lander, the Surface Habitat Lander, travels and lands robotically on Mars. The crew transfers to the Surface Habitat Lander once they are on the surface. [64]

Table 3-20 Location Factors for Near-Term Missions

	Location Factor [kg/kg]		
Mission Element (Segment)	**Lower**	**Nominal**	**Upper**
Moon			
Lunar Transfer Vehicle (Full Trip)		9.1:1 (1)	
Lunar Transfer Vehicle (Earth Orbit to Lunar Orbit then destroyed with the Service Module)		7.3:1 (1)	
Lunar Lander (Earth Orbit to Lunar Surface and back to Lunar Orbit)		13.8:1 (1)	
Lunar Lander (Earth Orbit to Lunar Surface Only)		7.2:1 (1)	
Mars [65]			
Mars Transfer Vehicle (Full Trip)	5.77 (2)	5.77 (2)	10.14 (2)
Mars Transfer Vehicle (To Mars Orbit Only)	2.16 (3)	2.16 (3)	3.37 (3)
Mars Lander (Earth Orbit to Martian Surface and back to Martian Orbit)	9.50 (2)	9.50 (2)	14.83 (2)
Mars Lander (Earth Orbit to Martian Surface Only)	2.77 (2)	2.77 (2)	4.33 (2)

Reference

(1) ESAS (2005)
(2) Geffre (2003)
(3) Geffre (2004)

Per ESM GD (2003), location factors multiply the equivalent system masses to which they apply. The location factors given in Table 3-20 have units of "kilograms of total vehicle in low-Earth orbit divided by kilograms of life support hardware [payload] in low-Earth orbit." Thus, an equivalent system mass corrected for location is the product of the equivalent system mass contributions due to the physical attributes of the hardware and the location factor.

Example: A piece of equipment with an equivalent system mass of 2.0 kg as payload on a Mars Transfer Vehicle using nominal technology would have an equivalent system mass corrected for location of 11.54 kg if it remains on board during the entire mission from Earth, to Mars, and back again to Earth. Or, equivalently, this value may be expressed as an equivalent system mass is 2.0 kg for the payload hardware and other payload equivalencies and an additional 9.54 kg in equivalent system mass for propulsion and other vehicle infrastructure in low-Earth orbit to move the payload to Mars and back.

Alternatively, location factors in Table 3-20 may be expressed as ratios. Thus, the location factor for a full trip to and from Mars aboard a Mars Transfer Vehicle may be expressed as 5.77 kg of additional mass in low-Earth orbit for every 1 kg of payload that travels to Mars and back, or, in shorthand notation, 5.77:1. Using this approach yields the same result as the second form in the example above.

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[64] "Mars Transit Vehicle," "Mars Descent / Ascent Lander," and "Surface Habitat Lander" are specific names for vehicles from the Mars Dual Lander architecture. "Transfer Vehicle" and "Lander" are more generic names used here to differentiate between two types of vehicles that commonly appear in NASA advanced studies.

[65] Mars Dual Lander architecture.

3.3 CREW CHARACTERISTICS

As the life support system's primary purpose is to maintain the crew, the crew characteristics will drive equipment requirements. From an analysis perspective, the human metabolic rate and available time are necessary input values.

In section 3.3.1 the crew metabolic rate is described according to equations developed during a prior update of the NASA HIDH (2014) reference. The Constellation program also developed a Table 3-23 , giving metabolic rates for sleep and exercise as well as nominal activities, which are being used for Orion. In section 3.3.2, additional metabolic profiles for exercise have been added as potential design cases for longer exploration missions. Final determination will depend on decisions about exercise devices and protocols for various missions.

3.3.1 CREW METABOLIC RATE

Metabolic activity as a result of conversion of food to energy by the crew affects air revitalization and heat production directly but will also affect water use, waste production, and power consumption. The NASA HIDH (2014) lists empirical equations for calculating metabolic energy requirements as shown in Table 3-22. Here, crewtime is expressed in "crewmember-hours" (CM-h) or "crewmember-days" (CM-d) where the prefix "crewmember" (CM) identifies a single individual conducting a task for the appended duration. Actual metabolic rate varies with lean body mass, environment, and level of physical activity. However, because lean body mass data is difficult to collect, a combination of total body mass and gender are often substituted for this parameter. Embedded in this substitution is the generalization that males have a greater percentage of lean tissue than females for the same total body mass. Thus, NASA HIDH (2014) defines the crewmember mass range from a 95th percentile American male, with a total body mass of 99.16 kg, to a 5th percentile Japanese female, with a total mass of 53.69 kg (See Table 3-21). Metabolism increases due to physical exertion and a heavy workload can generate more than 800 W/CM of thermal loading. Few people can continue this level of exertion for long, though the total energy expenditure for an exceptionally active 82 kg male could be as high as 18 megajoule per crewmember-day (MJ/CM-d) (208.3 W/CM) of thermal loading on the crew cabin or extravehicular mobility unit (Muller and Tobin, 1980). Thus, EVA, as noted in Section 4.6, and exercise protocols can elevate metabolic rate. This data does not account for any metabolic effects due to low gravity. Data given in following sections are scaled for low and high levels of activity and for small and large people. The values derived using Equation 3-2 and Equation 3-3 account for a moderate level of crew activity.

Table 3-21 Crewmember Mass Limits

		Limits			
	Units	**Lower (5% female)**	**mean male**	**Upper (95% male)**	**Reference**
Crewmember Mass	kg	53.69	82.00	99.16	NASA HIDH (2014)

Table 3-22 Human Metabolic Rates

Gender	**Age [y]**	**Height [m]**	**Mass [kg]**	**Metabolic Rate [66] [MJ/CM-d]**	**Reference**
Male	40	1.75	82	12.996	NASA HIDH (2014)
Female	40	1.75	82	11.292	

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[66] The metabolic rate is the product of a basal rate and an activity factor. The basal rate, in parentheses, depends on crewmember mass [kg], m, and a second, mass-independent coefficient. The activity factor here is correlated as a function of gender while the other coefficients are correlated as functions of both gender and age.

Human Metabolic Rate Equation for males > 19 years of age (NASA HIDH (2014)):

$$\left(\frac{622 - 9.53 \times \text{age(years)} + 1.25\left(15.9 \times \text{mass(kg)} + 539.6 \times \text{height(m)}\right)}{0.239006 \times 10^3}\right) = \text{Energy}\left(\frac{\text{MJ}}{\text{CM-d}}\right)$$

Equation 3-2

Human Metabolic Rate Equation for females > 19 years of age (NASA HIDH (2014)):

$$\left(\frac{354 - 6.91 \times \text{age(years)} + 1.25\left(9.36 \times \text{mass(kg)} + 726 \times \text{height(m)}\right)}{0.239006 \times 10^3}\right) = \text{Energy}\left(\frac{\text{MJ}}{\text{CM-d}}\right)$$

Equation 3-3

3.3.2 EXPLORATION METABOLIC LOADS

The vehicle ECLSS needs to be able to handle the crew metabolic loads during the mission. In addition to nominal intravehicular activity (IVA), there also needs to be provision for crew exercise in order to keep the crew healthy and eliminate muscle degeneration. On ISS, each crewperson typically exercises for more than an hour a day on the exercise devices. Future exploration type missions will likely use different types of exercise devices and possibly for different durations. The oxygen use and carbon dioxide output are directly proportional to the crewmember's metabolic rate but the heat output and perspiration rate is dependent on the cabin conditions as well as the crew physiology. The metabolic rate will be split into sensible heat rejection, latent heat rejection, crew stored heat and a minor work done due to the exercise device. The crew will continue to release the stored heat from the exercise for an hour or more after the completion of the exercise. The size and fitness of the crewmember will also impact the vehicle ECLSS because the larger and more fit crewmembers generally have a higher metabolic rate.

3.3.2.1 *SHORT DURATION MISSION METABOLIC LOADS*

Table 3-23 provides a listing, in SI units, of the design metabolic outputs per crewmember for short duration missions on Orion. Values given in Table 3-23 represent predicted crew induced metabolic loads or thermal loads from a single crewmember. So, in addition to hardware induced thermal loads, a human vehicle must accommodate crew induced loads. For vehicle design, it is generally assumed that only one crewmember will exercise at a time and other crewmembers will remain at the nominal awake activity level. Total thermal loading from a single heat load component includes direct radiant thermal emission and heat convection from a crewmember. A crewmember metabolic load is the sum of the sensible (dry) heat load plus the total latent (wet) heat load. The total latent heat load includes moisture carried by exhaled gases, evaporated sweat from the skin or worn clothing, and sweat run-off. For purposes of vehicle design modeling, oxygen consumption and carbon dioxide production are assumed to be maximal during exercise, and they are assumed to return to nominal values as soon as the crewmember ceases exercising.

Using the 41-Node Metabolic Man algorithm and the judgment of a team of experts assembled to evaluate metabolic rates for deep space exploration, the metabolic outputs and requirements are listed in Table 3-23 and were computed assuming the following inputs: the cabin air temperature is 297.2 K, the cabin dew point is 283.2 K, the air velocity is 0.152 m/s, the overall cabin pressure is 101.3 kPa, the crewmember's gender is male with a mass of 82 kg and height of 1.75 m, the assumed maximal rate of oxygen uptake by the whole-body during exercise ($VO_{2\,max}$) is 45 mL/kg-min., the work efficiency for the exercise device is 15%. Additionally, in the most recent iterations of these analyses, the respiratory quotient (RQ), which is a factor of carbon dioxide produced to oxygen consumed, has been allowed to vary depending on crewmember activity. That is RQ = 0.86 for the nominal and sleeping crewmember; RQ = 0.95 for the crewmember undergoing aerobic exercise; and RQ = 0.96 for the crewmember undergoing resistive exercise. During short missions, each crewmember's exercise routine is assumed to be 30 minutes of aerobic exercise followed by 60 minutes to recover and return to the nominal awake metabolic level in a weightless environment. The crewmember's assumed clothing is a T-shirt and shorts. These assumptions were part of an effort between 2015 to 2020 to use Metman to define crew induced loads for exploration type missions (Ewert (2021) and Keener (2019)) and differ from the original NASA HIDH (2014) assumptions in the cabin pressure, air temperature, wall temperature, and efficiency of the exercise device as well as prescribing different exercise periods depending on mission length. Additional information can be found in the references.

In addition to varying with exercise or activity, RQ can vary with diet for nominal crewmember activity. As the body uses inhaled oxygen to convert its stored fat, carbohydrates, and protein reserves into energy, carbon dioxide is released. RQ values, defined as the ratio between exhaled carbon dioxide exhaled and inhaled oxygen, can vary from 1.0 to 0.7 depending on the reserve type. Carbohydrates yield RQ values of ~1.0, protiens yield RQ values of ~

0.8, and fats/alcohols give RQ values of ~ 0.7 (Prentice, 2013). In the general population, a mixture of said reserves produces RQ values of ~ 0.8 (Patel, 2021). However, given the dietary consumption of the average astronaut, nominal RQ values of 0.86 can be calculated for crewmembers (Duffield, 2008).

Table 3-23 includes oxygen consumption and carbon dioxide production values for each of the listed metabolic output values. From the exercise physiology computations, these values are given in terms of volumetric flowrates at standard conditions defined as a pressure of 101.3 kPa, a temperature of 273.2 K, and no moisture in the air. The oxygen consumption and carbon dioxide production values in Table 3-23 are converted from volumetric flowrates at standard temperature and pressure to mass flowrates using the ideal gas law. The comparison between the metabolic rate in Table 3-22 and the rate in Table 3-23 is not a perfect comparison. One is taken from an empirical equation, and one is based on an evaluation of a team of experts. Assuming the experts have the correct value, the empirical value differs by 8%.

Table 3-23 Crew Induced Metabolic Loads for HIDH Reference Crewmember – Short Mission [67]

Crew Member Activity Description	Duration of Activity (hr)	Metabolic Rate (kJ/hr)	Sensible (dry) Heat Output (kJ/hr)	Wet Heat Output (includes latent and sweat run-off) (kJ/hr)	Total Heat Output Rate (kJ/hr)	Water Vapor Output (g/min)	Sweat Runoff Rate (g/min)	O_2 Consumption (g/min)	CO_2 Output (g/min)
Sleep	8	316	160	157	316	1.08	0.00	0.37	0.44
Nominal	14.5	500	306	194	500	1.33	0.00	0.59	0.69
Exercise 0-15 min at 75% VO_2max	0.25	3,484	479	978	1,457	6.72	1.19	3.99	5.22
Exercise 15-30 min at 75% VO_2max	0.25	3,484	465	1,953	2,417	13.41	11.45	3.99	5.22
Recovery 0-15 min post 75% VO_2max	0.25	500	339	999	1,339	6.87	1.53	0.59	0.69
Recovery 15-30 min post 75% VO_2max	0.25	500	324	613	937	4.21	0.18	0.59	0.69
Recovery 30-45 min post 75% VO_2max	0.25	500	315	458	773	3.15	0.03	0.59	0.69
Recovery 45-60 min post 75% VO_2max	0.25	500	311	372	683	2.56	0.00	0.59	0.69
Total Per Day	24 hr	12,027 kJ	6,283 kJ	5,512 kJ	11,795 kJ	2.27 kg	0.22 kg	0.84 kg	1.01 kg

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[67] Ewert, *et al.* (2021)

3.3.2.2 *LONG DURATION MISSION METABOLIC LOADS*

In order to estimate metabolic loads for longer duration exploration missions (>30 days), alternate exercise protocols were evaluated at NASA/JSC as prescribed by exercise physiologists. These protocols were analyzed using the 41-Node Metabolic Man computer program after VO_2 and VCO_2 measurements were made on a variety of test subjects following these protocols (Ryder, 2022). These simulations were run with some updated assumptions similar to those in section 3.3.2.1 except for exercise type and duration (Ewert*, et al.*, 2021 and Keener, 2019). In addition, a variable respiratory quotient was implemented to differentiate nominal/sleep periods with exercise periods. The assumptions and boundary conditions are as follows:

Crewmember mass = 82 kg
Crewmember = height = 1.75 m
VO_2max = 45 mL/kg-min at STPD
Work efficiency of the exercise device = 15%
Air and wall temperature = 297.2 K
Air velocity = 0.152 m/s
Dew point = 283.2 K
Cabin pressure = 101.3 kPa
Respiratory quotient = 0.86 (Nominal/Sleep), 0.95 (Aerobic Exercise), 0.96 (Resistive Exercise)
Microgravity loading
Crewmember wearing shorts and T-shirt

The HIDH reference crewmember in these simulations is larger than the 50th percentile male but is representative of the astronaut population. In this section, the metabolic analyses for the 5th percentile (1.54 m, 50 kg), 95th percentile (1.84 m, 100 kg), and the HIDH reference crewmember (1.75 m, 82 kg) are included. The exclusion of the previous 50th percentile crewmember (1.70 m, 75 kg) is due to its close similarity to the HIDH reference crewmember and due to the expectation, that the HIDH reference is better representative of the current astronaut population. Furthermore, fitness level is a stronger driver for metabolic output during exercise than size. The VO_2 data taken during the sessions allowed for computation of the metabolic rate. The VO_2 and VCO_2 data, reported in Standard Temperature and Pressure Dry (STPD), was used to determine the metabolic rate via Equation 3-4 (Weir (1949)). The metabolic rate was calculated for the 30-minute exercise test scenario.

$$MR = 0.166 \times (3.941 \times VO_2 + 1.106 \times VCO_2) \qquad \text{Equation 3-4}$$

Where:
MR = Metabolic rate (MJ/CM-d)
VO_2 = Oxygen consumed (L/min)
VCO_2 = Carbon Dioxide produced (L/min)

A summary of the different activity periods is given in Table 3-24. Some additional cases that investigate interval exercise profiles are documented in Pantermuehl and Miranda (2015) and Ryder, *et al.* (2022). These protocols are being considered by NASA for Orion and may reduce the moisture load on the ECLSS. The protocol to be used for long-term spaceflight are still being evaluated and may include this concept. The resistance exercise protocol is generally used in addition to aerobic exercise and is not intended as an alternate exercise protocol. For a full day (24 hours) of activity, the crewmember activity would include aerobic exercise plus the resistance exercise activity and cool-down, 8 hours of sleep, and the balance would consist of the nominal activity.

Table 3-24 Comparison of Metabolic Rates for Reference Crewmember

Description	Total time (hr)	Metabolic Rate (kJ/hr)	O_2 Consumption g/min	CO_2 Output g/min
Aerobic Exercise	0.5	3,484	3.99	5.22
Resistive Exercise	1	1,250	1.43	1.89
Recovery	1	500	0.59	0.69
Nominal	13.5	500	0.59	0.69
Sleep	8	316	0.37	0.44

Table 3- presents the results of the exercise scenario for the HIDH reference crewmember. The HIDH reference was assumed to be a medium fit individual with a VO_2max of 45 mL/kg/min as in the NASA HIDH (2014).

The convective and radiative surface areas were determined from the nomographic relationships in the 41-Node man program based on the height and mass of the different percentile crewmembers. The convective and radiative areas differ due to blockage of parts of the body to the radiative heat transfer exchange.

These values are for a single crewmember with the constant cabin conditions as stated previously. While it is expected that only one crewmember will exercise at a time, the cool-down period will still add latent and sensible heat to the cabin atmosphere. This needs to be accounted for in the design of the ECLSS.

To develop a daily profile from the exercise tables, the sensible and latent heat addition can be added to the vehicle ECLSS load for each crewmember. The rest of the daily total will be a combination of sleep and nominal awake loads to sum up to a 24-hour day for each crewmember. It is assumed that the vehicle ECLSS will control the atmosphere so there will not be any adverse effects for multiple crew. Ideally only one person would be exercising at a time, but it could overlap with another crewmember's cool-down period.

Table 3-25 Crew Induced Metabolic Loads for HIDH Reference Crewmember – Long Mission

Crew Member Activity Description	Duration (hr)	Metabolic Rate (kJ/hr)	Sensible Heat (kJ/hr)	Total Latent Heat (kJ/hr)	Water Vapor Output (g/min)	Sweat Output (g/min)	O_2 Consumption (g/min)	CO_2 Output (g/min)
Sleep	8	316	160	157	1.08	0.00	0.37	0.44
Nominal	13.5	500	306	194	1.33	0.00	0.59	0.69
Exercise: Aerobic 0-15 min	0.25	3,484	482	1,018	6.99	1.34	3.99	5.22
Exercise: Aerobic 15-30 min	0.25	3,484	467	1,962	13.48	11.82	3.99	5.22
Exercise: Resistive 0-15 min	0.25	1,250	417	1,689	11.60	11.86	1.43	1.89
Exercise: Resistive 15-30 min	0.25	1,250	347	1,231	8.44	2.18	1.43	1.89
Exercise: Resistive 30-45 min	0.25	1,250	338	972	6.66	0.78	1.43	1.89
Exercise: Resistive 45-60 min	0.25	1,250	340	864	5.93	0.45	1.43	1.89
Recovery 0-15 min	0.25	500	298	301	2.07	0.00	0.59	0.69
Recovery 15-30 min	0.25	500	301	260	1.79	0.00	0.59	0.69
Recovery 30-45 min	0.25	500	295	320	2.20	0.00	0.59	0.69
Recovery 45-60 min	0.25	500	300	271	1.86	0.00	0.59	0.69
Total Per Day	24 hr	12,778 kJ	6,308 kJ	6,118 kJ	2.52 kg	0.43 kg	0.90 kg	1.08 kg

In addition to the HIDH reference individual, crew size cases for both the 5th and 95th percentile crewmember were analyzed with the 41-Node man program to steady state conditions to yield results for the sleep and nominal metabolic rates. These steady state values could be used to determine the metabolic loads for variable times for individual crewmembers or to determine the time variant loads for multiple crewmembers. The steady state loads are presented in Table 3- and the daily totals are in Table 3-. The daily total assumes an 8-hour sleep period, the exercise as presented in the previous tables and the remainder of the day using nominal metabolic rates. It must be noted that for conservatism, the 95th percentile case also used high fitness level ($VO_2max = 55$ mL/kg-min) rather than medium fitness level as in the reference and 5th percentile cases.

Table 3-26 Steady State Metabolic Output for all Crewmembers

Case	Metabolic Rate (kJ/hr)	Sensible Heat (kJ/hr)	Total Latent Heat (kJ/hr)	Water Vapor Output (g/min)	Sweat Output (g/min)	O_2 Consumption (g/min)	CO_2 Output (g/min)
Reference CM - Sleep	316	160	157	1.08	0.00	0.37	0.44
Reference CM - Awake	500	306	194	1.33	0.00	0.59	0.69
5th Percentile - Sleep	218	126	92	0.63	0.00	0.26	0.30
5th Percentile - Awake	345	238	107	0.74	0.00	0.41	0.48
95th Percentile - Sleep	367	233	134	0.92	0.00	0.43	0.51
95th Percentile - Awake	580	332	248	1.70	0.00	0.68	0.81

Table 3-27 Daily Total Metabolic Output for all Crewmembers

Case	Metabolic Rate (kJ)	Sensible Heat (kJ)	Total Latent Heat (kJ)	Water Vapor Output (kg)	Sweat Output (kg)	O_2 Consumption (kg)	CO_2 Output (kg)
Reference CM	12,778	6,308	6,118	2.52	0.43	0.90	1.08
5th Percentile	8,676	4,931	3,516	1.45	0.09	0.61	0.74
95th Percentile	15,402	7,420	7,463	3.07	1.44	1.08	1.31

The data from all the previous tables in this section were determined by the 41-Node Man metabolic analysis program. The nominal awake and sleep values were determined by running the program until steady-state values were attained and applying the final values to the table. The exercise and recovery values were calculated as the average value of each parameter for the activity duration. The total heat stored is not shown in the tables, but this value can be calculated as the difference between the metabolic rate and the total heat rejected. During exercise this value would be increasing and during recovery it would be decreasing.

The 95th percentile case, which also assumes high fitness ($VO_2max = 55$ mL/kg-min), would be the most extreme design load for the vehicle ECLSS, but it is unlikely that the entire crew would consist of 95th percentile crewmembers. In considering the vehicle architecture, the impact of the minimum load case should also be considered. Since the values listed in this section all come from analysis, there is some uncertainty in the numbers. This uncertainty stems from both the assumptions in the model as well as individual variability between crewmembers.

3.3.2.3 RESPIRATORY RATES DURING "EXCITED" PERIODS

The previous sections have discussed the metabolic loads of crew members on both short and long duration missions under nominal conditions. This section serves to describe periods of "excitation" which may correspond to launch and entry scenarios, and in particular, it notes on the increased respiratory rates accompanying such "excited" periods. These scenarios may also apply to periods of high physical exertion with higher than nominal respiratory rates. Please note that this section does not serve to be completely guiding of "excited" crew periods as each individual's reaction may vary substantially. This section provides ranges of respiratory rates which may be expected during such periods as well as some current standards applied in other flight vehicles.

Periods of physical exercise and "excitation" result in higher than nominal respiratory rates that vary between individuals. These respiratory rates can vary from approximately 30 to 60 breaths per minute whileventilation rates can range from approximately 50 to 100 liters per minute. These rates typically occur for short periods of time, i.e. a few minutes, when the crew are wearing masks. This scenario describes both launch and entry. These breathing and ventilation rates are dependent on the type of mask worn by the crew and its associated blow-by O_2 flow rate. The current standards are masks capable of peak, which describes a highly excited person, inspiratory and expiratory flow rates of 253 L/min for a single crew member per regulator or 284 L/min for two crew member per regulator (Personal Communication with H. Rotter in 2018). A similar value for a single person is described in MIL-STD-3050 (US Department of Defernse, 2015) with peak inspiratory and expiratory flow rate of 258 L/min ATPD (Ambient Temperature Pressure Dry). This value from MIL-STD-3050 is prescribed for fighter aircraft with O_2 concentrations supplied to the mask of a minimum of 99.5% O_2 at elevations greater than 25,000 ft.

3.3.3 METABOLIC ANALYSIS PROGRAMS

3.3.3.1 *41-NODE MAN AND WISSLER*

The 41-Node Man Program (METMAN) is a Fortran-based thermal model that simulates the human body with 10 body compartments or "segments" representing the torso, arms, legs, hands, feet, and head of a person (see Figure 3-2). The model simulates heat transfer and heat generation within the body. Heat generation comes from the basal metabolism, work, and shivering. Heat transfer between segments occurs from conduction and blood flow (advection). Heat is transferred between the skin and the suit or environment by conduction, sweating, convection, and radiation. Heat loss from the body also occurs due to respiration.

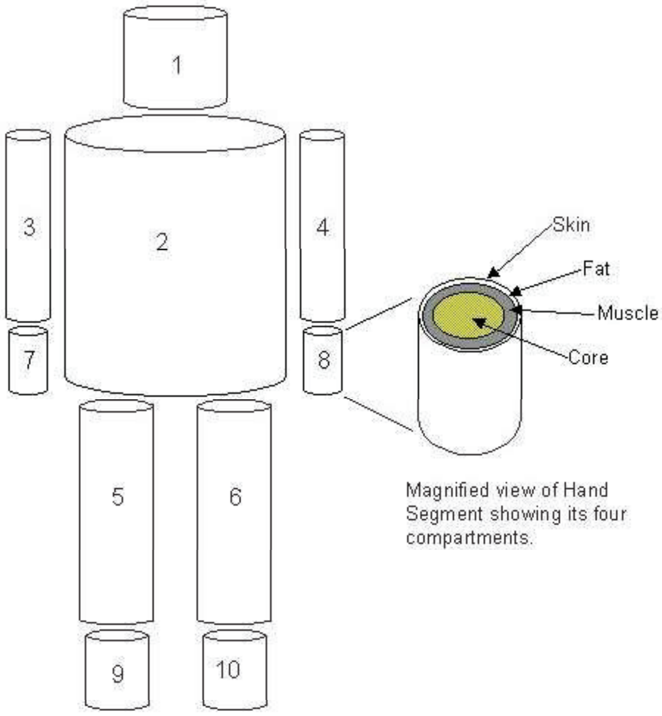

Figure 3-2 METMAN Segments and Layers

METMAN results are coarse since it uses just 41 nodes to model the entire body. Each segment is made up of four concentric cylinders (i.e. nodes) that loosely represent skin, fat, muscle, and "core". The cylindrical nodes are assumed to be axisymmetric. The 41st node represents the central blood pool, which is in contact with the nodes in all body segments (Bue, 1989).

A more detailed human thermal model was developed and refined over many years by Dr. Eugene H. Wissler at the University of Texas at Austin. His Fortran-based program uses a thermal difference network to simulate a human performing transient work profiles in user specified clothing and thermal environments (Wissler, 1985).

The Wissler model body segments (also referred to as elements) are composed of 15 unequally spaced nodes arranged as cylindrical shells to model the viscera, bone, muscle, fat and skin of the human body (Figure 3-3). Arterial and venous blood in each segment is represented by discrete nodes that are interconnected among the segments. Up to 6 more nodes per segment are used to represent clothing and protective garments. Sweat collection and evaporation in the clothing layers is modeled, as is active fluid cooling of the skin or clothing.

Like METMAN, the segment's cylindrical nodes are assumed to be axisymmetric. Note that Wissler uses forearm and calf segments, not hand and foot segments like METMAN. Thus, clothing including the liquid cooling garment (LCG) cover parts of the forearms and the calves.

Physiological processes such as ventilation, metabolism, muscular work, perspiration, shivering, vasoconstriction, and oxygen and carbon dioxide concentrations in tissues are modeled. Thermoregulation of the body is accomplished via feedback from the physiological processes and heat transfer with the local thermal environment. The Wissler model has successfully predicted the body's response to work in a variety of thermal environments from immersion in cold water to exercise in hot humid climates to flight at high altitude (Wissler, 1986).

The experience at NASA/JSC has shown that the Wissler model can have issues converging to a solution at high metabolic rate or within high humidity environments. Conversations with Dr. Wissler indicated that the higher fidelity 3-D model (Wissler (2009)) may yield better results. The 3-D model does not have a suit or cooling garment so those aspects would need to be added to the model.

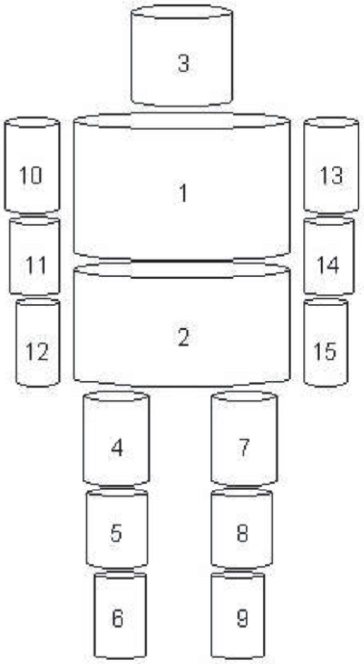

Figure 3-3 Wissler Segments

Use of the higher fidelity Wissler Human Thermal Model was first proposed to allow advanced spacesuit analysis outside of the crew comfort envelope. METMAN results may be less accurate outside of this envelope. The Wissler model has been updated to support suited applications, but METMAN may currently be the better option for suited scenarios due to a significant history of being correlated to suited test results. Work continues to improve these models.

3.3.3.2 *EXAMPLE METMAN USES AND APPLICATIONS*

METMAN has been utilized to assess human thermal performance in various NASA applications including Shuttle cabin, ISS Sleep Station, Shuttle extravehicular mobility unit (EMU), Shuttle Advanced Crew Escape Suit (ACES), Orion space suit, Orion Air Revitalization System, and Exploration extravehicular mobility unit (xEMU). Some of these applications have been modeled using the stand-alone METMAN program while other applications have been simulated by integrating the METMAN program into various thermal and life support models over the years to assess human thermal conditions in various environments and conditions. Brief descriptions of a few of the stand-alone and integrated applications follow.

- Metabolic profile information including crewmember heat, water vapor, sweat runoff, and carbon dioxide generation as well as oxygen consumption is being developed for exploration missions (Ewert, *et al.*, 2021). Stand-alone METMAN is being correlated to exercise testing results and is being used to recommend profiles for exercise, nominal, and sleep portions of exploration missions. These metabolic profiles provide guidance to exploration thermal and life support system designers on the thermal and humidity loads expected during the various exploration mission phases.
- The thermal performance of the overall xEMU is being predicted with a Thermal Desktop model (Barnes, 2019) that incorporates METMAN into the integrated system that among other things includes evaporative cooling within the suit, cooling provided by the liquid cooling and ventilation garment (LCVG) and heat transfer through the suit and PLSS walls to or from the surrounding environment.
- METMAN has been integrated into the Orion Air Revitalization System Thermal Desktop model (Stambaugh, 2015) and continues to be upgraded and utilized to assess astronaut thermal comfort during various Orion mission phases.
- The Orion Crew Survival Systems (OCSS) space suit has been modeled using stand-alone METMAN and the METMAN OCSS model continues to be upgraded based on testing at JSC (Miranda, 2018). This model is being utilized to verify human heat storage requirements during all phases of the planned Orion missions.
- Human comfort within the Shuttle Advanced Crew Escape Suit (ACES) has been evaluated using the stand-alone METMAN and Wissler (Pisacane, 2007) programs to assess failure scenarios of the Shuttle thermal control system while accounting for the cooling provided with the liquid cooling garment (LCG).
- The ISS Temporary Sleep Station (TESS) was modeled utilizing METMAN (Keener, 2002) which was incorporated into G-189A (Generalized ECLS Program developed for NASA/JSC) to evaluate human thermal comfort and carbon dioxide levels within the TESS. CFD modeling of the TESS was also performed as a part of this effort using FLUENT. The G-189A and FLUENT models complemented each other and increased confidence in the results was achieved by comparing the output information from these models.
- The Advanced Suit Design Analyzer (ASDA) program was built in the 1990’s to evaluate early Mars and other advanced spacesuit concepts by modeling a detailed spacesuit built around METMAN (Bue, 1992), composed of three layers of 10 nodes, a backpack, and the Mars environment. One layer of the suit model allows for evaluation of phase change material concepts. All suit layers may be permeable in varying degrees to water and carbon dioxide depending upon user input.
- The SINDA Shuttle extravehicular mobility unit (EMU) thermal model (Lin, 1978) was correlated to human-in-the-loop EMU certification testing in JSC Chamber B performed in 1981 using a simplified human thermal model. METMAN was successfully added to the Shuttle EMU SINDA model in the mid 1980’s and provided numerous evaluations of thermal conditions associated with Shuttle EVAs.

3.3.3.3 *EXAMPLE WISSLER USES AND APPLICATIONS*

The Wissler model is being utilized in numerous NASA applications and to-date most of these applications are simulating suited operations. Nyberg (1998) describes the effort to upgrade Wissler to include the capability of simulating a liquid cooling garment (LCG) worn by suited crewmembers. The Wissler modeling approach has been utilized in several cases to evaluate LCG performance and potential improvements to LCG's including those documented in Miranda (2018), Rhodes (2013), Trevino (2006), Kesterson (2006), and Nyberg (1997). Example Wissler modeling efforts related to system level EVA spacesuit applications are documented in Cognata (2014) and also in Durrant and Dobarco-Otero (2001). The Wissler model is also being used to evaluate launch and entry suits and examples of these applications are discussed in Mayer (2011), and Rains (2008). Carrasquillo (2010) discusses the effort to evaluate Orion crew thermal comfort characteristics during post landing operations that include both suited and unsuited simulations with the Wissler model.

3.3.4 CREWTIME ESTIMATES

Crewtime is an important commodity on any human mission. In fact, wise usage of the crew's time is at the core of all exploration in which human beings take part. Historically, crewtime for life support functions has been limited to monitoring equipment and replacing expendables or making repairs. Support for the biomass production within a food subsystem, however, could easily consume a substantial fraction of the crew's time.

The information here is meant to outline the time available to a crewmember during a standard workweek. Langston (2005) outlines a generic schedule for crewtime on ISS. This is assumed with slight modifications here as shown below in Table 3-28.

Table 3-28 Time Allocation for a Nominal Crew Schedule in Weightless Environment - Current ISS [68]

Activity	Weekday [CM-h/CM-d]	Weekend Day [CM-h/CM-d]	
Daily Planning Conferences	0.5	0.0	Variably-Scheduled Time
Daily Plan Review / Report Preparation	1.0	0.0	
Work Preparation	0.5	0.0	
Scheduled Assembly, Systems, and Utilization Operations [69]	6.5	0.3	
Meals – prepackaged ready to eat system[70]	3.0	3.0	
Housekeeping, and Laundry	0.0	2.0	
Post Sleep	0.5	0.5	Invariantly-Scheduled Time
Exercise, Hygiene, Setup / Stow	2.5	2.5	
Recreation	0.0	6.0	
Pre-Sleep	1.0	1.0	
Sleep	8.5	8.5	
Total	**24.0**	**24.0**	

Several of the categories in Table 3-28 deserve some additional explanation. The category "scheduled assembly, systems, and utilization operations" includes, among other things, system and vehicle maintenance. Thus, life support system maintenance deducts crewtime from other mission objectives. The category "meals"

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[68] From Langston (2005) for International Space Station crews. Note: Time estimates are given for a nominal week inside of ISS excluding variations for critical mission functions such as docking/undocking operations and/or extravehicular activities.

[69] This category includes payload operations. Langston (2005) allots up to 80 minutes per day to support experiments that may require daily tending, although such usage of crewtime is discouraged. Here, in round terms, this is represented as 0.3 hours per day per crewmember assuming the total time for daily payload operations will not increase and rounding to the nearest 0.1 hour.

[70] Langston (2005) allots a uniform 1.0 hour per meal for preparation, consumption, and cleanup.

includes pre-meal preparation and post-meal cleanup in addition to actual meal consumption. It is assumed here that the time for meals would not diminish on a vacation day. "Housekeeping, including laundry" is assumed here to include laundry operations, if applicable, in addition to general vehicle cleaning operations. For ISS this is scheduled as four hours per crewmember per week during the weekend, i.e., two hours per crewmember per weekend-day. "Exercise, hygiene, setup / stow" is assumed to include pre- and post-exercise operations, such as post-exercise hygiene operations. In short, exercise includes some overhead in addition to the actual time spent exercising. "Sleep" denotes time for rest.

The ISS schedule devotes up to 80 minutes total of "daily payload operations" per non-weekday to support experiments that demand tending daily (Langston, 2005). This is included above in "scheduled assembly, systems, and utilization operations" during both weekdays and weekend days. [71] Assuming the overall magnitude of these daily payload operations will not increase, these operations for a crew of four (rounding to the nearest 0.1h) would equate to 0.3 CM-h/CM-d.

Here, the last five categories in Table 3-28, post sleep, exercise, hygiene, setup stow, recreation, pre-sleep, and sleep, are not available for life support operations under nominal scheduling scenarios. For purposes here, they are classified as Invariantly-Scheduled Time (IST).

Time other than IST, theoretically, might be available for either maintaining the life support system or for other activities if the life support system uses less time. This time block is designated here as Variably-Scheduled Time (VST). VST includes not only time for mission objectives, but also time scheduled for life support operations, such as equipment maintenance, meal preparation, consumption, and cleanup, and laundry operations. Realistically, using the entire block of VST for life support functions is unacceptable, though the total VST places an upper limit on available time. Further, any time not used for life support operations may be employed to accomplish mission objectives while not impacting the IST.

As outlined in Langston (2005), ISS will operate on a standard week of seven 24-hour days. The standard workweek, for planning purposes, is five weekdays followed by a two-day weekend. Vacation is allotted as eight days per crewmember per year regardless of nationality.

Assuming a workweek schedule as outlined in Table 3-28 and an ISS vacation schedule, a crewmember will have, on average, 67.2 CM-h/wk of VST and 100.8 CM-h/wk of IST in a weightless environment. [72] Assuming the exercise time is 0.5 CM-h/d shorter due to working against gravity, a crewmember will have 69.7 CM-h/wk of VST and 98.3 CM-h/wk of IST on a planetary surface. Minimally, a crewmember might be expected to work at least 50 CM-h/wk, recalling that this VST includes maintaining the life support equipment and meal operations (Table 3-29). The maximum available VST might be 10% greater than the average values but, based on Skylab experience, this rate can only be maintained for periods of 28 days or less.

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[71] During the weekday the daily payload operations are included within the allotment of 6.5 h/CM-d. They only appear as a "separate item" on weekend days.

[72] The term "microgravity" is often used to designate the condition experienced in Earth orbit. However, until one is relatively far away from the Earth, gravity is still present, and an older term, "weightlessness," is more accurate. In low-Earth orbit, the force of gravity is still about 95% of what it is on the surface of the Earth, but objects falling freely – whether in orbit or falling towards the atmosphere or in any other trajectory not involving non-gravitational external forces, such as propulsion or atmospheric drag – do not feel any force. "Weight" is the term used for the force felt when a human's feet press against the Earth, and thus holds the individual back against the force of gravity. In free fall, there is no such force, hence the term "weightless" is more accurate. To get true microgravity – a millionth of that on the surface of the Earth – the Sun's gravity must be considered also. At the distance of the Moon, this is about twice that of the Earth. To encounter true microgravity, one would have to travel out to near the edge of the Solar System, about as far as the orbit of Uranus. In many situations, the difference between microgravity and weightlessness does not matter. However, it may affect the behavior of fluids, rotational movement, and large structures, and the use of tethers.

Table 3-29 Crewtime per Crewmember per Week

Mission Phase	Assumptions [CM-h/wk]		
	Lower	Nominal	Upper [73]
Transit/Weightlessness	50 (1)	67.2 (2)	73.9 (1)
Surface/Hypogravity	50 (1)	69.7 (1)	76.7 (1)

References

(1) Estimated (see above)
(2) Based on Langston (2005)

To assess the cost associated with adding an operation that requires crew intervention, a crewtime mass penalty is computed by dividing the total per capita life support system mass by the VST crewtime. This penalty may be applied to determine the ESM associated with crew operations. Typical values might vary between 0.1 kg/CM-h and 10 kg/CM-h.

Two philosophies are commonly employed by researchers to determine a crewtime-mass-penalty (CTMP). The first assumes that each hour of crewtime required by the life support systems is equally valuable. The second, as forwarded by Levri, *et al.* (2000), assumes that each additional hour of time required by the life support system is more valuable than the previous hour. The first approach is consistent with the philosophy adopted to compute the other mass-equivalencies (See Section 3.2), while the second tends to more severely penalize a life support system architecture that makes large demands on crewtime. The first approach is recommended for general use.

The first approach used to determine CTMP assumes each hour of crewtime is equally valuable. Once a value for crewtime is established, changes in crewtime have a linear effect on the overall equivalent mass of a life support system. Table 3-30 provides CTMP values for several mission scenarios computed using Equation 3-6. Inputs for these values come from or are based on the Advanced Life Support Research and Technology Development Metric for Fiscal Year 2006 (Metric, 2006). The lower and nominal values in Table 3-30 are derived from life support systems using advanced technologies, while the upper values reflect current technologies from historical programs such as the Space Transportation System, or Shuttle, or the International Space Station. [74]

Table 3-30 Crewtime-Mass Penalty Values Based Upon the Fiscal Year 2006 Advanced Life Support Research and Technology Development Metric

	Assumptions [kg/CM-h]		
Mission Destination	**Lower**	**Nominal**	**Upper**
Low Earth Orbit			
	0.333	0.333	0.724
Moon			
Crew Exploration Vehicle	3.640 (2)	5.050 (1)	--
Lunar Surface Access Module	13.98 (2)	15.66 (1)	--
Lunar Outpost [75]	1.480 (2)	2.100 (1)	--
Mars			
Mars Transit Vehicle	0.526 (2)	0.802 (1)	--
Mars Descent / Ascent Lander	1.810 (2)	2.850 (1)	--
Surface Habitat Lander	0.506 (2)	0.940 (1)	--

Reference

(1) Baseline Technologies from Metric (2006)
(2) Exploration Technologies from Metric (2006)

The second approach to determine CTMP values assumes that each hour of crewtime required by the life support system is more valuable than the previous hour. Thus, the CTMP is computed by dividing the life support

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[73] The listed upper limit for crewtime per week is 10% above the average values discussed in the text. Firm upper limits are not currently known, but they are likely to be no greater than these values, especially for operations lasting more than a week or two.

[74] Please note that the Advanced Life Support Research and Technology Development Metric for Fiscal Year 2006 may not be identical to the infrastructure values presented above in Section 3.2; the infrastructure values should, however, be comparable, so the values here may be used as approximate values.

[75] Metric (2006) calls the "Lunar Outpost" the "Destination Surface System."

system mass, excluding crewtime, by the total available crewtime that is not devoted to personal activities or to maintaining the life support system. Equivalently, this latter denominator is VST minus time devoted to the life support system. This value is effectively fixed once the total crewtime, crewtime devoted to the life support system, and the life support system mass are determined. However, this value is a function of the crewtime required to service and maintains the life support system, so it will vary if its component values change.

Assuming each hour of crewtime is more valuable than the previous hours of crewtime, Levri, *et al.* (2000) present a formulation for the second crewtime-value formulation. They define the following terms:

Symbol	Units	Physical Meaning
$ESM_{w/o\ ch}$	[kg]	Equivalent system mass (ESM) for the life support system without accounting for crewtime spent for life support. Or, the "non-crewtime" portion of ESM.
ESM_{LSS}	[kg]	Component of life support ESM to support crewtime involved in life support. Or, the "crewtime" portion of ESM.
ESM_{Total}	[kg]	Total life support system ESM; $ESM_{w/o\ ch} + ESM_{LSS}$.
t_{LSS}	[CM-h/wk]	Crewtime spent on the life support system. This is identical to the portion of VST spent of life support.
t_{MP}	[CM-h/wk]	The total crewtime per week available for life support system maintenance or mission-related objectives. This is equivalent to VST.
$t_{MP\text{-}LSS}$	[CM-h/wk]	Crewtime per week not devoted to the life support system or to personal activities; t_{MP} - t_{LSS}. This is crewtime available for mission-related objectives such as science or exploration.

Levri, *et al.* (2000) then assume that the overall ESM of the life support system, including the crewtime, is proportional to the total mission production time as the ESM of the life support system without crewtime is proportional to mission production time less the time for life support, or:

$$\frac{ESM_{Total}}{t_{MP}} = \frac{ESM_{w/o\ ch}}{t_{MP-LSS}}$$ Equation 3-4

Alternatively, the overall ESM of the life support system is:

$$ESM_{Total} = ESM_{w/o\ ch}\left(\frac{t_{MP}}{t_{MP-LSS}}\right)$$ Equation 3-5

Using this approach, as crewtime for life support increases, the crewtime per week not devoted to life support or to personal activities, $t_{MP\text{-}LSS}$, decreases, and the overall ESM for the life support system increases in a non-linear manner. In fact, as $t_{MP\text{-}LSS}$ approaches zero, the overall ESM for the life support system approaches infinity.

Thus, here CTMP is derived by dividing the life support equivalent system mass excluding crewtime by the total available crewtime not devoted to personal activities or life support maintenance.

$$CTMP = \frac{ESM_{w/o\ ch}}{t_{MP}}$$ Equation 3-6

3.3.5 NOMINAL HUMAN INTERFACES

Nominal balances of major life support commodities are summarized in Table 3-31, for a standard 82 kg crewmember with a respiratory quotient of 0.86 [76] during intravehicular activities. The balance includes a rigorous daily exercise regimen which includes 30 minutes of aerobic and 60 minutes of resistance training. Masses consumed by the crewmember are denoted by "+ *m*," while masses rejected by the crewmember are denoted by "- *m*." Likewise, energy entering the crewmember is denoted by "+ *E,*" while energy rejected by the crewmember is denoted by "- *E*." Actual values depend on many factors, including physical workload, diet, and individual metabolism. This balance uses inputs and outputs from 2019 runs of an updated MetMan model (Ewert, *et al.*, 2021) which are correlated to 2018 "sweat test" results (Crowell, J.B. 2018). The assumptions, sources, and rationale for Table 3-31 are discussed below in the order of their appearance in the table. Figure 3-4 shows a graphical representation of the mass inputs and outputs given in Table 3-31.

Table 3-31 Summary of Nominal Human Metabolic Interface Values

Balance	Interface	Units	Nominal Value
	Basis		
	Overall Body Mass	kg/CM	82 (1)-(3)
	Respiratory Quotient		0.860 (3),(4)
	Air		
– *m*	Carbon Dioxide Load	kg/CM-d	1.085 (1),(3)
+ *m*	Oxygen Consumed	kg/CM-d	0.895 (1),(3)
	Food & Drink		
+ *m*	Food Solids; Mass (without packaging)	kg/CM-d	0.800 (1)
+ *E*	Food Consumed; Energy Content	MJ/CM-d	12.778 (1),(3)
+ *m*	Potable Water Content	kg/CM-d	3.217 (1),(2)
+ *m*	Water in Food Prior to Rehydration	kg/CM-d	0.760 (1),(2)
	Metabolic Water	kg/CM-d	0.490
	Thermal		
– *E*	Total Metabolic Heat Load	MJ/CM-d	12.426 (1),(3)
	Sensible Metabolic Heat Load	MJ/CM-d	6.308 (1),(3)
	Latent Metabolic Heat Load	MJ/CM-d	6.118 (1),(3)
	Solid Waste		
– *m*	Fecal Solid Waste (dry basis)	kg/CM-d	0.032 (5)
– *m*	Perspiration & misc. Solid Waste (dry basis)	kg/CM-d	0.027 (1)
– *m*	Urine Solid Waste (dry basis)	kg/CM-d	0.061 (5)
	Wastewater		
– *m*	Fecal Water	kg/CM-d	0.101 (5)
– *m*	Respiration and Perspiration Water	kg/CM-d	2.946 (3)
– *m*	Urine Water	kg/CM-d	1.420 (5)

References

1. Ewert (2019)
2. NASA HIDH (2014)
3. Ewert (2021)
4. Crowell (2018)
5. Rose (2015)

Overall Body Mass: An 82 kg/CM reference astronaut who is eating and exercising well (30 minutes of aerobic and 60 minutes of resistive exercise per day) in order to maintain constant body mass and health during an extended

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[76] The respiratory quotient (RQ) is defined as the ratio of exhaled carbon dioxide to inhaled oxygen. Section 3.3.2.1 provides more detail on RQ and its variations with diet and physical activity.

(greater than 30 day) mission. This 82 kg/CM mass represents that of a mean male astronaut in the year 2015 (Ewert MK 2019a).

Respiratory Quotient: Respiratory quotient is defined as moles of carbon dioxide produced by moles of oxygen consumed. Respiratory quotient values used in the 2019 runs of the 41-Node Man (Ewert*, et al.*, 2021) simulations are: 0.86 for nominal activity and sleeping, 0.95 for aerobic exercise, and 0.96 for resistive exercise.

Carbon Dioxide Load: The "sweat test" (Crowell, 2018) correlated MetMan model was used to generate this value. This 1.085 kg/CM-day was also used in the 2019 ICES paper sourced above.

Oxygen Consumed: The "sweat test" (Crowell, 2018) correlated MetMan model was used to generate this value. [77]

Food Consumed; Mass (without packaging): Ewert*, et al.* (2019) and Table 4-47 give an average food supply planning value of 2.39 kg of food (including packaging) per person per day on the International Space Station. From this value, 0.43 kg was subtracted for packaging mass, and 0.20 kg (10%) subtracted to account for food packages that are not opened and consumed. An additional 0.2 kg of prepared food (60% hydrated) is wasted due to food left behind in packages. A total of 1.56 kg of food at 48.7% hydration is consumed (not including the 0.5 kg of water needed for hydration). All assumptions and calculations were taken from the Ewert*, et al.* (2019). (2019). The 0.8 kg consumed dry mass of food is calculated by:

$$1.56 \text{ kg} \times (1-0.487) = 0.8 \text{ kg/CM-d (dry)}$$

Food Consumed; Energy Content: The metabolic rate used in the 2019 MetMan runs was 12.778 MJ/CM-d (Ewert*, et al.*, 2021); to maintain constant body mass the food energy consumed was set to the same value.

Potable Water Content: This water mass consists of 0.5 kg used for food preparation, 2.00 kg for drinking water, and an additional 0.717 kg added due to increased perspiration as a result of the increased exercise profile (the 0.717 kg also acts as the "lever" used to ensure the mass balances). The 2.00 and 0.5 kg were sourced from NASA HIDH (2014).

Water in Food Prior to Rehydration: This value includes the losses described in the "*Food Consumed"* section above. The 0.76 kg of water can be found by:

$$1.56\text{kg} \times (0.487) = 0.76 \text{ kg/CM-d of Water}$$

Metabolic Water: Metabolic water is generated as the body metabolizes food. This value is calculated as the difference between the water load sum of fecal water, respiration & perspiration water, and urine water, with the total water consumed. This value is "internal" to the overall mass balance that is presented here as a convenience.

Total, Sensible, and Latent Metabolic Heat Load: All three of these values were taken from the updated 2019 MetMan outputs (Ewert, 2021). It is important to note that these values differ slightly with Ewert*, et al.* (2019) as the mended error in the MetMan model produced different results. The values in Table 3-31 reflect the outputs of the mended model. [78] Not included with Table 3-31 is the heat load into the exercise device (-0.377 MJ/CM-d) and the heat load storage within the astronaut (+0.025 MJ/CM-d).

Fecal Solid Waste (dry basis): Fecal dry mass is highly variable with individual and diet. Solid waste content can range from 4 to 102 g/CM-day (Rose, 2015); the fecal solid waste of an individual on a predominantly vegetarian diet will trend to the higher end of this range due to the increased dietary fiber. The 32 g/CM-day represents the mean value of solid waste.

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[77] The 0.90 kg/day value in Table 3-31 differs from the value in the 2019 ICES paper as a small error was discovered and mended in the MetMan model, 0.90 kg/CM-day is from the mended model.

[78] Induced error due to averaging effects of the five-minute data intervals is the likely source for the total metabolic heat load being less than (-0.0012 MJ/CM-day) the total metabolic rate.

Perspiration & misc. Solid Waste (dry basis): Perspiration solid waste is taken as 0.02 kg/CM-d (Ewert*, et al.,* 2021) and miscellaneous solid waste is taken as (NASA HIDH, 2014): desquamated epithelium 3.0 g/CM-d; hair-depilation loss 0.03 g/CM-d; hair-facial-shaving loss 0.3 g/CM-d; nails 0.01 g/CM-d; sebaceous excretion-residue 4 g/CM-d; and solids in saliva 0.01 g/CM-d.

Urine Solid Waste (dry basis): The urine dry mass is taken as the mean of 61 g/CM-d, this mean has a sample range of 50 to 75 g/CM-d.

Fecal Water: The fecal water is taken as the mean of 0.101 kg/day, this mean has a sample range of 0.053-0.265 kg/CM-d (Rose, 2015).

Respiration & Perspiration Water: These values were taken as outputs of the 2019 MetMan model (Ewert*, et al.*, 2021). They can also be found in the Ewert*, et al.* (2019) with the exception that the values in Table 3-31 differ slightly as they are from the mended MetMan Model. Ewert*, et al.* (2019) gave a value of 3.04 kg/CM-d, the mended model gives a new value of 2.946 kg/CM-d.

Urine Water: Urine output varies substantially with fluid intake and amount of perspiration. The mean value of 1.42 kg/CM-d with a range of 0.8 to 2.45 kg/CM-d (Rose. C 2015) was used for Table 3-31 .

In addition to the gross metabolic balance, human beings also emit other compounds in trace concentrations, products of metabolic processes, as noted below in the appropriate sections. Additionally, human beings also generate solid and water loads associated with personal hygiene. These hygiene loads are more variable than metabolic loads and, thus, tend to be mission dependent. Nominal hygiene loads are also summarized below. Please refer to the tables listing design water and waste loads in section 4.2.

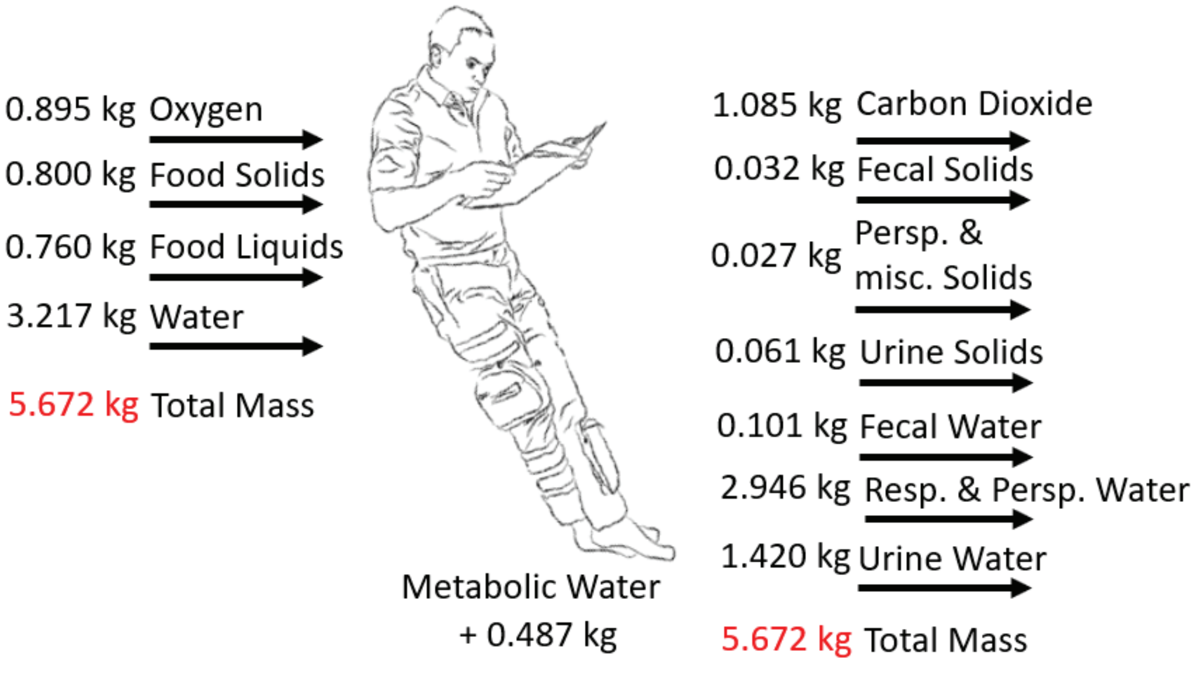

Figure 3-4 Daily mass balance of an 82 kg astronaut

4 LIFE SUPPORT SUBSYSTEM ASSUMPTIONS AND VALUES

The function Life Support consists of three subsystems: Air, Water, and Waste. There are also a considerable number of subsystems that impact these subsystems: Food, EVA, Habitation, Power, Radiation Protection, Thermal Control, Medical Care, In situ Resource Recovery, Control Systems, and Biomass Production. Organization of these topics in this document is based on the perception of criticality to life support from a time point of view, and if time criticality is judged equivalent, then overall impact to the life support system is considered. For example, biomass production will be extremely important in years to come and there has been considerable work done in this area, but its use is not on the near horizon. It was therefore put at the end of the section so the reader would not have to look through that large body of material each time the document is referenced. The Food System has references to the Biomass Production System which comes later in the document, but it is also extremely important near term, so it is placed relatively high on the list of interfaces with ELS subsystems.

4.1 AIR SUBSYSTEM

4.1.1 DESIGN VALUES FOR ATMOSPHERIC SYSTEMS

Air supply is the most time-critical of the life support functions. Typical steady-state values are given in Table 4-1. Total pressure could vary from 20.7 kPa (3 psia) to greater than 117.2 kPa (17 psia) with oxygen content from 17 kPa (2.48 psia) partial pressure to 34% by volume (NASA HIDH, 2014). The Apollo Program used 34.5 kPa (5 psia) 100% oxygen (Cortright, 1975) and the Skylab Program used 34.5 kPa (5 psia) and 74% oxygen (Belew, 1977). However, in the interest of fire safety, experts at NASA feel that very high oxygen concentration should be avoided due to the threat of fire and the belief pure oxygen causes some damage to the lungs if used for extended periods of time without interruption. The NASA (2010b) report is the result of the worked conducted by the NASA Exploration Atmospheres Working Group in 2005 provides information and assessments of the historical (Mercury, Gemini, Apollo, *etc.*), at the time present (Shuttle and ISS), and candidate atmospheres for exploration missions.

One of NASA's major goals is suited operations on the Lunar and Martian surfaces (see further discussion in section 4.6). ISS EVA operations originate from 21% oxygen and 101.3 kPa (14.7 psia) of pressure, with a prebreathe period at 70.3 kPa (10.2 psia). Under this protocol, exploration EVA would be possible, but it would be inefficient and challenging since frequent EVA is expected. An extended prebreathe protocol would be necessary to gradually move the nitrogen from tissues, into the blood, and finally out of the crewmember's lungs prior to embarking on EVA. Without this protocol, the crewmember would likely be at risk of decompression sickness, where nitrogen bubbles form in the tissue spaces causing pain and in extreme cases neurological damage or even death. By stabilizing the crew in an atmosphere where pressure is closer to the eventual EVA suit pressure, the prebreathe protocol can be shortened and therefore is less risky and more efficient, allowing EVA goals to be reached. At lower total pressure, the crewmember's lungs still must see a similar oxygen partial pressure as seen at Earth sea- level conditions. The percentage by volume of oxygen in the cabin atmosphere must therefore be higher than an Earth sea-level atmosphere. This represents a compromise where there is somewhat more risk of fire in order to accomplish EVA exploration goals. The fire risk must then be mitigated further by limiting cabin construction materials for the specified percentage of oxygen.

The most recent recommendation for atmospheres that will enable high frequency EVA phases of a mission is 57 kPa (8.2 psia) total pressure and 34% oxygen content (Norcross, 2013). This is most likely to be required for pressurized rovers and surface habitats. Vehicles without expected EVA (such as launch and transport vehicles) are still expected to operate with Earthlike atmospheres as the ISS does and be pressurized at 101 kPa (14.7 psia) with 21% oxygen. A habitat that operates at 57 kPa (8.2 psia) during high frequency EVA operations would also be required to operate at 101 kPa during other phases because the majority of flight data experience is at these higher pressures. Landers and other vehicles with intermediate requirements and any vehicle that supports a contingency EVA capability would operate at 70.3 kPa (10.2 psia) and 26.5% oxygen (Norcross, 2013). These design recommendations will result in a particular vehicle having different set points for operation during different phases of the mission. A vehicle may also be driven to add a setpoint by an interface requirement with element operating at a different specific pressure. Typically, the highest total pressure and highest oxygen concentration drive requirements for structural design and the materials used for components inside. As a result, ECLSS hardware should be developed to operate at all three conditions to enable operations of a vehicle with multiple set points and enable technology commonality across multiple vehicle elements.

Carbon dioxide (CO_2) levels are another critical parameter when examining requirements for atmospheric conditions. Humans are susceptible to hypercapnia in varying degrees based on elevated carbon dioxide levels in the atmosphere. Table 4-1 provides historical spacecraft maximum allowable concentrations (SMAC) for CO_2; however, as noted in the footnote of Table 4-1, ISS has recently adopted a lower maximum value for CO_2 of ≤ 0.40 kPa as per directive from Mission Control. Investigation of symptoms associated with elevated CO_2 levels is ongoing (Law, 2014).

A variety of symptoms occur from exposure to elevated CO_2 (Table 4-2). At partial pressures of carbon dioxide ($ppCO_2$) between 0.307 – 0.360 kPa CO_2, fatigue and full headedness will occur. At levels between 0.360 – 0.400 kPa CO_2, self-reports of performance decrements, missed procedure steps, and prolonged procedures have been recorded (Law/Alexander, 2016). The actual onset of symptoms to CO_2 concentration is highly variable and depend on the individual characteristics. The effects of longer duration exposure to even 0.507 kPa (0.5%) CO_2 in microgravity is unknown but thought to be adverse (Law 2014).

The ISS has developed flight rules pertaining to high CO_2 concentration partly derived from SMAC's, National Institute for Occupational Safety and Health (NIOSH) guidelines and Occupational Safety and Health Administration (OSHA) standards. These flight rules are listed below (Law, 2010).

- If $ppCO_2$ levels average higher than 0.707 kPa over 5 days or 0.800 kPa over 1 day, the flight surgeon must be consulted when planning crew activities.

- If $ppCO_2$ levels reach or exceed 1.01 kPa, measures must be taken to lower the $ppCO_2$ to permissible levels per Flight Rule B17-5 ("CO_2 Partial Pressure Limits and Actions"), which details specific actions to troubleshoot and scrub CO_2. The same corrective actions are required if $ppCO_2$ is 0.600 kPa or greater and CO_2-related symptoms not attributed to another cause are present.

- Off-nominal situation: Immediate action to minimize adverse CO_2 effects on the crew must be taken at CO_2 levels of 1.33 kPa or 2.00 kPa. The gas environment is scrubbed down to allowable CO_2 levels. If signs of illness develop, the crew must use individual breathing devices (IBD). If the $ppCO_2$ remains above 1.01 kPa or if the IBDs get expended, the crew must evacuate the affected area. Exposure to CO_2 levels of 1.33 kPa or 2.00 kPa are limited to 8 hours or less.

- Emergency: Immediate action with the highest priority to prevent crew exposure must be taken at CO_2 levels of 2.00 kPa or 2.67 kPa. The crew is to use IBDs when performing repair operations, scrub down the gas environment, and evacuate the affected area if $ppCO_2$ remains higher than 2.00 kPa or if IBDs become expended.

Spacecraft or module air leakage is another atmosphere design consideration and typical values are given in Table 4-1. Realistic atmospheric pressure leakage values of 0.01 kg/day/module have been determined during ground testing to capture the performance of each module considering their penetrations, type, and size. However, the nominal value used here for atmospheric leakage is twice that (i.e., 0.02 kg/day/module) to account for uncertainty and variability. This 2× multiplier was established based on historical data that compared the leakage specification values, test results, and on-orbit leakage data for ISS modules and is documented in the Gateway Level 2 ECLSS Subsystem Specification (NASA. 2019b).

Table 4-1 Typical Steady-State Values for Vehicle Atmospheres

		Assumptions [79]			
Parameter	**Units**	**Lower**	**Nominal**	**Upper**	**References**
Carbon Dioxide Generated	kg/CM-d	0.74 [80] (1)	1.08 [81] (1)	1.31 [82] (1)	(1) Table 3- (2) NASA HIDH (2014) (3) Norcross (2013) (4) Earth normal (5) accepted optimum for plant growth (6) ALS RD (2003) (7) Boeing (2002) (8) NASA (2019a, b) (9) NASA Std. 3001, Vol 2 Rev A, (2015) (10) Typical ISS (11) Law (2010)
Oxygen Consumed	kg/CM-d	0.61 [80] (1)	0.90 [81] (1)	1.08 [82] (1)	
p[O_2] for Crew; nominal no impairment [10]	kPa	20.7 (9)	21. 2 (2)	50.6 (9)	
p[O_2] for Crew; measurable impairment until acclimatized [10]	kPa	17.2 (2)	18.6 (2)	18.6 (2)	
p[O_2] for Crew; allowable for 1 hour [10]	kPa	15.2 (2)		17.2 (2)	
p[CO_2] for Plants	kPa	0.04 (4)	0.13 (5)	3.4 (12)	
p[CO_2] for Crew	kPa	0.267 (11)	0.507 (11) [83]	1.01 (11)	
Total Cabin Pressure	kPa	48.0 (6) [84]	101 or 70.3 or 56.5 (3)	102.7 (6)	
Temperature	K	291 (9)	296 (6)	300 (9)	
Relative Humidity	%	25 (9)	40 (10)	75 (9)	
Perspired Water Vapor	kg/CM-d	0.036 (7)	0.699 (7)	1.973 (7)	
Respired Water Vapor	kg/CM-d	0.803 (7)	0.885 (7)	0.975 (7)	
Air Leakage Rate	kg/d/module (%/day)	0.01	0.02 (8)	0.09 (0.14) (8)	

Table 4-2 Symptoms of Carbon Dioxide Toxicity

Signs/Symptoms at increasing levels	**References**
Fatigue	(Law/Alexander, 2016)
Headaches	
Hyperventilation	
Difficulty concentrating	
Irritability	
Performance decrements	
Hearing and vision affected	

In addition to the carbon dioxide load noted above in Table 4-1, human beings also emit volatile compounds, products of metabolic processes, on a per crewmember per day basis and cabin equipment on a per

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[79] The values here are averages for nominal operation of the life support system. Degraded or emergency life support system values may differ.

[80] Values are for a 5th percentile crewmember (1.54 m, 50 kg) with a long duration mission exercise profile

[81] Values are for the HIDH reference crewmember (1.75 m, 82 kg) with a long duration mission exercise profile

[82] Values are for a 95th percentile crewmember (1.84 m, 100 kg) with a long duration mission exercise profile

[83] May be reduced to 0.267 kPa nominal 24-hour average in future NASA-STD-3001 document updates

[84] An almost pure oxygen atmosphere, such as was utilized for early spacecraft (Mercury, Gemini, and Apollo), has a total pressure of 34.5 kPa. Skylab used an atmosphere at 34.4 kPa (258 mmHg), but the crews reported numerous discomforting effects.

mass of equipment per day basis, as noted in Table 4-3 (Perry, 2009). Spacecraft maximum allowable concentration (SMAC) values are established by NASA for many compounds. The load model contains all the primary life support system design driving compounds. These include NH_3, CH_4, CO, dichloromethane, methanol, 2-propanone, and several low molecular weight alcohols. Good functional class representation is provided with the most prevalent compounds reported from in-flight cabin air quality sample analyses included in the listing.

This load model is recommended for future design basis for trace contamination control effort. This replaces the 58-compound load model used previously (Perry, 1998). The new load model decreases the NH_3 production rate by 86% from the previous value of 350.0 mg/person-d based on greater number of literature sources.

Table 4-3 Model for Trace Contaminant Generation [85]

Contaminant	**SMAC** [a] **(mg/m^3)**	**Rate**	
		Equipment (mg/kg-d)	**Metabolic (mg/CM-d)**
Methanol	26	1.3×10^{-3}	0.9
Ethanol	2,000	7.8×10^{-3}	4.3
n-Butanol	40	4.7×10^{-3}	0.5
Formaldehyde [Methanal]	0.12	4.4×10^{-6}	0.4
Acetaldehyde [Ethanal]	4	1.1×10^{-4}	0.6
Benzene	0.2	2.5×10^{-5}	2.2
Toluene [Methylbenzene]	15	2.0×10^{-3}	0.6
Xylenes [Dimethylbenzene]	37	3.7×10^{-3}	0.2
Furan	0.07	$1.8 \text{ x } 10^{-6}$	0.3
Dichloromethane	10	2.2×10^{-3}	0.09
Acetone [2-Propanone]	52	3.6×10^{-3}	19
Trimethylsilanol	4	1.7×10^{-4}	0
Hexamethylcyclotrisiloxane	9	1.7×10^{-4}	0
Ammonia	2	8.5×10^{-5}	50
Carbon monoxide	17	2.0×10^{-3}	18
Hydrogen	340	5.9×10^{-6}	42
Methane	10% LEL [b]	6.4×10^{-4}	329

[a] 180-day SMAC, Ryder*, et al.* (2020).

[b] Toxicity occurs at much higher levels than explosive limit, so ceiling limit is set at 10% of the lower explosive limit (LEL).

4.1.2 GAS STORAGE

Gas storage is necessary for any life support system. Gas can be stored in pressure vessels, as a cryogenic fluid, adsorbed, or chemically combined. The "costs" of storage depends on the gas, with the "permanent" gases, such as nitrogen and oxygen, requiring higher pressure and remaining in the gaseous state at normal temperatures, while the "non-permanent" gases, such as carbon dioxide, can be stored as liquids under pressure. Cryogenic storage requires either continuous thermal control or use of a small quantity of the gas to provide cooling by evaporation. Adsorption and chemical combination are very gas-specific and vary in performance. See Table 4-4 for known gas storage tank masses.

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[85] From Perry (2009).

Table 4-4 Gas Storage

	Performance [kg of tankage/kg of gas]	
Type of Storage	**Nitrogen**	**Oxygen**
Pressure Vessel (based on NORS tanks)	1.93 (1)	1.45 (1)
Cryogenic Storage	0.524 (2)	0.275 (3)

References

(1) Cook (2018)
(2) Hamilton Sundstrand (1970)
(3) Wagner, *et al*. (1993)

4.1.3 PLANETARY DUST

Apollo astronauts learned first-hand how problems with dust impact Lunar surface missions. After three days, Lunar dust contamination on EVA suit bearings led to such great difficulty in movement that another EVA would not have been possible. Dust clinging to EVA suits was transported into the Lunar Module. During the return trip to Earth, when micro gravity was reestablished, the dust became airborne and floated through the cabin. Crews inhaled the dust and it irritated their eyes. Some mechanical systems aboard the spacecraft were damaged due to dust contamination. (Wagner, 2006)

As NASA embarks on future exploration missions, the effects of these extraterrestrial dusts must be well understood, and systems must be designed to operate reliably and protect the crew in the dusty environments of the Moon, Mars and Asteroids.

4.1.3.1 *REGOLITH*

Regolith is defined as the layer of loose material covering the bedrock of the Earth and Moon, *etc*., comprising soil, sand, rock fragments, volcanic ash, glacial drift, *etc*. Because the Moon does not have an atmosphere and running water, erosion forces that weather the loose material on Earth do not exist. Asteroids and meteors strike the Lunar surface creating craters and large rocks. High energy particles and micro-meteors continuously bombard the Moon further breaking these rocks into very fine dust.

When Lunar samples were brought to Earth during the Apollo missions, scientists in the receiving laboratory sorted and catalogued rocks greater than 1 centimeter. The sub-centimeter portion was further broken down into “coarse fines” (1cm-1mm) and “fine-fines” (sub-millimeter) and although the definition was sub-centimeter, in practice, the sub-millimeter fine-fines are called soil. The portion of the soil less than 50 micrometers was informally called dust.

“Roughly 10% to 20% of the Lunar soil is finer than 20 μm, and a thin layer of dust adheres electrostatically to everything that comes in contact with the soil: spacesuits, tools, equipment, and lenses. The shapes of individual Lunar soil particles are highly variable, ranging from spherical to extremely angular. In general, the particles are somewhat elongated and are subangular to angular. Because of the elongation, the particles tend to pack together with a preferred orientation of the long axes (Heiken, 1991). As particle size decreases, adhesive, cohesive, and excitatory forces become very strong. This is important from an engineering perspective because the smaller particles tightly adhere to surfaces they contact and tend to stick together.

The Mars terrain consists of a combination of windblown sand, dust, and fragments of bedrock. The Martian dust, in contrast to the sand which consists predominantly of basalt that has undergone minimal chemical change, is bright red and consists of small, oxidized particles of basaltic rock. The dust in particular readily adheres to exposed surfaces (John Hopkins University - Applied Physics Laboratory, 2021).

The Viking Lander 1, later renamed the Mutch Memorial Station (MMS), touched down on the Martian surface in 1976. At the MMS landing site, two types of fine-grained sediment deposits are present: (1) drift material and (2) blocky material. The drift material is very fine and has the “consistency of loose kitchen flour.” The drift material covers approximately 14% of the landing site area. Blocky material, like its name suggests, exists in clumps and has the consistency of “dry, cloddy garden soil.” This material takes up approximately 78% of the landing site area and tends to be covered by the drift material (Arvidson, *et al*. 1989). Study results obtained by robotic Martian missions indicate that Martian surface soil is oxidative and reactive. Exposure to the reactive Martian dust may pose a concern to crew health and the integrity of mechanical systems.

Describing Martian dust, Morris (2006) wrote, “Bright Martian dust can therefore be described as an assemblage of particles in the clay plus fine silt size range (<5 μm) that contain primary igneous minerals (olivine, pyroxene, feldspar, and magnetite) and sulfate-bearing alteration/weathering products (nanophase ferric oxides but not phyllosilicate minerals). Discrete dust particles are predominately composites of these phases rather than predominantly monophase [e.g., Madsen*, et al.*, 1999; Goetz*, et al.*, 2005]. The strongly magnetic mineral in the dust (and Laguna Class soil in general) is magnetite [Morris*, et al.*, 2004, 2006; Goetz*, et al.*, 2005].” This paper included Table 4-5 (shown below) which provides chemical composition of Martian dust. Readers can find more information about Martian dust in Tomasko (1999).

Table 4-5 Elemental Data for Martian Dust, Panda Subclass Soil, and MoessBerry Subclass Soil, Adapted from Morris (2006)

	Martian Dust			Panda Subclass Soil[86]		MoessBerry Subclass[87]			
	GC,[a] %	MP,[a] %	Average,[b] %	GC,[c] %	MP,[c] %	Observed,[c] %	Spherule,[d] %	CBS2A,[e] %	CBS2B,[f] %
SiO_2	44.71 ± 0.52	44.97 ± 0.29	44.84 ± 0.52	46.52 ± 0.57	46.78 ± 1.22	38.54 ± 1.10	0.00	45.69 ± 1.32	45.81 ± 1.19
TiO_2	0.89 ± 0.08	1.01 ± 0.07	0.95 ± 0.08	0.87 ± 0.15	1.02 ± 0.18	0.73 ± 0.05	0.00	0.86 ± 0.06	0.99 ± 0.17
Al_2O_3	9.49 ± 0.16	9.14 ± 0.09	9.32 ± 0.18	10.46 ± 0.71	9.67 ± 0.49	7.63 ± 0.23	0.00	9.05 ± 0.28	9.50 ± 0.46
Cr_2O_3	0.31 ± 0.04	0.32 ± 0.03	0.32 ± 0.04	0.36 ± 0.08	0.41 ± 0.08	0.28 ± 0.03	0.00	0.33 ± 0.04	0.37 ± 0.04
Fe_2O_3	6.58 ± 0.07	7.97 ± 0.03	7.28 ± 0.70	4.20 ± 0.54	4.36 ± 0.74	20.24 ± 4.37	99.70	5.62 ± 0.97	5.82 ± 0.98
FeO	10.52 ± 0.11	10.31 ± 0.04	10.42 ± 0.11	12.18 ± 0.57	13.75 ± 1.00	11.17 ± 3.55	0.00	13.24 ± 4.26	12.09 ± 0.88
MnO	0.31 ± 0.02	0.34 ± 0.01	0.33 ± 0.02	0.33 ± 0.02	0.38 ± 0.02	0.28 ± 0.02	0.00	0.34 ± 0.02	0.36 ± 0.02
MgO	8.20 ± 0.15	7.57 ± 0.08	7.89 ± 0.32	8.93 ± 0.45	7.31 ± 0.30	6.55 ± 0.25	0.00	7.76 ± 0.30	7.60 ± 0.31
CaO	6.13 ± 0.07	6.54 ± 0.04	6.34 ± 0.20	6.27 ± 0.23	7.12 ± 0.28	5.23 ± 0.37	0.00	6.20 ± 0.44	6.73 ± 0.26
Na_2O	2.89 ± 0.29	2.22 ± 0.19	2.56 ± 0.33	3.02 ± 0.37	2.23 ± 0.23	2.16 ± 0.11	0.00	2.56 ± 0.13	2.40 ± 0.25
K_2O	0.48 ± 0.07	0.48 ± 0.06	0.48 ± 0.07	0.41 ± 0.03	0.49 ± 0.07	0.38 ± 0.03	0.00	0.45 ± 0.04	0.49 ± 0.07
P_2O_5	0.90 ± 0.09	0.93 ± 0.07	0.92 ± 0.09	0.83 ± 0.23	0.82 ± 0.05	0.81 ± 0.04	0.00	0.96 ± 0.05	0.87 ± 0.05
SO_3	7.56 ± 0.13	7.28 ± 0.07	7.42 ± 0.13	4.90 ± 0.74	4.97 ± 0.58	5.17 ± 0.42	0.00	6.13 ± 0.50	6.20 ± 0.72
Cl	0.88 ± 0.03	0.78 ± 0.01	0.83 ± 0.05	0.61 ± 0.08	0.57 ± 0.06	0.69 ± 0.03	0.00	0.81 ± 0.04	0.70 ± 0.07
Br (× 10^4)	29 ± 22	26 ± 14	28 ± 22	49 ± 12	39 ± 27	56 ± 22	0	66 ± 26	34 ± 24
Ni (× 10^4)	636 ± 73	467 ± 42	552 ± 85	544 ± 159	399 ± 100	854 ± 182	3000	479 ± 106	476 ± 119
Zn (× 10^4)	406 ± 32	401 ± 14	404 ± 32	204 ± 71	238 ± 63	329 ± 25	0	391 ± 30	321 ± 85
Total	99.85	99.87	99.86	99.89	99.89	99.84	100.00	100.00	99.88
Fe^{3+}/Fe_T	0.36 ± 0.03	0.41 ± 0.03	0.39 ± 0.03	0.24 ± 0.02	0.22 ± 0.03	0.66 ± 0.06	1.00	0.28 ± 0.02	0.30 ± 0.02

[a] GC, Gusev crater; MP, Meridiani Planum. Analyses of Desert_Gobi and MontBlanc_LesHauches are from Gellert*, et al.* [2006a,b].

[b] Uncertainty is larger of deviation from average value and maximum value for analytical uncertainty

[c] Data are average ±1σ of data from Gellert*, et al.* [2006] and R. Gellert (manuscript in preparation, 2006).

[d] Model spherule elemental composition

[e] CBS2A is the composition of the basaltic soil that would have to be mixed with the spherule composition to give the observed composition. Calculated composition of basaltic soil (CBS2A) from Observed = 0.16 × (Spherule) + 0.84 × (CBS2A). In this calculation, the spherules account for ~50% of the total Fe.

[f] CBS2B is the composition of the basaltic soil as determined from a mixture of 50% average Martian dust and 50% Meridiani Planum Panda Subclass soil. Calculated composition of basaltic soil (CBS2B) from CBS2B = 0.50 × (Ave. Dust) + 0.50 × (MP Panda Subclass).

4.1.3.2 *PLANETARY DUST SYSTEM IMPACTS*

A NASA team of multi-disciplined engineers and scientists was tasked to identify systems that will be affected by dust and how they will be affected (Wagner 2008). The tables that follow resulted from that study.

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[86] At the Gusev Crater and Meridiani Planum landing sites, the Laguna soil is found to be widespread, which is are basaltic soils containing minersals such as olivine, pyroxene, and nanophase ferric oxides. Of the Laguna class soils are subclasses, Panda, Liberty, and Gobi subclasses where Panda contains the least nanophasic ferric oxides and Gobi the most.

[87] Berry class soils were only present at the Meridiani Planum site and have high hematite, ferrous oxide, and ferric oxide concentrations due to the presence of hematite spherules (hence the name Berry). The MoessBerry subclass is very hematite rich compared to the other subclass (Nougat), which is intermediate to those of the MoessBerry and Laguna soil.

Table 4-6 Air Revitalization System Effects of Dust Exposure

Subsystem/Component	Effect of Dust Exposure
Ventilation System	Mechanical components of vents, fans, intakes, louvers, may be compromised. Certain failures in these systems have the potential to become active dust spreaders rather than dust eliminators.
Trace Contaminant Control	Impaired system would decrease the capacity to scrub contaminants.
CO_2 Removal	Desiccant and sorbent beds may become fouled with dust, reducing performance.
CO_2 Reduction	Catalytic beds may become fouled with dust, reducing performance.
O_2 Generation	May become fouled with dust, reducing performance
CO_2 Compressor	May become fouled with dust, reducing performance
Particulate Control System	Possible system overload and/or drastic increase in mass due to high use of expendables

Table 4-7 Water Recovery System Effects of Dust Exposure

Subsystem/Component	Effect of Dust Exposure
Biological Water Processor	Bacterial organisms may be poisoned by chemicals in dust.
Water Quality Monitor	Clogging or blocking of chemically reactive sites or physical pathways of instrument resulting in performance degradation.

Table 4-8 Solid Waste Effects of Dust Exposure

Subsystem/Component	Effect of Dust Exposure
Waste Collectors	If salts and metals from the dust are present biological processes may not be able to remove said materials from the system and if trying to use recycled materials contaminated with dust constituents, time dependent buildup to unacceptable levels could occur. Affects crops and water.
Waste Compactor	Compactor tubes may be scratched, scored, damaged.
Particle Size Reducer	Dulled cutting blades
Waste Disposal	Filters and other components will be frequently replaced placing a burden on waste disposal processes and storage.

Table 4-9 Thermal Effects of Dust Exposure

Subsystem/Component	Effect of Dust Exposure
Radiators	Deposits on the radiator surface may degrade performance.
Humidity Control	Clogging of pitot tubes, small orifices in rotary separators, and porous media used to separate condensate from the air stream

Table 4-10 Other Life Support Systems Effects of Dust Exposure

Subsystem/Component	Effect of Dust Exposure
Crop Growth	If dust is used in the root substrates, when it dries, circulating air around the plants may stir up dust. Chemicals in dust may poison plant organisms.
Crop Harvesting	Harvesting of dry crops may produce organic dust.
Valves	Compromise sealing surfaces, corroding or scoring turning shafts
Pumps	Plugging, eroding bearings, moving parts
Membranes	Chemical attack, fouling, puncturing, plugging
Filters	Plugging
Seals	Plugging or compromising sealing surfaces
Heat Exchangers	Internal clogging, covering of external heat exchanging surfaces.
Flow Tubes	Clogged, scratched, scored, damaged
Fluid Connectors	Sliding seals can get scratched and lead to leakage.

Table 4-11 Airlock Effects of Dust Exposure

Subsystem/Component	Effect of Dust Exposure
QDs/Connectors	Seal degradation, leaks, higher spares/maintenance
Hatch Seals	Seal degradation, leaks, higher gas makeup, spares/maintenance, dust transfers into habitat/vehicle

Table 4-12 Space Suit Assembly Effects of Dust Exposure

Subsystem/Component	Effect of Dust Exposure
Outer Garment	Dust accumulation/transfer to airlock-habitat; materials degradation
Bearings	Seal degradation, leaks, higher spares/maintenance
Visor Coatings	Scratches/severe abrasion; loss of coatings
Lighting	Reduced illumination due to dust coating illumination source

Table 4-13 Portable Life Support System (PLSS) Power and Communications Effects of Dust Exposure

Subsystem/Component	Effect of Dust Exposure
Electrical Circuits	Charged dust particles could result in static shock to electronics
Battery/Fuel cell	Dust in battery contacts cause power drain and potential short circuit

Table 4-14 PLSS Cooling Effects of Dust Exposure

Subsystem/Component	Effect of Dust Exposure
Evaporative Membrane	Contamination of membrane surface; transport blockage
QD's and Connectors	Seal degradation, leaks, higher spares/maintenance
Radiator Surface	Thermal coating degradation/loss of cooling efficiency

Table 4-15 PLSS O2 Effects of Dust Exposure

Subsystem/Component	Effect of Dust Exposure
QD's and Connectors	Seal degradation, leaks, higher spares/maintenance
Regulators	Contamination of orifices; transport blockage

Table 4-16 PLSS Vent Effects of Dust Exposure

Subsystem/Component	Effect of Dust Exposure
QDs and Connectors	Seal degradation, leaks, higher spares/maintenance
Venting Membranes	Contamination of membrane surface; transport blockage

Table 4-17 Ancillary Equipment Effects of Dust Exposure

Subsystem/Component	Effect of Dust Exposure
Power Tools	Dust in battery contacts cause power drain & potential short circuit
Wrenches	Buildup and restriction of working parts
Sockets	Buildup and restriction of working parts
Drills	Buildup and restriction of working parts
Joints on Translation Aids	Buildup and restriction of working parts
Structures	Buildup and restriction of working parts. Corrosive constituents in dust may lead to degradation of structures if water used in EVA operations contacts dust on surfaces.
Tools/Hardware	Buildup and restriction of working parts

Table 4-18 Advance Food Systems Effects of Dust Exposure

Subsystem/Component	Effect of Dust Exposure
Food Storage System	Contamination
Processing Equipment	Contamination
Food Preparation Equipment	Contamination

4.1.3.3 *REGOLITH CONTAMINATION MANAGEMENT - LAYERED ENGINEERING DEFENSE STRATEGY*

> *"A common sense, layered, engineering design defense can solve any apparent problem with dust during long-term human activity and habitation in the Lunar environment."*
>
> *Harrison H. Schmitt*
> *Ames Research Center*
> *Lunar Dust Symposium*
> *February 2, 2004*

Space systems engineers design their individual components and systems for reliability, as they should. And, for cross-cutting challenges, such as regolith contamination, an integrated systems strategy needs to be considered. Such a strategy is described in (Wagner 2014). An integrated systems approach incorporates contamination prevention, exterior cleaning and protection, interior cleaning and protection, and maintaining air quality. It depends mostly on sound operations and engineering design though some technology investments will be required.

The first two layers of defense are materials and engineering design. Materials, when possible, should consist of smooth, dust and abrasion resistant surfaces. Pockets, folds, and other points on space suits that could trap dust should be minimized and designed so they do not collect dust. Specialized surfaces that reject dust, either because of inherent surface properties or through active means, should be considered in original design where appropriate.

Engineering design should incorporate dust covers for sensitive equipment and employ grates on floors to collect dust. Best practices for cleanable design should be followed and include minimizing gaps where dust and dirt can collect, designing rounded corners, and including human factors experts throughout the design process to assess crew access.

Operational design is another key component for particulate management. Suit and contaminated equipment ingress to habitable volumes should be eliminated, where practical. Where feasible, automated operations, such as continuously active or automated cleaning systems, will reduce the amount of crew-time required for managing regolith particulate contamination. "Asteroid, Lunar and Planetary Regolith Management: A Layered Engineering Defense" NASA/TP-2014-217399 identifies the technology capabilities needed to implement the layered engineering defense strategy. It includes example technologies that would allow NASA to reach each capability and it identifies the missions that each of these technologies support.

4.2 WATER SUBSYSTEM

Water will not be the most time-critical life support commodity, but water regeneration streams are the most massive of the life support subsystems. Further, water quality is of great concern with respect to crew health. A complimentary regimen of technologies must be employed, which address contaminant removal issues mechanically and chemically. In the past, power use has driven water regeneration. However, other infrastructure "costs" are also important.

4.2.1 DESIGN VALUES FOR WATER SUBSYSTEMS

Clean water is required for drinking, food preparation, personal hygiene, and possibly for cleaning clothes and equipment. Water quality standards will vary, but they might include potable, and hygiene, and water purified to technical grade. The tables here provide anticipated usage rates for several scenarios. The values are averages during nominal operation of the life support system. Degraded or emergency life support system values may be different. Table 4-19 lists steady-state water usage estimates for missions of 30 days or less. Table 4-20 lists steady-state water usage estimates for longer duration missions. More importantly here,

Table 4-21 details anticipated wastewater generation rates to be processed by the Water Subsystem for long-duration missions. Please note that the water usage rates and wastewater generation rates sometimes differ, as a quick comparison of Table 4-20 to

Table 4-21 confirms. In some cases, either the water usage or wastewater generation rates are unknown. In other cases, water usage does not correspond to wastewater generated and sent to the Water Subsystem, depending upon the configuration of the system using the water.

The mission scenarios are defined as: (1) Devon Island (described below, for comparison), (2) International Space Station, assumed as lacking a hygiene water facility (i.e. sink), (3) A transit mission, currently assumed to have similar hygiene capabilities as ISS, (4) Early Planetary Base, assumed to have the capability for limited hygiene water use, and (5) Mature Planetary Base, assumed to have the capability for full hygiene water use as well as a biomass production chamber for food cultivation. For more information on the ISS state-of-the-art water recover system, see (Carter*, et al.* 2013).

Table 4-19 Steady-State Values for Vehicle Water Usage for Short Duration Missions

		Assumptions		
Parameter	**Units**	**Lower**	**Nominal**	**Upper**
Crew Water Allocation, assuming Minimal Hygiene Water for a Mission Less Than 30 days	kg/CM-d	--	2.7 (1)	--

Notes:

(1) Based on Orion

(2) This 'steady-state' value does not include additional per mission water requirements of 0.5 L/CM for eyewash, 1 L/CM for pre-landing fluid loading or 0.5 L/CM for post-landing.

The Haughton-Mars Project (HMP) is an international interdisciplinary field research project. The project is centered on Devon Island, in the High Arctic which is viewed as a terrestrial analog for Mars. The rocky polar desert setting, geologic features, and biological attributes of the site offer unique insights into the possible evolution of Mars; in particular, the history of water and of past climates on Mars, the effects of impacts on Earth and on other planets, and the possibilities and limits of life in extreme environments. In parallel with its science program, the HMP supports an exploration program aimed at developing new technologies, strategies, human factors experience, and field-based operational know-how key to planning the future exploration of the Moon, Mars and other planets by robots and humans. The concept of simulating some aspects of a Martian mission: EVA, Long Range Pressurized Rover, medical telemedicine and communication, studying immune system changes, plant growth using artificial light, and water-formed geologic features, all suggest that possibly Mars had a similar geologic past to the Devon Island environment.

The section in Table 4-20 which contains the water use numbers for the Devon Island Mars analog study is valuable in that it demonstrates actual water use values that are reasonably close to the projected figures from other studies that they serve as a terrestrial analog comparison for other modeling and analysis projections on water use, (Bamsey, *et al*., 2009).

Table 4-20 Typical Steady-State Water Usage Rates for Various Missions [88]

Parameter	Units	Devon Island Mars Research Station Study[6]	International Space Station	Transit Vehicle	Early Planetary Base	Mature Planetary Base
Drinking Water	kg/CM-d	2.59	2.00 (2)	2.00 (2)	2.00 (2)	2.00 (2)
Food Rehydration Water	kg/CM-d	1.03	0.50 (2)	0.50 (2)	0.50 (2)	0.50 (2)
Total Human Consumption	*kg/CM-d*	*3.62*	*2.50*	*2.50*	*2.50*	*2.50*
Urinal Flush	kg/CM-d	0	0.30 (1)	0.30 (1)	0.50 (2)	0.50 (2)
Personal Hygiene	kg/CM-d	0.46 (4)	0.4 (2)	0.4 (2)	0.4 (2)	0.4 (2)
Hand Wash	kg/CM-d	0.64	n/a	n/a		TBD
Shaving	kg/CM-d	0.05				TBD
Cleaning Science & Engineering	kg/CM-d	0.08	n/a	n/a		TBD
Shower[89]	kg/CM-d	1.08	n/a	n/a	1.08 (6)	1.08 (6)
Laundry	kg/CM-d	1.95	n/a	n/a	n/a	1.1 (7)
Dish Wash	kg/CM-d	3.54	n/a	n/a	n/a	3.54 (6)
Total Hygiene	*kg/CM-d*	*7.80*	*0.7*	*0.7*	*1.98*	*6.62*
Payload	kg/CM-d		2.18 (1)	TBD (3)	TBD (3)	TBD (3)
Total Payload Consumption	*kg/CM-d*		*2.18*			
Total Water Consumption	***kg/CM-d***	***11.42***	***5.38***	***3.2***	***4.48***	***9.12***
Biomass Production Water Consumption[90]	kg/m^2·d	0.10[91]	n/a	n/a	n/a	4.00
Medical water	kg/CM-d		0.5 (2) + 5 kg	0.5 (2) + 5 kg	0.5 (2) + 5 kg	0.5 (2) + 5 kg

References

(1) NASA (2004)

(2) NASA HIDH (2014) Values assumed for all future missions. Additional water is specified for pre-landing and post-landing (see NASA HIDH)

(3) Architecture dependent.

(4) oral hygiene

(5) Jeng & Ewert (2015)

(6) Bamsey, *et al*., 2009

(7) Ewert (2021a)

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[88] Note that additional water may enter the system through moist food and metabolically generated water. Actual usage has been substantially less.

[89] Assuming the value from Bamsey, *et al*., 2009.

[90] The water quality may differ from the standards for crew use for water provided to plants as nutrient solution. In fact, plants might provide some water reclamation functions even while providing raw agricultural products.

[91] Bamsey, *et al*., 2009 uses units of kg/CM-d for biomass water consumption.

Table 4-21 Typical Steady-State Wastewater Generation Rates for Various Missions

Parameter	**Units**	**International Space Station**	**Transit Vehicle**	**Early Planetary Base**	**Mature Planetary Base**
Urine	kg/CM-d	1.20 (1)	1.50 (2)	1.50 (2)	1.50 (2)
Urinal Flush	kg/CM-d	0.30 (1)	0.30 (1)	0.50 (2)	0.50 (2)
Total Urine Wastewater Load	*kg/CM-d*	*1.50*	*1.80*	*2.00*	*2.00*
Oral Hygiene	kg/CM-d	n/a	n/a	0.37 (2)	0.37 (2)
Hand Wash	kg/CM-d	n/a	n/a	4.08 (2)	4.08 (2)
Shower [92]	kg/CM-d	n/a	n/a	1.08 (5)	1.08 (5)
Laundry	kg/CM-d	n/a	n/a	n/a	1.1 (6)
Dish Wash	kg/CM-d	n/a	n/a	n/a	3.54 (5)
Food Preparation and Processing	kg/CM-d	n/a	n/a	n/a	TBD
Total Hygiene Wastewater Load	*kg/CM-d*	*0.00*	*0.00*	*5.53*	*10.17+*
Crew Latent Humidity Condensate	kg/CM-d	2.27 (2)	2.27 (2)	2.27 (2)	2.90 (2)
Animal Latent Humidity Condensate	kg/CM-d	n/a	n/a	TBD	TBD
Total Latent Wastewater Load	*kg/CM-d*	*2.27*	*2.27*	*2.27+*	*2.90+*
Payload	kg/CM-d	n/a	n/a	TBD (3)	TBD (3)
Total Payload Wastewater Load	*kg/CM-d*	*0.00*	*0.00*	*0.00+*	*0.00+*
Total Wastewater Load	***kg/CM-d***	***3.77***	***4.07***	***9.80+***	***15.07+***
Biomass Production Wastewater [93]	kg/m^2·d	n/a	n/a	n/a	TBD

References

(1) NASA (2004)

(2) NASA (1991)

(3) Architecture dependent

(4) Ewert & Jeng (2015)

(5) Bamsey, *et al.*, 2009

(6) Ewert (2021a)

4.2.2 WASTEWATER COMPONENT CONTAMINANT LOADING

Studies by Carter (1998) and Putnam (1971) provide the data for Table 4-22 through Table 4-27 which presents wastewater stream, aqueous contaminant loadings. Work by Carter (1998) focuses on anticipated wastewater streams from ISS systems to aid sizing the ISS water processor. Thus, some contaminants, especially those associated with ISS cleansing agents in the originally-planned shower (Table 4-24) and hygiene (Table 4-25) streams may be unique to ISS. Likewise, wastes listed for the extravehicular mobility unit (Table 4-22) are specific to equipment employed by the Shuttle and ISS programs. However, such loadings are likely representative. Work by Putnam (1971) characterized only human urine. The corresponding values given by Carter (1998) for urine reflect the urine processor product stream, as passed to the other ISS water processing equipment, and not an untreated urine stream.

Table 4-22 through Table 4-27 have a similar format. The first column of each table provides the contaminant name. When the common name differs from International Union of Pure and Applied Chemistry (IUPAC) nomenclature, the IUPAC name appears in brackets. The next two columns, when checked with an "×," identify those compounds in the wastewater stream that are defined as either controlled inorganic compounds (CI) for potable water streams or have an associated SMAC for the cabin atmosphere. [94] The molecular weight (MW) and percent carbon are listed next. The loading density provides the concentration in milligrams of contaminant per liter of wastewater stream. Finally, the last column provides the percentage of the specific contaminant with respect to the total contaminant loading.

Each table is organized in order of descending concentration or loading density. Those components in aggregate comprising less than five percent of the total contaminant loading, or trace components, are listed below

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[92] Assuming one shower per person per week. ISS does not have a shower despite early space station plans for that capability.

[93] The water quality may differ from the standards for crew use for water provided to plants as nutrient solution. In fact, plants might provide some water reclamation functions even while providing raw agricultural products.

[94] See ELS RD (2008) for CI and SMAC requirements.

the thick line near the bottom of each table. Trace components that are CI or have a SMAC are listed individually while all other trace components are listed under the generic heading of "constituents totaling less than 5%."

Table 4-22 lists the anticipated contaminants from the latent condensate derived from the crew cabin. Carter (1998) developed this list based on the International Space Station program. Updated values from Schultz, *et al.* (2006) are included as well.

Table 4-22 Wastewater Contaminants in Crew Latent Condensate

Component	CI	SMAC	MW	Percent Cabon [%C]	Concentration [mg/L]	Percent of Total Contaminants [%]
2-propanol [isopropanol]		×	60.1	60.0	56.0[95]	11.2[95]
1,2 propanediol [propylene glycol]			76.1	47.4	70.6[95]	14.2[95]
bicarbonate			61.0	19.7	33.17	6.70[95]
acetic acid [ethanoic acid]		×	60.1	40.0	56.3[95]	11.3[95]
ammonium	×		18.0	0.0	13.527	2.70[95]
caprolactam			113.2	63.7	38.9[95]	7.80[95]
ethylene glycol [1,2-ethandiol]		×	62.1	38.7	11.7[95]	2.30[95]
glycolic acid [hydroxy acetic acid]			76.1	31.6	10.194	2.00[95]
ethanol		×	46.1	52.1	108.4[95]	21.8[95]
formaldehyde [methanal]		×	30.0	40.0	10.9[95]	2.20[95]
formic acid [methanoic acid]			46.0	26.1	18.5[95]	3.70[95]
propanoic acid			74.1	48.6	5.90[95]	1.20[95]
methanol		×	32.0	37.5	7.10[95]	1.40[95]
lactic acid [2-hydroxy-propanoic acid]			90.1	40.0	11.2[95]	2.20[95]
4-ethyl morpholine			115.2	62.6	4.10[95]	0.80[95]
urea			60.1	20.0	9.20[95]	1.80[95]
chloride	×		35.5	0.0	1.465	0.30[95]
4-hydroxy-4-methyl-2-pentanone			116.2	62.0	1.50[95]	0.30[95]
2-butoxyethoxy-ethanol			162.2	59.2	5.30[95]	1.10[95]
4-acetyl morpholine			129.2	55.8	1.092	0.20[95]
1-butanol		×	74.1	64.8	1.80[95]	0.400
2-butoxyethanol			118.2	61.0	1.10[95]	0.20[95]
carbon disulfide	×	×	76.1	15.8	0.785	0.20[95]
octanoic acid			144.2	66.6	1.00[95]	0.20[95]
zinc	×		65.4	0.0	0.650	0.10[95]
N,N-dimethylformamide			73.1	49.3	1.20[95]	0.200
total protein			3,206.3	53.0	0.600	0.10[95]
hexanoic acid			116.2	62.0	1.20[95]	0.200
isocitric acid [1-hydroxy-1,2,3-propanetricarboxylic acid]			192.1	37.5	0.576	0.10[95]
dibutyl amine			129.2	74.3	0.566	0.10[95]
potassium	×		39.1	0.0	0.542	0.10[95]
constituents totaling less than 5%					*9.546*	*1.9*[95]
nitrite	×		*46.0*	*0.0*	*0.517*	*0.1*[95]
2-ethoxyethanol		×	*90.1*	*53.3*	*1.3*[95]	*0.3*[95]
acetone [2-propanone]		×	*58.1*	*62.0*	*0.348*	*0.100*
magnesium	×		*24.3*	*0.0*	*0.282*	*0.100*
phenol		×	*94.1*	*76.6*	*0.5*[95]	*0.100*
silver	×		*107.9*	*0.0*	*0.200*	*0.0*[95]
acetaldehyde [ethanal]		×	*44.1*	*54.5*	*0.098*	*0.000*
cyclohexanone		×	*98.1*	*73.4*	*0.089*	*0.000*
nickel	×		*58.7*	*0.0*	*0.087*	*0.000*
acetophenone		×	*120.2*	*80.0*	*0.083*	*0.000*
calcium	×		*40.1*	*0.0*	*0.060*	*0.000*
sulfate	×		*96.1*	*0.0*	*0.052*	*0.000*
methylene chloride [dichloromethane]	×	×	*84.9*	*14.1*	*0.050*	*0.000*
manganese	×		*54.9*	*0.0*	*0.035*	*0.000*
methyl ethyl ketone [2-butanone]		×	*72.1*	*66.6*	*0.023*	*0.000*
iron	×		*55.9*	*0.0*	*0.008*	*0.000*
tetrachloroethene	×	×	*165.8*	*14.5*	*0.005*	*0.000*
copper	×		*63.6*	*0.0*	*0.004*	*0.000*
isobutyl methyl ketone [4-methyl-2-pentanone]		×	*100.2*	*72.0*	*0.002*	*0.000*
cadmium	×		*112.4*	*0.0*	*0.001*	*0.000*
lead	×		*207.2*	*0.0*	*0.001*	*0.000*
toluene		×	*92.1*	*91.2*	*0.001*	*0.000*
ethyl benzene		×	*106.2*	*90.5*	*trace*	*0.000*
benzene		×	*78.1*	*92.3*	*trace*	*0.000*
chloroform [trichloromethane]	×	×	*119.4*	*10.1*	*trace*	*0.000*
Total					**498.359**	**100**

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[95] Schultz, *et al.* (2016)

Table 4-23 details the contaminants from a potential crew shower stream. Depending on the actual cleansing agent employed, actual components in a shower greywater stream may vary. Carter (1998) developed this list based on early space station plans. Verostko, *et al.* (1989) and Wydeven and Golub (1990) also provide crew shower greywater models. Sodium coconut acid-n-methyl taurate is the major surfactant component of the cleanser originally planned for Space Station. If a different cleansing agent is used, this component would be replaced with the major components of the new cleanser.

Table 4-23 Wastewater Contaminants in Crew Shower Stream

Component	**CI**	**SMAC**	**MW**	**Percent Carbon [%C]**	**Concentration [mg/L]**	**Percent of Total Contaminants [%]**
sodium coconut acid-n-methyl taurate			341.0	58.0	449.96	47.6
chloride	×		35.5	0.0	106.54	11.3
sodium			23.0	0.0	106.10	11.2
bicarbonate			61.0	19.7	39.10	4.1
total protein			3,206.3	53.0	36.77	3.9
urea			60.1	20.0	36.15	3.8
acetic acid [ethanoic acid]		×	60.1	40.0	30.11	3.2
propanoic acid			74.1	48.6	30.00	3.2
lactic acid [2-hydroxy-propanoic acid]			90.1	40.0	24.16	2.6
potassium	×		39.1	0.0	17.50	1.9
ammonium	×		18.0	0.0	16.80	1.8
sulfate	×		96.1	0.0	12.33	1.3
constituents totaling less than 5%					*32.39*	*3.4*
ethanol		×	*46.1*	*52.1*	*3.08*	*0.3*
ethylene glycol [1,2-ethandiol]		×	*62.1*	*38.7*	*2.51*	*0.3*
methanol		×	*32.0*	*37.5*	*0.90*	*0.1*
phenol		×	*94.1*	*76.6*	*0.37*	*0.0*
acetone [2-propanone]		×	*58.1*	*62.0*	*0.21*	*0.0*
formaldehyde [methanal]		×	*30.0*	*40.0*	*0.10*	*0.0*
propionaldehyde [propanal]		×	*58.1*	*62.0*	*0.09*	*0.0*
Total					**945.2**	**100**

Table 4-24 details the contaminants from a crew hygiene stream derived from hand and oral cleansing operations. Depending on the actual cleansing agent employed, actual components in a hygiene greywater stream may vary. Carter (1998) developed this list based on early space station plans. Wydeven and Golub (1990) also provides a crew hygiene greywater model. As in Table 4-23, Table 4-24 assumes the use of a cleanser based on sodium coconut acid-n-methyl taurate. If a different cleansing agent is used, this component would be replaced with the major components of the new cleanser.

Table 4-24 Wastewater Contaminants in Crew Hygiene Stream

Component	CI	SMAC	MW	Percent Carbon [%C]	Concentration [mg/L]	Percent of Total Contaminants [%]
sodium coconut acid-n-methyl taurate			341.0	58.0	638.85	62.8
sodium			23.0	0.0	85.00	8.3
chloride	×		35.5	0.0	76.12	7.5
lactic acid [2-hydroxy-propanoic acid]			90.1	40.0	34.34	3.4
acetic acid [ethanoic acid]		×	60.1	40.0	28.59	2.8
total protein			3,206.3	53.0	25.04	2.5
bicarbonate			61.0	19.7	24.44	2.4
sulfate	×		96.1	0.0	11.09	1.1
formic acid [methanoic acid]			46.0	26.1	11.05	1.1
potassium	×		39.1	0.0	10.78	1.1
propanoic acid			74.1	48.6	9.56	0.9
ethanol		×	46.1	52.1	8.57	0.8
phosphate			95.0	0.0	7.20	0.7
constituents totaling less than 5%					*32.09*	*3.2*
methanol		×	*32.0*	*37.5*	*6.36*	*0.6*
ammonium	×		*18.0*	*0.0*	*5.81*	*0.6*
ethylene glycol [1,2-ethandiol]		×	*62.1*	*38.7*	*1.58*	*0.2*
1-propanol		×	*60.1*	*60.0*	*0.58*	*0.1*
2-propanol		×	*60.1*	*60.0*	*0.26*	*0.0*
phenol		×	*94.1*	*76.6*	*0.16*	*0.0*
dimethyl disulfide	×		*94.2*	*25.5*	*0.13*	*0.0*
acetone [2-propanone]		×	*58.1*	*62.0*	*0.09*	*0.0*
pentane		×	*72.2*	*83.2*	*0.09*	*0.0*
formaldehyde [methanal]		×	*30.0*	*40.0*	*0.07*	*0.0*
propionaldehyde [propanal]		×	*58.1*	*62.0*	*0.05*	*0.0*
1-butanol		×	*74.1*	*64.8*	*0.05*	*0.0*
dimethyl sulfide	×	×	*62.1*	*38.7*	*0.05*	*0.0*
carbon disulfide	×	×	*76.1*	*15.8*	*0.02*	*0.0*
Total					**1,018.0**	**100**

Table 4-25 lists the composition of unprocessed urine as derived from the human metabolic process. The reference is Putnam (1971). For more recent information on calcium in urine issues during spaceflight, see Smith (2012) and Smith (2014).

Table 4-25 Wastewater Contaminants in Crew Urine Stream

Component	**CI**	**SMAC**	**MW**	**Percent Carbon [%C]**	**Concentration [mg/L]**	**Percent of Total Contaminants [%]**
urea			60.1	20.0	13,400	36.2
sodium chloride	×		58.4	0.0	8,001	21.6
potassium sulfate	×		174.3	0.0	2,632	7.1
potassium chloride	×		74.6	0.0	1,641	4.4
creatinine			113.1	42.5	1,504	4.1
ammonium hippurate	×		196.2	55.1	1,250	3.4
magnesium sulfate	×		120.4	0.0	783	2.1
ammonium nitrate	×		80.0	0.0	756	2.0
ammonium glucuronate	×		211.2	34.1	663	1.8
potassium bicarbonate	×		100.1	12.0	661	1.8
ammonium urate	×		185.1	32.4	518	1.4
ammonium lactate	×		107.1	33.6	394	1.1
uropepsin (as tyrosine)			181.2	59.7	381	1.0
creatine			131.1	36.6	373	1.0
glycine			75.1	32.0	315	0.9
phenol		×	94.1	76.6	292	0.8
ammonium L-glutamate	×		164.2	36.3	246	0.7
potassium phosphate	×		212.3	0.0	234	0.6
histidine			155.2	46.4	233	0.6
androsterone			290.4	78.6	174	0.5
1-methylhistidine			169.2	49.7	173	0.5
glucose			180.2	40.0	156	0.4
imidazole			68.1	52.9	143	0.4
magnesium carbonate	×		84.3	14.2	143	0.4
taurine [2-aminoethanesulfonic acid]			125.1	19.2	138	0.4
constituents totaling less than 5%					*1,487*	*4.0*
ammonium aspartate	×		*150.1*	*32.0*	*135*	*0.4*
ammonium formate	×		*63.1*	*19.0*	*88*	*0.2*
calcium phosphate	×		*310.2*	*0.0*	*62*	*0.2*
ammonium pyruvate	×		*105.1*	*34.3*	*44*	*0.1*
ammonium oxalate	×		*124.1*	*19.4*	*37*	*0.1*
Total					**37,057**	**100**

Table 4-26 lists the anticipated contaminants from the latent condensate derived from experimental animals. Carter (1998) developed this list based on the International Space Station program.

Table 4-26 Wastewater Contaminants in Animal Latent Condensate

Component	**CI**	**SMAC**	**MW**	**Percent Carbon [%C]**	**Concentration [mg/L]**	**Percent of Total Contaminants [%]**
ammonium	×		18.0	0.0	581.88	81.9
acetic acid [ethanoic acid]		×	60.1	40.0	33.58	4.7
2-propanol		×	60.1	60.0	14.76	2.1
acetone [2-propanone]		×	58.1	62.0	14.69	2.1
phosphate			95.0	0.0	12.09	1.7
glycerol [1,2,3-propanetriol]			92.1	39.1	11.23	1.6
total protein			3,206.3	53.0	8.81	1.2
constituents totaling less than 5%					*16.36*	*2.3*
potassium	×		*39.1*	*0.0*	*5.07*	*0.7*
ethylene glycol [1,2-ethandiol]		×	*62.1*	*38.7*	*4.18*	*0.6*
sulfate	×		*96.1*	*0.0*	*1.47*	*0.2*
methanol		×	*32.0*	*37.5*	*1.25*	*0.2*
nitrate	×		*62.0*	*0.0*	*0.87*	*0.1*
chloride	×		*35.5*	*0.0*	*0.74*	*0.1*
calcium	×		*40.1*	*0.0*	*0.74*	*0.1*
2-butanol		×	*74.1*	*64.8*	*0.60*	*0.1*
magnesium	×		*24.3*	*0.0*	*0.56*	*0.1*
barium	×		*137.3*	*0.0*	*0.53*	*0.1*
zinc	×		*65.4*	*0.0*	*0.41*	*0.1*
acetaldehyde [ethanal]		×	*44.1*	*54.5*	*0.33*	*0.0*
formaldehyde [methanal]		×	*30.0*	*40.0*	*0.12*	*0.0*
nickel	×		*58.7*	*0.0*	*0.08*	*0.0*
copper	×		*63.6*	*0.0*	*0.07*	*0.0*
phenol		×	*94.1*	*76.6*	*0.04*	*0.0*
arsenic	×		*74.9*	*0.0*	*0.03*	*0.0*
iron	×		*55.9*	*0.0*	*0.02*	*0.0*
silver	×		*107.9*	*0.0*	*0.01*	*0.0*
manganese	×		*54.9*	*0.0*	*0.01*	*0.0*
Total					**710.55**	**100**

Table 4-27 details the anticipated aqueous contaminants in the greywater stream from an extravehicular mobility unit. This stream reflects Shuttle or International Space Station program technology so a similar stream for an advanced spacesuit may differ. Carter (1998) developed this list based on the International Space Station program. Currently, the condensate from the ventilation loop of the extravehicular mobility unit (EMU) is fed into its sublimator along with pre-existing circulating EMU feedwater Steele (2017). The EMU sublimatior consists of a porous steel plate which freezes the entering water and then subsequently sublimates the ice to space vacuum to reject excess heat Margiott (2014). For future long duration space missions, newer EMUs will likely evaporate off the condensate and feedwater within the cooling loop directly to ambient vacuum as it passes through the Spacesuit Water Membrane Evaporator (i.e., thin-walled hydrophobic hollow fibers) Izenson (2015) and Storming (2019).

Table 4-27 Wastewater Contaminants in Extravehicular Mobility Unit Air Stream

Component	CI	SMAC	MW	Percent Carbon [%C]	Concentration [mg/L]	Percent of Total Contaminants [%]
acetone [2-propanone]		×	58.1	62.1	0.0256	34.4
caprolactam			113.2	63.7	0.0227	30.6
Freon 113 [1,1,2-trichloro-1,2,2-trifluoroethane]	×	×	187.4	14.1	0.0108	14.5
ethylene glycol [1,2-ethandiol]		×	62.1	38.6	0.0035	4.7
tetraoxadodecane [2,5,8,11-tetraoxadodecane]			178.2	53.9	0.0035	4.7
tetradecanol [1-tetradecanol]			214.4	78.4	0.0029	3.9
sulfolane [tetrahydrothiophene-1,1-dioxide]			120.2	40.0	0.0020	2.7
*constituents totaling less than 5%**					*0.0029*	*3.9*
benzene		×	*78.1*	*92.3*	*0.0002*	*0.3*
toluene		×	*92.1*	*91.3*	*0.0002*	*0.3*
Total					**0.0742**	**100**

4.2.3 WASTEWATER AND INTERMEDIATE WATER SYSTEM SOLUTION FORMULATIONS FOR TESTING

Formulations for standardized wastewater solutions for developmental hardware are presented in (Verostko and Carrier, 2006). Verostko (2009) defined formulations of wastewater streams in spacecraft closed loop life support systems. The document includes procedures to prepare ersatz wastewaters of urine, humidity condensate, and hygiene. The urine ersatz consists of 21 organic compounds and 7 inorganic salts. The document summarizes minimum, average, and maximum physiological values of major urinary constituents. The humidity condensate ersatz consists of 26 ingredients for a total organic concentration, TOC, of 453 mg/L and 5 inorganic compounds with a total concentration of 131 mg/L. Approximately 90% of TOC is attributed to ten organic compounds with concentrations greater than 10 mg-TOC/L. The major inorganic constituent in humidity condensate is ammonium bicarbonate at a concentration of 125 mg/L.

4.3 WASTE SUBSYSTEM

The Waste Subsystem collects waste materials from life support subsystems and interfaces. Commonly, wastes are perceived as materials that have no further utility. However, because of the need for increased material loop closure for exploration missions, "wastes" encompass a variety of materials with varying degrees of possible future utility. Wastes might include crew metabolic wastes, food packaging, wasted food, paper, tape, soiled clothing, brines, inedible biomass, expended hygiene supplies, and equipment replacement parts from the other subsystems. The traditional definition of a waste within this document excludes most gases, depending on the system configuration. For example, crew-expelled carbon dioxide might not be recycled within a given life support system architecture. In such a case, although carbon dioxide is technically a waste material, the Air Subsystem typically assumes the responsibility for waste gases. However, the Waste Subsystem might ultimately collect the expended carbon dioxide scrubbing materials and trapped gases if those gases are not vented. Subsystem definitions can be somewhat blurry. For example, a waste-processing device might incorporate off-gassing contaminant control hardware, which is usually an Air Subsystem function, to control the release of potentially harmful gases. When the waste system incorporates it, it is referred to as Source Contamination Control (SCC).

When the function is provided by the Air Subsystem, it is referred to as Trace Contamination Control (TCC). Further information related to waste types and characteristics are included below.

Wastes sent to the Waste Subsystem may be handled in many ways. Wastes accepted by the Waste Subsystem may be collected, immediately prepared for short-term or long-term storage, processed to recover resources, processed to render them safe for disposal, and/or disposed of, depending on the mission-specific requirements and constraints. The mission requirements and constraints consider cost, safety, planetary protection if applicable, integration with other subsystems, resource recovery, and any other pertinent issues defined for a specific vehicle or habitat.

Current NASA spacecraft waste-handling approaches rely on venting and/or storage. On Shuttle missions, most waste was stored and returned to Earth with little or no processing. Consequently, the volume of wastes was significant. Fecal waste on the Shuttle was processed by drying fecal material via exposure to the vacuum of space as a form of SCC. Wet trash was similarly vented to space vacuum with special bags and compartments as a form of SCC. Urine and excess fuel cell water was vented to space vacuum on Shuttle missions to avoid the breakdown of urea to ammonia and to reduce reentry mass. On ISS wastes can be returned to Earth either previously aboard the Shuttle (in the Orbiter mid-deck or, within a multi-purpose logistics module in the payload bay), or currently with a commercial cargo vehicle (such as the Space X Dragon). However, the majority of ISS wastes are removed using a disposable vehicle that is intentionally incinerated during re-entry (such as the Russian Progress, the Japanese H-II Transfer Vehicle (HTV), the European Automated Transfer Vehicle(ATV), and/or expendable commercial cargo vehicles such as Cygnus).

Future long-duration mission wastes may be disposed directly like past missions. However, they are more likely to be processed (Pisharody, *et al.*, 2002; Broyan, *et al*., 2014) with the goals of reducing microbial growth and its accompanying odors, reducing its stored volume, processed to recover oxygen or water, or partly processed and stored. For example, during transit to Mars, jettisoning trash might be acceptable, though waste might be more useful if retained for radiation shielding. Jettisoning waste on the Martian surface may be constrained by planetary protection protocols for exploration missions. Waste processing options will depend upon the mission scenario, requirements, and cost/benefit ratio.

4.3.1 HISTORICAL DATA ON SKYLAB

Within the Gemini and Apollo programs, wastes were either returned to Earth in the vehicle, or dumped, most notably on the Lunar surface. On Skylab, the Saturn S-IVB [96] oxygen tank was used as a waste storage tank. The tank was vented to space through non-propulsive vents. Wastes were placed in the tank through an airlock and off-gassed to space. This eliminated the possibility of contamination of the interior crew areas, but likely contaminated the Skylab's exterior surfaces.

4.3.2 HISTORICAL WASTE LOADS FROM SPACE TRANSPORTATION SYSTEM MISSIONS

On Shuttle missions, waste was contained and stowed for return to Earth in either "dry" trash bags, or in the volume F "wet" trash. [97] Waste stream characterization and water content studies were performed for each of six Shuttle missions: STS-29, STS-30, STS-35, STS-51D, STS-99, and STS-101. The waste analyses for STS-29 through STS-51D were conducted to improve solid waste management for the Shuttle program (Peterson 2004). The waste analyses for STS-99 and STS-101 provided data to develop a waste model to support planning for future waste handling within the Life Support Project. Some data on waste composition has also been provided from STS 122 and STS-123.

In 1985, wastes for STS-51D were analyzed at NASA Ames Research Center to determine the chemical composition of wastes and characterize the trash (Wydeven and Golub, 1991). This study found that for 49.2 kg of total waste, 27.8 kg was food-related trash. Approximately 22 %, or 10.8 kg, of the trash recovered was comprised of food-related plastic packaging materials. Another 12.2 kg of other plastics and paper brought the total for packaging materials within the trash to almost 47 %. This data is presented in Table 4-28 and summarized in Table 4-29 and is equivalent to 49 CM-d.

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[96] The Skylab space station was fabricated from a modified Saturn S-IVB rocket stage.

[97] Shuttle stores trash generated within the vehicle itself in plastic bags or liners that are housed within designated storage areas on the middeck. Volume F is one such trash storage cabinet.

Table 4-28 Waste Analysis for STS-51D Trash

Trash Item	Mass [kg]	Moisture Content [%]	Fraction of Total Mass [%]	Reference
Food and Food Packaging				Wydeven and Golub (1991)
Plate Waste	4.8	70	9.8	
Plastic Food Containers	10.8	0.2	22.0	
Uneaten Food and Beverages [98]	12.2	0.2	24.7	
Biomedical	6.4		13.0	
Aluminum and Tape				
Grey Duct Tape	1.6		3.3	
Aluminum Cans	1.2	2	2.4	
Plastic and Paper				
Paper (mixed)	6.4	10.2	13.0	
Plastic Bags	3.2	0.2	6.5	
Miscellaneous Plastic	2.6	0.2	5.3	
Total	49.2		100.0	

Storage of wastes on-orbit during early Shuttle missions of 30 CM-d or less posed no challenge for the allotted resources of the Orbiter vehicle. However, as Shuttle missions lengthened for Extended Duration Orbiter of 112 CM-d or more, the volume allocated was inadequate for the safe stowage of trash. Research to determine future waste stowage requirements for Shuttle missions was initiated in 1989 by the Personal Hygiene and Housekeeping Laboratory at Johnson Space Center. The study objectives were to determine the mass and volume of waste generated per crewmember per day, and the amount of liquid stored in trash per crewmember per day (Grounds, 1990). Trash from Shuttle missions STS-29 (Garcia, 1989), STS-30 (Garcia, 1989), and STS-35 (Grounds, 1990) were analyzed. STS-35 differed from the two previous missions because STS-35 used pouches, and not boxes, for beverages and carried a prototype trash compactor (Grounds, 1990). Thus, there is a marked decrease in the volume of trash from STS-35 compared with the previous missions, probably in large part due to the change in drink packaging. This reduction in volume was consistent with data collected for STS-99 and STS-101 (Maxwell, 2000a and 2000b). The data from these missions is summarized in Table 4-29.

Not included in the trash data for Shuttle missions are dirty laundry or life support expendables, such as filters, that return to Earth separately from the trash. STS-101 generated ~50 kg of dirty laundry, consisting of clothing and towels, occupying ~0.5 m^3 (Maxwell, 2000b). Laundry was returned to Earth in mesh laundry bags. Storage, stabilization, and odor control for laundry, some of it wet, will require dedicated facilities on longer duration missions if no change is made to the current storage process. No data was available on life support system expendables for STS-101.

Table 4-29 summarizes waste stream analyses completed for STS-99 and STS-101, as well as historical data from STS-29, STS-30, STS-51D, STS-122, and STS-123.

The data from STS-122 and STS-123 was tabulated and recorded by an email by J. Villarreal in 2008.

Solid Waste Management for the International Space Station Mission

While limited containment and stowage planning is acceptable for Shuttle, ISS, with its 90-day resupply requires additional planning and controls.

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[98] This value corresponds to food and drink food packages that were never opened.

Table 4-29 Space Transportation System Crew Provision Wastes from Past Missions

		Trash (Solids)		Water	
Mission	Duration [CM-d]	[kg /CM-d]	[m^3 /CM-d]	[kg /CM-d]	Percent of Total Trash (by mass) [%]
STS-29 (1)	25	1.49	0.0139	0.345	27.35
STS-30 (1)	20	1.63	0.0133	0.417	35.35
STS-35 (2)	63	1.14	0.0067	0.218	26.80
STS-51D (3)	49	1.01		0.096	9.61
STS-99 (4)	66	1.47	0.0029	0.290	19.75
STS-101 (5)	63	1.62	0.0041	0.439	27.09
STS-122 (6)	91	1.16	0.0120	0.211	15.3 [99]
STS-123 (6)	49	1.57	0.0125	0.231	13.3 [99]
Average	54	1.39	0.0093	0.281	21.82

Reference

(1) Garcia (1989)
(2) Grounds (1990)
(3) Wydeven and Golub (1991)
(4) Maxwell (2000a)
(5) Maxwell (2000b)
(6) E-mail by J. Villarreal in 2008

4.3.3 HISTORICAL WASTE LOADS ON THE INTERNATIONAL SPACE STATION

In 1998, the first components of the International Space Station (ISS) were launched marking the beginning of its assembly and tenure. The ISS solid waste management is similar to that for *Mir*. Wastes are contained either in metal containers for human wastes, or plastic bags for crew provision and housekeeping wastes. Filled containers are returned to Earth either by Progress, ATV, HTV, or Cygnus which incinerate upon re-entry. During its tenure, significant changes to the waste management system of the ISS have been made to improve efficiencies and to reduce logistical masses. Specific examples of these improvements are the addition of the Water Recovery System (WRS) in 2009 which consists of the Urine Processor Assembly (UPA) and Water Processor Assembly (WPA). The UPA utilizes Vacuum Compression Distillation (VCD) process to recover water in the distillate which is then pumped to the WPA to further purify the distillate urine water to provide potable water for life support. The UPA takes water from the Waste and Hygiene Compartment (WHC) which consists of a Russian urinal system (called the ACY) or accepts manual transfer from the Russian EDV (Russian urine containers) in the Russian segment. With the addition of the UPA, approximately 70% or 85% of distillate is recovered from urine for the Russian and US segment, respectively (Carter*, et al.*, 2016). In recent years, demonstrations of new waste management technologies, such as the Universal Waste Management System (UWMS) in 2020 (Autrey*, et al.*, 2020) and the Brine Processor Assembly (BPA) in 2021 (NASA, 2021b) , have been brought to the ISS in hopes of further improving mass efficiencies and providing better closure of the water subsystem. From November 21, 2008 to May 10, 2018 the UPA produced 16,175 kg (35,659 lb_m) of distillate water versus a resupplied water mass of 2,215 kg (4,884 lb_m) representing significant mass savings (Carter*, et al.*, 2018). However, with these additions, new logistics waste masses associated with the operation of the WRS should also be noted. The ISS WPA relies on expendable multifiltration beds to remove contaminants in the wastewater as well as an ion exchange bed to remove oxidation products from the volatile removal assembly reactor. These expendable parts on the WPA represent an associated resupply requirement of approximately 472 kg/year (1,040 lb_m/year) (Carrasquillo, 2005). Additionally, distillation of urine to recover water leads to additional waste product in the form of urine brine. This brine is currently disposed of together with its container. The WRS represents one of the most significant improvements to the waste management of the ISS.

In consideration of the historical waste loads on the ISS, a significant portion of the total waste on the ISS is a result of both food and food packaging wastes where meals are individually packaged as well as bulk packaged in bulk overwrap bags (BOBs). Since the inception of the ISS, the amount of food provided to each crewmember per day has increased significantly from 1.83 kg/CM-d to 2.39 kg/CM-d (including packaging),

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[99] Assumed the Shuttle category wet trash is 30% moisture and so the total percentage of water is 30% of wet trash mass divided by the total trash mass.

resulting in increased logistical and waste values (Table 4-47). In addition to food wastes, hygienic items (wipes, towels, washcloths, *etc*.) and disposable clothing also constitute a significant portion of the total waste load from the ISS with masses of 719 and 439 kg per year, respectively, with 6 crewmembers on ISS [Ewert (2017) AES Logistics Reduction Project model]. As the ISS currently operates, there is no means of performing laundry, thus cloth items which are used for hygiene or worn are disposed. Due to the frequent resupply missions, typically every 2-3 months, historical waste values exhibited by the ISS may overestimate those expected for future long-duration missions where particular waste efficiencies may need to be improved without resupplies occurring, for example the generation of office paper waste. As part of NASA's Logistics Reduction (LR) project, the estimated logistical and waste masses and volumes for exploration missions have been provided in Ewert*, et al.* (2013) and in more recent LR model updates, which use ISS data as-is or scaled in some manner to account for improved efficiencies (NASA, 2021a).

The waste generation rates, including both Russian and United States On-Orbit Segments listed in Table 4-30, include known waste streams at the time of the assembly of the US segment of the ISS. These values do not take into account changes made to the ISS since its inception. The purpose of this table is to provide a broad estimate of the referenced ISS mission waste values. There are, however, significant gaps in the data.

Calculated overall waste generation rates, according to the life support subsystem and interface categories, using data from ISS human missions, are shown in Table 4-30, for reference missions associated with International Space Station. Some data here is inferred, such as air filters. These tables present generation of storable or disposable wastes based on the assumed configurations. A common list of hardware is used for all vehicles. In cases where particular hardware is not part of the configuration for a specific reference mission, the location within the table is marked with an "×." When hardware is present, but a storable or disposable waste is not produced, a "☑"appears. When hardware is present and a storable or disposable waste is produced, a rate, in terms of mass per crewmember per day, is listed. These tables list only wastes delivered from the hardware or elements for disposal or storage listed, including any containers.

The technology suite for segments or vehicles in Table 4-30 are denoted by prefixes. Vehicles or segments with a prefix of "ISS" assume a hardware suite using primarily technologies listed in Carrasquillo, *et al.* (1997) for the ISS. Vehicles or segments with a prefix of "ADV" use advanced technologies, as appropriate. Segments listed as Russian On-Orbit Segments of ISS use Russian ISS hardware and are provided as a reference. See RMD (2001) for details.

Possible types of waste are virtually unbounded, so Table 4-30 does not encompass all possible waste within a space mission. Further, the waste types are organized according to the subsystems and interfaces defined in Section 2.4 and detailed in RMD (2001). The configurations are not unique, nor are they necessarily complete. However, they provide a documented baseline. The crew contribution to the waste stream can enter more than one subsystem or interface. For example, the crew respiration and perspiration load is first received by the Air Subsystem, in the form of water vapor, or by the Human Accommodations Interface, on the clothing or as the result of crew hygiene maintenance.

Table 4-30 International Space Station Reference Mission Vehicle Wastes

	Assumptions [kg/CM-d]			
Component	**Russian Segment**	**ISS United States Segment**	**ADV. TECH. United States Segment**	**Notes**
Waste Subsystem Hardware				
Compactor	×	☑	☑	Compactors reduce waste volume and waste storage containment mass
Commode	☑	☑	☑	
Dryer	×	×	☑	
Fecal Storage	0.50 (1)	0.50 (1)	0.13 (1)	This entry includes the Russian KTO (Russian solid waste container). Usage is based on mass of waste. Mass of waste depends on moisture content, which varies between options.
Lyophilization	×	×	×	This technology yields a dry, stable solid waste and a separate greywater component.
Solid Waste Storage	☑	☑	☑	
Urine Collection	☑	☑	☑	
Urine Pretreatment	0.04 (2)	0.01 (2)	× (3)	This entry reflects chemical pretreatment, whether Russian or U.S. This is the mass of chemicals only.
Subtotal	**0.54**	**0.51**	**0.13**	

In cases where particular hardware is not part of the configuration for a specific reference mission, the location within the table is marked with an "×." When hardware is present, but a storable or disposable waste is not produced, a "☑"appears. When hardware is present and a storable or disposable waste is produced, a rate, in terms of mass per crewmember per day, is listed.

References: (1) Jones (2000); (2) Wieland (1998a and 1998b); (3) Personal Communication with M. Flynn 2003; (4) Carrasquillo, *et al.* (1997);(5) This current document Table 4-40; (6) Lange (1998); (7) Lin (1998).

Table 4-31 International Space Station Reference Mission Vehicle Wastes (continued)

	Assumptions [kg/CM-d]			
Component	**Russian Segment**	**ISS United States Segment**	**ADV. TECH. United States Segment**	**Notes**
Waste Subsystem Interfaces				
Air Subsystem	0.13 (4)	0.13 (4)	0.13 (4)	Based on ISS data. Reflects spares for the Air Subsystem.
EVA Support Interface Wastes	0.02 (5)	0.02 (5)	0.02 (5)	The difference in values reflects variations in EVA workload.
Food Interface Wastes				
Prepackaged Food Wastes	0.32 (5)	0.32 (5)	0.28 (5)	Assumption: Biomass production reduces prepackaged food mass slightly but increases infrastructure and other mass requirements.
Inedible Biomass	×	×	×	
Habitation Interface Wastes				
Expended Clothing		0.23 (5)	0.02 (5)	Clothing mass reduced by a factor of 40 with laundry.
Hygiene Wipes	0.23 (5)	0.23 (5)	0.15 (5)	
Thermal Interface Wastes	0.03 (4)	0.03 (4)	0.03 (4)	Based on ISS data.
Waste Subsystem to Environment				
Urine to Earth	0.16 (1)	×	×	Assumption: Stowage in EDV.
Solid Waste to Earth	☑	☑	☑	
Vacuum Vent (Lyophilizer)	×	×	×	Mass losses for Air and Water to be determined.
Subtotal	**1.71**	**1.55**	**0.63**	

In cases where particular hardware is not part of the configuration for a specific reference mission, the location within the table is marked with an "×." When hardware is present, but a storable or disposable waste is not produced, a "☑"appears. When hardware is present and a storable or disposable waste is produced, a rate, in terms of mass per crewmember per day, is listed.

References: (1) Jones (2000); (2) Wieland (1998a and 1998b); (3) Personal Communication with M. Flynn 2003; (4) Carrasquillo, *et al.* (1997);(5) This current document Table 4-40; (6) Lange (1998); (7) Lin (1998).

Table 4-32 International Space Station Reference Mission Vehicle Wastes (concluded)

	Assumptions [kg/CM-d]			
Component	**Russian Segment**	**ISS United States Segment**	**ADV. TECH. United States Segment**	**Notes**
Water Subsystem				
Air Evaporator Wicks	×	×	0.04 (6)	This value includes air evaporator wicks and urine solids. Assumption: Cases with a biological water processor are 50% less massive.
Flush Water	0.00 (2)	0.00 (2)	0.00 (2)	None identified to date.
Greywater from Dryer to Water Subsystem	×	×		
Urine Processing System Brine to Waste Subsystem	☑	☑	×	
Urine to Water Subsystem	☑	☑	☑	
Urine Processor	☑	0.33 (1,7)	☑	This entry based on vapor compression distillation performance. Brine is stored in an EDV (Russian wastewater container).
Water Processor Spares	0.33 (4)	0.33 (4)	TBD	
Miscellaneous	0.89 (5)	0.89 (5)	0.89 (5)	Based on ISS data.
Subtotal	**1.22**	**1.55**	**0.93**	
Overall Total	**3.47**	**3.61**	**1.69**	

In cases where particular hardware is not part of the configuration for a specific reference mission, the location within the table is marked with an "×." When hardware is present, but a storable or disposable waste is not produced, a "☑"appears. When hardware is present and a storable or disposable waste is produced, a rate, in terms of mass per crewmember per day, is listed.

References: (1) Jones (2000); (2) Wieland (1998a and 1998b); (3) Personal Communication with M. Flynn 2003; (4) Carrasquillo, *et al.* (1997);(5) This current document Table 4-40; (6) Lange (1998); (7) Lin (1998).

4.3.4 SOLID WASTE MANAGEMENT FOR FUTURE LONG-DURATION MISSIONS

Waste treatment and removal for missions to Mars and other likely near-term destinations will be more challenging due to the longer mission duration, regardless of complications from the environment. Waste management for such missions may employ more efficient versions of technologies developed for Shuttle and ISS, or completely different approaches may be more cost effective. Future missions will also generate significant amounts of inedible biomass. In later or far-term missions, inedible biomass may dominate all other waste sources. (See Table 4-92 and Section 4.13). Finally, depending on the mission protocols, indefinite stable storage for the end products of any waste-processing scheme will be necessary.

Historically, wastes generated during human space flight are materials with no further utility requiring only storage until mission's end. However, Exploration Waste Subsystems may reclaim resources from input wastes allowing greater closure within the overall life support system. It is also plausible that wastes from previous missions could be processed for useful resources on subsequent missions as additional technologies become available during accumulation of infrastructure.

The following tables provide data for various waste products, organized with references. Though not listed here, waste volumes can be significant. Further, although wastes are listed separately below, some wastes may be contained in or associated with other wastes. For example, feces may adhere to toilet paper, waste food may adhere to corresponding food packaging, and miscellaneous body wastes may adhere to hygiene wipes and dissolve or suspend in hygiene water. Also, various degrees of source separation are possible. For example, contaminated toilet paper might be collected in a container separate from the feces collector, or contaminated food packages might be collected separately from waste food.

These tables do not list all possible waste types for human space flight. Because many spacecraft systems routinely replace parts during scheduled maintenance on long-duration missions, a comprehensive list of wastes is contingent upon the hardware and configurations used throughout the vehicle. Thus, for a full understanding of equipment-related wastes during a particular mission, the replaceable units for each piece of hardware must be known, including any associated packaging. Rather, the tables list the wastes that are commonly of interest to advanced waste technology developers, due to an anticipated presence or processing potential. Processing potential may be related to resource recovery potential and anticipated pre-disposal treatment requirements. The tables list materials that have historically been sent to the Waste Subsystem. Thus, wastes such as carbon dioxide gas and trace gas contaminants are not included here.

As noted above, most wastes depend upon the life support system or vehicle design. For example, the rate of clothing supply and associated waste generation depends on the presence of a laundry system. The rate waste is generated from food packaging depends on the degree of food bioregeneration, or crop growth, within the vehicle. Further, the quantity and composition of metabolic wastes depend on the composition and quantity of food consumed; greater metabolic demands and greater consumption of dietary fiber may alter the generation rate for feces.

The tables present several mass values for some wastes. In such cases, an asterisk denotes the "preferred" or suggested value for waste models if there is an appropriate entry for that particular waste with other important defining factors about the waste being unknown. The suggested values are also summarized in Table 4-33. The variability between sources is somewhat indicative of the variability in data collection methods. When known, the data variability is provided below. Additionally, when known, variation of waste mass and composition with particular environmental parameters are noted, allowing for customization of waste characteristics for a specific purpose. The degree of confidence in data values is highly variable and often unknown. In some cases, data have not been diligently collected, and mass estimates are included. In other cases, the values are contingent upon environmental variables. Finally, the original or earliest data source available for a particular value is listed first, followed by other sources that reference the earliest source.

Table 4-33 Summary Information on Wastes for Developing Waste Models for Future Long-Duration Missions [100]

		Assumptions		
Waste	**Units**	**Lower**	**Nominal**	**Upper**
Equipment Wastes	g/CM-d		TBD (1)	
Experiment Wastes	g/CM-d		TBD (1)	
Extravehicular Activity Maximum Absorption Garments (MAGs)	g/CM-EVA		173 (1)	
Feminine Wastes:				
Menstrual Hygiene Products	g/CM-month		97.2 (2)	
Menses	g/CM-month	28 (2)	113.4 (2)	
Food Packaging and Adhered Food	g/CM-d	307 (3)	372 (3)	537 (3)
Gloves	g/CM-d		16 (4)	
Grey or Duct Tape	g/CM-d		33 (5)	
Greywater	g/CM-d		TBD (6)	
Greywater Brine	g/CM-d		TBD (6)	
Human Detritus:				
Finger and Toe Nails	g/CM-d		0.01 (7)	
Hair	g/CM-d		0.33 (7)	
Mucus	g/CM-d		0.4 (7)	
Saliva Solids	g/CM-d		0.01 (7)	
Skin Cells	g/CM-d		3 (7)	
Skin Oils	g/CM-d		4 (7)	
Sweat Solids	g/CM-d	3 (7)	18 (7)	
Hygiene Products, Miscellaneous	g/CM-d		781 (5)	
Inedible Biomass and Wasted Crop Materials	g/CM-d		TBD (3)	
Laundry: Clothing, Towels, and Wash Cloths	g/CM-d		230 (11)	
Medical Wastes	g/CM-d		TBD (1)	
Metabolic Wastes:				
Feces	g/CM-d	95.5 (8)	123 (8)	132 (8)
Urine	g/CM-d	1,390 (9)	1,562 (9)	2,142 (9)
Paper	g/CM-d	6.5 (5)	26 (5)	77 (5)
Wipes:				
Toilet Paper	g/CM-d		28 (10)	
Wipes, Disinfectant	g/CM-d		22 (4)	
Wipes, Dry	g/CM-d		37 (4)	
Wipes, Wet	g/CM-d		89 (4)	

References

(1) Table 4-42
(2) Table 4-36
(3) Table 4-40
(4) Table 4-39
(5) Table 4-41
(6) Section 4.3.4.9
(7) Table 4-38
(8) Table 4-34
(9) Table 4-35
(10) Table 4-37
(11) Ewert & Jeng (2015)

4.3.4.1 *FECES*

The mass and composition of feces varies with, among other factors, the quantity and composition of consumed food. Additional fiber in the diet is known to increase daily stool mass (Tucker, *et al.*, 1981). Wydeven and Golub (1990) provide detail for dry human feces. Hawk (1965) states "…the amount of fecal discharge varies with the individual and diet. Various authorities claim that on an ordinary mixed diet the daily excretion by an

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[100] This table includes both wet and dry components. Component moisture content is presented in the references.

adult male will aggregate 110-170 g with a solid content ranging between 25 and 45 g; the fecal discharge of such an individual on a vegetable diet will be much greater and may even be as great as 350 g and possess a solid content of 75 g."

Feces composition is described in Wignarajah, *et al.* (2006). The physical consistency of feces is also highly variable between crew members and within the same crew member over the mission.

NASA HIDH (2014) states that the fecal collection system "must be capable of collecting and containing an average of 150 grams (by mass) and 150 mL (by volume) of fecal matter per crewmember per defecation at an average two defecations per day". Consult the HIDH for additional information on maximum design values such as containment of 1.5 L of diarrhea discharge. Table 4-34 summarizes mass and composition information on feces from several sources. Note that values in this table are more typical average values versus conservative design values from the HIDH in the paragraph above.

Table 4-34 Feces

Waste	Units	Value	Comments
Feces	g/CM-d	123 (1)	Composition: 32 g/CM-d solids and 91 g/CM-d water. Ingested Food Composition: not available.
	g/CM-d	114 (2,3,7)	Composition: 32 g/CM-d "dehydrated residue" (4.5 g/CM-d fat, 4.5 g/CM-d protein, 1.8 g/CM-d cellulose, 9.5 g/CM-d inorganic matter, 11.4 g/CM-d bound water) and 82 g/CM-d water. Ingested Food Composition: not available.
	g/CM-d	95.5 (4,5)	Composition: 20.5 g/CM-d solids (19.5 g/CM-d standard deviation) and 75 g/CM-d water. Ingested Food Composition: "relatively low fiber diet, not unlike that eaten while in space." Note: 24 h mean sample; standard deviation of 95.7 g/CM-d.
	g/CM-d	132 (6)	Composition: 31 g/CM-d solids and 111 g/CM-d water. Ingested Food Composition: not available.
	g/CM-d	30 (8)	Composition: 30 g/CM-d solids. Ingested Food Composition: not available. Note: ***Dry mass only.*** Wet mass unavailable.
	g/CM-d	128 (9)	Composition: 29 g/CM-d solids and 99 g/CM-d water. Note: This study comprises a compilation of data from different literature sources constituting 112 data points. The reported values herein are the median wet and dry mass produced by the sample populations.
	g/CM-d	139.7 (10)	Composition: 30.1 g/CM-d solids and 109.6 g/CM-d water. Note: Composition of feces used in the URWARE wastewater treatment plant computer model.

Table References: (1) NASA (1991), (2) LSDB (1962), (3) BDB (1973), (4) Parker and Gallagher (1992), (5) Wydeven and Golub (1990), (6) Diem and Lentner (1970), (7) Schubert, *et al.* (1984), (8) Tucker, *et al.* (1981), (9) Rose, *et al.* (2015), (10) Jönsson, *et al.* (2005).

4.3.4.2 *URINE*

The mass and composition of urine varies with the individual, with the quantity and composition water and food consumed, as well as with other factors. Wydeven and Golub (1990) provide detailed estimates of human urine. For more recent information on calcium in urine issues during spaceflight, see Smith (2012) and Smith (2014).

(NASA HIDH, 2014) states that the urine collection devices shall have the capacity to accommodate urine output volume of 3,000 mL/CM on the first flight day and 2,000mL/CM-d after that and a discharge up to 1000 mL in a single urination event at a delivery rate of up to 50 mL/s.

Depending on the post-urination-event cleansing methods, urine may adhere to toilet paper or wipes. Depending on the life support system configuration, urine may or may not be included with greywater. Table 4-35 summarizes information on urine. Quantity varies based on fluid intake, which has been increasing on board ISS in recent years.

Table 4-35 Urine

Waste	Units	Value	Comments
Urine	g/CM-d	* 1,562 (1-4)	Composition: 59 g/CM-d solids and 1,503 g/CM-d water. Ingested Food Composition: not available.
	g/CM-d	1,700 (5)	Composition: 70 g/CM-d solids and 1,630 g/CM-d water. Ingested Food Composition: not available.
	g/CM-d	1,470 (6)	Composition: 70 g/CM-d solids and 1,400 g/CM-d water. Ingested Food Composition: not available.
	g/CM-d	2,107 (7)	Composition: not available. Ingested Food Composition: not available. Note: 24 h mean sample; standard deviation of 1,259 g/CM-d where 78% of the variation in urine output could be explained by variations in fluid consumed. The wet mass was calculated from urine volumes assuming a density of 1.02 g/mL.
	g/CM-d	1,390 (8)	Composition: not available. Ingested Food Composition: not available. Note: The wet mass was calculated from urine volumes assuming a density of 1.02 g/mL.
	g/CM-d	1,311 (9)	Composition: not available. Note: 24 hr mean mean sample taken during flight on the ISS for years 2006 – 2009. The wet mass was calculated from urine volumes assuming a density of 1.02 g/mL.
	g/CM-d	2,142 (9)	Composition: not available. Note: 24 hr mean mean sample taken during flight on the ISS for years 2010 – 2011. The higher urine volumes compared to 2006 – 2009 urine collections is a result of increasing fluid intake starting from crews that launched in 2010. The wet mass was calculated from urine volumes assuming a density of 1.02 g/mL.
	g/CM-d	1,420 (10)	Composition: 59 g/CM-d solids and 1,361 g/CM-d water. Note: This study comprises a compilation of data from different literature sources. The reported values herein are the median urine generation rate of the sample populations.
	g/CM-d	1,507 (11)	Composition: 20 g/CM-d solids and 1,487 g/CM-d water. Note: Composition of feces used in the URWARE wastewater treatment plant computer model. The lower solids content utilized in this model accounts for the urine solids entering a sewage treatment plant. It is expected that a significant portion of urea is rapidly degraded to ammonium and carbon dioxide in the piping system prior to entering the sewage treatment plant.

Table References: (1) BDB (1973), (2) NASA (1991), (3) Wydeven and Golub (1990), (4) Schubert, *et al.* (1984), (5) MSIS (1995), (6) LSDB (1962), (7) Parker and Gallagher (1988), (8) Leach (1983), (9) Smith, *et al.* (2012), (10) Rose, *et al.* (2015), (11) Jönsson, *et al.* (2005).

4.3.4.3 *MENSTRUATION*

Normally, adult female human beings menstruate once every 26 to 34 days for a duration of 4 to 6 days (NASA HIDH, 2014). These excretion products provide another waste generation source. Menstrual flow is highly variable between individuals. Consequently, menstrual pad and tampon use is also highly variable between individuals. Some female crewmembers on ISS use medication before flight to prevent menstruation for up to six months during flight. This approach, for many reasons, may not be acceptable for longer duration flights. Depending on the menstruation management and cleansing method used, menses may adhere to tampons, menstrual pads, toilet paper, or wipes. Table 4-36 summarizes information on menstruation using units of grams per crewmember per month [g/CM-month] which is representative of the average time between menstruation periods. To generate these waste production values, the total menses and menstrual product usage has been normalized assuming an average of 30 days, i.e. 1 month, between menstruation periods. The table comments can be read for further details on the derivation.

Table 4-36 Menstruation Byproducts

Waste	Units	Value	Comments
Menses	g/CM-month	* 113.4 (1)	Composition: 80% is released during the first 3 d of menstruation. Note: Menstrual period duration is 4 to 6 d every 26 to 34 d. Monthly rates are calculated assuming 113.4 grams per menstrual period and an average of 30 days between menstruation periods.
	g/CM-month	28 (2,3)	Composition: 10 g/CM-d solids (estimated). Note: Monthly rates are calculated assuming 28 grams per menstrual period and an average of 30 days between menstruation periods.
Menstrual Pads and Tampons	g/CM-month	97.2 (3)	Note: Monthly rates are calculated using a mean estimated tampon or menstrual pad usage of 15.2 products per menstrual period with an average of 30 days between menstruation periods. The average menstrual product (menstrual pads or tampons) is 6.4 g/product (clean).

Table References: (1) NASA HIDH (2014), (2) Hallberg and Nilsson (1964), (3) Parker and Gallagher (1992).

4.3.4.4 *TOILET PAPER*

Toilet paper usage varies with production rates and consistency of metabolic waste excretions. For all crewmembers, toilet paper is an important cleansing agent. Because of relatively frequent resupply, toilet paper usage on current human missions, such as ISS, may not be as frugal as possible for longer-duration missions with more-limited or no resupply. Some values can be found in Table 4-37.

Table 4-37 Toilet Paper

Waste	Units	Value	Comments
Toilet Paper	g/CM-d	28 (1)	Notes: Charmin (2002) claims that “the average person uses 57 sheets [of toilet paper] per day,” or 23 g/CM-d.
	g/CM-d	11.7 - 19.4 (2)	Note: Average toilet paper use based on a compilation of different literature sources. The toilet paper usage may also be categorized by men (Average Toilet Paper Use = 6 - 10.3 g/CM-d) and women (Average Toilet Paper Use = 17.9 - 36 g/CM-d)
	g/CM-d	23.0 (3)	Note: Composition of feces used in the URWARE wastewater treatment plant computer model.

Table References: (1) S. Maxwell (2001), (2) Rose, *et al.* (2015), (3) Jönsson, *et al.* (2005).

4.3.4.5 *MISCELLANEOUS BODY WASTES*

In addition to metabolic excretions, human beings also shed various wastes from the exposed surfaces of their bodies. These include sweat solids, dead skin cells and associated oils, hair, saliva solids, mucus, and finger and toe nails. Estimates and data for these waste stream components are detailed in Table 4-38.

Sweat solids may adhere to clothing, hygiene wipes, towels, wash cloths, and dissolve or suspend in hygiene greywater. Wydeven, and Golub (1990) and BDB (1973) provide approximate compositions for dry solids in sweat.

Dead skin cells, once free from the surface of the body, exist as cabin “dust,” and collect in the cabin air filter. However, some skin cells may adhere to clothing, hygiene wipes, towels, washcloths, or suspend in hygiene greywater. Wydeven, *et al.* (1989) provides estimates for particle and dust generation rates by human beings within a space station.

Table 4-38 Miscellaneous Body Wastes

Waste	Units	Value	Comments
Sweat Solids	g/CM-d	18 (1)	
	g/CM-d	3 (2,3)	
Skin Cells	g/CM-d	3 (2,3)	
Skin Oils	g/CM-d	4 (2,3)	
Hair	g/CM-d	0.33 (2,3)	Composition: 0.3 g/CM-d for facial shaving and 0.03 g/CM-d for depilation. Note: The study used only male subjects.
Saliva Solids	g/CM-d	0.01 (2,3)	
Mucus	g/CM-d	0.4 (2,3)	
Finger and Toe Nails	g/CM-d	0.01 (2,3)	

Table References: (1) NASA (1991), (2) LSDB (1962), (3) NASA HIDH (2014).

4.3.4.6 *DISPOSABLE HYGIENE AND CLEANING PRODUCTS*

Aboard ISS, crewmembers use a variety of wipes and gloves for various housekeeping and hygiene tasks, as shown in Table 4-39. Four types of wipes are listed below, and usage rates are based on recent ISS experience.

Table 4-39 Disposable Hygiene and Cleaning Products

Waste	Units	Value	Comments
Gloves	g/CM-d	16 (1)	Usage: Nitrile gloves to clean the toilet and other surfaces.
Wipes			
Dry	g/CM-d	37 (1)	Usage: Tempo wipes for various cleaning tasks.
Wet	g/CM-d	89 (1,2)	Usage: Huggies® brand Natural Care wet baby wipes/CM-d. K. Clark (2003) states that Huggies® wet baby wipes at 75% moisture have a mass of 10.9 g/wipe.
Russian gauze-y	g/CM-d	37 (1)	
Disinfectant	g/CM-d	22(1)	
Total: Cleaning Products	g/CM-d	201(1)	Includes Dry Wipes, Wet Wipes, Disinfectant Wipes, and Nitrile Gloves. Calculated rate references ISS launch rates and crew usage rates.

Table Reference: (1) Ewert (2017), (2) K. Clark (2003)

4.3.4.7 *FOOD PACKAGING, INEDIBLE BIOMASS, AND WASTED FOOD*

The food system, whether prepackaged or based on the conversion of crops, invariably generates a significant and unique waste stream. Prepackaged food systems generate waste streams including packaging, comprised of plastic bonded to a metallic layer, with adhered food. Crop-based food systems generate wastes associated with the crops and with the conversion of crops to finished entrees. Finally, the crew for many reasons may waste food in either system.

The first estimate in Table 4-40 provides an estimate of the minimal waste stream from a prepackaged food system. Levri, *et al.* (2001) assumed ambient-stored, prepackaged food, similar in nature to the Shuttle Training Menu. Further, each crewmember requires metabolic energy from food and only 3% of all prepackaged food and rehydration water was assumed to be wasted. This is a lower practical wastage limit to estimate the material wasted if the crew attempted to eat all of the food in every package that was opened. The food wastage represents approximately 3% of prepackaged food and rehydration water adhered to the sides of the packaging. Additionally, this study assumed that a small salad crop provides less than 1% of the crew's food energy needs.

The second estimate, from personal communication with S. Maxwell (2001b), an unpublished source to date, studied actual ISS food usage rates. This study collected information on the preferred menus of three ISS occupants during one expedition and computed the daily average per crewmember usage rates for food, packaging, and rehydration water. This study additionally assumed that 15% of all food packages shipped to ISS were unopened and discarded and that 5% of all opened food with any rehydration water was discarded while adhered to the food packaging. The actual values in Table 4-40 assume modified packaging numbers to reflect more recent food packaging mass data as presented in Levri, *et al.* (2001).

Crops and food processing may generate wastes during crop production, in the form of inedible biomass and expended nutrient solution or other growth support agents, and post-harvest during the production of food products and meals from the crops, in the form of wasted edible biomass, cleansing agents, food preparation fluids and agents, and even plate waste. These waste generation rates are highly variable and mission dependent.

Table 4-40 summarizes information on food packaging, inedible biomass, and wasted food.

Table 4-40 Selected References on Food Packaging, Inedible Biomass, and Wasted Food

Waste	Units	Lower	Nominal	Upper	Comments
Food Packaging Waste	kg/ CM-d	0.25 (2)	0.274 (2)	0.40 (3)	Lower and Nominal values: Assumes 1.83 kg/CM-d of food and packaging upmass. The lower value assumes that 10% of the food packaging never reaches the trash because there will be food reserves left at the end of mission. Whereas, the nominal value considers all food and packaging upmass to be utilized during mission. Upper value: Assumes 2.36 kg/CM-d total food and individual packaging mass (not including the bulk overwrap bag) where 17% of the total mass is packaging mass.
Waste Food Adhered to Packaging	kg/ CM-d	0.06 (1)	0.10 (2)	0.14	Lower value: 62 g/CM-d adhered food (~73% moisture content, including beverages). Nominal value: Assumes 7% adhered of 90% of mission food consumed (46.4% moisture). Upper value: Based on the assumption from the 2017 LR Model v 3.2(3) that 7% of the consumed food adheres to the packaging, and additionally, the upper value assumes all mission food is consumed.
Inedible Biomass and Wasted Crop Materials	kg/ CM-d	0.07	4.29	6.66	Note: Highly mission dependent. The lower value listed considers a diet where only salad crops are grown; the nominal value considers a diet where both salad and carbohydrate crops are grown; and the upper value considers a diet where all crops are grown. See Table 4-90 for inedible biomass productivity under typical crop growth chamber conditions. See Table 4-92for examples of diets using crops.

Table References: (1) Levri, *et al.* (2001), (2) Ewert (2017), (3) Goodliff (2021)

4.3.4.8 *PAPER, TAPE, MISCELLANEOUS HYGIENE PRODUCTS, AND CLOTHING*

Human activities generate a number of waste streams not related to metabolic activity. In particular, documentation generates waste paper, tape is used to seal plastic garbage bags, crew hygiene activities contribute many items to the waste stream, and clothing, when used, adds another waste stream for long-duration missions.

ISS uses paper for documentation and the data points in Table 4-30 is based on ISS usage rates. Waste paper generation rates can vary significantly between ISS increments and may not be closely correlated to the number of crewmembers. It is theorized that the relatively frequent upload and download of supplies to ISS is strongly related to the somewhat high rate of waste paper generation from documentation. Much lower waste paper generation rates for documentation are likely on longer-duration missions with little or no resupply.

Grey or duct tape has traditionally been used on Shuttle and ISS missions to bind bags of trash. On future missions, the crew may utilize other approaches for sealing trash bags and other tasks where tape might be used. Thus, tape usage is contingent on vehicle design.

As noted in Table 4-39, waste generation rates associated with personal hygiene products can be significant. The data here are based on ISS usage rates. These values may include items such as commercial-off-the-shelf (COTS) dental floss, toothbrushes, and containers for toothpaste, shave cream, razors, mouthwash, shampoo, moisturizing lotion, deodorant, sun block, lip balm, makeup, and similar personal hygiene products. It may be possible to reduce these through custom design containers but given the emphasis on COTS to reduce costs, that may be unlikely. Theoretically, the relatively frequent resupply schedule for ISS is strongly correlated to the surprisingly high rate of miscellaneous hygiene product waste generation because the individual crew products may not be completely used during an ISS crew rotation.

Clothing usage and associated dirty clothing generation rates are also significant historically, as documented in Table 4-45 for the early years of ISS. Actual expended clothing generation rates have been less than these early projections and a more recent value is found in Table 4-33. A laundry can increase clothing life, thus reducing waste generation rates associated with discarded clothing, at a cost of other vehicle resources such as power, crewtime, and water usage.

As a simplifying assumption, clothing is comprised of 100% cotton and has 8.5% moisture content when clean and dry, which is an industry standard for cotton. Actual clothing may be comprised of other materials that are more efficient and fire retardant, but historically crewmembers prefer clothing with higher cotton content. Cotton has also been used for ISS due to fire considerations. Clothing is in close contact with skin and will char rather than melt during a fire or high heat event. Recent Advanced Exploration Systems (AES) Logistics Reduction and Repurposing Project research has investigated wool, monoacrylic, and cotton polyester blends as possible replacements for cotton-based clothing (Broyan, 2014).

However, clothing will probably not be discarded in clean form. Rather, clothing, towels, and washcloths will likely contain skin cells, sweat solids, skin oil, hair, and other miscellaneous body wastes. Towels and washcloths will likely also contain moisture from sweat and bathing. McGlothlin (2000) reports that the average 49-g Class III [101] Shuttle washcloth, measuring 30.5 cm by 30.5 cm and comprised of 100% cotton, retains up to 202 g of water when completely soaked. On ISS, crew members typically allow their washcloths, towels, and clothes to air dry prior to disposal to allow recovery of the moisture.

Table 4-41 summarizes information on waste streams from paper, tape, miscellaneous hygiene products, and clothing.

Table 4-41 Composition of Paper, Tape, Miscellaneous Hygiene Products, and Clothing

Waste	Units	Lower	Nominal	Upper	Comments
Paper	g/CM-d	6.5 (4)	26 (4)	77 (1)	Composition (1): 6% moisture content. Note (4): Nominal value is based on ISS usage rates and lower value assumes a 75% reduction for exploration missions
Grey or Duct Tape	g/CM-d		33 (2)		Note: This value is highly design contingent. The value here represents ISS usage.
Misc. Hygiene Products	g/CM-d		781 (1)		Note: This value is highly design contingent. The value here represents ISS usage. Future missions may allow much lower waste generation rates from miscellaneous hygiene products.
Clothing, Towels, and Washcloths	g/CM-d		230 (3)		Composition: 100% cotton solids, with 8.5% moisture content (clean and dry).

Table References: (1) Maxwell (2001), (2) Wydeven, *et al.* (1989), (3) Ewert (2013), (4) Ewert (2017).

4.3.4.9 *GREYWATER AND BRINE*

Wastewater and brines, though historically processed by the Water Subsystem, may initially or after processing pass to the Waste Subsystem. Section 4.2.2 lists wastewater generation rates and stream compositions. However, these tables do not provide greywater generation data for configurations with crop production or food processing. Greywater production from such activities depends on the crops produced, the growing techniques, the crop processing approaches following harvest, the food processing technology, and the processing equipment and crop cleansing approaches. Finally, greywater may also include urine.

In general, greywater production rates and, more importantly here, the rate of wastewater transfer to the Waste Subsystem, are highly dependent upon the vehicle design. The individual greywater production rates are

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[101] Note: "Class III" hardware is dimensionally the same and functionally similar to flight, or "Class I," hardware. However, Class III hardware is not, in general, identical to Class I hardware.

variable, and decisions about how the wastewater streams are managed significantly influence the wastewater and brine loads passed to the Waste Subsystem.

Brine production rates depend primarily upon the architecture of the water system. If greywater is processed for reuse, the degree of recovery determines the composition of the brine remaining after treatment. Most advanced physicochemical water processors recover up to 95 to more than 99% of the water from the input greywater stream.

4.3.5 ELEMENTAL COMPOSITION OF WASTE

4.3.5.1 *MODELING WASTE SYSTEMS*

Table 4-44 represents approximate elemental compositions for some components that make up the waste stream. Approximations of the major constituents of the waste stream and an assumed end product of carbon dioxide (CO_2) and water (H_2O) or methane (CH_4) will allow a quantitative look at mass of end products in the proposed reaction. Using tools such as this can lead to system mass balances that can be quite useful in looking at loop closure modeling for life support by tracking carbon, oxygen, nitrogen, and hydrogen. This approach yields a simplified but beneficial model.

Different missions will likely have different requirements in the waste stream produced and in the amount of waste produced. A transit mission, to the Lunar surface might be roughly equivalent to a Space Shuttle mission because they all originate from relatively short missions. From the initial mass of input components, all the product and waste components can be calculated. The feces produced is 123 g/CM-d (Table 4-34) and is 70% water by mass initially. The dry initial mass of feces is 36.9 g/CM-d. A 300-day mission for four crew members could produce 44 kg of feces. If completely oxidized, this could produce 32 kg of water in addition to the 103 kg from the initial drying step. This approach provides insight into the amount of waste generated and the potential yield of useful commodities gained from waste component recycling. The results of some calculations based on stoichiometry by assuming waste is composed of only major elements, are shown in Equation 4-1.

Usually the waste product is a polymer, and the estimation is made assuming the molecular weight of the polymer building block. For example, cellulose is composed of linked chains of glucose molecules. Paper is made of wood pulp which consists mainly of hexose and pentose chains of simple carbohydrates. This allows a modeling relationship between the mass of wastes on prior missions and the stoichiometry used to predict the product. [102]

$$C_{42}H_{69}O_{13}N_5 + 52.75O_2 \rightarrow 42CO_2 + 34.5H_2O + 2.5N_2$$ Equation 4-1

(A stoichiometric approach to oxidation of feces)

4.3.5.2 *OTHER WASTE STREAMS*

Several other notable waste streams are possible. Wastes associated with extravehicular activities depend on the frequency of extravehicular activities. Other waste streams from equipment, experiments, and medical tests are highly variable and depend on the vehicle and mission architecture.

Extravehicular activities (EVA) supply waste streams to the life support system. While some wastes are gaseous, others are solid wastes. Most significantly, crewmembers are provided with a maximum absorption garment (MAG) to catch metabolic wastes. A used garment may be contaminated with urine, feces, and other wastes associated with exposure to human skin. The data in Table 4-42 is based on ISS equipment and production rates in terms of grams per crewmember per EVA sortie [g/CM-EVA]. Data on other likely EVA wastes, such as food sticks, drink pouches, and batteries, were unavailable. EVA consumption rates for consumables are given in Table 4-42 although these values do not reflect solid waste production rates. Equipment wastes are highly variable and depend upon the overall vehicle design. Equipment wastes include supplies for life support hardware, such as filters and plastic bags. Generally, the Waste Subsystem design depends upon the life support system

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[102] Serio, *et al.* (2008) measured an oxygen-carbon molar ratio of 0.6-0.8. There is, however, a great deal of variability in feces composition due to dietary variability. This should be considered by analysts because the literature is not exhaustive due to the inherent variability.

architecture, including the degree of resource recovery and containment for pre-processing storage, post-processing storage, and disposal. For example, a system in which there is no recovery from solid wastes, such as on ISS, may require more Waste Subsystem resupply items than a system that reuses or recovers resources. Regarding storage options, some equipment wastes might be returned to its original stowage volumes, although cleaning may be required before such an approach is acceptable. For example, contaminated membranes from the Water Subsystem might be cleaned to remove water wastes and then stowed in the original stowage volume for membranes. Experimental wastes are highly variable and depend upon experimental procedures and the mission objectives. Some waste materials may be hazardous. Medical wastes are also highly variable and depend upon medical protocols. These waste loads could be very sporadic and may require special handling. Some waste product materials may even be a biohazard. Table 4-42 summarizes information on EVA, equipment, experiment, and medical waste streams.

Table 4-42 Other Waste Streams

Waste	Units	Value	Comments
EVA Wastes	g/CM-EVA	173	Note: This value represents the maximum absorption garment (clean and dry)
Equipment Wastes	g/CM-d	TBD	Note: Highly variable and dependent on vehicle design.
Experiment Wastes	g/CM-d	TBD	Note: Highly variable and dependent on mission design. Waste streams delegated to the Waste Subsystem will depend on mission protocols. Some wastes may be hazardous.
Medical Wastes	g/CM-d	TBD	Note: Highly variable and dependent on mission medical protocol. Waste streams delegated to the Waste Subsystem will depend on mission protocols. Some wastes may be biohazards.

Table References: (1) EDCC (1998)

4.3.6 WASTEWATER RECOVERY MODEL FOR A LUNAR SURFACE MISSION

Prior to performing a system level trade study to evaluate the potential effect of recovering water from waste, it is necessary to have a waste model that reasonably characterizes the anticipated waste streams. Similarly, in combination with Research and Technology Development (R&TD), and Waste Management System (WMS) requirements and drivers, this waste model will drive technology development. A significant amount of previous work has been performed that identified potential wastes from various historical mission scenarios, both from post-mission analyses of discarded wastes as well as supply uploading information. This information is largely kept current within this document. There is no widely established waste model for a long-duration Lunar surface mission at this time. Therefore, mission analyses are often conducted using analysis-specific (customized) waste models that employ varying assumptions and design values.

A major goal of this waste model development effort is to generate a central "working document" that is widely accessible and that could serve as a focal point for continuing refinement. Developing this type of waste model for new classes of missions that are still in initial planning creates a significant amount of uncertainty. Therefore, it is anticipated that data contained in this model could change significantly as mission definition and development progresses. This waste model is therefore not intended to be a final product, but rather a beginning point. With this in mind, the model was constructed using a spreadsheet format that allows users to readily change mission assumptions, mission design values and even add functionality (Hogan, 2010).

A full characterization of wastes requires a large number of parameters. The most pertinent waste characteristics that require examination for a water balance study include the waste type, mass, and moisture content. These data are sufficient to estimate the water recovery potential and are the central data for this model development. Additional data will eventually be needed for a more refined analysis to support detailed waste processing equipment selection, sizing, and integration studies. These additional data may include waste volume in relevant waste mixtures and under different levels of compaction (e.g., none, manual, mechanical, heat-melt), including materials of construction, elemental composition, and biodegradability. As such, the wastes would need to be generated in a realistic fashion and processed in actual WMS technologies to obtain much of this information.

4.3.6.1 *MODEL DEVELOPMENT AND CHARACTERISTICS*

The data collected for this model were obtained or derived from a number of sources including various technical papers, textbooks and previous waste model studies. The general approach was to identify the anticipated wastes and to classify them according to waste similarity and/or subsystem/operation. Although certain waste streams are currently difficult to predict or are unplanned (e.g., experiment wastes, biomass production), those classes were included to ensure they are addressed as data become available.

The model is designed to allow the user to select various mission parameters. This includes the crew size during the nominal mission, as well as during any mission overlap period. The mission overlap period is that time between when a new crew arrives, and the old crew departs. Estimates appear to vary with exactly how long this overlap period will be, but 30 days appears to be the current maximum. Likewise, the mission duration and overlap period are specified as model parameters. The average percent of female crewmembers is required in that males and females impose different hygiene waste loads.

EVA is accounted for by requesting the average number of EVA sorties per day. Currently, the only calculation that EVA pertains to is the generation of Maximum Absorbency Garments (MAGs). It is assumed that each EVA performed by a crewmember requires a fresh MAG, and that the EVA duration is approximately 7-8 hours. Even though the assumed average EVA rate may be fractional, in total the number will be equivalent to the total number of MAGs utilized. An important feature of the MAG as a waste item is that it will contain human urine and feces. Extended EVA will result in a significant portion of a crewmember's daily urine generation to be trapped in the MAG. No data were found that approximate the average percentage, so a value of 33% was estimated. It is also unclear what percentage of fecal wastes will be contained in a used MAG, but it is assumed that the crew will be resistant to defecate in the MAG during EVA. Therefore, it was assumed that MAGs contain 10% of fecal waste. This is equivalent to defecating a one-day amount of feces once out of every ten EVA operations. This appears reasonable considering the long duration of EVA periods.

Another related assumption is that a certain fraction of defecations will be diarrheal. This is important in that diarrhea will contain much higher amounts of water than nominal feces. From NASA HIDH (2014), it was assessed that each diarrheal event would be 0.5 L on average. Additionally, it is assumed that the same amount of fecal solids are contained in that volume, and that the remainder is composed of water. As no data were found with regards to the average number of diarrhea events, particularly for a Lunar mission, it was assumed that one defecation per month was diarrheal.

The data inputs for the actual mass and water content of wastes expected for the model waste components were provided as nominal, minimum, and maximum values. The nominal values were selected to be the most likely value at this point in the mission planning. The minimum and maximum values were provided to give a reasonable design range. This is anticipated to be valuable for technology developers when sizing waste processing and storage equipment. These upper and lower values were synthesized by evaluating data ranges (when available) or by alternatively assuming a percent variance from nominal.

Using the various mission parameters, waste component design mass values and moisture content are calculated and listed separately in a separate area of the spreadsheet. These data are summarized in the final section to allow the user to easily discern the totals of various waste stream component mixtures. This was performed because there are uncertainties within the mission architecture that will play a critical role in what the WMS will receive, and therefore, what the WMS must accommodate. For example, if wastewater brine is not processed further by dewatering, this waste stream will exert a strong influence on overall waste stream water content and how the waste system must be designed to process/store it.

4.3.6.2 *LUNAR OUTPOST WASTE MODEL RESULTS*

Table 4-43 contains a model used to calculate Lunar outpost wastes. These values were obtained both from personal communication with J. Hogan (2010) as well as adapted from Fisher, *et al.* (2010). It must be noted that certain design assumptions are under development, and significant changes in the assumptions are likely with time. Therefore, it is valuable to approach the results of this model as preliminary guidance, rather than final results.

Hogan (2010) and Fisher, *et al.* (2010) have provided results for the total mass of Lunar outpost mission wastes for the case of 4 crew staying 210 days and a second crew of 4 overlapping for the last 30 days. Here only normalized data will be presented on a per crewmember per day basis. The water mass contained in waste is also presented in Table 4-43. In this model each crew member produces a nominal average of 1.49 kg/CM-day at a moisture content of 41.9% when brine is not included.

The data in the table is presented in a manner that facilitates understanding how waste production rates will vary in accordance with future WMS designs. For example, the nominal crew-member production rates will increase from 1.49 to 1.90 kg/CM-day if wastewater brines are not further dried for both water recovery and volume reduction. This significant increase, which is mostly water, points to serious consideration of drying wastewater brines. The waste mass will increase only slightly due to the inclusion of the brine solids obtained after drying (1.56 kg/CM-day).

If a laundry system is utilized and clothes are not discarded, the waste production rate drops significantly. Because this mixture does not contain feces, laundry items or brines, it is likely akin to the waste fraction typically referred to as trash in past missions. It should be noted that some clothes will eventually be discarded as they age beyond functional use. A value of 0.0373 kg/CM-day can be used as a clothes attrition rate with a laundry system for a 180-day mission and can replace the laundry values used in this spreadsheet if a clothes washing system is implemented.

The rate of feces production increases from 0.123 to 0.140 kg/CM-day by including a single diarrheal event per month. Further definition is required to fully reflect the issues of fecal production rates, including the effect of high rates of EVA, which may increase food intake and concomitant feces generation.

Another waste source that was revealed to be a significant source of water was the urine contained in the maximum absorbency garments (MAGs) used during EVA. The model assumed that 33% of a crew-member's total daily urine production was collected in the MAG per EVA event (EVA events were assumed to be of long duration, 7-8 hrs). Although it is likely that the crew will take measures to empty their bladder prior to EVA, the EVA will be conducted for a long period, and a substantial amount of water will be consumed by the crew while inside the suit. The 33% value represents approximately 0.515 kg/CM-day, which is a significant portion of the overall waste produced per day. This is also the principal reason why the moisture contents presented in Table 4-43 are substantially higher than previous waste model values. This is an important issue when evaluating the potential for water recovery from wastes, as the MAGs would likely need to be stored in the Lunar rovers and processed at the core habitat to recover that water. The assumed rate of EVA used in this model (22.3 hrs EVA per day) is substantially higher than the value used in a previous analysis (7.3 hrs EVA per day, Lange, 2009). This value was the result of a Lunar architecture study aimed at surface systems (R. Bagdigian, 2009). One area that remains undefined and is not addressed in this model is the issue of packaging used for items other than food. There is the potential that consumable items may come individually wrapped in plastic, paper or in foam. While paper and plastic (film) can readily be incorporated with most other wastes, the foam that often protects shipped hardware can be stiff and bulky. It must be decided where such wastes will be processed and/or stored. They are unlikely to contain any significant water, so these types of additional wastes are unlikely to serve as a significant water source/sink, and the exclusion of them from this model will affect only the waste mass estimates as definition is required.

4.3.6.3 *RECENT WASTE MODEL EFFORTS*

From 2012-2017 researchers developed an ”exploration” logistics and waste model for NASA's Logistics Reduction and Repurposing project (Ewert, 2013; Broyan, 2014; Goodliff, 2017). This model predicted 1.1 kg/CM-d of crew solid waste, including feces, but excluding brine, plus an additional 0.4 kg/CM-d of life support systems waste such as filters, waste tanks, *etc*. In comparison, the Lunar outpost waste model (Table 4-43) waste model predicts 0.87 kg/CM-d of nominal solid waste, excluding brine, with water content of 41.9%. The nominal water content (41.9%) of the Lunar outpost waste model (Table 4-43) is higher than that assumed in the Logistics Reduction and Repurposing waste model (30.0%). This may be due to the Lunar outpost waste model (Table 4-43) being based on the Shuttle program when water recycling was not implemented thus resulting in greater wastewater. Current and future missions have and will place greater emphasis on mass savings from water recovery. Additionally, one waste item that was quite a bit lower than the Lunar outpost waste model's (Table 4-43) earlier estimates was clothing and towels.

Table 4-43 Lunar Outpost Mission Waste Sources Design Values and Water Content

Waste Components	Nominal Design Values	Minimum Design Values	Maximum Design Values	Units	Nominal Moisture Content (%)	Minimum Moisture Content (%)	Maximum Moisture Content (%)
Lunar Outpost Mission - Waste Sources Design Values and Water Content Food System Wastes:							
Food Packaging	262	236	288	g/CM-d	0.0	0	0
Food Adhered to Packaging	62	59	68	g/CM-d	73.0	68	78
Equipment Wastes:							
TBD	0	0	0	g/CM-d	0.0	0	0
Experiment Wastes:							
TBD	0	0	0	g/CM-d	0.0	0	0
Feminine Wastes:							
Menstrual Hygiene Products	3.7	3.3	4.1	g/CM-d	0	0	0
Menses	1	0.8	5	g/CM-d	36	36	36
Wastewater Recovery System Wastes:							
Hygiene Wastewater (no urine)	7,170	6,453	7,887	g/CM-d	99.8	99.5	99.9
Humidity Condensate	2,270	2,043	2,497	g/CM-d	99.99	99.9	99.999
Urine	1562	1390	2107	g/CM-d	96.2	95.7	96.7
Solids in Brine After Processing	18	15	20	% Solids	na	na	na
Human Detritus:							
Finger and Toenails	0.01	0.01	0.01	g/CM-d	0	0	0
Hair	0.33	0.30	0.36	g/CM-d	0	0	0
Mucus	0.40	0.36	0.44	g/CM-d	95	95	95
Saliva Solids	0.01	0.01	0.01	g/CM-d	0	0	0
Skin Cells	3.00	2.70	3.30	g/CM-d	0	0	0
Skin Oils	4.00	3.60	4.40	g/CM-d	0	0	0
Sweat Solids	18.00	16.20	19.80	g/CM-d	0	0	0
Hygiene Products:							
Miscellaneous	0.00	0.00	0.00	g/CM-d	0	0	0
Biomass Production Wastes:							
Inedible Biomass/ Waste Crop Materials	0.00	0.00	0.00	g/CM-d	0	0	0
Clothing (without laundry):							
Clothing, towels, washcloths	343	309	377	g/CM-d	8.5	8.5	15
Medical Wastes:							
Miscellaneous	0.00	0.00	0.00	g/CM-d	0	0	0

Table 4-43 Lunar Outpost Mission Waste Sources Design Values and Water Content (cont)

Waste Components	Nominal Design Values	Minimum Design Values	Maximum Design Values	Units	Nominal Moisture Content (%)	Minimum Moisture Content (%)	Maximum Moisture Content (%)
Lunar Outpost Mission - Waste Sources Design Values and Water Content							
Metabolic Wastes:							
Feces (nominal non-diarrheal)	123.00	95.50	132.00	g/CM-d	74	69	79
Diarrheal Feces	500.00	450.00	550.00	g/CM-event	93.6	92.8	94.2
Vomitus	11.70	11.70	50.00	g/CM-d	80	70	90
Urine	1,562	1,390	2,107	g/CM-d	96.2	95.7	96.7
Extravehicular Activity:							
Extravehicular Activity Maximum Absorbency Garment (MAG)	173.00	173.00	173.00	g/ MAG	8.0	7.0	10.0
Urine contained in MAG per EVA event	25	20	30	% of total daily urine production	96	96	96
Feces contained in MAG per EVA event	5	2	10	% of total daily feces production	75	70	80
Wipes:							
Toilet Paper (Clean and Dry)	6	5	28	g/CM-d	8.0	7.0	10.0
Wipes, Detergent	58	52	64	g/CM-d	75	70	80
Wipes Disinfectant	56	50	62	g/CM-d	75	70	80
Wipes: Dry	13	12	14	g/CM-d	8	7	10
Wipes, Wet	51	46	56	g/CM-d	75	70	80
Miscellaneous:							
Gloves	7.00	7.00	14.00	g/CM-d	0.0	0.0	0.0
Tape	33	0	40	g/CM-d	0	0	0

Table 4-43 Lunar Outpost Mission Waste Sources Design Values and Water Content (Results)

Moisture Content (%)	% Water (Nominal)	% Water (Minimum)	% Water (Maximum)
Waste (no brine or brine solids)	41.9	38.9	49.2
Waste (includes brine and brine solids)	50.5	54.2	54.6
Waste (includes brine solids)	39.9	36.2	47.2
Waste (no brine/solids, laundry items)	51.9	48.7	58.1
Waste (no brine/solids, laundry items, feces)	48.6	45.7	55.5
Feces only (normal and diarrheal)	76.4	72.3	80.9
Crew Production Rates	**kg/CM-d (Nominal)**	**kg/CM-d (Minimum)**	**kg/CM-d (Maximum)**
Waste (no brine or brine solids)	1.49	1.26	1.84
Waste (includes brine and brine solids)	1.90	1.89	2.23
Waste (includes brine solids)	1.56	1.36	1.92
Waste (no brine/solids, laundry items)	1.15	0.95	1.46
Waste (no brine/solids, laundry items, feces)	1.01	0.85	1.32
Feces only (normal and diarrheal)	0.14	0.11	0.15
Wastewater Brine (urine, humidity cond., hygiene)	0.41	0.39	0.63

Table 4-44 Estimated Stoichiometric Model of Useful Waste Products

Waste Processing Stoichiometry					
			Theoretical Products, kg/CM d	H_2O, kg/CM-d	CH_4 kg/(CM-d)
feces	See Volk (1987)	$C_{42}H_{69}O_{13}N_5$	0.123	0.09	
food pkg, kg/CM*d	polyethylene, polystyrene, polypropylene (equal 3rds)	C_nH_{2n}	0.220		0.13
plus adhered food	50% CHO(glucose), 27.5% fat(squalene), 22.5% Protein(isoleucine)	$C_6H_{12}O_6$, $C_5H_9O_2$, $C_6H_{15}O_2N_2$	0.098	0.07	
uneaten food	50% CHO(glucose), 27.5% fat(squalene), 22.5% Protein(isoleucine)	$C_6H_{12}O_6$, $C_5H_9O_2$, $C_6H_{15}O_2N_2$	0.249	0.21	
Maximum Absorbency Garment, kg/CM d	Lunar, Long Duration Mission: 4 EVA/CM-week or 0.57 EVA/CM-d (Coan ,2020)	CH_2-CH(COONa)	0.173	0.058	
Gray Tape, kg/CM*d	80% polyethylene polymer + 20% butadiene polymer	C_2H_4+C_5H_{10}	0.033		0.14
Paper	Cellulose (glucose polymer); wood fiber (analysis the components showed glucose (65.8%), xylose (19.8%), galactose (12.5%) and mannose (1.3%))	$C_6H_{12}O_6$, $C_5H_{10}O_5$	0.105	0.08	
Towels & Washcloths	Cotton (95% cellulose)	$C_6H_{12}O_6$	if “x” is the mass sent to waste	0.09x	
Clothing	With polybenzimidazole fire retardant	$C_{11}H_{15}N_2$	“x” is the mass sent to waste		0.37x

4.4 HABITATION INTERFACE

Habitation functions are diverse and cross many systems, including environmental control & life support, crew health & safety, and logistics. There are many potential definitions of habitability depending on the vehicle level assumed. At the highest vehicle level, habitation consists of the entire crew module including the pressure shell structure, Environmental Control and Life Support Systems (ECLSS), power/avionics systems, human systems architecture, and crew health/medical equipment. At the lower vehicle levels, habitation consists of discrete hardware systems ranging from tools and crew quarters structures to specific human factors requirements. For purposes of this section, Habitability is defined as crew hardware and logistics required to utilize vehicle systems and to maintain crew productivity. It does not include primary vehicle structure (the habitat), ECLSS, or medical equipment. Habitation areas that do not impact ECLSS (i.e., autonomous logistics management, quiet acoustic interiors, logistics packaging, crew structures) are generally not discussed in this document.

Habitation systems are needed for (1) future crewed weightless transits, (2) reduced gravity planetary Lunar or Martian surfaces, and (3) long duration, deep-space environments. Logistics required to support humans are generally proportional to the duration of the space mission and may amount to 3.7 kg/CM-d (Ewert, 2013). Exploration missions away from low-Earth orbit greatly limit allowable consumables and require development of innovative low maintenance, re-configurable, and reusable systems. Minimal volume configurations (or dual use) during non-use mission phases are highly desirable.

4.4.1 CLOTHING SYSTEMS

Clothes have not traditionally been part of an environmental control and life support system. However, the data here detail some of the many interfaces between crew clothing, overall crew support mass, and the Water and Waste Subsystems. The approach for ISS is to resupply disposable clothes as needed. Alternately, clothes could be cleaned and reused to significantly reduce the mass of clothes allotted per mission.

The main interfaces between other life support subsystems and a traditional laundry subsystem would be the mass of water to support an aqueous washer and the corresponding water vapor load. Fu*, et al.* found the total laundry water mass required for a crew of three to be 4.79 kg/d during a 105-day, multicrew, closed integrative bioregenerative life support systems experiment which integrated water-processing with atmospheric management, crop production, insect breeding, and waste recovery (Fu, 2016). The water vapor load would depend on the performance of the laundry system, but assuming that most of the wash water is removed mechanically, leaving a mass of water within the fabric equal to the mass of the clothes. Table 4-45 provides a summary of clothing and laundry options. Estimates of water use for laundry have decreased over time, indicating improvements in washing machine technology.

Table 4-45 Clothing and Laundry Options

	Mass [kg]	Mass [kg/CM-d]	Volume [m^3/CM-d]	Power [kW]
ISS Approach (clothes shipped, single use):				
From Chaput (2003)		0.343 (1) [103]		
From JCPC (1999)		0.718 (2)	0.0013 (2)	
From Branch (1998)		1.69 (3)	0.00135 (3)	
From Reimers and McDonald (1992)		1.47 (4)	0.00140 (4)	
From Jeng and Ewert (2015)		0.206(7)	0.00058(7)	
Using a Laundry:				
Clothes		0.267 (4)	0.000351 (4)	
		0.0746 (6a)	0.00044 (6a)	
		0.0373 (6b)	0.00022 (6b)	
		0.0191 (6c)	0.00011 (6c)	
		0.022 (7)	0.00010 (7)	
Laundry Equipment	118 (4)			0.31 (4)
	80 (6)			0.751 (6)
Interfaces (Water)		12.47 (5) [104]		
		7.33 (6)		
		1.6 (8)		

References

(1) Chaput (2003). Based on clothing allocation "as planned" for ISS
(2) JCPC (1999). Based on clothing "as planned" for ISS.
(3) Branch (1998)
(4) Reimers and McDonald (1992)
(5) NASA (1990)
(6) Jeng and Ewert (2002)
(6a) Jeng and Ewert (2002); 90 d mission duration
(6b) Jeng and Ewert (2002); 180 d mission duration
(6c) Jeng and Ewert (2002); 600 d mission duration
(7) Ewert & Jeng (2015) for ISS type mission
(8) Fu (2016)

4.4.2 STOWAGE SYSTEMS

Interior/exterior stowage systems are required that maximize usable volume and include contents identification and inventory control systems. Long-term external stowage for biological or other wastes on a planetary surface that is safe and consistent with planetary protection policies will be needed. One example of a planned stowage system is the EVA and Crew Survival System currently planned for Orion (i.e., Table 4-46).

Table 4-46 Estimates of Mass and Volume for Stowed EVA Suits and Emergency Suits

System	Subsystem	Unit Volume [m^3]	Length [m]	Width [m]	Height [m]	Unit Mass [kg]	Stowed Volume - 4 CM [m^3]	Mass [kg]
EVA & Crew Survival	Pressure Suits & Equipment for Launch	0.188	0.575	0.574	0.574	37.3	0.750	149.1
	Suits&Equipment for Post Landing	0.004	0.160	0.160	0.160	1.81	0.016	7.21
	Emergency O_2	0.495	0.457	0.178	0.040	4.54	0.209	18.1
	Umbilicals (5 CM)	0.025	3.050	0.090	0.090	6.35	0.124	31.8

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[103] Chaput (2003) gives ISS planning values for clothing of 10.3 kg per crewmember per 30 days.
[104] The laundry uses clean water and provides a waste stream of greywater to the water recovery system.

4.4.3 WARDROOM SYSTEMS

Wardroom systems are erectable or inflatable systems that support crew dining, conference, external viewing (windows), illumination, and relaxation activities. This includes off-nominal events, such as emergency medical or equipment repair. The Wardroom system typically does not have an ECLSS interface. However, some crew functions such as eating, emergency medical, or repair activities may require functions to capture particulate or liquid material.

4.4.4 CREW HYGIENE SYSTEMS

Crew Hygiene Systems are low maintenance/self-cleaning fecal, urine, menstrual, emesis, hand/body wash, and grooming systems. Specific areas include non-foaming separators and no-rinse/non-alcohol hygiene products. On ISS full body hygiene is conducted by dispensing a small amount of water into a washcloth and taking a sponge bath. The washcloth and towel are allowed to air dry to recover water via the air system condensing heat exchanger. No dedicated area is defined for drying hygiene items and it has resulted in periodic surface mold growth on ISS. Future areas should incorporate a dedicated drying area with antimicrobial treatments. Long term missions should improve full body hygiene.

Toilet systems should consider air, liquid, vacuum, and low-gravity transport methods. Collected waste should be prepared for recovery or long-term stabilization. Urine pretreatment systems may be part of the toilet hardware system, but their development is part of the water recovery system. Integrated hygiene systems should provide, acoustic and odor isolated private crew volumes compatible with multi-gravity interfaces.

4.4.5 CREW ACCOMMODATION SYSTEMS

Habitation systems should consider the following general crew accommodation system functions: re-configurable crew volumes), multi-use workstations, crew radiation exposure mitigation, physically and psychologically ergonomic personal volumes, automated deployment, quiescent operations between missions, multi-purpose stowage systems for, and automated housekeeping/self-repairing habitat surfaces.

ISS currently has dedicated crew quarter (CQ) volumes with ~250lbs of integrated radiation shielding material. For exploration, minimal mass deployable crew quarters that can utilize logistics and processed waste for radiation shielding are desired. Approximately 5% of ISS CQ mass and ~15% of ISS CQ volume was dedicated to acoustic mitigation. For exploration, low mass and volume acoustic mitigation using active noise cancellation of ventilation ducts and open cabin environments are potential approaches. Active quiet fan development will also reduce the need for both passive and active noise mitigation.

4.4.6 GALLEY SYSTEMS

Galley systems are systems requiring minimal crew preparation (heating, cooling, and rehydration) for food heating and accurate water dispensing. Specific areas include systems that allow individual crew meal flexibility and high-energy efficiency. Conductive heating of food is typically used because of its low average power and ability to minimize hot spots in foods that may have variable water content (dehydrated foods to which water has been added). A forced convective oven may offer reduced heating times when combined with a conductive heating element. Although microwave ovens are typically faster for terrestrial applications the variability of rehydrated food moisture and the use of metallic foil food packaging to help limit oxygen diffusion into the food (which shortens shelf life), generally prevents the use of microwaves in space flight.

The rehydration system is generally one of the distribution points of the water processing system. The rehydration system requires protection of back contamination of food and microorganisms that may develop from the food/rehydration system interface. On ISS the food package septum and rehydration system needle leaked water due to crew manipulation of the food package and resulted in fouling and eventual replacement of the food hydration interface. The rehydration system also requires long life point-of-use microbial filters to protect the water processor. The rehydration system may also require removal of the water processor biocide if the crew cannot tolerate consumption for long periods of time (e.g. ISS iodine/iodide biocide must be removed by ion exchange (I/X) prior to rehydrating food).

4.4.7 HABITAT LIGHT OUTPUT AND DISTRIBUTION

ISS originally was outfitted with primarily florescent lighting which typically required small amounts of mercury within the glass tubes. The glass tubes of florescent lighting needed to be protected to contain glass particles in the event the tubes were inadvertently broken. In recent years the efficiency of florescent lights has been matched and exceeded by light emitting diode (LED) based lighting and is an inherently directional light offering better control than sources like incandescent, fluorescent, or metal halide lamps. In addition, LEDs are solid state devices that contain no mercury and have a long operating life, up to five times that of arc discharge lamps (Bourget, 2008). If properly designed to direct light where it is needed, LED fixtures can provide efficient, uniform lighting at the desired illumination for space habitats and vehicles (Roberts, 2008; Bourget, 2008; Shultz 2009). LED technology is envisioned to be the primary technology for future vehicles. In general, commercial industry will drive the technology and only require adaption of thermal dissipation from LED technology for microgravity space applications. LED operating temperature must be controlled to prevent excessive heating from decreasing their high light output efficiency and long life. There is medical research in the area of multispectral lighting to control circadian rhythm and improve sleep. These may be useful in future long duration missions, especially if more than one crew shift is required.

4.5 FOOD INTERFACE

Food, though historically omitted from life support analysis, has significant impacts on closure and the cost of crew support. In particular, food resupply to maintain the daily energy requirements for crewmembers to properly fulfill mission operations as well as a potable water source, make up a substantial mass consideration. In this section, food will be discussed in both a historical context, that is what have typically been the food plans on prior space flight missions, as well as a in a future planning context. In the latter case, values have been provided for a nominal intravehicular activity (IVA) and extravehicular activity (EVA) operations as well as the parameters for refrigeration options. In addition, bulk food packaged options have been considered and highlighted for their ingredient mass, volume, and nutritional content. Food, if grown on-site, can regenerate some or all of the crew's air and water. If more than about 25% of the food, by dry mass, is produced locally, all the required water can be regenerated by the same process. If approximately 50% or more of the food, by dry mass, is produced on site, all the required air can be regenerated by the same process (Drysdale, *et al.*, 1997). The former value depends on the crop and growth conditions. The latter number, however, depends on the cropping scenario and the overall harvest index. These considerations are discussed in the latter subsections.

4.5.1 PHYSICAL PARAMETERS FOR HISTORICAL FOOD FLIGHT SYSTEMS

The crew food energy requirement will depend on the crew themselves, their lean body mass and the amount of physical work they perform. EVA, for example, requires additional food energy compared with crews conducting only IVA because more physical work is typically associated with an EVA. As per the NASA (2019), the food system shall provide crewmembers with the minimum amount required for their daily energy demands, based upon the estimated energy requirements (EER) equation (Equation 3-2). The typical average energy intake using these requirements is 12.707 MJ/CM-d which assumes the mean astronaut population values of 82.4 kg, 1.786m, and 45 years of age (NASA, 2010). However, because EVA operations require significantly higher energy expenditure, the NASA (2019) requires an additional 837 kJ/EVA-hr above the nominal metabolic intake. Thus, the average caloric intake can change depending on the EVA load. Analysis in this area should use the EER equation and the +837 kJ/EVA-hr above nominal requirement to plan out the required energy intake based on specific mission details. Within the Food Interface Subsection of this document, in addition to the current average requirement of 12.707 MJ/CM-d, the previous NASA requirement of 11.82 MJ/CM-d (NASA, 1991) has also been referenced in the provided data throughout.

The mass of food required depends heavily on the lipid content and the degree of hydration. A 30% lipid content, by metabolic energy, is generally recommended though much lower levels of lipids have been suggested by some sources. Degree of hydration is largely a function of the type of food and the method of processing and storage. Fresh foods can have as much as 99% water content, by mass, while dehydrated foods have as little as 3% moisture.

Food quality is not specifically discussed here, because this topic is addressed when the Food Subsystem is designed. However, food quality can have a tremendous impact on crew morale and the success of a long-duration mission. The mass of food also depends on food quality. Digestibility will also vary, being lowest for vegetarian diets. As noted above, these factors are currently beyond the scope of this discussion.

Besides the mass of food itself, food requires packaging and/or appropriate containment to protect it from degradation and contamination. Packaging includes wrapping and/or boxes around the food itself, such as for individual servings. The material of the packaging is a strongly driven by the requirement to minimize oxygen permeation from the atmosphere. Oxygen will generally react with food enabling spoilage and reducing shelf life. Currently the ISS type food packaging provides a shelf life of approximately 2 years (Douglas*, et al.* , 2016), product/process/package dependent for most food items. NASA's Human Research Program (HRP) recognizes this as a risk for exploration but to date there has been limited development of new materials. Douglas*, et al.* (2016) presents the evidence for the negative impacts to crew performance and increased risk of crew illness due to an inadequate food system. The information provided in the document is presented relative to the desire for exploration missions and hence notes the capability gaps, as identified by NASA's HRP. The document describes the methods, technologies, and requirements that increase food stability, maintain adequate nutrition, quality, and variety, and enable the growth and supplementation of the diet with salad crops while reducing resource use. Appropriate containment describes stowage, such as food lockers, provision of a suitable atmosphere, temperature, and other environmental conditions, such as freezers for some foods, and secondary structure to house the stowage and environmentally conditioned chambers. Section 3.2.3 provides estimates for supporting secondary structure with the Food Subsystem. Analysis indicates that an additional ~17 % mass penalty, based on fresh food mass, is appropriate for individually packaged meals. Note that the values presented in Table 4-47 are historical or predicted averages for the indicated programs and, therefore, may or may not provide the current requirements for metabolic energy.

Table 4-47 Historical and Near-Term Food Subsystem Masses

Parameter	Mass [kg/CM-d]	Volume [m^3/CM-d]	Comments	Water Content [%][105]
IVA Food, dry mass	0.67 (1)		A Reference Value	0 (1)
Space Transportation Food System				
STS Food[106] (see also Table 4-48)	0.66 (2)		Food Dehydrated, 11.82 MJ/CM-d	0 (2)
	1.147 (2)		Food As-Shipped, No Packaging, 11.82 MJ/CM-d	42 (2)
	0.26 (2)		Packaging Alone (clean)	
	0.35 (2)		Container Mass (ISS “Pantry-style storage”) without secondary structure	
	1.76 (2,3)	0.0048 (2)	Food As-Shipped, Packaged (ISS “Pantry-style storage”), and within a Container	42 (2)
International Space Station Food Systems				
ISS	1.83 (4) – 2.39 (5)	0.00472(4) - 0.006304(5)	Food As-Shipped, Packaged	48.7 (6)[107] 53 (7)[108]

References

(1) MSIS (1995), Section 7.2.2.2.3
(2) Levri (2002)
(3) Bourland (1999)
(4) Perchonok, *et al.* (2002)
(5) Douglas (2017)
(6) Ewert, *et al*. (2019).
(7) Douglas (2021).

Table 4-48 A 10-Day Menu for Short-Term Missions

Mission Day	Mass [kg]	Energy [MJ]	Rehydration Water [L]
1	1.60	12.41	2.99
2	1.68	13.01	2.67
3	1.45	12.41	2.45
4	1.26	12.33	2.67
5	2.04	13.27	2.31
6	1.38	12.37	2.81
7	1.82	13.21	2.16
8	1.16	11.97	2.70
9	1.23	12.36	2.52
10	1.68	12.53	2.72

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[105] The percentage of water content considers the food only and does not include packaging mass.

[106] Space Transportation System (STS) food systems are provided for reference only. They do not meet nutritional requirements for long-duration space flight. (For example, while this diet meets all minimum nutritional requirements, it exceeds the limit for sodium and iron for a weightless diet.) These food systems do not use any refrigeration. Historically, in a personal communication with C. Bourland (May 25, 1999) he reported an empty locker for food aboard Shuttle has a mass of 6.4 kg. Filled, this locker holds up to 42 individual meals (Perchonok, *et al.*, 2002). The overall locker mass, when filled, is 24.5 kg (personal communication with C. Bourland (May 25, 1999)). This is equivalent to 0.583 kg/meal, or 1.75 kg/CM-d. The Shuttle food system is shelf-stable without any frozen components. Note that assessments from Levri (2002) assume ISS “Pantry-style storage” and not Shuttle lockers.

[107] Estimate based on 1.83 kg/CM-d.

[108] Adjusted to remove packaging mass. Corresponds to 2.39 kg/CM-d value using the standard food system.

On the ISS, crew members generally have 180-day mission durations in which their food diet is composed of dried, vacuum packaged food, natural foods (i.e., nuts, cookies, granola, dried fruits), and thermostabilized foods. Table 4-47 shows the average food mass per person for Orion. The Orion mission may provide each crew member 2 full meals and a high calorie food bar. For longer duration space missions, prepackaged foods with a five-year shelf life are needed (Cooper, *et al.* 2011) and will be used en route to Gateway or on a Mars transit vehicle.

For a food system based on the Shuttle Training Menu, as detailed above (Table 4-47), Levri (2002) lists the properties of the rehydration apparatus and conduction oven collectively as 36.3 kg occupying 0.094 m^3 based on the Shuttle galley. During use, the rehydration apparatus consumes up to 0.540 kW to heat water. The conduction oven, when operational, consumes up to 0.360 kW for heaters and 0.060 kW for fans. Thus, the maximum total power load for the galley is 0.960 kW during operation.

Perchonok, *et al.* (2002) reports that a loaded ISS food container for ISS Phase II averages 5.5 kg each and contains nine meals plus snacks. This is equivalent to a single day's food for three ISS crewmembers. This is equivalent, on average, to 0.611 kg/meal, assuming snacks are extensions of the standard meals, or 1.83 kg/CM-d. Individual food container masses vary according to individual crew entrée preferences and nutritional requirements, and the containers themselves are placed in racks, incurring a secondary structure penalty not included in the masses above. These contents did not equate to the current 12.707 MJ/CM-d (~3000 kcal per day) requirement. It should also be noted that crews will choose what they want from these options, and this does result in some food waste. Over time the amount of food used on ISS has increased and the higher values of 2.39 kg/CM-d and 0.006304 m^3/CM-d in Table 4-47 are based on the maximum 6-month rate of food bags opened.

(Cooper, 2011) and (Cooper, 2012) discuss exploration food systems, including those which contain a bio-regenerative component.

4.5.2 PHYSICAL PARAMETERS OF REFRIGERATION EQUIPMENT

Table 4-49 presents characteristics for the ISS refrigerator/freezer technology. These units were designed, but the ISS Program decided not to launch them or the planned frozen food system. The internal volume and internal load apply to the internal refrigerator or freezer cargo capacity within a single unit assigned to a single rack, while the other parameters generally describe the exterior properties of the overall unit. ISS later added a small refrigerator for the crew.

Each previously mentioned ISS refrigerator/freezer was designed to fit within one ISS rack and had four cold volume compartments, each with a dedicated thermoelectric thermal control system. The refrigerator/freezer could operate in one of three modes, depending on the thermostat settings for the internal compartments. In the freezer mode all four compartments operate as freezers, in the refrigerator mode all four compartments operate as refrigerators, and in the refrigerator/freezer mode two compartments operate as refrigerators while the other two compartments operate as freezers. The overall system thermodynamic coefficient of performance (COP_S) for the ISS refrigerator/freezer in freezer mode is 0.36 (Ewert, 2002a). Waste heat is rejected to the internal thermal control loops. The unit was designed to have an operational lifetime of 10 years, with servicing provided on the ground once a year.

Table 4-49 International Space Station Refrigerator / Freezer Properties

	Units	Freezer Mode	Refrigerator / Freezer Mode
Unit Mass	kg	321.0 (1)	321.0 (1)
Secondary Structure Mass	kg	91 (2)	91 (2)
Volume, Including Rack	m³	2.00 (3)	2.00 (3)
Volume, Without Rack	m³	1.16 (3)	1.16 (3)
Power	kW	0.268 (4)	0.205 (4)
Thermal Control	kW	0.297 (4)	0.228 (4)
Crewtime	CM-h/y	0 (1)	0 (1)
Logistics	kg/y	321.0 (1)	321.0 (1)
Internal Load	kg	295 (1)	295 (1)
Internal Volume	m³	0.614 (1)	0.614 (1) [109]

References

(1) Toups, *et al.* (2001)
(2) Shepherd (2001)
(3) Vonau (2002)
(4) Winter, *et al.* (2001)

More generally, Table 4-50 lists properties for frozen food storage per frozen-food-mass (ffm) basis. The nominal and low values reflect advanced or anticipated technologies, while the high values are based on ISS technology. Vapor compression and Stirling refrigeration technologies are more efficient, generally exhibiting higher COP_S values than thermoelectric approaches. However, these advanced technologies are at low technology readiness and require further development to meet space flight requirements, especially with respect to weightlessness and acoustics (Ewert, 2002a).

As described in Ewert (2002b) and presented in Equation 4-2, the specific power consumption for a cooled volume within a cabinet, $\widehat{W}_{RF}$ [kW/kg_{ffm}], may be expressed as an empirical function of two system-level values, the composite thermal resistance, R_S [$m^2 \cdot K/kW$], and COP_S [$kW_{electrical}/kW_{thermal}$]. R_S characterizes the overall resistance to heat transfer to or from a cooled volume, such as a refrigerator or freezer, through the cabinet wall accounting for insulation, door seals, and any other pathways for heat transfer. COP_S is the system-level coefficient of performance defined as the net heat removed from the cooled volume divided by the total electrical power consumed by the refrigerator or freezer unit including the heat pump cycle and all supporting equipment. The assumed frozen food density within the cooled volume, including packaging and gaps, is 480 kg/m³. The current ISS-based volume is larger than the data used for this calculation which will drive the density lower. The assumed air temperature within the cooled volume is -22 °C, while the ambient external cabin temperature is 23 °C.

$$\widehat{W}_{RF} = 1.028 \left(\frac{1}{R_S}\right) \left(\frac{1}{COP_S}\right) \qquad \text{Equation 4-2}$$

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[109] In refrigerator / freezer mode, half of the internal cold volume is a refrigerator while the other half is a freezer.

Table 4-50 Frozen Food Storage on a Property per Frozen-Food-Mass Basis

		Assumptions		
Characteristic	**Units**	**Low**	**Nominal**	**High**
$1/COP_S$	$\frac{kW_{\text{electrical}}}{kW_{\text{thermal}}}$	0.5 (1)	1.0 (1)	9.2 (1)
$1/R_S$	$kW/m^2 \cdot K \times 10^{-3}$	0.28 (1)	0.32 (1)	0.32 (1)
Mass [110]	kg		220 (4)	321 (2)
	kg/kg_{ffm}		0.75	1.09
External Volume, Including Rack	m^3		TBD	2.00 (3)
	$m^3/kg_{ffm} \times 10^{-3}$			6.78
External Volume, Excluding Rack	m^3		1.16 (4)	
	$m^3/kg_{ffm} \times 10^{-3}$		3.93	
Power	kW	0.048 (1)	0.096 (1)	0.268 (1)
	$kW/kg_{ffm} \times 10^{-3}$	0.16	0.33	0.91
Thermal Control	kW	0.053 (1)	0.106 (1)	0.297 (1)
	$kW/kg_{ffm} \times 10^{-3}$	0.18	0.36	1.01
Crewtime	CM-h/y	0.0	0.0	0.0
	$CM\text{-}h/(y \cdot kg_{ffm})$	0.0	0.0	0.0
Logistics	kg/y	0.0	0.0	321 (2)
	$kg/(y \cdot kg_{ffm})$	0.0	0.0	1.09

References

(1) Ewert (2002)
(2) Toups, *et al.* (2001)
(3) Rodriguez and England (1998)
(4) Vonau (2002)

4.5.3 *Crewtime for the Food Subsystem*

Overall crewtime requirements in the galley depend on the form in which food is shipped and its preparation requirements. Crewtime required for food preparation during Space Transportation System (STS, or Shuttle) missions was 45 - 90 minutes per day for a crew of up to six (NASA, 1996). This approach uses individually packaged servings. If food preparation requires more than heating and/or re-hydration, then the additional preparation complexity increases crewtime for preparation compared with current systems. However, more involved preparation may allow for higher quality food.

Personal communication with J. Hunter (1999) provides another estimate of crewtime for food preparation. Hunter's model assumes that each crewmember eats ten different food dishes per day. For a crew of six, each dish prepared using ingredients provided by bioregenerative methods requires 15 to 45 minutes each, while each dish taken from resupplied stocks requires an average of 6 minutes to prepare based on NASA (1996). Assuming meals prepared using bioregenerative methods each require 30 minutes, on average, to prepare, a diet based on crops grown on-site would require 5.0 CM-h/d, or 0.83 CM-h/CM-d, assuming a crew of six. Daily meals prepared completely from resupplied foods would require 1.0 CM-h/d, or 0.17 CM-h/CM-d. Assuming five dishes are prepared from crops grown on site and five dishes are prepared from resupplied stocks, daily meal preparation time would be 3.0 CM-h/d or 0.50 CM-h/CM-d.

Kloeris, *et al.* (1998) report meal preparation time during the Lunar Mars Life Support Test Program (LMLSTP) Phase III test while using the 10-day BIO-Plex menu averaged 4.6 CM-h/d.

There will also be crewtime requirements to process the crops into edible food ingredients. These times, though expected to be significant, have not been estimated to date.

4.5.4 *Food Subsystem Waste Generation*

Wastage will depend on the type of food and the type of preparation but can be quite large. For example, during the 10-day BIO-Plex menu test conducted during the LMLSTP Phase III, total waste, including preparation, plate waste, and unused, leftover food, was 42% (Kloeris, *et al.*, 1998). Typically, much lower values are assumed for prepackaged food systems. Wastage occurs both due to food adhering to packaging and due to plate wastage.

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[110] Including the freezer mass and rack but excluding the secondary structure.

Waste model values are noted below and in Section Table 4-40 for both historical pre-packaged food systems and projected food systems based on crops from bioregenerative life support systems.

4.5.5 OVERALL FOOD SUBSYSTEM PARAMETERS

Typical values from literature for food-related masses are shown in Table 4-51. This includes both the IVA food and water quantities as well as the additional allotments that may be required to accommodate EVA operations. The values listed herein are based off the ISS average food supply planning value of 2.39 kg/CM-d to provide a nominal amount of energy. The energy basis of 12.778 MJ/CM-d used in this table is the result of the MetMan model which mimics the values found in Section 3.3.5. A more in-depth breakdown of the nominal metabolic requirements based upon the ISS food allotment (2.39 kg/CM-d, including packaging) can be found in Table 3-31 and its accompanying text.

Table 4-51 Food Quantity and Packaging

		Assumptions		
Parameter	**Units**	**Lower**	**Nominal**	**Upper**
IVA Food, dry mass	kg/CM-d	0.617 (1)	0.80 (2)	0.96 (2)
IVA Human Metabolic Water Production	kg/CM-d	0.345 (1)	0.490 (2)	
IVA Energy	MJ/CM-d	11.820 (1)	12.778 (2)	
IVA Potable Water Consumption	kg/CM-d	3.524 (1)	3.217 (2)	
EVA Food, dry mass, added [111, 112]	kg/CM-h	+0.029 (4) [113]	+ 0.052 (2)	
EVA Metabolic Water Production added[111, 112]	kg/CM-h	+0.016 (4) [113]	+ 0.032 (2)	
EVA Energy added [111]	MJ/CM-h	+0.570 (7)	+ 0.837 (3)	
EVA Potable Water Consumption [111]	kg/CM-h			+0.240 (3)
Packaging	kg/kg food		+ 18.0 % (2)	
Crewtime	CM-h/d	1 – 1.5 (5)	1.5 (5)	4.6+ (6) [114]

References

(1) NASA (1991)
(2) Ewert, *et al.* (2019a)
(3) NASA (2019)
(4) Derived from McBarron, *et al.* (1993)
(5) NASA (1996)
(6) Kloeris, *et al.* (1998)
(7) Rouen (2001)

4.5.6 FOOD SUBSYSTEM BASED ON BULK PACKAGING [115]

French and Perchonok (2006) recently developed a 10-day menu using a bulk commodity supply approach that may serve as a basis for estimates for supplying food via such an approach. Specifically, this approach endeavors to reduce packing mass and storage volume by packing food commodities in bulk. This benefit is offset by increasing crewtime to prepare meals and adding some additional food processing equipment to enable more complicated food preparation processes. This approach also increases overall menu shelf-life by storing food commodities in a form that is inherently more stable, thus assuring better food quality for longer-duration missions. Finally, because some commodities cannot be successfully stored in any form, this approach assumes a biomass production facility to provide salad crops, white potatoes, and sweet potatoes. The initial study assumed a 600-day surface mission on Mars, but the format presented below should be applicable to missions of any duration with the most direct benefit derived from those of longer durations. The presentation here is, by

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

[112] Additional EVA food and water requirements are derived from the nominal IVA food, dry mass, and water scaled by the additional EVA energy relative to the nominal IVA energy.

[113] Metabolic rate of 293 W/CM and a respiratory quotient of 0.9.

[114] This value is derived using “ready to use” ingredients and includes no crop processing to develop ingredients. An estimate including crop processing to develop ingredients might be double this value, or ~9 CM-h/d, or more.

[115] Unless noted otherwise, all material in this section is derived from French and Perchonok (2006).

necessity, abbreviated and interested readers should consult French and Perchonok (2006) for additional information.

4.5.6.1 *COMMODITIES*

Table 4-52 provides a listing on the ingredients for the 10-day, bulk-commodity menu on a per-crewmember, per-day basis. The "daily menu ingredient mass" is the ingredient mass required by the menu recipes. The list containing "nominal unprocessed ingredient mass" also contains the expected ingredient input prior to processing assuming the "nominal yield", to produce the "daily ingredient mass." When the yield varied, French and Perchonok (2006) also provided different minimum and maximum yield values. More precisely, these values are a specific volume of 1.33×10^{-3} m^3/kg for dry beans, peanuts, rice, soybean, wheat, and liquid resupply items. Specific volume factors of 1.78×10^{-3}, 7.69×10^{-3}, and 7.3×10^{-4} m^3/kg are used for powder, leafy, and granule resupply items, respectively, while a specific volume factor of 2.5×10^{-3} m^3/kg is used for resupply pasta items. Because some ingredients, denoted as salad, sweet potato, or white potato inputs in the "source" column, are derived from a limited biomass production facility, the corresponding volume is not listed implying that these ingredients are used shortly after harvest and occupy no appreciable storage volume beyond that associated with the biomass production facility. Volume for "water" is also omitted because this commodity is drawn from the life support system stores as needed. It should be noted that this 10-day, bulk-commodity menu averages out to an energy content of 7.44 MJ/CM-d as indicated in Section 4.5.6.4 which is far below the NASA requirements. This menu does not include snacks and beverages which when added to the astronaut's diet can bring the daily energy intake closer to both the previous (11.82 MJ/CM-d) and current NASA requirements (12.707 MJ/CM-d).

Table 4-52 Ingredients, Commodity Sources, and Yield Values on a Per-Crewmember Per-Day Basis for 10-Day, Bulk-Commodity Menu

Ingredient	Source	Daily Menu Ingredient Mass [g/CM-d]	Minimum Yield	Nominal Yield	Maximum Yield	Nominal Unprocessed Ingredient Mass [g/CM-d]	Specific Volume Factor [m³/kg]	Nominal Unprocessed Ingredient Volume [m³/CM-d]
allspice	resupply	0.015	100%	100%	100%	0.015	0.00178	2.670×10^{-8}
baking powder	resupply	1.108	100%	100%	100%	1.108	0.00178	1.973×10^{-6}
baking soda	resupply	0.020	100%	100%	100%	0.020	0.00178	3.560×10^{-8}
basil, dried/leaves	resupply	0.363	100%	100%	100%	0.363	0.00769	2.794×10^{-6}
bay leaf, dried	resupply	0.007	100%	100%	100%	0.007	0.00769	5.127×10^{-8}
bell pepper, whole	salad	21.500	40%	45%	50%	47.778	n/a	n/a
black beans, uncooked	dry bean	9.540	100%	100%	100%	9.540	0.00133	1.269×10^{-5}
black pepper	resupply	0.249	100%	100%	100%	0.249	0.00178	4.440×10^{-7}
bouillon cube, beef	resupply	0.600	100%	100%	100%	0.600	0.00073	4.380×10^{-7}
bouillon cube, chicken	resupply	1.508	100%	100%	100%	1.508	0.00073	1.100×10^{-6}
brown rice, uncooked	rice	8.992	100%	100%	100%	8.992	0.00133	1.196×10^{-5}
butter sprinkles	resupply	0.020	100%	100%	100%	0.020	0.00073	1.460×10^{-8}
cabbage, shredded	salad	3.750	85%	90%	95%	4.167	n/a	n/a
carrot, whole	salad	45.957	55%	60%	65%	51.063	n/a	n/a
carrots, grated	salad	7.661	55%	60%	65%	12.769	n/a	n/a
carrots, shredded	salad	8.272	55%	60%	65%	13.786	n/a	n/a
carrots, sliced/chopped	salad	11.437	55%	60%	65%	19.061	n/a	n/a
cayenne pepper	resupply	0.025	100%	100%	100%	0.025	0.00178	4.450×10^{-8}
chili powder	resupply	0.250	100%	100%	100%	0.250	0.00178	4.450×10^{-7}
cilantro, dried	resupply	0.030	100%	100%	100%	0.030	0.00769	2.307×10^{-7}
cinnamon	resupply	0.155	100%	100%	100%	0.155	0.00178	2.759×10^{-7}
cloves, ground	resupply	0.004	100%	100%	100%	0.004	0.00178	7.417×10^{-9}
cocoa powder	resupply	4.938	100%	100%	100%	4.938	0.00178	8.790×10^{-6}
coffee, instant	resupply	0.133	100%	100%	100%	0.133	0.00073	9.733×10^{-8}
coriander, ground	resupply	0.035	100%	100%	100%	0.035	0.00178	6.181×10^{-8}
coriander, seeds	resupply	0.016	100%	100%	100%	0.016	0.00073	1.196×10^{-8}
cornstarch	resupply	1.070	100%	100%	100%	1.070	0.00178	1.905×10^{-6}
cumin	resupply	0.284	100%	100%	100%	0.284	0.00178	5.053×10^{-7}

Table 4-52 Ingredients, Commodity Sources, and Yield Values on a Per-Crewmember Per-Day Basis for 10-Day, Bulk-Commodity Menu (continued)

Ingredient	Source	Daily Menu Ingredient Mass [g/CM-d]	Minimum Yield	Nominal Yield	Maximum Yield	Nominal Unprocessed Ingredient Mass [g/CM-d]	Specific Volume Factor [m³/kg]	Nominal Unprocessed Ingredient Volume [m³/CM-d]
dill weed, dried	resupply	0.091	100%	100%	100%	0.091	0.00769	6.964×10^{-7}
egg, dried/white	resupply	0.233	100%	100%	100%	0.233	0.00178	4.153×10^{-7}
egg, dried/whole	resupply	2.912	100%	100%	100%	2.912	0.00178	5.183×10^{-6}
elbow macaroni, uncooked	resupply	3.150	100%	100%	100%	3.150	0.00250	7.875×10^{-6}
extract, almond	resupply	0.173	100%	100%	100%	0.173	0.00133	2.298×10^{-7}
extract, maple	resupply	0.010	100%	100%	100%	0.010	0.00133	1.293×10^{-8}
extract, vanilla	resupply	3.738	100%	100%	100%	3.738	0.00133	4.971×10^{-6}
garlic, granulated	resupply	0.606	100%	100%	100%	0.606	0.00073	4.421×10^{-7}
garlic, powder	resupply	0.514	100%	100%	100%	0.514	0.00178	9.147×10^{-7}
ginger, dried/ground	resupply	0.078	100%	100%	100%	0.078	0.00178	1.389×10^{-7}
green onion, chopped	salad	11.335	85%	95%	95%	11.932	n/a	n/a
kidney beans, uncooked	dry bean	3.017	100%	100%	100%	3.017	0.00133	4.012×10^{-6}
lemon juice	resupply	0.808	100%	100%	100%	0.808	0.00133	1.075×10^{-6}
lentils, uncooked	dry bean	13.007	100%	100%	100%	13.007	0.00133	1.730×10^{-5}
lettuce	salad	2.815	85%	90%	95%	3.128	n/a	n/a
lime juice	resupply	0.009	100%	100%	100%	0.009	0.00133	1.219×10^{-8}
mustard, ground	resupply	0.273	100%	100%	100%	0.273	0.00178	4.851×10^{-7}
navy beans, uncooked	dry bean	7.313	100%	100%	100%	7.313	0.00133	9.726×10^{-6}
nutmeg, ground	resupply	0.015	100%	100%	100%	0.015	0.00178	2.670×10^{-8}
oil, peanut	peanuts	24.578	30%	35%	40%	70.223	0.00133	9.340×10^{-5}
onion, dried/flakes	resupply	9.173	100%	100%	100%	9.173	0.00769	7.054×10^{-5}
oregano, dried/whole	resupply	0.279	100%	100%	100%	0.279	0.00769	2.147×10^{-6}
paprika	resupply	0.035	100%	100%	100%	0.035	0.00178	6.230×10^{-8}
parsley, dried	resupply	0.294	100%	100%	100%	0.294	0.00769	2.260×10^{-6}
peanut butter	peanuts	11.022	90%	95%	100%	11.602	0.00133	1.543×10^{-5}
peanuts w/o shell	peanuts	0.677	92%	95%	98%	0.713	0.00133	9.481×10^{-7}
pinto beans, uncooked	dry bean	4.962	100%	100%	100%	4.962	0.00133	6.599×10^{-6}

Table 4-52 Ingredients, Commodity Sources, and Yield Values on a Per-Crewmember Per-Day Basis for 10-Day, Bulk-Commodity Menu (continued)

Ingredient	Source	Daily Menu Ingredient Mass [g/CM-d]	Minimum Yield	Nominal Yield	Maximum Yield	Nominal Unprocessed Ingredient Mass [g/CM-d]	Specific Volume Factor [m³/kg]	Nominal Unprocessed Ingredient Volume [m³/CM-d]
potato, white	white potato	41.933	65%	70%	75%	59.905	n/a	n/a
potato, white/peeled	white potato	15.237	60%	65%	70%	23.441	n/a	n/a
potato, white/shredded	white potato	11.067	65%	70%	75%	15.810	n/a	n/a
potato, white/sliced/diced	white potato	2.833	65%	70%	75%	4.048	n/a	n/a
radish	salad	1.068	45%	50%	55%	2.137	n/a	n/a
red pepper flakes	resupply	0.014	100%	100%	100%	0.014	0.00769	1.047×10^{-7}
rosemary, dried	resupply	0.005	100%	100%	100%	0.005	0.00769	4.059×10^{-8}
sage, dried	resupply	0.041	100%	100%	100%	0.041	0.00769	3.161×10^{-7}
Salt	resupply	4.790	100%	100%	100%	4.790	0.00073	3.497×10^{-6}
savory, dried	resupply	0.033	100%	100%	100%	0.033	0.00769	2.563×10^{-7}
soy sauce powder	resupply	2.852	100%	100%	100%	2.852	0.00178	5.076×10^{-6}
soybeans, uncooked	soybean	4.750	100%	100%	100%	4.750	0.00133	6.318×10^{-6}
soymilk	soybean	237.862	688%	750%	816%	31.715	0.00133	4.218×10^{-5}
spinach	salad	27.750	85%	90%	95%	30.833	n/a	n/a
starch, instant	resupply	7.908	100%	100%	100%	7.908	0.00178	1.408×10^{-5}
strawberries	salad	28.708	30%	35%	40%	82.024	n/a	n/a
sugar, brown	resupply	0.346	100%	100%	100%	0.346	0.00073	2.523×10^{-7}
sugar, granulated	resupply	63.389	100%	100%	100%	63.389	0.00073	4.627×10^{-5}
sweet potato	sweet potato	46.567	35%	40%	45%	116.417	n/a	n/a
sweet potato, mashed	sweet potato	5.925	35%	40%	45%	14.813	n/a	n/a
sweet potato, sliced	sweet potato	22.667	35%	40%	45%	56.667	n/a	n/a
tarragon, dried	resupply	0.017	100%	100%	100%	0.017	0.00769	1.282×10^{-7}
textured soy protein	soybean	2.575	100%	100%	100%	2.575	0.00133	3.425×10^{-6}
thyme, dried	resupply	0.280	100%	100%	100%	0.280	0.00769	2.153×10^{-6}
tofu, firm	soybean	39.913	367%	400%	433%	9.978	0.00133	1.327×10^{-5}
tofu, soft	soybean	20.513	367%	400%	433%	5.128	0.00133	6.821×10^{-6}
tomato, diced	salad	51.755	40%	45%	50%	115.010	n/a	n/a
tomato, dried	salad	0.373	40%	45%	50%	0.830	n/a	n/a

Table 4-52 Ingredients, Commodity Sources, and Yield Values on a Per-Crewmember Per-Day Basis for 10-Day, Bulk-Commodity Menu (concluded)

Ingredient	Source	Daily Menu Ingredient Mass [g/CM-d]	Minimum Yield	Nominal Yield	Maximum Yield	Nominal Unprocessed Ingredient Mass [g/CM-d]	Specific Volume Factor [m³/kg]	Nominal Unprocessed Ingredient Volume [m³/CM-d]
tomato, paste	salad	1.027	40%	45%	50%	2.281	n/a	n/a
tomato, sauce	salad	85.703	40%	45%	50%	190.450	n/a	n/a
tomato, whole	salad	39.385	40%	45%	50%	87.523	n/a	n/a
vinegar	resupply	7.450	100%	100%	100%	7.450	0.00133	9.909×10^{-6}
water	water	317.263	100%	100%	100%	317.263	n/a	n/a
water, cook	water	238.943	100%	100%	100%	238.943	n/a	n/a
water, ice	water	20.737	100%	100%	100%	20.737	n/a	n/a
water, rinse	water	39.500	100%	100%	100%	39.500	n/a	n/a
wheat flour	wheat	59.574	98%	99%	100%	60.176	0.00133	8.003×10^{-5}
white flour	wheat	94.234	67%	72%	77%	130.881	0.00133	1.741×10^{-4}
white pepper	resupply	0.061	100%	100%	100%	0.061	0.00178	1.078×10^{-7}
white rice, uncooked	rice	5.682	110%	115%	120%	4.941	0.00133	6.571×10^{-6}
yeast, dried	resupply	2.663	100%	100%	100%	2.663	0.00073	1.944×10^{-6}
ziti, uncooked	resupply	5.677	100%	100%	100%	5.677	0.00250	1.419×10^{-5}

4.5.6.2 *EQUIPMENT*

Equipment allows food commodities to be processed into ingredients and ultimately into palatable and nutritious food entries. The equipment selected and described here addresses one or more necessary functions. These functions are to (1) provide the ingredients required by the 10-day menu, (2) keep ingredients or products viable, or (3) prepare menu items from ingredients. Because corresponding flight hardware is unavailable, the hardware below reflects commercial machines that are believed to be representative in both functionality and size to what might be designed ultimately for flight. French and Perchonok (2006) note that "the listed equipment, though smaller in size, may still be [over-sized] for missions supporting" the number of people associated with projected near-term crews. Table 4-53 and Table 4-54 list the recommended hardware to support preparation of the 10-day bulk commodity menu from bulk commodities, crops taken from a biomass production chamber, and other foodstuffs supplied to the finished menu listed by French and Perchonok (2006). Note that this level of food preparation would likely require a dishwasher, which is not listed here.

Table 4-53 Mechanical Processor Characteristics for 10-Day Bulk Commodity Menu

Technology	Manufacturer / Model[116]	Ingredient(s) Produced	Processing Rate	Unit Mass [kg]	Unit Volume [m³]	Unit Power [kW_e]	Duty Cycle
Grind Mill	Brabender /Quadramat Jr.	wheat flour, white flour	5.9 kg/h	69	0.22	0.46	
Dehydrator	L'Equip/528	tomato, dried	n/a	4.54	0.034	0.55	
Concentrator	Armfield/FT18	tomato, paste; tomato, sauce	3 L/h	220	0.54	2.2	
Soymilk /Tofu Maker	SoyaJoy	soymilk	6 kg/h	2.95	0.015	0.8	
		tofu, firm; tofu, soft	n/a				
Oil Press	Skeppsta Maskin AB /Type 20	oil, peanut	4 kg/h	5.9	0.069	0.4	
Refrigerator /Freezer [117]	Sub Zero /700 BC		n/a	86	0.37 [118]	1.725	0.030

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[116] This is for reference only and does not imply product endorsement.

[117] French and Perchonok (2006) recommend two refrigerator / freezer units, minimum, to support the 10-day bulk commodity menu.

[118] Internal capacity is 0.141 m³, divided as 0.082 m³ for the refrigerator and 0.059 m³ for the freezer.

Table 4-54 Food Preparation Equipment for 10-Day Bulk Commodity Menu

Equipment Name	Unit Mass [kg]	Unit Volume [m³]	Unit Power [kW$_e$]	Duty Cycle
Baking Dish/Pan	1.50	0.004		
Biscuit Cutter	0.03	0.000		
Blender	6.70	0.015	0.6	
Bowl (Large)	0.44	0.013		
Bowl (Medium)	0.35	0.009		
Bowl (Small)	0.30	0.006		
Breadmaker	6.62	0.026	0.52	
Brillo	0.03	0.000		
Cake Pan	0.19	0.005		
Colander	0.40	0.013		
Convection Oven	174.60	1.080	5.5	
Cookie Sheet	0.33	0.002		
Food Processor #2	6.70	0.020	0.72	
Fork	0.03	0.000		
Hot Pad	0.10	0.000		
Ice Cream Maker	2.75	0.012	0.01	
Juicer	4.33	0.023	0.4	
Knife (Bread)	0.14	0.000		
Knife (Chef)	0.22	0.000		
Knife (Paring)	0.07	0.000		
Loaf Pan	0.16	0.002		
Measuring Cup	0.30	0.001		
Measuring Spoons	0.10	0.000		
Muffin Cups	0.37	0.033		
Pan (Pie)	0.16	0.003		
Pasta Maker	3.05	0.005		
Pot (Large)	3.35	0.023		
Pot (Medium)	2.28	0.014		
Pot (Small)	1.20	0.006		
Potato Masher	0.16	0.002		
Potato Peeler	0.07	0.000		
Pressure Cooker	2.70	0.016		
Range	0.00	0.000	3.35	
Rolling Pin	0.64	0.002		
Saucepan (Large)	2.36	0.014		
Saucepan (Medium)	1.77	0.010		
Saucepan (Small)	1.18	0.006		
Skillet (Large)	1.47	0.018		
Slotted Spoon	0.04	0.001		
Spatula	0.07	0.001		
Spoon, Metal	0.03	0.000		
Spoon, Wooden	0.05	0.000		
Tongs	0.08	0.001		
Tortilla Press	15.50	0.047	1.8	
Whisk	0.13	0.001		
Wire Rack	0.15	0.001		
Total	243.16	1.43	12.9	

4.5.6.3 *CREWTIME*

Many food interface activities require additional mechanical inputs beyond what is currently associated with the hardware listed in Section 4.5.6.2. While it may be possible to automate some food preparation activities, historically such complex inputs are provided by human beings. Thus, here, without further analyses, it is assumed that mechanical inputs beyond those provided by the hardware listed above will be fulfilled by the crew. [119]

Per French and Perchonok (2006), crewtime has been classified as either active or passive time. Active time includes those activities that require the full attention of a crewmember, while passive time may not require the full attention of the crewmember, but the task does have some level of cognitive impact. French and Perchonok (2006) include estimates of crewtime for the following activities:

- Recipe preparation
- Meal consumption
- Ingredient processing
- Equipment maintenance

4.5.6.3.1 RECIPE PREPARATION, MEAL CONSUMPTION AND MEAL CLEANUP

French and Perchonok (2006) recorded preparation times for each recipe in the 10-day bulk commodity menu. Table 4-55 provides a breakdown of active and passive time for each day of the menu. For this study, French and Perchonok (2006) assumed a crew of six. Thus, a smaller crew will require less crewtime than is listed here for this same menu, but food preparation crewtime is not expected to scale linearly as a function of crew size for crews of four to six crewmembers or smaller. Note that there were many assumptions in this work. Some updates were made in Cooper (2012), but there are still gaps in assumptions. For instance, the study only looked at acceptability of individual foods tried once, rather than the food system as a whole (having to cook and process, risk of crop failure, and not having meat). These also don't include crop tending/harvest time.

Table 4-55 Crewtime Requirements for 10-Day Bulk Commodity Menu

Event	Active Time [min]	Passive Time [min]
Day 1	160	115
Day 2	145	397
Day 3	120	182
Day 4	210	700
Day 5	140	170
Day 6	155	357
Day 7	195	520
Day 8	190	185
Day 9	100	232
Day 10	115	345
Total	1,530	3,203

For this menu, a 30-minute allotment is assumed for meal consumption. Because there are three meals per day scheduled for this 10-day bulk commodity menu, this assumption becomes 90 minutes per crewmember per day. A 10-minute total allotment is assumed to cleanup each meal. Similarly, this assumption becomes 30 minutes per day to accommodate the three-meal schedule.

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[119] While this is one approach, it may or may not be an optimal approach. Additional testing and analysis of the benefits and costs of using automation versus the crew for various food preparation tasks is most likely necessary before this question can be addressed with any certainty.

4.5.6.3.2 INGREDIENT PROCESSING AND EQUIPMENT MAINTENANCE

French and Perchonok (2006) determined crewtime values for each piece of ingredient processing equipment based on the documented throughput capacity of the processing equipment, the mass totals of the associated ingredient(s), Table 4-52, the ingredient source nominal yield value, also Table 4-52, and estimated times for indirectly associated steps. Table 4-53 provides documented throughput capacity values and French and Perchonok (2006) provide the rationale surrounding determination of estimated ingredient processing equipment crewtime values for interested readers.

During long-duration missions, food processing equipment will require maintenance of some kind. It is assumed that an additional 10% of ingredient processing time will be required to perform this function. Table 4-56 lists the associated crewtime for each of the processed ingredients per 10-day menu cycle. As with the other work in French and Perchonok (2006), this assessment assumes a crew of six. [120]

Table 4-56 Ingredient Processing Equipment Crewtime Values for Each 10-Day Menu Cycle

Technology	Manufacturer / Model[121]	Associated Ingredient(s)	Crewtime [CM-h] [122]
Grind Mill	C. W. Brabender /Quadramat Jr.	wheat flour white flour	2.0
Dehydrator	L'Equip/528	tomato, dried	8.0
Concentrator	Armfield/FT18	tomato, sauce tomato, paste	1.0
Soymilk /Tofu maker	SoyaJoy	soymilk tofu, soft tofu, firm	8.1
Oil Press	Skeppsta Maskin AB /Type 20	oil, peanut	1.1
Subtotal			20.0
Maintenance (10% of Subtotal)			2.0
Total			22.0

4.5.6.4 *NUTRITION*

French and Perchonok (2006) analyzed their 10-day menu using bulk-packaged foods for nutrient content using the Nutritionist Five® database. Table 4-57 presents these results along with the corresponding Recommended Dietary Allowance (RDA) goals and NASA nutritional goals for each component. [123]

While the current requirement for the nominal daily metabolic intake for the mean astronaut population (82.4 kg, 1.786m, and 45 years of age) is 12.707 MJ/CM-d, and the overall metabolic energy value in Table 4-57 falls short of this goal, this menu assessment, according to French and Perchonok (2006) excludes snacks and beverages. Once they are added to this menu the daily metabolic energy will be closer to NASA's previous requirement (11.82 MJ/CM-d) but will still be short of the current requirement. Further, the inclusion of calcium fortified beverages will increase the calcium content of the menu; however, this is an area of continued focus. There may be other means of calcium delivery available to this bulk-ingredient menu that have not been used historically by NASA for human space flight programs.

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[120] While the crewtime values here may include some setup time, so the total time expended will not scale linearly with crew size, as a first approximation linear scaling should be sufficiently accurate.

[121] This is for reference only and does not imply product endorsement.

[122] French and Perchonok developed these estimates based on a crew of six. The values here represent crewtime for one 10-day menu cycle. While the crewtime values here may include some setup time, so the total time expended will not scale linearly with crew size, as a first approximation linear scaling should be sufficiently accurate.

[123] While these values apply for a generic menu, French and Perchonok (2006) note that "current menu planning for shuttle was and for the International Space Station (ISS) is personalized to kilocalorie and nutrient intake requirements; some vitamins and minerals such as vitamin C, iron and biotin have adjusted requirement levels to accommodate a reduced (microgravity) gravity environment." Further, they note "Vitamin D supplements are currently provided for the ISS crewmembers' daily use."

Table 4-57 Nutrient Values for 10-Day Bulk-Packaged Food Menu

Nutrition Parameter	Menu Value	Units	RDA Goal	NASA Goal	% RDA Goal	% NASA Goal
Metabolic Energy	1,777.8 7.44	kcal/CM-d MJ/CM-d	2,000 8.37	-- --	89 89	-- --
Macronutrients						
Protein	57.3	g/CM-d	50	--	115	--
Carbohydrates	299	g/CM-d	300	--	100	--
Fat	43.8	g/CM-d	65	--	67	--
Cholesterol	50	mg/CM-d	300	300	17	17
Saturated Fat	7.4	g/CM-d	20	20	37	37
Dietary Fiber	38.2	g/CM-d	25	25	153	153
Micronutrients						
Sodium	2,984.1	mg/CM-d	2,400	2,400	124	124
Potassium	2,915.9	mg/CM-d	3,500	3,500	83	83
Vitamin A	28,233.3	IU/CM-d [124]	5,000	5,000	565	565
Vitamin C	110.5	mg/CM-d	60	100	184	111
Calcium	369.3	mg/CM-d	1,000	1,000	37	37
Iron	18.9	mg/CM-d	18	10	105	189
Vitamin D	5.5	IU/CM-d [125]	400	400	1	1
Vitamin E	13.6	IU/CM-d [126]	30	30	45	45
Thiamin	2.1	mg/CM-d	1.5	1.5	138	138
Riboflavin	1.4	mg/CM-d	1.7	2	81	70
Niacin	16.8	mg/CM-d	20	20	84	84
Vitamin B_6	1.4	mg/CM-d	2	2	71	71
Folate	349.1	μg/CM-d	400	400	87	87
Vitamin B_{12}	0.1	μg/CM-d	6	2	2	5
Biotin	21.1	μg/CM-d	300	100	7	21
Pantothenic acid	3.4	mg/CM-d	10	5	34	68
Vitamin K	145.5	μg/CM-d	80	80	182	182
Phosphorous	983.7	mg/CM-d	1,000	1,000	98	98
Magnesium	379.3	mg/CM-d	400	350	95	108
Zinc	6.9	mg/CM-d	15	15	46	46
Copper	1.9	mg/CM-d	2	2	93	93
Manganese	5.2	mg/CM-d	2	5	259	104
Selenium	0.07	mg/CM-d	0.07	0.07	98	98
Chromium	0.07	mg/CM-d	0.12	0.12	58	58
Molybdenum	29.5	μg/CM-d	75	75	39	39

4.5.7 FOOD SUBSYSTEMS BASED ON BIOMASS PRODUCTION SYSTEMS

Crops within a biomass production chamber will likely be grown and harvested on a bulk basis, rather than quasi-continuously. This assumption is designed to minimize crewtime requirements by making crew activities more efficient and may be revisited when more data is available. The three diets presented here assume differing availabilities for crops grown on-site. Table 4-58 provides wet or fresh masses for the dietary components, as received from the Biomass Subsystem, while Table 4-59 provides the corresponding nutritional information.

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[124] 1 International Unit (IU) of Vitamin A is the biological equivalent of 0.3 μg retinol, or of 0.6 μg beta-carotene.

[125] 1 International Unit (IU) of Vitamin D is the biological equivalent of 1/40 μg, exactly, cholecalciferol / ergocalciferol.

[126] 1 International Unit (IU) of Vitamin E is the biological equivalent of 2/3 mg, exactly, of d-alpha-tocopherol or of 1 mg of dl-alpha-tocopherol acetate.

Table 4-58 Menu Masses for Diets Using Advanced Life Support Crops and Resupplied Foods [a]

Crop	Average Production Based on Consumption, Fresh Mass [kg/CM-d]		
	Diet Using Only ELS Salad Crops [127]	Diet Using Salad and Carbohydrate Crops [128]	Diet Using All ELS Crops [129]
Cabbage	0.0194	0.0025	n/a
Carrot	0.0365	0.040	0.0401
Celery	n/a	0.0075	n/a
Dry Bean, inc. lentil and pinto	n/a	0.013	0.0214
Green Onion	0.0045	0.034	0.0226
Lettuce	0.0156	0.021	0.0075
Mushroom	n/a	0.0013	n/a
Pea	n/a	0.0038	n/a
Peanut	n/a	n/a	0.0288
Peppers	n/a	0.031	n/a
Radish	0.009	n/a	0.0150
Rice	n/a	n/a	0.0214
Snap Bean	n/a	0.010	n/a
Soybean	n/a	n/a	0.2340
Spinach	0.0048	0.040	0.0463
Sweet Potato	n/a	0.18	0.0768
Tomato	0.0460	0.21	0.2854
Wheat	n/a	0.22	0.0963
White Potato	n/a	0.17	0.1047
Crop Sub Total	**0.1358**	**1.0**	**1.00**
Water [130]	1.1581	2.1	0.6053
Resupplied Foodstuffs	1.168 [131]	0.5 [131, 132]	0.0944
Total	**2.462**	**3.6**	**1.70**
Potable Water [133]	2.0	2.0	2.0
Food Processing Waste	TBD	TBD	0.094

[a] Note: this table is based on 11.82MJ/CM-d, whereas subsequent tables have been updated to a higher energy requirement.

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[127] From Hall, *et al.* (2000). This diet assumes a 10-day cycle.

[128] From Personal communication with Hall and Vodovotz (1999). This diet assumes a 20-day cycle.

[129] From Ruminsky and Hentges (2000). This diet assumes a 10-day cycle.

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

[131] Resupplied food is a combination of STS and ISS foodstuffs.

[132] Oil is included as resupply. No frozen or refrigerated foods are assumed for this calculation. Packaging is not included. Resupplied food is about 40 % moisture by mass. Resupplied food includes meat.

[133] The crew also requires 2.0 L/CM-d for drinks, again excluding packaging/tankage. (Perchonok, 2001)

In all cases, the menus given in Table 4-58 and Table 4-59 are designed for use as a unit in order to maintain nutritional integrity. However, minor changes might include moving small amounts of crops from the list to be grown and into the resupplied mass, especially for those items like rice that are prepared for consumption with Outpost-plant growth processing operations that reduce the total edible biomass from the original crop. All diets are comparable in nutritional content to the International Space Station food system.

Table 4-59 Nutritional Content of Diets Using Advanced Life Support Crops and Resupplied Foods [a]

Dietary Component	Units	Goal	Diet Using Only ELS Salad Crops [127]	Diet Using Salad and Carbohydrate Crops [128]	Diet Using All ELS Crops [129]
Energy	MJ/CM-d	11.82 [134]	9.31	9.74	7.74
Carbohydrate	g/CM-d	–	312.179	357.1	314.12
Fat	g/CM-d	–	71.9141	71.6	46.84
Protein	g/CM-d	–	91.2913	73.1	54.91
Calcium, Ca	mg/CM-d	1,000 – 1,200 [135]	925.557	812	545
Iron, Fe	mg/CM-d	≤ 10 [135]	19.2385	21.5	17.23
Magnesium, Mg	mg/CM-d	350 [135]	294.687	386	376.48
Phosphorous, P	mg/CM-d	≤ 1.5 Ca intake [135]	1,440.68	1,356	1,079.52
Potassium, K	mg/CM-d	~ 3,500 [135]	3,316.57	3,723	3,179.86
Sodium, Na	mg/CM-d	1,500 – 3,500 [135]	3,909.56	3,600	3,205.96
Zinc, Zn	mg/CM-d	15 [135]	12.8077	10	7.5
Dietary Fiber	g/CM-d	10 – 25 [135]	25.1129	33.3	28.5
Percentage of Energy Contributed to Diet					
Carbohydrate	%	50 – 55 [135]	55.5	61	68.1
Fat	%	30 – 35 [135]	28.7	27	22.4
Protein	%	12 – 15 [135]	16.2	12	12

[a] Note: This table is based on original 11.82MJ/CM-d since its purpose is nutritional integrity, whereas subsequent tables have been updated to a higher energy requirement.

The Diet Using Only Salad Crops (Hall, *et al.*, 2000) is aimed at near-term missions and supplements more traditional packaged food systems with fresh food in the form of salad crops. The bulk of the nutritional content is supplied by the packaged food and the degree of food system closure is low.

The Diet Using Salad and Carbohydrate Crops (Hall and Vodovotz, 1999) is also aimed at near-term missions, but this diet provides somewhere around half of the necessary mass through crops grown on-site. Resupply includes products high in protein, such as meat, in addition to seasonings and other supporting foodstuffs. Oil is also provided via resupply, as typical oil crops are not grown for this diet. Overall, this approach provides greater on-site food closure, adds only moderate additional food processing, and provides variety equivalent to that of a vegetable garden.

The Diet Using All Crops (Ruminsky and Hentges, 2000) uses a wide variety of species, and provides a high degree of closure. Oil is provided from peanut, but the specific processing has not been identified. With respect to closure, the resupply mass includes herbs and condiments. As the crop variety is limited, resupply items provide necessary nutrients that are not available in sufficient quantities within the grown biomass.

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[134] From NASA (1991).

[135] From Lane, *et al.* (1996).

Levri, *et al.* (2001) examined prepackaged food systems for exploration missions to Mars using the standard Shuttle Training Menu with a 7-day menu cycle as a basis. To support the nominal NASA crewmember, the standard Shuttle Training Menu was adjusted slightly to raise the energy content to 11.82 MJ/CM-d. The energy content was further increased to 12.707 MJ/CM-d, based on the EER equation (Equation 3-2), in order to match modern nutritional requirements for the average astronaut population as shown in the following tables. Data collected by Levri, *et al.* (2001) showed that the practical minimum wastage rate of resupplied food for situations in which the crew attempts to eat all of the food with which they are supplied is 3 % by mass. This remaining 3 % of the food mass adheres to the inside of the food packaging.

Table 4-60 presents mass and volume properties for three study food systems, as originally formulated by Levri, *et al.* (2001), which are modified from the standard Shuttle Training Menu, but do not take into account the newest ISS consumption rates in Table 4-47. Each system assumes crew metabolic loads consistent with intravehicular activities. "As-shipped" food contains any moisture present when the food is packaged for launch. Food "as-consumed" also includes any additional water that is added to rehydrate food items and powdered beverages before consumption. The additional drinking water is computed based on the assumption that a crewmember consumes at least 239.0 milliliters of water, either within food or in addition to food, for every Mega-Joule of metabolic energy within the consumed food to provide proper hydration for metabolic assimilation of the food.[136] Some sources, such as the NRC (1989), recommend as much as 358.5 milliliters of water per Mega-Joule of energy in the consumed food. Generally, these food systems are stored under ambient conditions in an ISS food locker. Frozen storage, when noted, assumes an ISS thermoelectric freezer (Section 4.5.2). Locker and freezer volumes are computed with respect to external dimensions.

Table 4-60 Properties of Early Mars Diets for Intravehicular Activities Using Resupplied Foods

	Units	Modified Shuttle Training Menu[137]	Low Moisture Content Menu	Menu Containing Some Frozen Food
IVA Food Properties, No Packaging				
Food, Dry Mass	kg/CM-d	0.71	0.71	0.72
Food "As-Shipped"	kg/CM-d	1.23	0.99	1.48
Moisture Content of Food "As-Shipped"	%	42.0	28.0	52.0
Food "As-Consumed," with Rehydration	kg/CM-d	2.58	2.37	2.56
Additional Drinking Water	kg/CM-d	1.22	1.42	1.24
IVA Food Packaging Properties				
Packaging Mass	kg/CM-d	0.28	0.29	0.26
IVA Food Locker Properties[138]				
Locker Mass	kg/CM-d	0.37	0.35	0.27
Locker Volume	m^3/CM-d	0.00519	0.00486	0.00381
IVA Food Freezer Properties				
Freezer Mass	kg/CM-d	n/a	n/a	0.866
Freezer Volume	m^3/CM-d	n/a	n/a	0.00231
IVA Food and Packaging Waste				
Trash Mass	kg/CM-d	0.35	0.34	0.31

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[136] Alternately, this guideline may be formulated as 1.0 milliliters of water per kilocalorie of food energy consumed.

[137] From Levri (2002), but values here have been scaled up to reflect a higher total daily energy content. The values here include material that normally clings to food packaging and is discarded.

[138] Food maintained at ambient conditions is stored in lockers aboard ISS. These values assume ISS "Pantry-style storage.

Table 4-61 provides the nutritional analysis for the food systems presented in Table 4-60. However, unlike Table 4-60 which is based on all food "as shipped," including food that adheres to the food packaging and is not consumed by the crewmember, values in Table 4-61 consider only the edible material a nominal crewmember consumes, and assume the crewmember attempts to eat all of the food within a package and only wastes material that adheres to the package walls. It is pertinent to note that the values in Table 4-61 are indicative of the old shuttle training menu, which has been scaled to the current metabolic energy requirement of 12.707 MJ/CM-d and is compared with a low moisture content menu and menu which contains some frozen food. The purpose of this table is not to provide absolute values that are representative of current dietary menus but to provide a comparison between different menu options. Although these three menus have been scaled to current energy requirements, they do not necessarily represent current food and water allocations as well as macromolecule content. It should thus be noted that the values contained in Table 4-61 will differ from those in Table 3-31 and Table 4-51 which contain the current, nominal human metabolic balance as well as the nominal IVA and EVA food, water, and packaging quantities.

Table 4-61 Nutritional Content of Early Mars Diets for Intravehicular Activities Using Resupplied Foods, for Levri, et al studies

Dietary Component	**Units**	**Modified Shuttle Training Menu** [139]	**Low Moisture Content Menu** [139]	**Menu Containing Some Frozen Food** [139]
Energy	MJ/CM-d	12.71	12.71	12.71
Carbohydrate	g/CM-d	404	411	399
Fat	g/CM-d	104	100	105
Protein	g/CM-d	122	124	125
Dietary Fiber	g/CM-d	35	36	40
Ash	g/CM-d	29	27	33
Water in Food [140]	g/CM-d	501	267	742
Rehydration Water	g/CM-d	1,321	1,350	1,057
Additional Drinking Water [141]	g/CM-d	1,218	1,423	1,241
Percentage of Energy Contributed to Diet				
Carbohydrate	%	53	54	53
Fat	%	31	30	31
Protein	%	16	16	16

Based on the dietary contributions of salad crops suggested by Perchonok, *et al.* (2002) and data compiled by Levri, *et al.* (2001), four diets using salad crops and resupplied food systems are presented in Table 4-62 The crop values listed here are based on fresh salad crops, as received from the Biomass Subsystem, less any biomass removed during preparation. Resupplied foodstuffs are listed "as-shipped," without rehydration water, and do not include packaging materials. Values here do not include material that adheres to packaging and is ultimately wasted. Drinking water is listed near the bottom of the table. As above, the drink water assumes that a

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[139] From Levri (2002), but values here have been scaled up to reflect a somewhat higher total daily energy content. The values here are based on food "as consumed" by a crewmember, excluding material that normally clings to the food packaging.

[140] Moisture, or water, held in the food as shipped before rehydration.

[141] The additional drinking water is computed based on the assumption that a crewmember consumes at least 239.0 milliliters of water, either within food or in addition to food, for every Mega-Joule of metabolic energy within the consumed food to provide proper hydration for metabolic assimilation of the food. These values are identical to those in Table 4-61 because losses were not measured or assumed.

crewmember consumes at least 239.0 milliliters of water, either within food or in addition to food, for every Mega-Joule of metabolic energy within the consumed food to provide proper hydration for metabolic assimilation of the food. The listings for food processing waste consider wasted edible biomass from preparation of the salad crops plus resupplied food that adheres to packaging materials. Here it is assumed that 3 % of the food mass within a prepacaged food item will adhere to the packaging.

Table 4-62 Menu Masses for Diets Using Advanced Life Support Crops and Resupplied Foods

	Average Production Based on Consumption, Fresh Mass [kg/CM-d]			
Crop	**Diet Using Shuttle Training Menu and ELS Salad Crops** [142]	**Diet Using Low Moisture Content Menu and ELS Salad Crops** [142]	**Diet Using ISS Menu with Some Frozen Food and ELS Salad Crops** [142]	**Diet Using Shuttle Training Menu and ELS Salad Crops plus Potato** [142]
Cabbage	0.0107	0.0107	0.0107	0.0107
Carrot	0.0357	0.0357	0.0357	0.0357
Celery	n/a	n/a	n/a	n/a
Dry Bean, inc. lentil and pinto	n/a	n/a	n/a	n/a
Green Onion	n/a	n/a	n/a	n/a
Lettuce	0.0097	0.0097	0.0097	0.0097
Mushroom	n/a	n/a	n/a	n/a
Pea	n/a	n/a	n/a	n/a
Peanut	n/a	n/a	n/a	n/a
Peppers	n/a	n/a	n/a	n/a
Radish	0.0114	0.0114	0.0114	0.0114
Rice	n/a	n/a	n/a	n/a
Snap Bean	n/a	n/a	n/a	n/a
Soybean	n/a	n/a	n/a	n/a
Spinach	0.0134	0.0134	0.0134	0.0134
Sweet Potato	n/a	n/a	n/a	n/a
Tomato	0.0143	0.0143	0.0143	0.0143
Wheat	n/a	n/a	n/a	n/a
White Potato	n/a	n/a	n/a	0.0840
Crop Sub Total	**0.0953**	**0.0953**	**0.0953**	**0.1793**
Rehydration Water [143]	1.3115	1.3409	1.0492	1.2744
Resupplied Foodstuffs [144]	1.187	0.951	1.421	1.154
Total	**2.5942**	**2.3872**	**2.5656**	**2.6075**
Drinking Water [145]	1.14	1.35	1.17	1.13
Food Processing Waste [146]	0.0397	0.0324	0.0469	0.0412

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[142] From Levri (2002). The values here are reflect food “as-shipped,” for prepackaged food, and “as-received” from the Biomass Subsystem less preparation waste, for food grown locally. Wasted food mass is listed separately at the bottom of the table. Thus, crewmembers consume all other masses in this table except for wasted mass.

[143] Water for rehydration only. Water for cleanup is not included. Water tankage is not included.

[144] Masses are for food “as shipped,” without packaging, storage lockers, or water for hydration.

[145] Again, this listing excludes packaging/tankage.

[146] These values include the wasted portion of fresh, edible biomass, as well as the wasted portion of resupplied, “as-consumed” food. These values do not include packaging.

Table 4-63 provides the nutritional analysis for the food systems presented in Table 4-62. As above, values in Table 4-63 consider only the edible material a nominal crewmember consumes, and the crewmember only wastes food material that adheres to the package walls or serving dishes and some edible biomass from crop preparation.

Table 4-63 Nutritional Content of Diets Using Advanced Life Support Crops and Resupplied Foods

Dietary Component	Units	Diet Using Shuttle Training Menu and ELS Salad Crops [147]	Diet Using Low Moisture Content Menu and ELS Salad Crops [147]	Diet Using ISS Menu with Some Frozen Food and ELS Salad Crops [147]	Diet Using Shuttle Training Menu and ELS Salad Crops plus Potato [147]
Energy	MJ/CM-d	12.71	12.71	12.71	12.71
Carbohydrate	g/CM-d	405	412	400	413
Fat	g/CM-d	103	100	104	101
Protein	g/CM-d	122	124	125	121
Dietary Fiber	g/CM-d	37	38	42	38
Ash	g/CM-d	30	28	33	30
Water in Food [148]	g/CM-d	585	352	825	631
Percentage of Energy Contributed to Diet					
Carbohydrate	%	53	54	53	54
Fat	%	31	29	31	30
Protein	%	16	16	16	16

The four diets, presented in Table 4-62 and Table 4-63 are derived from the standard Shuttle Training Menu and work by Levri, *et al.* (2001), subsequently scaled to an energy basis of 12.707 MJ/CM-d. The first and fourth diets included prepackaged items from the Modified Shuttle Training Menu. See Table 4-60 and Table 4-61. The second diet considers prepackaged items from the Low Moisture Content Menu, while the third diet employs the Modified Shuttle Training Menu with some frozen items to simulate a food system similar to what was (at the time) planned for the space station.

Perchonok, *et al.* (2002) provides estimates for salad servings based on preliminary menus for early mission scenario testing. This overall approach assumes a prepackaged food system augmented with grown salad crops. Thus, this diet is analogous to the Diet Using Only Salad Crops from (Hall*, et al.* 2000). Note that Table 4-64 provides inputs only for the dietary contributions derived directly from the vegetables. The supporting prepackaged food items are not included.

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[147] From Levri (2002), but values here have been scaled up to reflect a higher total daily energy content. The values here are based on food "as consumed" by a crewmember, excluding edible material that normally clings to food packaging or serving dishes.

[148] Moisture, or water, held in the food as shipped before rehydration.

Perchonok, *et al.* (2002) assumes:

- Salad is served four times per week.
- Raw carrots are served as a snack once per week.
- Carrots are served once per week steamed.
- Spinach is served once per week either steamed or raw.
- Bok choy can be served as Cole slaw once per week.

Table 4-65 provides overall values for locally grown crops for this diet. See also (Cooper, 2011) and (Cooper, 2012) for recent work on exploration food systems.

Table 4-64 Updated Salad Crop Only Dietary Contributions

Menu Item	Vegetable	Serving Size [149] [g]	Number per Week	Serving Rate [150] [kg/CM-d]
Salad 1	Lettuce	34	2	0.00971
	Carrot	40	2	0.01114
	Radish	40	2	0.01143
Salad 2	Spinach	20	2	0.01086
	Tomato (Cherry)	50	2	0.01429
Snack	Carrot	85	1	0.01214
Steamed Side Dish	Spinach	55	1	0.00786
Cole Slaw	Cabbage	63	1	0.00900

Plant environmental demands differ compared to the crew's requirements. For example, the optimum partial pressure of carbon dioxide for plant growth is roughly 0.10 to 0.20 kPa (Wheeler, *et al.*, 1993); below this, productivities decrease. Sensitivity may vary from species to species, but plants do appear to have reduced productivity at very high partial pressures of carbon dioxide that are considered within the normal range for crew (up to about 1.0 kPa). Similarly, plants require higher relative humidity – about 75% – to avoid water stress and minimize nutrient solution usage. Such humidity levels are at the high end for crew comfort. Further, some key plants, such as wheat and potatoes, are most productive at temperatures below the standard crew comfort zone. Finally, at nominal Earth ambient carbon dioxide partial pressures (p [CO_2] = 0.04 kPa), plants grow better under atmospheres with reduced partial pressures of oxygen (p [O_2] less than 21 kPa). If the partial pressure of carbon dioxide is elevated to 0.1 to 0.2 kPa, the benefits of reduced oxygen partial pressure are negligible. However, because human beings live with plants on Earth, plants and crew can live in a common atmosphere as demonstrated in the bioregenerative lifr support systems experiment in Lunar Palace 1 (Fu*, et al.*, 2016).

Table 4-92enumerates growing areas and fresh weight inedible biomass production associated with the ELS Project diets presented in Section 4.5.7. The edible biomass values are the nominal values listed in Table 4-92. The total inedible biomass production is based on the edible biomass production and the harvest index and does not include any waste associated with uneaten portions or the material removed during food preparation.
Table 4-92.

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[149] Mass "as prepared."

[150] Mass per crewmember per day "as grown." This is listed as fresh edible biomass. The associated inedible biomass is also produced as given in

Table 4-65 Overall Crops Masses for Updated Salad Crop Only Diet

Vegetable	Serving Rate [150] [kg/CM-d]
Cabbage	0.00900
Carrot	0.03542
Lettuce	0.00971
Radish	0.01143
Spinach	0.01872
Tomato (Cherry)	0.01429
Total	**0.09857**

4.5.8 FOOD PROCESSING

Food processing takes the edible biomass produced by plant crops, either fresh or as prepared for storage, and produces food products and ingredients such as pasta and flour. These food products may be stored or used immediately, together with ingredients supplied from the Earth (or, for analog testing, from outside the facility), and prepared as menu items.

For long duration missions beyond low-Earth orbit, current planning envisions that crops will be grown and processed on a bulk basis. Hunter and Drysdale (1996) estimated the equipment mass to perform food processing for a crew of four to be about 655 kg. However, this is a very preliminary estimate, and the actual processing equipment will likely differ. Thus, the value here is a suitable “placeholder” until more definitive values are available.

4.6 EXTRAVEHICULAR ACTIVITY SUPPORT INTERFACE [151]

Extravehicular activity (EVA) for planetary exploration missions will exhibit significant differences from current EVA in low-Earth orbit. On a planetary surface, the presence of gravity raises the importance of suit mass, so surface space suits must be lighter than current systems, especially when considering Mars missions. Lunar missions may not need mass reductions since gravity is lower and muscle deconditioning during transit will be less than on Mars missions. Such new space suits must also be designed for walking, assembly and setup of equipment, picking up surface samples, hammering, *etc*., to accommodate field geology and similar activities necessary for planetary exploration. The current space suit, or extravehicular mobility unit (EMU), does not have these attributes. It has a mass on the order of 154 kg and is designed for weightless mobility using foot restraints. Table 4-66 represents local accelerations due to gravity for planetary bodies and Table 4-67 presents historical EMU masses. Finally, Table 4-68 presents the weight [152] of an average 82 kg crewmember plus historical and current EMU designs under a variety of gravitational conditions. As noted, the current EMU, if not reduced in mass for Mars, would burden a crewmember with a weight 9 % greater than the weight of a nominal, unencumbered crewmember under terrestrial gravity, and this does not account for muscle deconditioning effects.

- ***Note: The analysis here is not meant to suggest that a historical Apollo EMU or the current Shuttle Program EMU will be used for operations on the surface of the Moon or Mars, but rather to compare the effects of suits with similar mass. The current Shuttle Program EMU is inappropriate for surface operations, while the historical Apollo EMU has many limitations and would be inappropriate for Martian surface operations.***

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[151] This section on advanced extravehicular activities is from personal communication with M. Rouen (2001).

[152] Weight, a force, is defined as the mass of an object [kg], which is invariant with locale, multiplied by the local acceleration due to gravity [m/s²]. More specifically, weight is the force with which a planet pulls a mass towards its surface and, therefore, the “on back weight” experienced by a crewmember carrying something on the surface in that gravity field.

Table 4-66 Local Accelerations Due to Gravity

Locale	Mean Acceleration due to Gravity [m/s²]	Fractional Gravity compared to Earth Normal	Reference
Earth	9.798	1.000	Weast and Astle (2019)
Moon	1.620	0.165	
Mars	3.710	0.379	

Table 4-67 Historical Extravehicular Activity Masses

Item	Mass [kg]
Apollo Nominal Human Being	70.0 (1)
Apollo Program Spacesuit, A7L [153]	83.0 (1)
Apollo Program Spacesuit, A7LB [154]	90.7 (2)
Shuttle/ISS Program Spacesuit [EMU, including portable life support system (PLSS)]	154 (3)

References

(1) NASA (1969)
(2) Rouen (2002)
(3) UTC (2017)

Table 4-68 Weights of Historical Spacesuits under Gravitational Loadings

Locale and Loading	Total Mass [kg]	Weight for Human Alone [N]	Weight for Human Plus Space Suit [N]	Percentage of Unencumbered, Earth-Normal Weight [%]
Earth	82.0	804		100
Moon	82.0	133		16.5
Lunar Surface with Apollo A7L EMU	165.0		267	33.2
Lunar Surface with Apollo A7LB EMU	172.7		280	34.8
Lunar Surface with Shuttle EMU	217		352	43.8
Mars	82.0	305		37.9
Martian Surface with Apollo A7L EMU	165.0		614	76.4
Martian Surface with Apollo A7LB EMU	172.7		643	80.0
Martian Surface with Shuttle EMU	236		879	109.3

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[153] The value here corresponds to the Apollo A7L extravehicular mobility unit and a –6 portable life support system and associated equipment. Apollo 11 used this configuration on the lunar surface. The EVA surface duration per sortie was less than 8 hours in this configuration.

[154] The value here corresponds to the Apollo A7LB extravehicular mobility unit and a –7 portable life support system and associated equipment. The later Apollo missions used this configuration on the lunar surface. The EVA surface duration per sortie was increased to 8 hours in this configuration.

Although the details are not provided herein, both Mary (2018) and Coan (2020) represent excellent reference documents for exploration EVA. Mary (2018) provides details on the past, present, and future conceptual and real designs of airlocks, suitports and other EVA ingress/egress methods. This document provides records of past ingress/egress trade studies and addresses the impacts of ingress/egress methods on habitat concepts. Coan (2020) provides details on the EVA concept of operations for exploration missions including mission details of the Artemis program, information on the different spacecraft and surface mobility vehicles to be used, and the EVA mission parameters (duration, frequency, and tasks) at each specific destination (in low-Earth orbit, on a small natural body, i.e. an asteroid, on the Lunar surface, and on the Martian surface).

The entire EVA system, including airlocks, spacesuits, tools, and vehicle interfaces, must also be designed to minimize the mission launch mass. Thus, technology development is required. The final design solution depends upon the mission architecture as well as the success of development efforts. Several scenarios are described below that represent the best available assumptions with regard to EVA for planetary exploration missions.

4.6.1 OPERATIONS DURING TRANSIT TO MARS

On a Mars transit vehicle, EVA would likely be reserved for contingency only. If EVA from the transit vehicle is minimal, then the transit vehicle airlock system should be as lightweight as possible and intrude into the crew habitat as minimally as possible. Solutions that use an existing volume within the cabin that can be isolated and depressurized or a fabric, fold-up airlock stowed externally to the outer cabin wall are some possible minimum impact solutions to provide contingency EVA capability. In an event, current EVA protocol requires at least two crewmembers at any time, so the minimum airlock should accommodate at least two crewmembers at a time. As an example, the ISS crewlock has a habitable volume of 4.25 m^3.

4.6.2 SURFACE OPERATIONS

Because the gravity on Mars is about twice that of the Moon and about a third of that on Earth, the overall mass of a Mars spacesuit is critical. In the case where the Mars spacecuit and astronaut weight is heavier relative to the nominal astronaut weight on Earth, a possible mission design to provide the astronaut with a reprieve from the extra work load associated with carrying a spacesuit under Mars gravity is to reduce the standard EVA duration to 4 hours. Thus, to maintain the same time outside the vehicle during exploration, two 4-hour, or "half-day," EVA sorties per workday could replace the more traditional 8-hour EVA sortie. Assuming five workdays per week allows 520 half-day EVA sorties of two crewmembers per year without any allowance for holidays. This is also the maximum number of airlock cycles per year. Each EVA sortie normally requires at least two crewmembers outside. This strategy would be impossible on ISS because of the long prebreathe times required for the crewmembers to adjust from the 101 kPa (14.7 psia) and 21% oxygen environment. Using the recommended exploration atmosphere of 57 kPa (8.2 psia) and 34% oxygen (Norcross 2013) can reduce the prebreathe time to effectively zero for some suit operation pressures. In other cases, it may at least reduce the time so it fits within other necessary activities such as suit checkout that would be conducted at 100% oxygen already. EVA operations may initially be performed at an elevated suit pressure, compared to the nominal suit pressure of 4.3 psia, until prebreathe time is met, and then the suit pressure will be reduced to the nominal for greater mobility and reduced leak rate. It should be noted that any predictions made on possible pre-breathe times for exploration atmospheres is assumed at this point, and has not yet been verified by test.

One method of reducing EVA consumables is to use a radiator to reject thermal loads from the spacesuit backpack rather than rely solely on consuming water to reject thermal loads, as is the current practice in low-Earth orbit. This could reduce cooling water usage to 0.19 kg/h from 0.57 kg/h, which is a typical value when a radiator is not used. The calculation here assumes a human metabolic rate of 1.06 MJ/CM-h (295 W). Water, which remains within the spacesuit, also provides the thermal working fluid to transport heat from the astronaut's skin to heat rejection equipment in the portable life support system (PLSS).

Another concept, which might eliminate loss of water to the environment for cooling, is a cryogenic spacesuit backpack. The cryogenic spacesuit backpack rejects thermal loads both to the environment, via a radiator, and to vaporize cryogenically-stored oxygen for metabolic consumption. As above, water still provides the heat transport working fluid.

Oxygen usage and losses during EVA depend on the technologies employed in the PLSS. If a completely closed-loop system is used, oxygen is only consumed by metabolic activity and leakage. Under such conditions, oxygen usage is 0.3 kg per 4-hour EVA sortie, or 0.076 kg/h. If carbon dioxide generated while on EVA is stored by the PLSS and recycled once the crewmembers return to the vehicle actual oxygen loss is associated only with leakage. Oxygen leakage alone accounts for a loss rate of 0.02 kg per 4-hour EVA sortie, or 0.005 kg/h. If the spacesuit PLSS employs a swing bed carbon dioxide removal technology to reject carbon dioxide and water to the Martian environment, then some additional oxygen is lost as a sweep gas to aid the bed's operation. In this case, oxygen loss rates are 0.6 kg per 4-hour EVA sortie, or 0.15 kg/h. If cryogenic oxygen is used for thermal control as well as breathing, the overall oxygen usage rates are 4.0 kg per 4-hour EVA sortie, or 1.0 kg/h.

Normally flight rules require two exits to provide redundant means to enter and egress a vehicle. If pressurized rovers are used, one exit would be dedicated to docking rovers while an airlock would support on-foot EVA operations. As exits are only useful if coupled with a corresponding airlock, the contingency airlock for a secondary exit when another pressurized vehicle is not docked is often to depressurize the entire vehicle cabin.

Although the hatch size increases in an environment with gravity, the required airlock volume remains constant. A two-crewmember airlock has an empty volume of 4.25 m^3. During use, the free gas volume within the airlock is 3.7 m^3 and two suited crewmembers fill the remaining volume. Though not generally acceptable under current rules, a single person airlock has an empty volume of 1.02 m^3 and a free gas volume of roughly 0.89 m^3. About 10% of the free gas within the airlock is lost to space and not recovered by the airlock compression pump during depressurization. These losses could be reduced to 5 % at the expense of additional time and power consumption for the airlock pump. Other advanced concepts, however, may reduce the gas losses without corresponding time and power penalties. Suitports, for example, allow for the spacesuit to attach and detach from the cabin volume (e.g. lander or pressurized rover) without the need for the spacesuit to fully enter the pressurized volume. The spacesuit "hangs" outside of the pressurized cabin volume via a Suitport Interface Plate (SIP). The PLSS is attached to the SIP and is hinged so that the rear of the suit can be opened for donning and doffing. Once the astronaut is in the suit, the PLSS is swung closed and after the pre-EVA activities are complete, the EMU is detached from the suitport and the EVA commences. The details of airlocks, suitports and other EVA ingress/egress methods are discussed in Mary (2018). This document provides highly detailed records of past trade studies for future exploration EVA capability and addresses the impacts of alternative ingress/egress methods including various airlock, suitport, and even habitat concepts.

Table 4-69 summarizes the estimates above for EVA operations on the surface of the Moon. Values are provided by personal communication with M. Rouen (2001). Losses in Table 4-69 denote mass that leaves the pressurized volume of the spacesuit and, therefore, does not return to the vehicle at the end of EVA operations. Suitport operations could reduce some of the values shown in Table 4-69 as follows. The xEMU average design metabolic rate is 1.27 MJ/CM-h (352 W) and based on that metabolic rate, the oxygen losses related to suitport scenarios are predicted to be 0.1 kg/CM-h during EVAs plus 0.54 kg/CM-EVA. The 0.1 kg/CM-h accounts for metabolic O_2, xEMU leakage and swingbed CO_2 removal unit ullage losses. The 0.54 kg/CM-EVA accounts for pre- and post-EVA activities with the largest contributor being the N_2 purge performed prior to each EVA. For example, if one person does 4 x 8-hour EVAs for a total of 24 hours O_2 losses come to 4.57 kg. Adding a second crewmember performing the same EVAs brings the total to 9.14 kg. Consumption listed in Table 4-70, denotes usage of a commodity by the crewmember regardless of whether that commodity leaves the pressurized spacesuit volume or is retained within that volume and later recycled. Table 4-70 provides overall values describing the metabolic loads and inputs for an EVA crewmember assuming an average metabolic rate of 1.06 MJ/CM-h (295 W) and a respiratory quotient of 0.90. Also, metabolic rates have been observed to vary based on the types of mission and EVA activities performed as shown Table 4-71 from NASA HIDH (2014).

Table 4-69 Summary of Extravehicular Activity Values for Lunar Surface Operations

Value	Units	Low	Nominal	High	Notes
Human Metabolic Rate During EVA	W/CM		352		1. Campbell (2012)
EVA Crewmember Hours per Week	CM-h /wk		80	80	2. LAT2 (2007)
EVA Sorties [155] per Week	Sorties /wk	7	10	14	3. High Mobility Scenario
Cooling Water Losses (North & South Poles)	kg /CM-h	0.25	0.3375	0.5	
Cooling Water Losses (Equator)	kg /CM-h	0.4625	0.625	0.7625	
Oxygen Losses including leakage (high value includes RCA ullage)	kg /CM-h	0.069	0.092	0.110	See prior paragraphs for example suitport values for O_2 losses
Airlock Volume	m^3		4.25		
Airlock Free-Gas Volume	m^3		3.7		
Airlock Cycles per Week	Cycles /wk	3.5	5	7	
Airlock Gas Losses per Cycle as a Percentage of Airlock Gas Volume [156]	%	5	10	10	

Table 4-70 Typical Extravehicular Activity Metabolic Loads

Parameter	Units	Rate
Oxygen Consumption	kg/CM-h	0.086 (1)
Potable Water Consumption [157]	kg/CM-h	0.240 (2)
Food Energy Consumption [158]	MJ/CM-h	1.062 (3)
Carbon Dioxide Production	kg/CM-h	0.109 (1)
Respiration and Perspiration Water Production	kg/CM-h	highly variable
Urine Production	kg/CM-h	highly variable

References

(1) Scaled based on NASA HIDH (2014) Table 6.2-10.

(2) MSIS (1995); a maximum value.

(3) Rouen (2001)

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[155] Each EVA sortie assumes two crewmembers.

[156] As given, these values are as a percentage of the mass of gas occupying the free airlock volume when depressurization begins.

[157] For EVA sorties longer than 3 hours.

[158] This is the total energy expended, and thus consumed, per crewmember per hour of extravehicular activity.

Table 4-71 Crewmember Metabolic Rates for Suited Operations, kJ/h (Btu/h) (NASA HIDH (2014))

Data Source	Minimum	Average	Maximum[1]
μ Gravity EVA (ISS and STS)	575 (545)[2]	950 (900)[3]	2320 (2200)
Apollo Lunar Surface EVA	517 (490)[2]	1030 (980)	2607 (2471)
Advanced Walkback Test[4]	1767 (1675)[1]	2505 (2374)	3167 (3002)

[1] Transient condition less than 15 min in duration, individual instance
[2] Minimum for low-activity EVA durations
[3] Includes Orlan ISS EVAs, which trend to slightly higher metabolic rates
[4] Simulated 10-km (6.2-mile) Lunar surface walk requiring 1 to 2 hours to complete, in case of rover failure, n = 6

Future EVA scenarios on the Lunar surface are likely to be similar to those described above for Mars, because Lunar surface exploration is often cited as a precursor to Martian surface exploration missions. However, due to lower gravity on the Moon, it is easier to extend the EVA sorties to 8 hours, thus saving time and airlock cycle gas losses. However, radiant heat rejection would be a greater challenge during the Lunar day.

4.6.3 RECOMMENDED PREBREATHE INTERVALS FOR EVA

4.6.3.1 *DECOMPRESSION SICKNESS PREVENTION*

> *Decompression sickness takes place when the inert gas (generally nitrogen) that normally is dissolved in body tissues at one pressure forms a gas phase ("bubbles") at a lower ambient pressure, when the tissues become supersaturated with nitrogen.* [Powell, *et al.* (1993)]

Decompression sickness (DCS) is an important consideration for mixed cabin atmospheres when EVAs are performed in lower-pressure space suits, and when changes in cabin pressure can occur as a result of planned activities and emergencies. DCS symptoms can include pain ("the bends"), pulmonary manifestations ("the chokes"), skin manifestations, circulatory collapse, and neurological disorders (NASA (1995)). A common approach for preventing or minimizing DCS is to prebreathe pure oxygen prior to depressurization to wash out nitrogen from body tissues. Minimizing the risk of DCS and the operational impact of prebreathe protocols is one of the primary drivers for the recommended reduction in cabin pressure for surface habitats and rovers (Norcross 2013).

The occurrence and severity of DCS has been found to correlate with the ratio of the final partial pressure of inert gas in equilibrium with body tissue to the final ambient total pressure. This ratio, R (or TR), is known as the tissue ratio or bends ratio. R can be expressed as follows:

$$R = \frac{p_{\text{N2-Tissue}}}{P_{\text{Suit}}} \qquad \text{Equation 4-3}$$

The inert gas is nitrogen, and the final ambient pressure is the space suit pressure. $p_{N2\text{-}Tissue}$ is defined as the nitrogen partial pressure in equilibrium with body tissue whereas P_{suit} is defined as the space suit pressure. The incidence of DCS, as well as venous gas emboli, increases with increasing R (see, for example, Horrigan, *et al.* (1993)). In addition to the dependence on R, DCS has been found to depend on the duration at reduced pressure, and the degree of physical activity and ambulation at reduced pressure (Conkin, *et al.* (1996), Conkin and Powell (2001)). Test data also suggest that at the same R-value, a higher space suit pressure will result in a lower probability of DCS (Conkin, *et al.* (1996)).

During a pure-oxygen prebreathe, the elimination of nitrogen from body tissue follows an exponential decay curve with a tissue-dependent half-time, $t_{1/2}$, related to the blood perfusion rate, inert gas diffusion rate, and inert gas solubility in the tissue (Conkin, *et al.* (1987)):

$$p_{\mathrm{N2-Tissue}}(t) = p_{\mathrm{N2-Tissue}}(0)\exp\left[-(\ln 2)\frac{t}{t_{1/2}}\right] \qquad \text{Equation 4-4}$$

In terms of *R* value,

$$R(t) = R(0)\exp\left[-(\ln 2)\frac{t}{t_{1/2}}\right] \qquad \text{Equation 4-5}$$

The initial nitrogen partial pressure in equilibrium with body tissue prior to prebreathing is most appropriately assumed equal to the alveolar nitrogen partial pressure, p_{AN2}, that exists for the spacecraft cabin atmosphere. In correlating the incidence of DCS against *R*, Conkin and coworkers (1987) have used the atmosphere nitrogen partial pressure instead of p_{AN2} to avoid the complexity of using the Alveolar Gas Equation during intermediate exposures. These authors have also used a theoretical tissue type with a 360-minute half-time for modeling the dependence of DCS incidence on *R*.

For any given spacecraft cabin atmosphere and space suit pressure, Equation 4-8 can be used calculate the prebreathe time necessary to achieve a final required R-value prior to EVA. In establishing a bound on the atmosphere design space based on DCS prevention, the final required *R*-value and the maximum allowable prebreathe time must be established.

4.6.3.2 *FINAL R VALUE*

Current NASA ISS prebreathe protocols are based on a final *R* value of 1.65-1.68 after oxygen prebreathe (see Horrigan (1993), and NASA (2002, 2003)). Actual operational values are frequently lower. For surface-exploration EVAs, DCS risks from mixed cabin atmospheres have not been established, nor has the acceptable level of DCS risk. Higher physical loads imposed by partial gravity suggest higher DCS risk than in microgravity. DCS symptoms must also be treated locally without the option for a quick return to Earth. A final *R*-value of 1.3-1.4 (following prebreathe) has been suggested by Conkin (2004) as a reasonable starting point based on current knowledge.

4.6.3.3 *MAXIMUM PREBREATHE TIME*

Minimization of the prebreathe time is highly desirable in missions with frequent EVAs to maximize crew productivity. An operational prebreathe of approximately 20 minutes is expected during space suit purge and checkout procedures. Additionally, depending on the cabin environment, the minimum prebreathe time may vary drastically in order to appropriately denitrogenate the brain and spinal cord to guard against serious (Type II) DCS symptoms. (Gernhardt (2004)). The figures in the following Section 4.6.3.4 show the bounding cabin environments to enable a shortened prebreathe relative to current ISS protocol. A prebreathe time of 1 hour is assumed as a tentative upper bound for surface exploration EVAs.

4.6.3.4 *PREBREATHE BOUND*

Equation 4-8 was used to map curves of constant prebreathe time over the spacecraft cabin atmosphere pressure and oxygen concentration design space. Results are shown in Figure 4-1-Figure 4-4 for space suit pressures of 29.6 kPa (4.3 psia) and 41.4 kPa (6 psia), and for final R-values of 1.3 and 1.4. These results were calculated taking $p_{\mathrm{N2-Tissue}}(0)$ equal to the cabin atmosphere nitrogen partial pressure, and using a tissue half-time of 360 minutes. Curves are shown for prebreathe times ranging from 0 minutes to 240 minutes. The 60-minute prebreathe curve (shown dashed and bolded) represents the assumed upper bound on prebreathe time. The strong dependence on space suit pressure is evident by comparing Figure 4-1 and Figure 4-2 with Figure 4-3 and Figure 4-4.

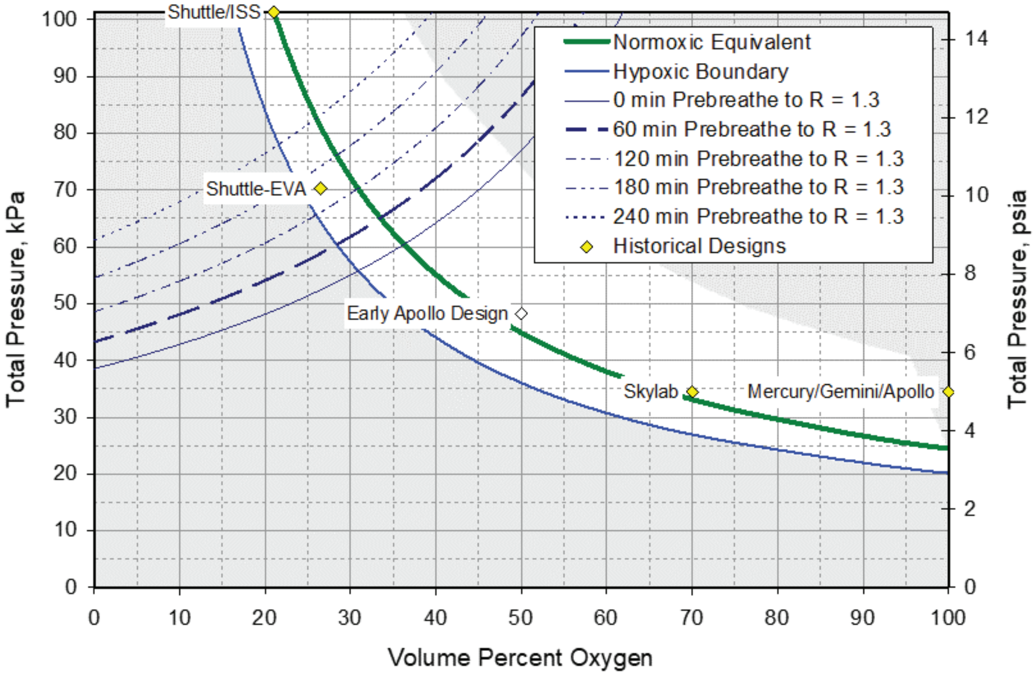

Figure 4-1 **Curves of constant EVA prebreathe time for a 29.6 kPa space suit with a final R-value of 1.3. Assumed upper bound on prebreathe time is 60 minutes.**

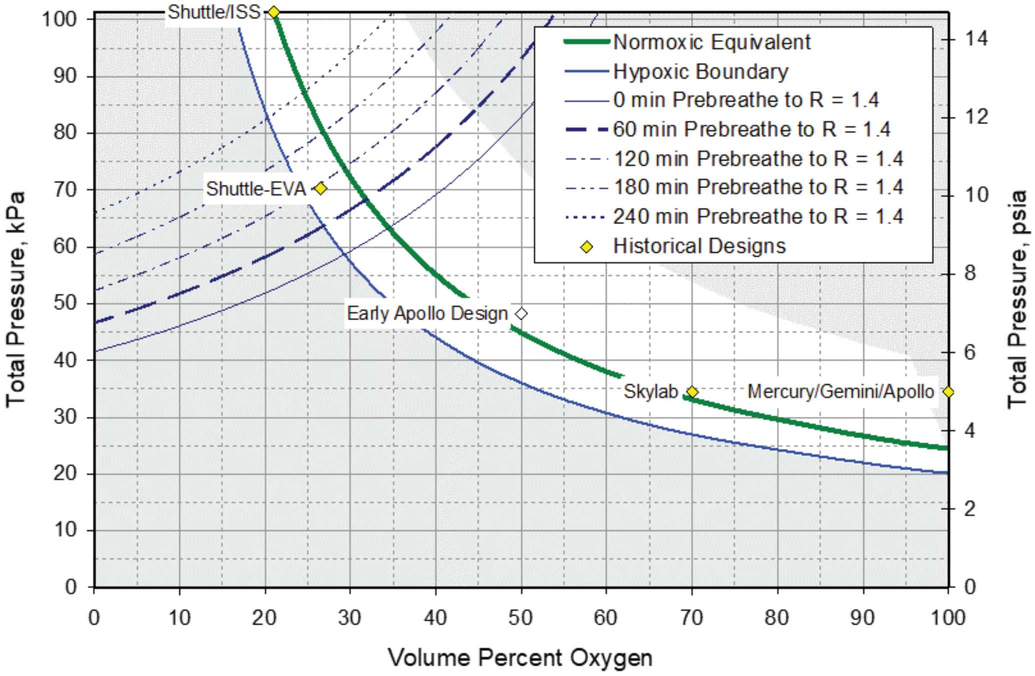

Figure 4-2 **Curves of constant EVA prebreathe time for a 29.6 kPa space suit with a final R-value of 1.4. Assumed upper bound on prebreathe time is 60 minutes.**

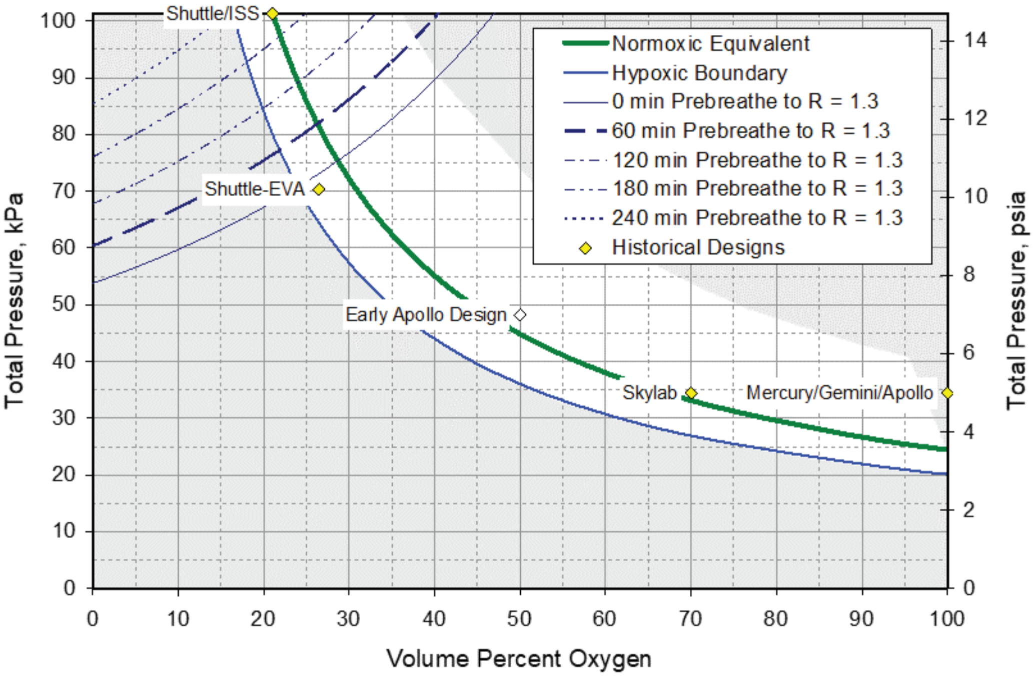

Figure 4-3 **Curves of constant EVA prebreathe time for a 41.4 kPa space suit with a final R-value of 1.3. Assumed upper bound on prebreathe time is 60 minutes.**

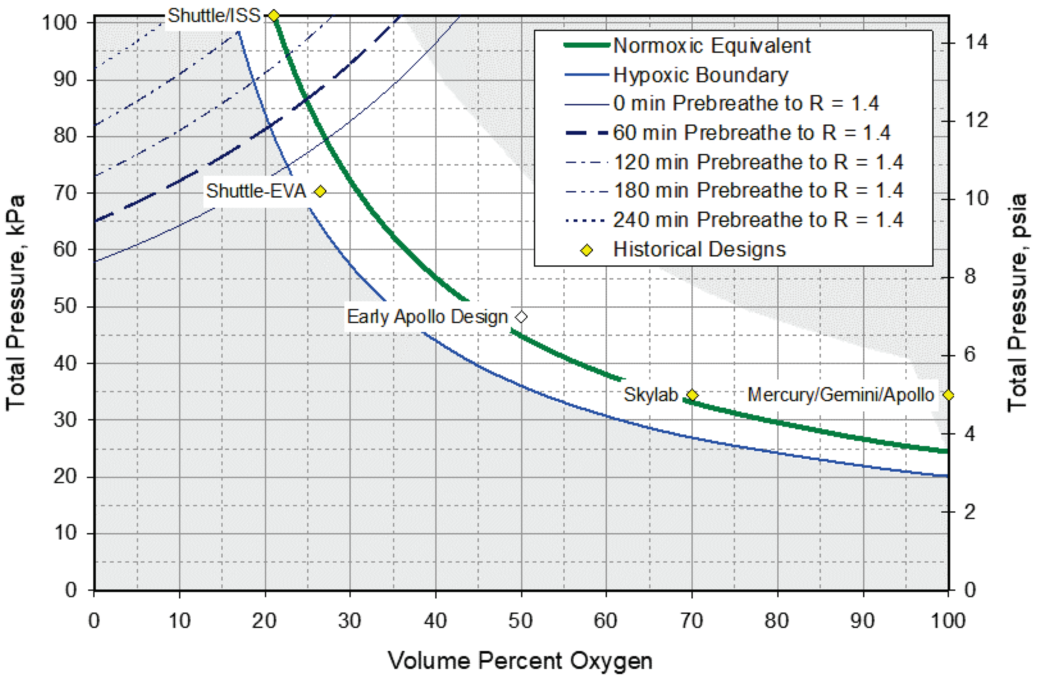

Figure 4-4 **Curves of constant EVA prebreathe time for a 41.4 kPa space suit with a final R-value of 1.4. Assumed upper bound on prebreathe time is 60 minutes.**

4.6.3.5 *ISS Prebreathe Protocols*[159]

The International Space Station (ISS) uses four prebreathe protocols with the 29.7 kPa (4.30 psia, 222 mmHg) Extravehicular Mobility Unit (EMU) suit. A different prebreathe protocol is used for the Russian Orlan suit since it has a higher operating pressure of 40.0 kPa, (5.80 psia, 300 mmHg). All of these protocols are significantly longer that those specified in the exploration maximum prebreathe time due to the much higher cabin pressure. The ISS nominally operates at 101 kPa (14.7 psia) while exploration missions could be 57 kpa (8.2 psia). The selection of protocols for a given EVA depends on the mission objectives, DCS risk, crew timeline, and overall operational risks. The four prebreathe protocols for EMU are:

Exercise – Exercise while breathing 100% O_2 has been shown to eliminate N_2 from the body tissues more quickly. This protocol includes intense exercising for 10 minutes of an 80-minute mask prebreathe of 100% O_2, with the cabin starting at 101 kPa and decompressing the airlock to 70.3 kPa over the 20 or more minutes required to don the suit. This is followed by a 60-minute in-suit prebreathe that is completed before the airlock begins its purge to vacuum.

Airlock Campout – This is a 2-day protocol. On the first day, crewmembers preparing for EVA use a mask to prebreathe 100% O_2 for 60 minutes while the pressure in the airlock decompresses from 101 kPa to 70.3 kPa. On the second day a 70-minute mask prebreathe of 100% O_2 is performed 8 hours and 40 minutes after 70.3 kPa pressure is reached in the airlock. A final 50-minute in-suit prebreathe is performed to conclude this protocol.

In-suit Light Exercise (ISLE) – For the ISLE protocol does not engage in a short bout of intense exercise but instead performs a longer bout of mild exercise in the EMU. The ISLE prebreathe protocol shares many steps with the Exercise prebreathe protocol. It differs in that 40 minutes are spent breathing 100% O_2 by mask, followed by a 20-minute depressurization to 70.3 kPa. Once the crewmember has completed suit donning, there is a

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[159] NASA HIDH (2014)

repressurization to 101 kPa followed by in-suit arm and leg motions performed for 50 minutes with a minimum O_2 consumption of 6.8 ml/kg-min. An additional 50 minutes of in-suit rest completes the prebreathe protocol followed by a 30-minute depressurization of the airlock to vacuum.

4-hour In-Suit Prebreathe – Includes 4 hours of unbroken breathing 100% O_2 at an airlock pressure above 86.2 kPa.

4.6.3.6 *EXPLORATION PREBREATHE*

To enable a high frequency of EVAs during exploration missions an atmosphere of 57 kPa (8.2 psia) total pressure and 34% O_2 content has been recommended (Norcross, 2013). This would be required for pressurized rovers and surface habitats where EVAs are expected to be frequent in order to reduce time spent in prebreathe. This recommended atmosphere assumes a space suit pressure of 29.6 kPa (4.3 psia). Landers and other vehicles with intermediate EVA requirements and any vehicle that supports a contingency EVA capability would operate at 70.3 kPa (10.2 psia) and 26.5% O_2. Under these reduced pressure atmospheres, relative to the Earth atmosphere, preberathe times are significantly reduced to 15 minutes and 40 minutes for the 8.2 psia/34% O_2 and 10.2 psia/26.5% O_2 atmospheres. Additional details of the various prebreathe protocols, which accompany the exploration atmosphere, as well as their effect on decompression sickness risks may be seen in Abercromby (2013).

4.6.3.7 *CONTINGENCY EVA*

A contingency EVA is one that is required to affect the safety of the vehicle and crew. If time allows it a nominal prepreathe protocol should be used. If the EVA preparation time needs to be minimized in order to assure crew safety a minimum of 2.5 hours of unbroken prebreathe with greater than 95% O_2 is recommended at a vehicle pressure above 86.2 kPa and assuming a space suit pressure of 29.6 kPa (4.3 psia). A minimum prebreathe of 2.5 hours would reduce the estimated risk of incapaciting bends to less than 50% for an EVA up to 6 hours in duration. This recommended time is very approximate and should be extended if possible. Preparations for decompression treatment should be conducted as early as possible in case of an incident. The flight surgeon needs to be consulted for recommended prebreathe protocol for any contingency EVA. (NASA, 2011a)

4.7 POWER INTERFACE

Within this manuscript, power enters analyses and modeling through use of a power-mass penalty. Thus, information on power systems is provided under the description of infrastructure in Section 3.2.

4.8 RADIATION PROTECTION INTERFACE

Radiation may impact numerous systems and is a critical issue for human exploration beyond LEO. Vehicle structure, including the primary structure, avionics, and propulsion system can provide varying degrees of protection just due to the nature of their mass (Duffield, 2010). The Life Support System contains several items that could because of their high hydrogen content, act as effective radiation shields. However, the most likely interaction for the Radiation Protection Interface is with the Water Subsystem and then only as a contingency source. For operations in near Earth space, the spacecraft is likely to be designed to limit the lifetime radiation exposure of the crew. While the initial activity from solar particle events enters from the direction of the Sun, the radiation field soon becomes effectively isotropic, so any effective radiation protection must provide a complete enclosure for the crew. This radiation shelter may include the entire crew cabin. On short duration missions, such as a Lunar transit, such protection may only encompass a portion of the crew cabin, such as the sleeping quarters, due to the added mass associated with complete radiation shielding. Perhaps something like a polyethylene garment could be worn, as suggested in the last line of Section 4.8.

As implied above in Section 3.2.2 on infrastructure using inflatables, galactic cosmic radiation is much more difficult to stop. For extended duration transit missions, all mass to protect against galactic cosmic radiation must come with the spacecraft. On a planetary surface, local resources, such as regolith packed into “sandbags” or underground caverns might be used to protect against radiation. Additionally, the carbon dioxide atmosphere of Mars, as well as the mass of the planet itself, provides some protection.

The most effective way to shield a transport vehicle may be to develop materials that serve both as structural elements and as shields. Polymeric materials, like polyethylene or polyetherimide, with high hydrogen content, perhaps sandwiched between fire resistant materials, would offer both structural strength and provide radiation shielding (Duffield 2010).

4.9 THERMAL CONTROL INTERFACE

Thermal control, in terms of its most direct impact on a spacecraft, maintains temperatures throughout the vehicle. Or, from another perspective, thermal energy, or heat, transfers from regions of high temperature to regions of low temperature and the thermal control hardware regulates when and how thermal energy transfers from regions of high temperature within the spacecraft to regions of low temperature outside of the spacecraft so that all components within the spacecraft are maintained between their prescribed temperature limits. As a distinguishing attribute, thermal control does not directly address heating associated with aerodynamic drag, although aerodynamic heating may impose greater thermal loads for the thermal control hardware, such as when heat conducts through the vehicle structure and into the crew cabin. Heating generated by aerodynamic drag is managed by the thermal protection system.

4.9.1 HEAT TRANSFER MECHANISMS

In order to appreciate heat management technology some background in the underlying mechanisms is beneficial. Thus, a brief discussion of heat transfer mechanisms follows. Please see Incropera and DeWitt (1985), the primary reference for this section, for a more thorough discussion.

Physically, heat transfers from high to low temperature via one of three distinct mechanisms. These mechanisms are conduction, convection, and radiation, although heat transfer with a phase change is sometimes discussed separately and thus might be viewed as a fourth heat transfer mechanism[160].

4.9.1.1 *CONDUCTION*

Conduction describes the transfer of heat within matter by diffusion or heat transfer through matter in the absence of macroscopic bulk motion of the matter. An example is heat moving up the shaft of a metal spoon sitting in a heated pot on a stove. The thermal energy, which is expressed as vibrational, rotational, and translational energy on atomic scales, is transferred from more-quickly vibrating atoms closer to the heated surface to less-quickly vibrating atoms further from the heated surface by interactions between adjacent atoms.

4.9.1.2 *CONVECTION*

Convection describes the transfer of heat in which matter acquires heat, by close molecular interaction, such as is described above for conduction, and then bulk motion of that matter carries both the matter and thermal energy away from its location of origin. For example, heat may diffuse from hotter metal to an adjacent cooler moving fluid, and then the bulk motion of the moving fluid carries the heat away from its origin. Likewise, the reverse process that of transferring heat from a hot moving fluid to a cooler solid, is also convection.

4.9.1.3 *RADIATION*

Radiant heat transfer is an exchange of heat between two surfaces without any intervening matter. Specifically, heat transfers from one surface to another surface that it can “see” simply by virtue of a temperature difference between the two surfaces. In a perfect vacuum, which is approximated in free space, no intervening matter is present to convey heat from one surface to another by either conduction or convection, yet heat does transfer from a hotter surface to a cooler surface via electromagnetic waves in the mechanism called radiation. Warm spacecraft reject their thermal loads from relatively hot surfaces to relatively cold space by radiant heat transfer. Please note that while radiation also describes the mechanism by which other forms of energy, such as solar particles and x-rays, pass through a vacuum, thermal radiation merely transfers heat and has no additional mutagenic effect on biological creatures exposed to it. Also please note that while radiant transfer is generally of the greatest importance in a vacuum, radiant transfer occurs in all situations where two surfaces that can “see”

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[160] As noted below, phase change represents a special case of one of the three heat transfer mechanisms with the additional stipulation that one of the participating materials changes its physical state as a result of gaining or losing heat. However, even though phase change is not a unique mechanism, it is sometimes useful to distinguish heat transfer operations with phase change from other heat transfer operations.

each other are at different temperatures, even if, for example, a fluid fills the gap between those two surfaces and heat is transferred to or from the surfaces also by conduction and/or convection. [161]

4.9.1.4 *HEAT TRANSFER WITH PHASE CHANGE*

Phase change describes heat transfer when matter accepts or discharges heat and changes its physical state. Thus, though it is mentioned here separately, phase change is really a specialized case of one of the three heat transfer mechanisms in which matter changes state. As an example, when water boils in a stovetop pan, liquid water approaches the bottom of the heated pan and leaves in the form of steam bubbles after accepting heat. Thus, this is really heat transfer by convection with the matter undergoing bulk motion and changing its state from liquid to vapor upon accepting heat from the solid. Likewise, phase change may occur in situations without bulk motion, such as when butter melts between two slices of hot bread, which is an example of conduction with phase change of a participating conducting material.

4.9.2 THERMAL CONTROL ORGANIZATION

Thermal control may be subdivided in several ways. One organization classifies thermal control as either passive or active. Passive thermal control hardware encourages or inhibits heat transfer as the heat passes directly through the hardware and eventually to the external environment, radiating from the vehicle's entire external surface. Active thermal control hardware acquires thermal loads near where the loads are generated and then transports those loads to some other portion of the vehicle before the loads are discharged to the environment by specifically designed radiating surfaces.

4.9.2.1 *PASSIVE AND ACTIVE THERMAL CONTROL*

Thermal control hardware may be classified as either passive or active. As outlined below, passive thermal control hardware is generally integrated into the vehicle structure and retards the flow of thermal energy either in to or out of the vehicle. Active thermal control hardware acquires thermal loads at or near their point of generation and transports those loads to the exterior of the vehicle for rejection.

4.9.2.2 *PASSIVE THERMAL CONTROL*

Passive thermal control hardware controls heat leakage from the vehicle and maintains cabin walls within prescribed temperature bounds. Passive thermal control hardware is deployed within the vehicle structure and generally takes the form of insulation and resistive heaters. Insulation impedes the transfer of heat in to and out of the vehicle, while resistive heaters allow active control of the wall temperatures when completely passive approaches are inadequate. Because passive thermal control hardware is generally incorporated into the vehicle structure, it is included within mass penalties for the vehicle structure.

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[161] Within a pressurized crew cabin, though all three heat-transfer mechanisms are active, conduction and/or convection usually dominate compared to radiant exchange. Physically, the driving potentials for conduction and convection heat transfer are proportional to the simple difference in temperature, while the driving potential for radiant heat transfer is proportional to the difference in temperature to the fourth power. Within the crew cabin, coupled with appropriate transport properties, conduction and convection are greater in magnitude than corresponding radiant exchanges. Thus, within a crew cabin, analysts often neglect radiant exchange with only a minor loss in accuracy. As a cautionary note, there are situations, especially within terrestrial industry, in which radiant exchange is significant or dominates as the preferred heat transfer mechanism even when conduction and/or convection are also viable modes. Please see Incropera and DeWitt (1985) for a more expansive discussion.

4.9.2.3 *ACTIVE THERMAL CONTROL*

Active thermal control hardware removes excess thermal loads from within the vehicle to the environment by physically transporting those loads from their site of generation to an appropriate rejection site. Active thermal control is comprised of three basic processes. These are acquisition of thermal energy, transport of thermal energy, and rejection of thermal energy. Acquisition hardware is comprised of fans, coldplates, and condensing heat exchangers for primary functionality. Transport hardware can, theoretically, use any mechanism. Historically for human spacecraft, transport relies on a liquid working fluid constrained within an enclosed flow channel, using the convection heat transfer mechanism to take loads from acquisition devices and to release loads to rejection devices. [162] Using this architecture, transport hardware consists of fluid tubes or pipes, pumps, accumulators, and valves. The working fluid may be two-phase, but historically NASA has employed single-phase working fluids. Finally, rejection hardware may be radiators, devices that reject expendable materials carrying thermal loads, such as a flash evaporator or a sublimator, or phase change devices such as packages containing phase change materials. Thermal control infrastructure penalties generally represent active thermal control hardware.

4.9.2.4 *GENERAL THERMAL CONTROL ARCHITECTURE*

Active thermal control may be divided into internal thermal control and external thermal control. In this arrangement, the internal thermal control system [163] (ITCS) initially acquires thermal loads from the crew cabin. The ITCS transports the thermal loads and releases them to a heat exchanger common to both the ITCS and the external thermal control system (ETCS). [164] The ETCS acquires thermal loads from the heat exchanger in common with the ITCS and from heat sources outside the crew cabin. The ETCS transports the combined heat loads to the vehicle heat rejection devices.

This architecture, using an ITCS with an ETCS, allows a non-toxic working fluid to circulate in all thermal control hardware located inside the crew cabin while allowing a fluid with greater heat transfer characteristics, to be used in thermal control hardware outside the crew cabin. With NASA vehicles, such as the Shuttle Orbiter and International Space Station, the ITCS working fluid was water, which is non-toxic and has ideal properties for transporting thermal loads, except that it has a relatively high freezing point compared to the external environment in low-Earth orbit. The Shuttle Orbiter and International Space Station both used more toxic working fluids in their ETCS that have lower freezing point temperatures. The Shuttle Orbiter used Freon 21 while International Space Station relies on anhydrous liquid ammonia.

While this architecture, using an ITCS with an ETCS, allows use of more toxic, freeze-resistant working fluids in the ETCS while circulating a non-toxic fluid in the ITCS, this approach is more complex than a single fluid system. In particular, a thermal control system using both an ITCS and an ETCS has the added mass of the heat exchanger common to the ITCS and ETCS plus the added mass of an additional pump for the additional loop. Noting that both the Shuttle Orbiter and International Space Station use two ITCS and two ETCS loops, for redundancy, this arrangement actually adds two extra heat exchangers and two extra pump packages. Further, while the ITCS and ETCS loops are cross-linked or plumbed in a manner that any heat load may be acquired and rejected by either of the two loops serving a particular location in the spacecraft, loss of either an ITCS loop or an ETCS loop degrades the overall heat transport and rejection capabilities of the thermal control system. Thus, the additional inherent complexity may actually reduce overall system reliability.

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[162] It is possible to envision thermal transport using either conduction or radiant heat transfer. For short distances, relatively small thermal loads, or even highly temperature-tolerant equipment, conduction via solid material pathways to the exterior of the vehicle is possible. In fact, passive thermal control uses conduction as its transport mechanism through the vehicle structure. Radiant transport mechanisms are also possible, but less likely, within a vehicle because convective heat transfer within a working fluid is generally more efficient for relatively small temperature differences associated with temperature variations within a vehicle than is radiant heat transfer.

[163] Likewise, this may be designated as the “internal thermal control subsystem.”

[164] The International Space Station also uses the terminology “internal thermal control system” for its corresponding water coolant loops. However, the corresponding International Space Station “external thermal control system” is referred to as the “external active thermal control system” (EATCS). Combined, the ITCS and EATCS are the “active thermal control system” (ATCS).

4.9.2.5 *INTERNAL THERMAL CONTROL SYSTEM*

The internal thermal control system (ITCS) acquires thermal loads from thermal acquisition sites within the crew cabin and transports those loads to a heat exchanger in contact with the ETCS. The ITCS acquires thermal loads through specified interfaces. These interfaces are usually coldplates, where the heat loads are cooled by conduction through the hardware's external structure, or heat exchangers, where the heat loads are initially cooled by convection to a working fluid. In the second case, the most common working fluid within a crew cabin is the enclosed atmosphere because many heat loads release their waste heat to the cabin atmosphere either by convection or radiant transfer. Gas-liquid heat exchangers transfer the atmospheric heat loads to the ITCS.

Cabin atmospheric thermal loads are removed by the gas-liquid heat exchanger through two approaches. Sensible heat is released from cabin atmospheric gases by convection to the gas-liquid heat exchanger. Latent heat is released by condensing water vapor, also called humidity, from the cabin atmospheric gases, removing both humidity and thermal energy by convection with phase change.

Though removal of sensible and latent thermal loads from the cabin atmosphere is a necessary function, because the cabin atmospheric gases and extracted condensate are involved in this process, it is possible that the cabin condensing heat exchanger may organizationally be grouped in whole or in part outside of the Thermal Subsystem even though the underlying processes remove heat. For completeness, here the condensing heat exchanger is grouped with the Thermal Subsystem.

4.9.2.6 *CABIN ATMOSPHERIC THERMAL LOADS*

The cabin has several types of thermal loads that get applied to the atmosphere. The most direct type would be forced air convection that would be applied by an electronics box that contains an internal cooling fan. Some passive devices, such as sensors or control valves, lose their heat via conduction to cabin structure. Some equipment and the crew reject heat via low speed convection and radiation to the cabin surfaces. In space natural convection is nonexistent as it depends on a contribution by gravity. Numerous commercial electronics packages depend on the presence of natural convection in order to maintain their component temperatures. Additionally, the surfaces of any powered device need to be maintained below touch temperature limits[165] (NASA, 2009) in order for the crew to be able to safely touch the device. Due to these factors extra effort is required by the provider to show that the equipment will not fail thermally in space. This usually is a combination of analysis and properly designed testing. Since the absence of gravity can only be simulated for a few seconds in a specially designed aircraft trajectory, most researchers try show acceptance by analysis.

4.9.2.7 *EXTERNAL THERMAL CONTROL SYSTEM*

The external thermal control system (ETCS) acquires thermal loads from the ITCS and from thermal acquisition sites outside of the crew cabin. Because the equipment outside of the crew cabin is almost universally in an unpressurized environment, thermal acquisition interfaces are almost universally coldplates. The ETCS rejects thermal loads to the environment using specified heat rejection devices, such as radiators, phase change devices, and devices that reject expendable materials carrying thermal loads. Mixing warm and cooled working fluid in the return line adjusts the temperature of the ETCS working fluid returning from the heat rejection suite to a prescribed set-point temperature. While the heat-rejection suite thermally cools working fluid, warm working fluid is routed around the heat rejection suite using a flow bypass as necessary to meet the set-point temperature for the ETCS heat acquisition devices.

Figure 4-5 illustrates the interrelationship between the various component definitions for the ATCS. The ITCS, denoted in black with plain type, acquires thermal loads within the crew cabin and rejects those thermal loads to the ETCS. The ETCS, denoted in green with italicized type, acquires thermal loads from the ITCS and equipment outside of the crew cabin and rejects those thermal loads to the environment.

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[165] The touch temperature limit in SSP 57000 is listed as 120°F. At this hardware temperature there is no problem with the crew touch temperature. At higher temperature an analysis would need to be performed based on the procedure in NASA HIDH to determine if the hardware is safe to touch. This analysis depends on the hardware temperature, material and contact time.

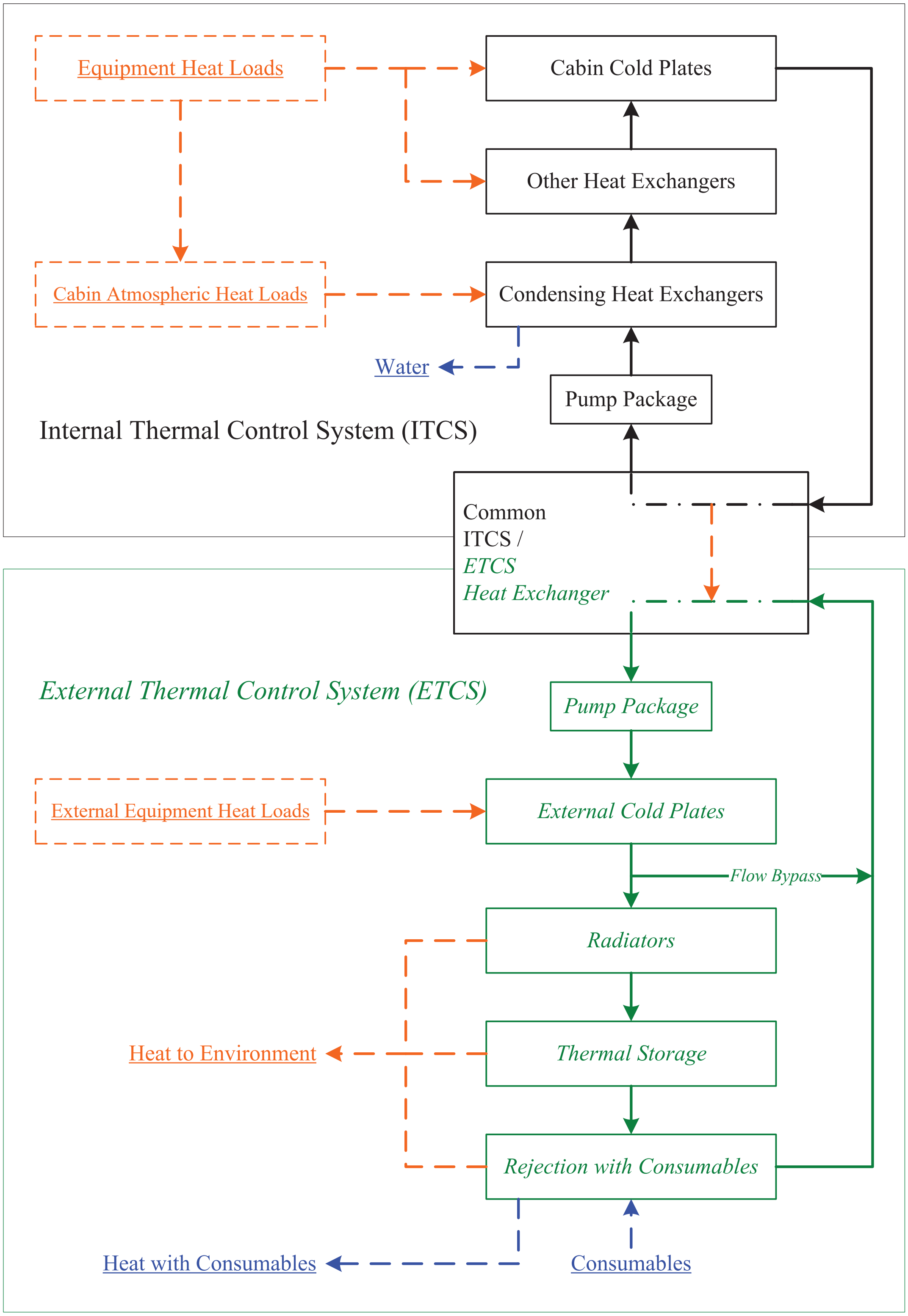

Figure 4-5 Active Thermal Control System component definitions.

4.9.3 THERMAL CONTROL TECHNOLOGY

4.9.3.1 *HISTORICAL THERMAL CONTROL APPROACHES*

While all NASA human-rated vehicles to date have used thermal control hardware to control the crew cabin atmospheric temperature and humidity, recent concerns over safety prohibit all but the most recent designs. In particular, some older spacecraft, such as Apollo, used a mixture of ethylene glycol with water as a working fluid within an active thermal control system loop that entered the crew cabin. Recent flight rules strongly advise against using ethylene glycol in any application within a vehicle in which a crewmember may contact it. Thus, the discussion of historical thermal control approaches is limited to designs for the Shuttle Orbiter and the International Space Station.

4.9.3.1.1 SHUTTLE THERMAL CONTROL

Figure 4-6 shows the ordering of components for one of two ETCS loops in a Shuttle Orbiter. A mechanical pump package, with two identical units plumbed in parallel, drives the single-phase Freon 21 working fluid. For this application, one pump is active and the second is a spare. The accumulator sets the low pressure for the fluid loop. When the working fluid contracts, the accumulator adds fluid, and when the working fluid expands, the accumulator stores any excess fluid. Because even liquid material properties are not truly invariant to temperature variations, the accumulator most often compensates for working fluid density variations associated with temperature changes.

The Shuttle is designed to reject heat through several means depending on the mission segment. On the launch pad and after the ground crew can make connections following landing, the ETCS rejects heat to ground facilities through the ground service equipment heat exchanger. On launch, re-entry, and when necessary on-orbit, the flash evaporator allows excess water to evaporate from the outside of the ETCS working fluid line, expelling the vapor, with its waste heat, to space. Upon re-entry, when the external atmospheric pressure is too great to operate the flash evaporator efficiently, the ammonia boiler evaporates anhydrous ammonia to cool the ETCS working fluid lines, again expelling the vapor to the environment. [166] The radiators, which are mounted on the inside of payload bay doors, reject heat by radiant transfer to space while the Shuttle is on-orbit. Shuttle controls the ETCS working fluid temperature from the radiators with a bypass loop as depicted. Varying internal flowrates or expendable fluid consumption rates controls the other heat rejection devices.

Heat is gathered by the ETCS from many sites throughout the vehicle. Those listed as heat exchanger are liquid/liquid devices where the second operating fluid is the coolant for the attached hardware. The water/Freon interchanger is the common ITCS/ETCS heat exchanger, while the oxygen restrictor is a heat exchanger between the ETCS loop and the pressurized cabin oxygen supply.

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[166] In practice, the ammonia boiler was rarely used as designed. Rather, just before the radiators are removed from service by closing the payload bay doors, the Shuttle flies an attitude so that the radiators face deep space. This maneuver fills the radiator panels with chilled Freon 21 and chills the metallic panels as well. Following this maneuver, the radiators are completely bypassed and the flash evaporator rejects the entire vehicle thermal load. When the flash evaporator ceases operations high in the atmosphere, flow through the now-stowed radiators is re-established, releasing the previously cooled working fluid. This approach provides sufficient cooling from when the flash evaporator ceases operations until about 15 minutes after touch down. If all proceeds on schedule, the ground-cooling cart that interfaces with the ground service equipment heat exchanger is operational by 15 minutes after touch down, and the ammonia boiler is not used. The ammonia boiler is provided on each mission as a contingency for heat rejection and would provide primary cooling if the ground-cooling cart was not available in time or the Shuttle executed a launch abort.

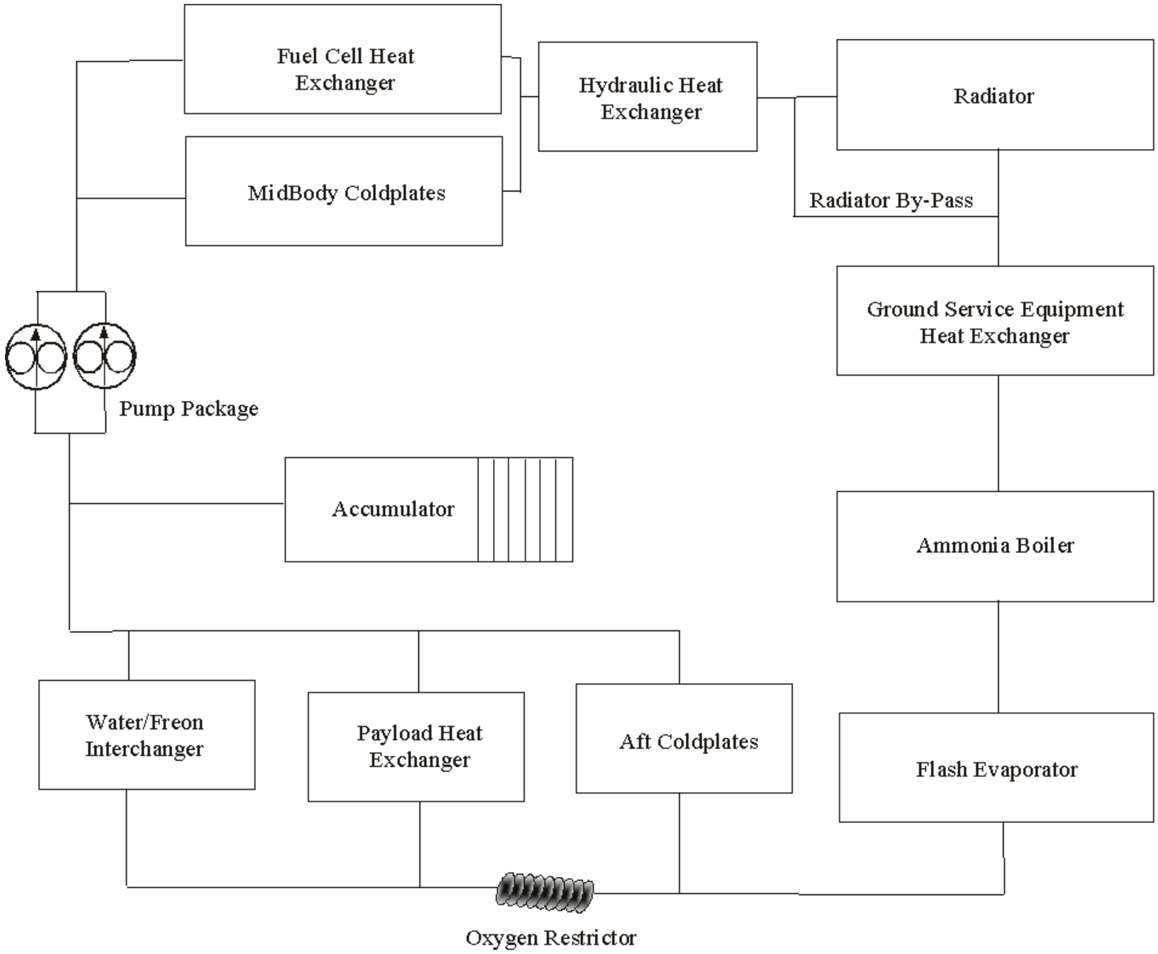

Figure 4-6 Active Thermal Control System hardware for the shuttle orbiter.

Figure 4-6 presents one of two Freon 21 loops in the Shuttle Orbiter ETCS. Coolant flow is clockwise. Because the ETCS loops run through an unpressurized portion of the vehicle, the heat exchangers are integral with the devices they cool. The Water/Freon Interchanger and the Oxygen Restrictor are heat exchangers between the ITCS water loop and the pressurized cabin oxygen supply, respectively. The Accumulator maintains pressure within the flow loop. The Radiator, Ground Service Equipment Heat Exchanger, Ammonia Boiler, and Flash Evaporator are all heat rejection devices.

4.9.3.1.2 INTERNATIONAL SPACE STATION THERMAL CONTROL

The external active thermal control system (EATCS) for ISS is very similar to the architectures presented above. The ISS EATCS uses single-phase, anhydrous liquid ammonia as its working fluid, although the corresponding ITCS uses water. The radiators are mounted on booms that connect to the P1 and S1 [167] truss segments through a thermal radiator rotary joint (TRRJ). The TRRJs orient the radiator panels so that they display their thinnest face, their “edges,” to the Sun, allowing their radiant face-sheets to be exposed only to relatively cooler environments.[168] While not depicted in Figure 4-7 , many of the fine details are similar to those in earlier diagrams.

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[167] The ISS truss segments are numbered in ascending order from the center of the vehicle. The S0, “starboard zero,” truss segment forms the base for the other truss segments and connects directly to the other ISS modules through the U. S. Laboratory. The first starboard segment outboard of S0 is S1, while the first port segment outboard is P1, or “port one.”

[168] In rare situations, the TRRJs are not able to completely orient the radiator edges at the Sun, but this case is not common and only occurs for brief periods.

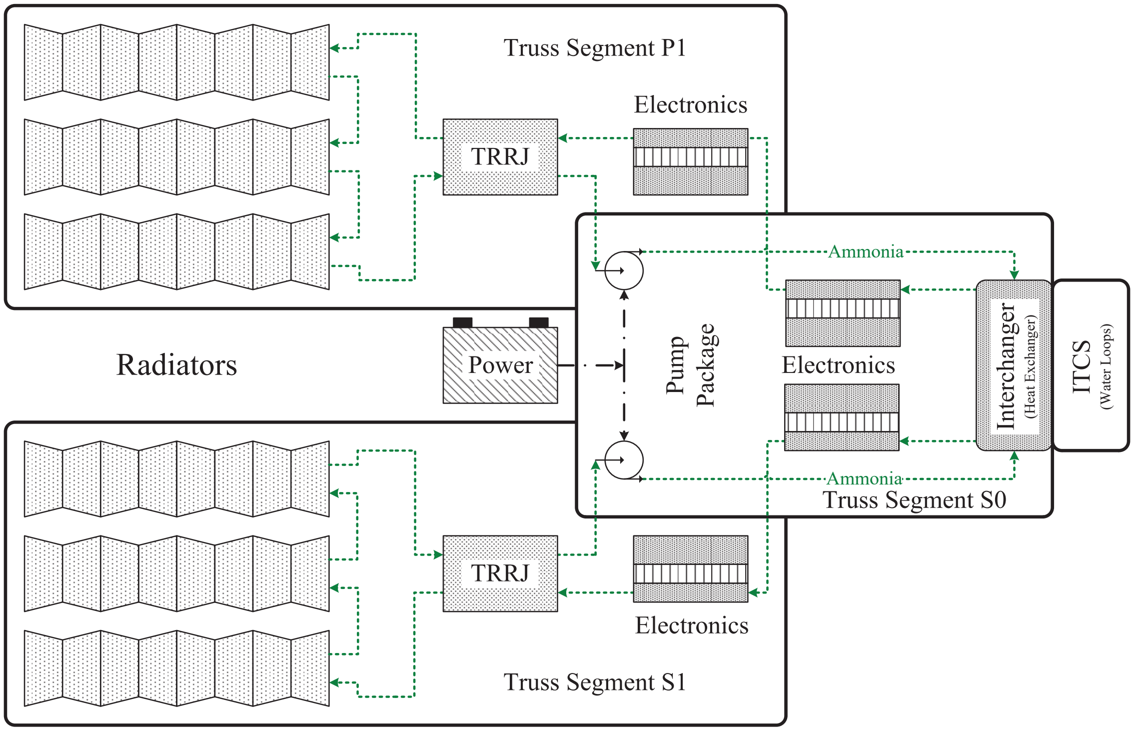

Figure 4-7 **External Active Thermal Control System hardware for International Space Station.**

As noted by the arrows in Figure 4-7, ammonia flows from radiators to the common ITCS/EATCS heat exchanger and then to the warmer thermal loads associated with electronics mounted on coldplates. Each TRRJ rotates to position the radiator panels so that they face anti-Sun, or "edge-on" to the Sun. The bulk of the EATCS is located on truss segments S0, S1, and P1.

4.9.3.1.3 ADVANCED THERMAL CONTROL APPROACHES

There are many concepts to increase the efficiency of thermal control hardware, and several of the more common ideas are summarized in the paragraphs below. Please, note, however, that this is not an exhaustive discussion and other viable approaches exist.

As noted above, the active thermal control system (ATCS) is the summation of both the ITCS and ETCS .[169] Further, dividing the ATCS into two loops when, physically, only one loop is required, adds inefficiency to the process of removing thermal loads from the vehicle even when there are benefits from this approach. An alternate approach employs only a single ATCS loop in place of each ITCS / ETCS combination. The working fluid requirements are more stringent because the working fluid may not be a significant hazard to the crew if leaked into the crew cabin, nor may it be overly susceptible to freezing when flowing through heat rejection equipment. While not employed currently, such systems are under development and the concept is mentioned here as background.

Another possible advanced concept is a two-phase thermal control working fluid. Thermal control loops using single-phase working fluids rely on the heat capacity of the working fluid to accept and transport thermal loads. However, single-phase working fluids are limiting in practice because acquiring a thermal load raises the temperature of the working fluid, so hardware downstream must reject their thermal loads to a working fluid at a higher temperature than hardware upstream, and this concern can lead to other inefficiencies. Secondly, a single-phase working fluid generally can acquire less heat over its entire liquid temperature range than is required to change the phase of the same mass of working fluid from a liquid to a vapor. If the thermal control working fluid is allowed to vaporize as it acquires thermal loads, the working fluid remains at a constant temperature and actually

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[169] Or the "External Active Thermal Control System" (EATCS) when using International Space Station nomenclature.

less fluid mass is required to carry the same thermal load. Issues associated with two-phase flows under non-terrestrial gravitational fields remain as challenges to this approach so far.

Heat pumps also offer promise as advanced thermal control technologies. While terrestrial heat pumps move heat either into or out of a volume, heat pumps as part of an advanced thermal control system move heat from the vehicle to the environment only. Specifically, heat pumps use work, either thermal or mechanical, to raise the temperature of waste heat loads to increase the ease of rejecting those loads by radiant heat transfer. While heat pumps add hardware and use power, the increased temperature of the heat load for radiant emission from the vehicle decreases the required radiator size so that the overall system may be less massive than a thermal control system without a heat pump, especially in a hot environment.

4.9.4 RADIANT ENERGY BALANCE

Heat transfer is a broad topic and any in depth treatment is beyond the scope of this document. See, for example, a heat transfer text such as Incropera and DeWitt (1985) for a more complete introduction. However, several definitions and assumptions are common when analyzing radiant heat transfer for space applications within NASA. Except as specifically noted, the development below follows Incropera and DeWitt (1985).

In general, heat emitted by a perfectly black body, q_{bb} [W], may be described by the Stefan-Boltzmann equation.

$$q_{bb} = \sigma A T^4 \qquad \text{Equation 4-6}$$

where σ is the Stefan-Boltzmann constant with a value of 5.67×10^{-8} W/(m²·K⁴), A is the body's surface area [m²], and T is the body's absolute temperature [K]. A black body is a perfect emitter and its emittance is a function only of its temperature once its geometry is fixed.

In practice, most real surfaces are not perfect emitters, and their surface emittance may be described as some fraction of the emittance from a perfectly black body. For a non-ideal body whose emittance fraction is constant, a slightly modified relation applies;

$$q_e = \sigma \varepsilon A T^4 \qquad \text{Equation 4-7}$$

q_e is emittance [W], and ε is the emissivity or the fraction of the surface's actual emittance compared to its ideal or black body emittance at its current absolute temperature, T. Alternately, ε is unity only for an ideal or black body.

As noted earlier, radiant exchange of thermal energy does not depend on intervening matter for transfer. Rather, radiant exchange is possible between any two surfaces with a view of each other. Physically, according to one theory, thermal energy transfers between the surfaces via electromagnetic waves. [170] According to classic physics, thermal radiation, which is a subset of a broader phenomenon known as electromagnetic radiation, varies between wavelengths of 0.1 and 100 μm. Visible light, according to the human eye, is confined to a range varying from 0.40 to 0.70 μm. In addition to visible radiation, classical physics defines thermal radiation at wavelengths less than 0.40 μm as also being ultraviolet radiation, and thermal radiation at wavelengths greater than 0.70 μm is also infrared radiation. As context, electromagnetic radiation at wavelengths less than 0.1 μm is classified, depending on its wavelength, as ultraviolet radiation,[171] x-rays, or gamma rays. Electromagnetic radiation at wavelengths immediately greater than 100 μm is classified as microwaves.

When thermal radiation strikes a solid object, it may be absorbed, reflected from the surface, or transmitted through the object. If the surface is opaque to the incident radiation, transmittance is zero and only absorbance or reflectance is possible.

$$\alpha + \rho = 1 \qquad \text{Equation 4-8}$$

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[170] Alternate theories describe the transfer via photons or quanta, but the image of an electromagnetic wave is most applicable to the current discussion.

[171] Ultraviolet radiation varies from 0.01 to 0.40 μm, and so overlaps the range classified as thermal radiation.

where α is the absorptivity and ρ is the reflectivity. For an ideal or black body, reflectivity is zero and absorptivity is unity.

At any given wavelength, λ, according to Kirchhoff's Law, absorptivity and emissivity are equal for a particular surface if (1) the incident irradiation is invariant with respect to direction, or diffuse, and (2) the surface properties are invariant with respect to direction, or diffuse.

$$\alpha_\lambda = \varepsilon_\lambda \qquad \text{Equation 4-9}$$

Additionally, if (3) the incident irradiation is diffuse and if (4) the surface properties, the absorptivity and emissivity, are independent of wavelength, λ, the surface is called a gray surface.

$$\alpha = \varepsilon \qquad \text{Equation 4-10}$$

While most real surfaces do not abide by this final requirement to qualify as gray surfaces, many are effectively gray over some subset of the range of thermal radiation. At Johnson Space Center, two thermal radiation sub ranges are often defined for radiant transfer calculations (Conger and Clark, 1997). Thermal irradiation between 0.25 μm and 2.5 μm, inclusive, is designated as solar thermal radiation (AZ Technology, 1993), while thermal irradiation above 2.5 μm is designated as infrared thermal radiation. Over each of these sub ranges, material surface properties are assumed gray.

$$\begin{aligned} \alpha_s &= \varepsilon_s \\ \alpha_{ir} &= \varepsilon_{ir} \end{aligned} \qquad \text{Equation 4-11}$$

where the subscript "s" denotes surface properties over the range of solar thermal radiation and the subscript "ir" denotes surface properties over the range of infrared thermal radiation. This does not imply that α_s equals α_{ir} or that ε_s is equal to ε_{ir}. This approach effectively considers Equation 4-6 applicable in a piecewise manner over two sub ranges for thermal radiation.

Physically, except during re-entry or similar operations with extremely high aerodynamic drag, the surface temperatures of spacecraft in space do not approach the range where surfaces emit in the solar range. Thus, surface emissions from spacecraft, planetary surfaces, and other non-glowing physical bodies have surface properties as defined by the second relation in Equation 4-7. Irradiation coming from the Sun, or reflected irradiation that originated from the Sun, however, emit in the solar range. Thus, incident or reflected irradiation from the Sun uses surface properties as defined by the first relation in Equation 4-8.

From the perspective of a spacecraft, which emits infrared thermal radiation but likewise absorbs incident solar thermal radiation, it is meaningful to define the ε_{ir}, for both infrared thermal emittance and absorptivity, and α_s, for solar thermal absorptivity.

4.9.5 THERMAL CONTROL VALUES

This section provides values necessary to estimate heat transfer both within a spacecraft and between a spacecraft and its environment. In fact, many values below may apply both to thermal control within a spacecraft as well as to heat rejection from the spacecraft.

Table 4-72 presents solar absorptivities and infrared emissivities for several common aerospace structural materials. The end-of-life properties reflect changes associated with external usage in near-Earth space and are not applicable within the crew cabin. While surfaces within the crew cabin certainly wear, aging mechanisms differ from those in the vacuum of space or even on the Martian surface. Thus, as a first approximation emissivities for new materials apply even for a used interior.

Table 4-72 Surface Optical Properties for Common Exterior Space Material

	New		End-of-Life [172]		
Material	α_s	ε_{ir}	α_s	ε_{ir}	**Reference**
Silverized Teflon	0.07	0.80	0.14	0.80	From Conger and Clark (1997) unless otherwise noted.
Aluminized Teflon	0.12	0.80	0.20	0.80	
Ortho Fabric [173]	0.18	0.84			
Beta Cloth	0.26	0.90			
A276 White Paint	0.28	0.87	0.36	0.90	
Clear Anodized Aluminum	0.38	0.83	0.58	0.79	
Gold Anodized Aluminum	0.55	0.81	0.63	0.81	
Black Anodized Aluminum	0.81	0.88	0.84	0.79	
Alodine Aluminum	0.45	0.35			
Bare Stainless Steel	0.42	0.11			
Sand-Blasted Stainless Steel	0.58	0.38			
Bare Titanium	0.52	0.12			
Tiodized Titanium	0.82	0.51			

Within the crew cabin, thermal considerations are dictated by two concerns. The first is crew comfort and maintaining equipment within its thermal bounds. The second concern is to maintain humidity within an acceptable range. If the overall cabin atmospheric temperature drops below the local dew-point temperature, water vapor is allowed to condense. Because liquid water poses a significant hazard to electronics especially in weightless situations, maintaining cabin atmospheric and humidity within prescribed limits is important. Table 4-73 presents applicable thermal limits for crew cabins.

Table 4-73 Crew Cabin Thermal Ranges

		Assumptions			
Parameter	**Units**	**Lower**	**Nominal**	**Upper**	**Reference**
Air Temperature [174]	K	291.15 (1)	295.15 (3)	300.15 (1)	(1) NASA HIDH (2014) (2) Plötner, *et al.* (2013) (3) Thirsk, *et al.* (2009)
Dew-Point Temperature	K	271	282.5	295	
Relative Humidity	%	25 (1)	45 (2)	75 (1)	
Ventilation	m/s	0.076 (1)	0.15(1)	0.6096 (1)	

Transport properties for several common thermal control working fluids are tabulated in Table 4-74 at likely operating temperatures. These values support basic thermal loop energy balances.

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[172] These values apply to external applications only because aging and wear mechanisms within the crew cabin differ considerably from external aging and wear mechanisms. As a first approximation, surface properties for materials within the crew cabin do not change with time.

[173] The exterior fabric on the extravehicular mobility unit.

[174] The cabin "dry bulb" atmospheric temperature.

Table 4-74 Properties for Common Thermal Control Loop Working Fluids

		Temperature = 280.0 K			Temperature = 297.0 K			Temperature = 300.0 K			
Fluid	**Hazards**	**Density [kg/m³]**	**Specific Heat [kJ/kg·K]**	**Viscosity [kg/m·s]**	**Density [kg/m³]**	**Specific Heat [kJ/kg·K]**	**Viscosity [kg/m·s]**	**Density [kg/m³]**	**Specific Heat [kJ/kg·K]**	**Viscosity [kg/m·s]**	**References**
Water		1,002.08	4.204	0.00148				998.35	4.187	0.00083	From Schoppa (1997) unless noted otherwise.
30% Ethylene Glycol /70% Water	Irritant	1,042.15	3.741	0.00311				1,033.34	3.788	0.00176	
60% Ethylene Glycol /40% Water	Irritant	1,083.84	3.130	0.00796				1,071.70	3.216	0.00417	Propylene glycol/water Properties from Dowfrost.com
50% Propylene Glycol /50% Water					1042	3.54	.0055				Glycerine/water properties from Lienhard (1981)
40% Glycerin /60% Water					1097	3.015	0.0029				
Fluorinert 72		1,722.12	1.025	0.00117				1,669.92	1.056	0.00092	
Hydrofluoroether HFE-7100		1,522.76	1.147	0.00088				1,477.38	1.187	0.00071	
Ammonia (liquid)	Toxic	628.20	4.679	0.000232				600.46	4.854	0.00021	
D Limonene	Flammable				847.5	2.05	0.00091				

Table 4-75 and Table 4-76 provide appropriate thermodynamic values to compute energy balances of phase-change materials for representative materials. Of the materials available, both here and more generally, water requires the greatest heat input for the least mass and is the "best" phase-change material available, although the temperatures at which it transitions from one phase to the next sometimes prohibits its use. While the temperature at which a liquid boils varies directly with pressure, melting point temperatures are effectively invariant with pressure for applications likely to see use in space flight.

Table 4-75 Thermodynamic Properties of Common Thermal Control Phase-Change Materials for Liquid-Vapor Transitions

Material	Formula	Liquid Density [kg/m³]	Saturation Pressure [kPa]	Saturation Temperature [K]	Heat of Vaporization [kJ/kg]	Reference
Ammonia	NH_3	702.2 (1)	40.7 (1)	223.2 (1)	1,425.8 (1)	(1) Howell and Buckius (1987)
		690.1 (1)	71.6 (1)	233.2 (1)	1,392.5 (1)	
		677.5 (1)	119.5 (1)	243.2 (1)	1,361.1 (1)	
Water	H_2O	1,000 (1)	0.61 (1)	273.2 (1)	2,500.0 (1)	
		1,000 (1)	1.23 (1)	283.2 (1)	2,478.4 (1)	
		998 (1)	2.34 (1)	293.2 (1)	2,455.0 (1)	

Table 4-76 Thermodynamic Properties of Common Thermal Control Phase-Change Materials for Solid-Liquid Transitions

Material	Formula	Solid Density [kg/m³]	Liquid Density at 293.2 K [kg/m³]	Melting Temperature [K]	Heat of Fusion [kJ/kg]	References
Water	H_2O	920 (1)	998 (2)	273.2 (3)	333.6 (3)	(1) Incropera and DeWitt (1985) (2) Howell and Buckius (1987) (3) Weast and Astle (2019)
Waxes (Paraffin)						
n-Dodecane	$C_{12}H_{26}$		749.5 (3)	263.6 (3)	216.0 (3)	
n-Tetradecane	$C_{14}H_{30}$		759.6 (3)	279.0 (3)	227.2 (3)	
n-Hexadecane	$C_{16}H_{34}$		770.1 (3)	291.3 (3)	235.6 (3)	
n-Octadecane [175]	$C_{18}H_{38}$		776.8 (3)	301.3 (3)	242.4 (3)	

4.10 CREW HEALTHCARE

Qualitative impact of the challenges for designers of medical care systems are complex. The health care system can't look like its Earth counterpart because of the effects of gravity as well as mass, power, volume, and crewtime restrictions that are certain to be levied on the system. It could be argued that the medical system has been minimal to this point and there's been little need to make it more inclusive, but as missions move farther from earth and have longer durations, the likelihood of necessary medical intervention becomes greater. Consider the possible illnesses and injuries divided into three classes (Table 4-77). Since treatment in Class I is unlikely to have a large impact on life support commodities and Class III treatment might be prohibitively expensive, the therapies likely to impact life support are those therapies in response to Class II illnesses and injuries.

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[175] The liquid density for n-octadecane is evaluated at 28 °C.

Table 4-77 Classification of Illnesses and Injuries in Healthcare (Houtchens, 1993)

Characteristics	Examples	Response
Class I		
Mild Symptoms	Gastrointestinal Distress	Self Care
Effects Performance Minimally	Headache	
No Threat to Life	Mild Ulcer	
Prognosis Is Self-Limited	Laceration of Abrasion	
	Sprains and Strains	
Class II		
Moderate to Severe Symptoms	Urinary Infection or Inflammation	
	Respiratory Irritation	
Marked Effect on Performance	Allergy, Conjunctivitis, or, Dermatitis	
	DCS	
	Air Embolism	
Potentially Life Threatening	Arrhythmia	Prompt adequate diagnosis and treatment
	Partial Circulatory Blockage	
	Ulcer	
	Respiratory Distress	
Could Be Protracted	Toxic Inhalation Exposure	
	Chemical burns	
	Stones	
	Diverticulitis	
	Appendicitis	
Class III		
Symptoms Immediate and Severe	Explosive Decompression	Evaluate Promptly and Transport or; Take Measures to Store, Return, or Destroy the Body
Incapacitating	Complicated Heart Malfunction	
Life Threatening If Not Immediately Fatal	Overwhelming Infection	
	Crush Injury	
Crewmember Won’t Survive If Not Treated Promptly	Brain Surgery	
	Burn > 40% of Body Surface Area	

The question from a life support perspective is how do medical activities affect ECLSS commodities? Certainly, some of the issues in Table 4-77 have been addressed by planners, as the EVA suit is required to have the capability of a one-time increase in pressure to 156.5 kPa for treatment of decompression sickness. Conceivably the suit could also act as an oxygen delivery device without increasing the cabin oxygen percentage, but such an arrangement would present obstacles for such activities as surgical procedures, intravenous therapy, or certain kinds of diagnostic testing. A rebreathing mask or a valved non-rebreathing mask might aide in oxygen delivery without significantly increasing cabin oxygen levels (Yam, 1993).

Medical care is mentioned in NASA-STD-3001 (2015) and five levels of care are identified. The levels of care are defined as the level and type of care that can be provided by an individual. Conversely, standard of care does not depend on the medical capabilities of the individual but on current clinical practices. Level of care zero has a low need for medical care for unplanned and unforeseen injury. Level of care one uses preventative medicine to mitigate medical maladies. Medical care in this case includes the materials provided by a routine first aid kit. Level of care two involves more robust medical attention to treat major illnesses using medications or equipment. Short mission duration does not require the equipment necessary to monitor long-term effects due to micro-gravity. Level of care three is a thicker layer of the previous level: sick, injured, or deconditioned crewmembers will require immediate and long-lasting life-saving care to withstand limited advanced life support and limited consumables.

The Lunar and Mars Sortie and Outpost missions would fall under “Level of Care Four”, which is listed as a moderate level of risk for medical issues (mission length from 30 days to 210 days). Preventative measures are still being stressed at this level, but intervention strategies should be available to reduce risk to an acceptable level. Medical capabilities will be limited because of limited ability to rapidly return to Earth in the event of a major crisis. Strategies to limit risk include increasing the advanced care in the form of medications, equipment, training, or consumables over and above previous levels. It is the level of consumables that will most affect life support and thus is an area where further definition is desirable. The following example may be used as a starting point.

Table 4-78 Medical Hardware and Stowage - Lunar Outpost

Item	Mass [kg]	Volume [m^3]	Development Concept
Medical System	136	1.50 (similar to ISS ISO rack)	Program Provided
Telemedicine Workstation	22.7	Technology development	
Contaminant Cleanup Kit	4.5	COTS	
Portable Imager (Ultrasound)	6.8	COTS	
Advanced Life Support/Trauma Stabilization Kit	11.3	Modified COTS	
Medical Procedure Kit - Dental - Laceration repair - Acute Care pack	9.1	COTS	
Environmental Hardware - Total Organic Carbon Analyzer - Volatile Organic Analyzer - Radiation Detection System - Compound Specific Analyzer - Microbiology Analyzer - Dust Monitor - Acoustic Monitoring - Hearing Protection Device	45.4	Based on ISS hardware, technology development will be necessary for miniaturization and better reliability.	
Contingency Breathing Apparatus (Possibly portable)	9.1	Modified COTS	
Other: - Biomedical Sensors - Assisted Procedure Device - Medical Grade Water Generation - Closed Loop Oxygen Concentrator/Delivery System		Technology Development	

Table 4-79 Medical Hardware and Stowage - Lunar Outpost Exercise Countermeasures or Dust Management

Item	Mass [kg]	Volume [m^3]	Development Concept
Aerobic	34	3.1	Technology Development
Resistive	56.7	5.7	Technology Development
Dust	Dust management: Suit Lock may reduce dust loading	No available data	Technology Development

Table 4-80 Medical Hardware and Stowage- Lunar Sortie

Item for Lunar Sortie	Mass [kg]	Volume [m^3]	Development Concept
Concept Medical Kit	4.5	0.007	COTS
Medical Contingency Kit	4.5	0.010	Modified COTS
EVA Contingency Response Kit (with Contamination Cleanup)	2.7	0.036	Modified COTS
Environmental Health Kit	0.23	0.007	Modified COTS
Exercise Equipment	2.3	0.003	Technology Development Required

4.11 ENVIRONMENTAL MONITORING

ECLSS provides a habitable environment in manned vehicles by fundamentally addressing the physical, chemical, and biological risks external to the human body that can impact the health of a person. Environmental health risks are mitigated not only by employing these active and passive controls, but also establishing environmental standards (SMACs, SWEGs, microbial and acoustics limits) and environmental monitoring. Because risks can vary during missions and change over time, environmental monitoring is considered a vital component to an environmental health management strategy for maintaining a healthy crew and achieving mission success. Environmental monitoring involves monitoring four aspects of the habitable environment of the vehicle to ensure crew health.

- Air Quality - assesses potential airborne contaminant exposures during spaceflight and establishes Spacecraft Maximum Allowable Concentrations (SMACs) that will protect crew while living and working in space;
- Water Quality - assesses and characterizes the quality of water sources, verifies these systems meet potability requirements, and establishes Spacecraft Water Exposure Guidelines (SWEGs);
- Microbiology - assesses bacterial and fungal contamination levels in the air, water, and surfaces and addresses issues related to infectious disease and microbial ecology of spacecraft; Microbiology also establishes pre-flight and in-flight acceptability levels;
- Acoustics Management- assesses the spacecraft environment and ensures noise levels are within acceptable limits so the crew can comfortably and safely live, communicate, and work; Acoustics also establishes noise exposure levels.

Figure: 4-8 below shows the parameters used to assess environmental health. The various concentration limits and levels for crew health can be found in the Medical Operation Requirements Document (MORD). Table 4-81 lists the typical volatile organic compounds (VOCs) found in the habitable cabin of ISS. The average low and average high are based on ground analyses of returned grab sample containers (GSCs) from January-2001 to March-2011. Table 4-82 to Table 4-84 are the microbial limits and acoustic limits for ISS. Oxygen and carbon dioxide are monitored primarily by the Major Constituents Analyzer (MCA) during nominal scenarios. During contingency scenarios, small, battery-powered, hand-held devices are used to back-up the MCA. System chemicals such as ammonia, used as the working fluid of the external thermal control system, are monitored for potential leaks.

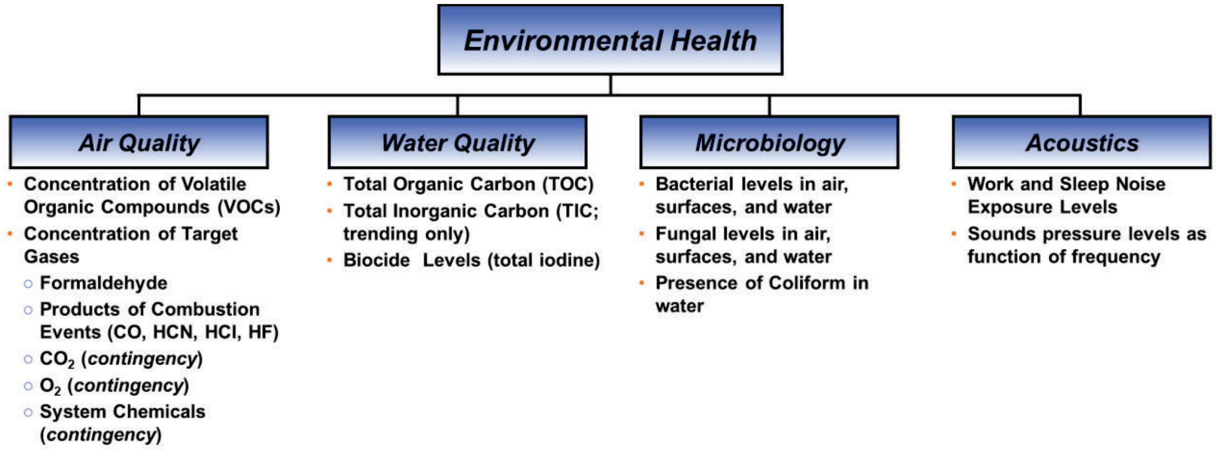

Figure: 4-8 Environmental Health

Table 4-81 Typical Volatile Organic Compound (VOC) Concentration Ranges Monitored on the ISS

Volatile Organic Compounds (VOCs) (1)		Concentration Range (ppm)	
VOC Type	**Chemical**	**Low**	**High**
Alcohols	**Ethanol	0.531	3.715
	**Methanol	0.076	0.763
	**2-Propanol	0.041	0.407
	**1-Butanol	0.016	0.330
	Propylene glycol	0.000	0.000
Aldehydes	Formaldehyde	0.008	0.081
	**Acetaldehyde	0.056	0.333
	**Acrolein (Propenal)	0.004	0.044
	Pentanal (C3-C8 Aliphatic Sat. Aldehyde)	0.003	0.142
	**Hexanal (C3-C8 Aliphatic Sat. Aldehyde)	0.002	0.122
Alkanes	Pentane (C5-C7 Alkanes)	0.003	0.169
	**Hexane (C5-C7 Alkanes)	0.003	0.142
Ketones	**Acetone	0.042	0.421
	**2-butanone	0.034	0.339
Organosilicones	**Octamethylcyclotetrasiloxane	0.008	0.165
	**Hexamethylcyclotrisiloxane	0.011	0.220
	**Decamethylcyclopentasiloxane	0.007	0.132
	**Trimethylsilanol	0.027	1.08
Aromatic	**Benzene	0.016	0.313
	Ethyl benzene	0.002	0.023
	**Toluene	0.027	0.265
	**ortho-Xylenes	0.023	0.230
	**meta, para-Xylenes	0.023	0.230
Halogenated	**Dichloromethane	0.014	0.288
	Freon 218 (perfluoropropane)	13.0	130
Esters	**Ethyl acetate	0.028	0.277

Combustion Products (2)	Monitoring Range	Accuracy
Carbon Monoxide (CO)	5 – 1000 ppm	5 - 50 ppm ±20% 50 – 1000 ppm ±10%
Hydrogen Cyanide (HCN)	1 – 50 ppm	1 – 50 ppm ±25%
Hydrogen Chloride (HCl)	1 – 50 ppm	1 – 50 ppm ±25%
Hydrogen Fluoride (HF)	1 – 50 ppm	1 – 50 ppm ±25%

References
(1) NASA (2003)
(2) James (2013)

**denotes VOC currently monitored in real-time on board the ISS

Table 4-82 Microbial Specifications of USOS air and surfaces for ISS

	Maximum for Bacteria	Maximum for Fungi
Air	1000 CFU/m^3	100 CFU/m^3
Internal Surfaces	10,000 CFU/100 cm^2	100 CFU/100 cm^2

*NOTE: Microbial specifications have been established to provide an alert level indicating that an assessment shall be performed to determine risk to crew health or systems performance.

Table 4-83 Microbial Specifications of ISS water in USOS

Water Parameter	Units	Russian Ground-Supplied potable SVO-ZV (2)	Regenerated Potable SRV-K	Hygiene	U.S Water Recovery System and CWC-I (3)
Bacteria(1) Count	CFU/mL	50	50	1000	50
Coliform Bacteria Count	CFU/100mL	Non-detectable	Non-detectable	Non-detectable	Non-detectable
Protozoa	N/A (4)	TT(5)	N/A	TT	TT

(1) Microbial acceptability limits have been established to provide an alert level indicating that an assessment shall be performed to determine risk to crew health or systems performance.
(2) SSP 50129 standards apply to Russian grade water delivered by ATV.
(3) SSP 50917 standards apply to U.S. grade water delivered by HTV.
(4) N/A = not applicable
(5) TT = Treatment Technique. Source water shall be filtered through a one micron filter. No analysis is required.

Table 4-84 Acoustic Noise Limits in the USOS of ISS

	Octave Frequency Band, Hz							
Work Area	63	125	250	500	1000	2000	4000	8000
(NC-50)	71	64	59	54	51	49	48	47
(NC-48 + NC-50) where payload complement applies	73	66	60	56	53	51	50	49
Sleep Area (NC-40)	64	56	50	45	41	39	38	37

4.12 SYSTEM RELIABILITY IMPACTS AND ANALYSIS

Mission success is highly dependent on the system, subsystem, and component reliabilities of the requisite life support systems necessary to sustain human exploration. With shorter duration missions or missions in close proximity to the Earth, such as the ISS in low Earth orbit (LEO), system and/or component failures may be easier to accommodate due to quicker spares delivery from the ground if they do not exist on site or the availability of evacuation to Earth. However, as longer mission durations (> 1,000 days) to further destinations (e.g. Mars) are desired, the ability to develop reliable systems for the entire mission duration and accurately model a system's reliability increases in importance. This section provides a brief overview on the various factors that can affect system reliability, as well as providing some basic details concerning systems reliability analysis.

A system's reliability is the probability that the system will perform its intended purpose for a specified interval under specific conditions. One such strategy is to design systems to be as reliable as possible to minimize the likelihood of failures during the missions. However, it becomes impracticable to expect that failures will not occur for long exploration missions. In Bagdigian*, et al.* (2015), equipment mass, hardware lifetime, and crew time spent on maintenance are provided as measures of reliability of the ISS ECLSS. These data are compared with the notional 1,000-day Mars mission to provide a survey of the ability of the current ISS ECLSS technologies to be able to meet the high reliability demands for extended Mars missions. This paper provides the operating history of the different ECLSS including the oxygen generation system (OGS) and the water recovery system (WRS). These systems represent readily accessible technologies for providing loop closure needed to support mission scenarios with high reliability; however, certain components were shown to have prematurely failed, such as the H_2 sensor of the oxygen generation assembly (OGA). This type of information may be useful for performing reliability analysis of systems to determine the requisite number of spares needed to sustain a mission with a high probability of success as well as enumerating the different failure modes.

There are many studies which present the methods for performing a reliability analysis. The details of a reliability analysis will not be discussed in detail herein; however, the papers listed in this section may provide a good starting point to the reader. In its simplest form, one may consider regular scheduled maintenance and replacement of parts according to their design life as one form of ensuring a reliable system. However, within a dynamic and complex system, such as the ECLSS, it has been shown that unexpected failures can occur (Bagdigian*, et al.* 2015). Classically, reliability analysis involves predicting component failures, cascading and dependency effects, contingency planning, and maintenance scheduling.

Reliability analyses tend to rely on databases of historical data or expert opinions where examples include: the ISS Risk Management Application (IRMA) for predicting the likelihood and consequence of an event, the Probabilistic Risk Assessment (PRA) tool which includes the failure modes from Space Shuttle, and analogous industry approaches such as the Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), What-If Analysis, and Hazard and Operability Method (HAZOP) (Jiang*, et al.*, 2011). Each type of assessment or tool has their own advantages or disadvantages. Common disadvantages include limitations due to the reliance on operational data, which may not exist for developmental systems; the large effort needed to enumerate the failure modes; and possible subjectivity in assessment which utilize a scoring matrix. The design and analysis of ECLSS reliability is further complicated due to the lack of statistical data where in many cases only a single unit may exist, which does not adequately sample the population. Additionally, with the ECLSS, additional complexity arises due to needing to address buffer capacity, which relates to the inherent storage of life support consumables in the system/habitat that provides the opportunity for repair in the case of system failure. Other aspects which may complicate the analysis of reliability is the consideration of repairable components, the effect of the quality of maintenance, and reliability degradation over time, which are all real effects in an operating system (Jiang*, et al.,* 2011). Additionally, outside of the hardware robustness is the consideration of the crew performance, which may affect how well the system is maintained as well as the probability that a failed system may be recovered. Thus, it is evident that the analysis of a system's reliability is not a trivial matter, depending on the degree of detail to be modeled.

A fundamental approach towards reliability analysis is the reliability block diagram (RBD). In these diagrams, component interactions are presented by a network of blocks and connections. As long as there is a path from the start to the end of the RBD, the system is operational. Figure 4-9 provides an illustration of an example RBD, which includes various types of system architectures. See Jiang*, et al.* (2011) for further details on the determination of reliability depending on the configuration.

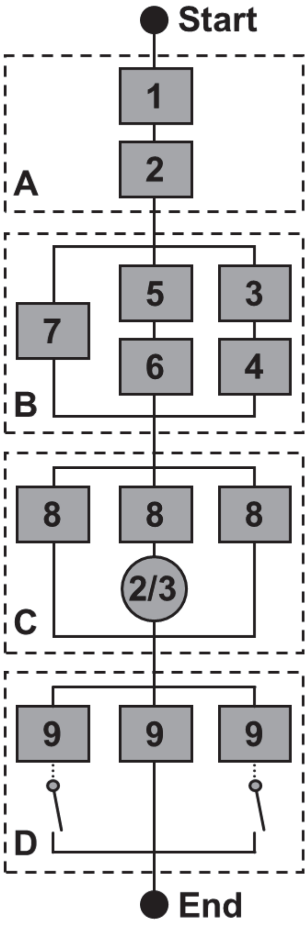

Figure 4-9 Reliability Block Diagram (RBD) where (A) represents a series system, (B) represents a parallel system, (C) represents a k-out-of-n system where only 2 out of 3 subsystems are needed to function, and (D) represents a system with redundancy where two additional dormant spares can be switch on in case of failure. Adapted from Jiang*, et al.* (2011).

Provided that the RBD depicts the component-system connectivity, the overall system reliability, R_S, may be calculated as the product of the component-system reliabilities, $R_{CS,i}$. where N_{CS} is the number of component systems.

$$R_S(t) = \prod_{i=1}^{N_{CS}} R_{CS,i}(t) \qquad \text{Equation 4-12}$$

The failure rate (λ) may be determined from the mean time between failures (MTBF) for a specified duty cycle as shown in Lange*, et al.* (2012). Sources for ECLSS related MTBF values include reliability handbooks (e.g, US Department of Defense, 1991) and NASA's reliability and maintainability database (Jones, 2020a; Jones, 2020b; Lange*, et al.,* 2012). These failure rates are utilized to calculate the component system reliability, which are described by failure and repair probability distributions. There is a variety of different probability distributions used to describe the component system reliability, and the form of these expressions depend on the RBD (series, parallel, k-out-of-n, redundant). Some examples of these are discussed in the works of Jiang*, et al.* (2011), Lange*, et al.* (2012), Owens*, et al.* (2014), Owens*, et al.* (2016), Stromgren*, et al.* (2016), and Jones (2020). Most of these studies adopt an exponential failure time probability distribution based on the failure rate (λ).

$$\lambda = \frac{Duty\ Cycle}{MTBF}$$ Equation 4-13

Perhaps one of the most complex approaches of reliability analysis is the use of Monte Carlo simulation to enumerate the various failure modes as stochastic processes. In Monte Carlo simulation of system failures, a large number of identical stochastic systems are simulated and random events, e.g. failures, are generated based on each component's failure distribution. This type of approach is advantageous in that it can produce results which may not come out of an analytical solution; however, the disadvantage, aside from the large effort these types of simulations tend to require, especially for large, complex systems, is that the results depend on the number of simulations, and it is not necessarily guaranteed that every failure mode is sampled due to the stochastic nature of the simulations. Simulation in system reliability analysis is based on the Monte Carlo simulation method that generates random failure times from each component's failure distribution. The overall system reliability is then obtained by simulating system operation and empirically calculating the reliability values for a series of time values. Numerically, Monte Carlo simulation has become a popular analysis tool that can produce results which may be difficult to solve analytically. For additional details on the application of Monte Carlo simulation for reliability analysis see the Zio (2013).

To provide a brief overview of some of the reliability analysis work concerning the ECLSS. The analyses by Lange*, et al.* (2012), Owens*, et al.* (2016), and Stromgren*, et al.* (2016) provide quantitative assessment of the system reliability versus the ESM, spares and maintenance masses, cost, and test time. In the work by Lange*, et al.* (2012) the analysis studied different life support architectures based on ISS technologies for a 1-year deep space mission. To improve system reliability, an increase in redundancy and spares was necessary, which adds to the ESM. The results suggest that achieving necessary reliabilities for deep-space missions will add substantially to the life support ESM. In the work of Owens*, et al.* (2016), the desire was to assess the time, cost, and logistics mass savings trends versus the MTBF of the components in a system. This work describes a scenario where development of more robust systems occur. The analysis shows that there is a point of diminishing returns where the attempt to improve each component's reliability, i.e. MTBF, is accompanied by a super-linear growth in test time, exponential growth in cost, and sublinear growth in logistics mass saved. The work of Stromgren*, et al.* (2016) utilizes Monte Carlo simulation to describe the required spares mass for a deep space habitat and finds similarly to Lange*, et al.* (2012) that greater desired system reliability over the life of a mission is accompanied by exponential growth in the mass of spares. Additional analysis was performed to assess the effect of MTBF uncertainty on the spares mass. This analysis showed that trying to account for component reliability uncertainty can significantly increase the necessary spares mass.

4.13 IN-SITU RESOURCE UTILIZATION INTERFACE

In-situ resource utilization (ISRU) is the ability to extract and process resources at the exploration site into useful product such as for propellants, power systems, life support functions, and radiation shielding. Depending on the destination, there may exist significant quantities of local resources available that are useful for life support. Allen and Zubrin (1999) suggested ISRU is available on the Moon, though the variety and source of commodities is different. The Lunar regolith – one of the natural resources on the Lunar surface – is primarily composed of silicate minerals (*i.e.*, ≥ 85%) and includes constituents such as pyroclastic glass, potassium, rare earth elements, and phosphorous. The Lunar regolith also contains more than 40% of oxygen by mass and can be found across the entire Lunar surface. Additionally, ice may be entrained within the Lunar soil in locations which are maintained at adequately low temperatures, *e.g.* shadowed regions and craters (these are typically considered polar water/ice). The Lunar Crater Observation and Sensing Satellite (LCROSS) experiment measured a water concentration in the regolith of 5.6 ± 2.9 wt% (Colaprete*, et al.,* 2010). The other important natural resource of the Lunar surface is polar volatiles (H_2S, NH_3, CH_4, CO_2, *etc*.) which occur only in the permanently shaded regions at the Lunar poles (NASA, 2020b; Colaprete*, et al.*, 2010).

One important resource from Mars is its atmosphere which contains carbon dioxide (95.32 vol% CO_2), nitrogen (2.7 vol% N_2), and Argon (1.6 vol% Ar) with minor amounts of oxygen (0.13 vol% O_2) and carbon monoxide (0.08 vol% CO) and trace amounts of water (210 ppm H_2O) and nitric oxide (180 ppm NO). Water is a high leverage item that can be used for crew support, plant/food production, and radiation shielding. It may also be utilized in conjunction with an electrolysis unit to generate oxygen and hydrogen, which may be used as propellant, for fuel cells, or life support function. Mars has three different water sources – granular surface soils (1.3 wt% H_2O), hydrated surface minerals (~8 wt% H_2O), and sheets of ice under its surface – that can be used to generate oxygen and hydrogen which can be utilized for rocket propellent, fuel cell power systems, or life support (NASA, 2020b).

Recent studies examined the conceptual design of a Lunar ISRU plant (Linne*, et al.*, 2020; Kleinhenz*, et al.*, 2020; Sanders*, et al.*, 2019) and Mars ISRU plant (Kleinhenz*, et al.*, 2017; Sanders*, et al.*, 2011). Current plans for developing ISRU O_2 production plants are focused on a pilot (1,000 kg of oxygen per year) and full-scale (10,000 kg of oxygen per year) system (Sanders*, et al.*, 2019). The Lunar studies on the development of an ISRU plant consider two architectures (oxygen from regolith and oxygen from polar water) for providing the necessary oxygen (and hydrogen). The oxygen from regolith strategy utilizes a carbothermal reduction reactor to extract oxygen from the native regolith into a form which is processable (CO and CO_2). The process for the carbothermal reduction and conversion to oxygen is illustrated in Figure 4-10. The first step upon excavation and collection of the Lunar regolith is carbothermal reduction, which entails the mixing of carbon, in the form of CH_4, with molten regolith at high temperatures (> 1650 °C). The products of the carbothermal reduction are CO and CO_2, which is delivered to a methanation rector to convert CO and CO_2 into H_2O and CH_4. Lastly, H_2O is converted to O_2 via electrolysis.

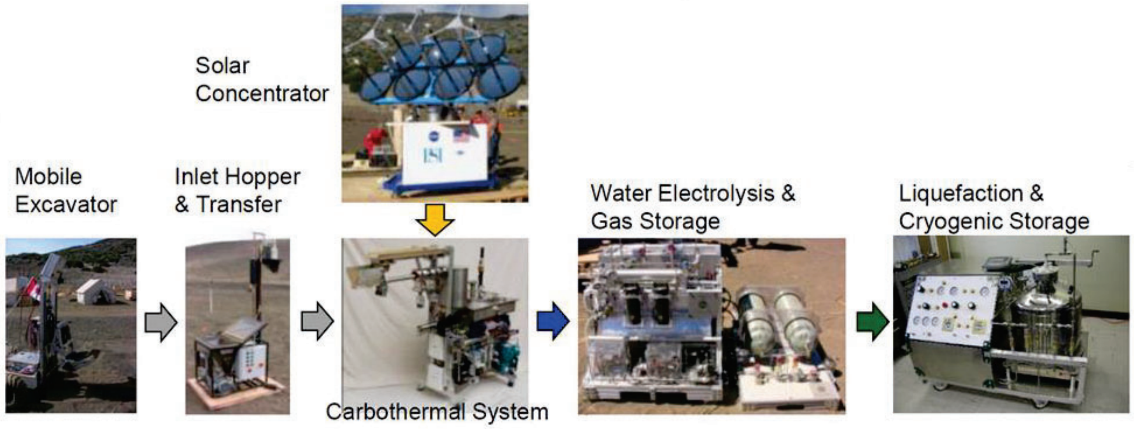

Figure 4-10 System diagram for a proposed O_2 from regolith ISRU production plant (Sanders*, et al.* 2019).

The second strategy for O_2 production is water from polar water. This strategy utilizes icy regolith, which can be found in the permanently shadowed region of the Lunar surface. A general diagram of this water from polar regolith process is provided in Figure 4-11 adapted from Kleinhenz*, et al.* (2020). The steps include (1) excavation and collection of icy regolith, (2) extraction of water from the icy regolith within the permanently shadowed region (PSR), (3) collection and transfer of water to a production plant on the ridge, and (4) electrolysis to generate oxygen and hydrogen.

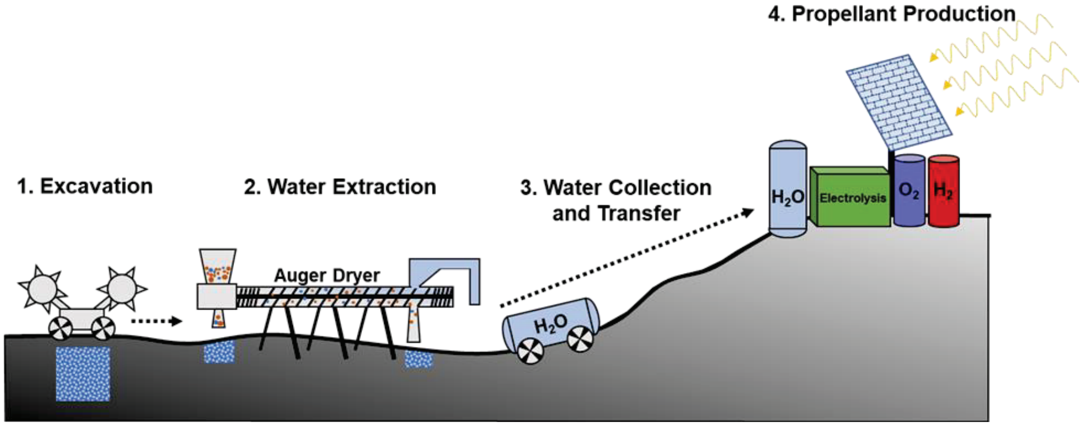

Figure 4-11 System diagram for a proposed O_2 from polar water ISRU production plant (adapted from Kleinhenz*, et al.* 2020)

From the Lunar studies (Linne*, et al.*, 2020; Kleinhenz*, et al.*, 2020), the requisite mass and power for the conceptual Lunar ISRU system are provided in Table 4-85. Comparing these against the amount of propellant and life support O_2 these systems produce shows viability of these ISRU architectures for sustaining long-term exploration missions. Note that these ISRU systems do not take into account the mass of a power system. These studies assume a nuclear reactor is delivered to the PSR to provide power for water extraction.

Table 4-85 Mass, Power, and Production from Different ISRU Systems

Architecture	**O_2 Produced (mT/year)**	**H_2 Produced (mT/year)**	**H_2O Produced (mT/year)**	**CH_4 Produced (mT/year)**	**System Mass (mT)**	**System Power (kW)**
Lunar: Oxygen from Regolith (1) [a]	10	--	--	--	2.7	11.8
Lunar: Oxygen from Polar Water (2)	1	0.125	--	--	1.2	6.7
Lunar Oxygen from Power Water (1) [b]	13	1.7			4.9	68
Martian: Oxygen-Only ISRU (3) [c]	22.7	--	--	--	0.93	~32
Martian: Methane and Oxygen ISRU (3) [c]	22.7	--	--	7.0	1.7	~51
Martian: Methane and Oxygen for Propellant; Oxygen and Water for Life Support (3) [c]	24.6	--	3.1	7.0	2.2	~80
References: (1) Klienhenz*, et al.*, 2020; (2) Linne*, et al.*, 2020; (3) Klienhenz*, et al.*, 2017						

[a] The oxygen from regolith architecture only produces O_2, and thus, requires a H_2 upmass of 2 mT per mission.

[b] The full-scale oxygen from polar water architecture is required to produce 10 mT of O_2 with a mixture ratio (oxidizer:fuel) equal to 6. This results in a production scale due to reaction stoichiometry of 13 mT O_2 and 1.7 mT of H_2 per year.

[c] The Mars architectures consider the processing of typical hydrated regolith with 1.3 wt% water yield.

Although at a low pressure, CO_2 can be extracted from the Martian atmosphere and processed into oxygen (via CO_2 reduction) or hydrocarbon fuels upon the addition of hydrogen. For example, extracted CO_2 can be converted into oxygen for crewmember respiration via Sabatier/electrolysis. Additionally, the inert gases present in the Martian atmosphere can be used to dilute crew cabin oxygen assuming the base air would not be pure oxygen. The high concentration of atmosphereic CO_2 is well poised to promote plant growth as well. The combined resources of Martian atmosphere and water present significant possibilities for mission consumable production, usage, and mass savings. Coupling CO_2 reduction systems with the water extraction techniques presented for the Lunar systems may allow for the production of propellants (O_2 and CH_4) as well as life support consumables (O_2 and H_2O). Table 4-85 provides some of the Martian architectures from the cited study.

Analogous studies to those performed for a Lunar mission have been performed for the Martian mission scenario (Kleinhenz*, et al.*, 2017; Sanders*, et al.*, 2011). In these cases, there is additional equipment necessary to enable utilization of the atmospheric gases (mostly CO_2), which is not present in the Lunar scenario. The case study provided examines the production of both liquid methane and oxygen to refuel a Mars ascent vehicle in support of the Evolvable Mars Campaign. From this case study, even the lowest yielding regolith type could displace 30 mT of ascent propellants from the mission manifest with a full-scale ISRU system mass of 1,700 kg and requiring 30 to 50 kW of power. Because the ISRU systems have been designed to operate during habitat dormancy, these systems may be able to draw their power from the habitat power system.

4.14 BIOMASS PRODUCTION

4.14.1 PLANT GROWTH CHAMBERS

4.14.1.1 *ESTIMATION OF PLANT GROWTH CAPABILITIES ON MARS*

Plants offer the greatest opportunity for self-sufficiency and, possibly, cost reduction for long duration missions, but at the same time have some of the greatest unknowns. An attempt has been made to estimate the mass of a plant growth system on the surface of an extraterrestrial body such as Mars. Two major uncertainties, however, exist: the cost of power and the availability of water. Sun light was intially assumued to be unsuitable for plant growth given that the solar radiation reaching Mars is only 43% that reaching Earth and Mars is susceptible to large dust storms that can reduce sunlight from reaching its surface. However, recent analyses suggest that some latitudes on Mars can receive up to 30 $\text{mol}/(\text{m}^2\cdot\text{d})$ for much of the year – nearly 50% of some of the brightest areas on Earth (Clawson, 2006) – hinting that future biomass production systems might use natural sunlight supplemented by electrical lighting to achieve optimal biomass production per infrastructure mass required.

Additionally, the importance of cultivating plants on Mars is underscored by the centrality of fresh food to crew welfare and nutritionists' recommendations of deriving food from original sources such as grown plants and/or livestock. Because livestock production is more expensive even terrestrially, early in-situ food production will likely concentrate on growing crops. As shipped, fresh foodstuffs from crops are heavier than dehydrated or low-moisture foods due to the significant mass associated with natural moisture. Thus, while plants will probably be grown on an extraterrestrial body, the question remains as to what proportion of the food will be grown locally versus what proportion will be shipped.

4.14.1.2 *PLANT GROWTH CHAMBER LIGHTING*

Table 4-86 Lighting Data

Parameter [Units]	Low	Nominal	High
Light Conversion Efficiency $[W_{\text{photosynthetically active radiation}}/W_{\text{electrical}}]$ [176]	0.18 (1)	0.84 (2)	
Light Delivery Efficiency $[PPF_{\text{delivered}}/PPF_{\text{emitted}}]$ [177]	0.3 (1)	0.8 (3)	0.8 (3)
Overall Lighting Efficiency	0.05 (1)	0.67	

References
(1) J. Sager in 1999
(2) J. Hardy (2020)
(3) J. Sager in 2006

A key parameter for plant growth is lighting, and electrical lighting might provide this. The efficiency of electrical lighting depends on the efficiency of the conversion of electricity into radiant energy and the direction of this energy onto the plant canopy. The conversion efficiency depends on the type of lamp. Thus, many factors impact photosynthetically active radiation (PAR). Photosynthetic photon flux (PPF) is another way of expressing PAR but specifically using quantum units, such as $\mu\text{mol}/(\text{m}^2\cdot\text{s})$, instead of W/m^2. Incandescent lamps are red-rich, which is good, but the conversion efficiency to PAR is low. High intensity discharge (HID) lamps produce more light, but their spectrum varies depending on the type of lamp, with metal halide lamps producing a broad spectrum and high-pressure sodium producing a yellow-orange light with a low amount of blue. Both types have proved acceptable for photosynthesis. Some lamp types, such as microwave lamps, have a high efficiency and a broad spectrum (Sager, 1999), yet improvements are needed in their magnetron power supplies to sustain long duty cycles. Direction of the energy to the canopy depends on the geometry of the lamp, the distance from the lamp to the canopy, and the quality of the reflectors. The Biomass Production Chamber (BPC) at Kennedy Space Center used relatively unsophisticated reflectors (Table 4-86) and only achieved a rating of about 10-15% (Wheeler, 2017). Much higher ratings can be achieved but maintaining these high ratings over long time periods requires upkeep, such as periodic cleaning and adjustments to the lamp reflectors. Nelson and Bugbee (2014) point out that artificial plant growth lights have been improving rapidly and report the following values for photosynthetic photons per Joule of electrical energy:

HPS (double ended)	1.70 micromoles/J
LED	1.66 micromoles/J
Fluorescent	0.95 micromoles/J

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[176] Light Conversion Efficiency describes the proportion of lighting system power that eventually becomes PPF.

[177] Light Delivery Efficiency describes the proportion of PPF at the lamp surface that is delivered to the canopy.

The authors explain that “Photosynthesis and plant growth is determined by moles of photons. It is thus important to compare lighting efficiency based on photon efficiency, with units of micromoles of photosynthetic photons per joule of energy input. This is especially important with LEDs where the most electrically efficient colors are in the deep red and blue wavelengths.”

If LEDs are run well below their rated current, their electrical efficiencies can be quite high. For the Veggie plant growth system on ISS, overall light cap efficiency is about 40% at maximum light (Bourget, M, 2014). Individual LED efficiencies are:

- Red 34.5%
- Blue 69%
- Green 24.5%

By 2020, LED efficiencies increased even more. See Nelson and Bugbee (2014) for a better understanding of this subject and Hardy, J. (2020) for more recent values.

Additional assumptions can be made about specific lighting systems. Data for 400 W high-pressure sodium lights (HPS) are shown in Table 4-87.

Table 4-87 High Pressure Sodium Lighting Data

	Units	Low	Nominal	High
Lamp Power (not including ballast)	kW	--	0.4 (2)	--
Lamp Mass	kg		0.21 (2)	
Lamp Life	10^3 h		20 (1)	24 (1)
Number of 400 W Lamps per Area to Give 1,000 µmol/(m^2·s)	lamps/m^2	1.43 (3)	4.504 (4)	9.259 (3)
Time to Change Out Lamps	CM-h		0.03 (5)	
Photoperiod per Day [178]	h/d	10 (1)	10-24 [179]	24 (1)
Lamp Volume for Resupply	$m^3 \times 10^{-3}$		0.625 (1)	
Ballast Power	kW/lamp	0.03 (1)	0.06 (2)	0.08 (1)
Ballast Mass	kg/lamp	2.85 (6)	4.76 (1)	9.52 (2)
Ballast Life	10^3 h		88 (7)	
Mass of Coldplate, Water Barrier, Condensing Heat Exchangers per Growing Area	kg/m^2	4.43 (8) [180]	7.02 (8) [181]	25.83 (8) [182]
Height of Lighting Assembly	m		0.15 (9)	0.3 (1)
Lamp Resupply Mass Factor	kg/kg		0.8 (10)	
Lamp Resupply Volume Factor	m^3/m^3		0.5 (1)	

References

(1) A. Drysdale (1999)
(2) Hanford (1997)
(3) Hunter and Drysdale (2002) based on communication with Sager (1999)
(4) Hunter and Drysdale (2002) based on Ewert (1998)
(5) A rough value from Hunter (1999)
(6) Ewert (2001)
(7) Barta and Ewert (2002)
(8) Ewert (1998)
(9) BIO-Plex drawings
(10) Table 3-12

Resupply mass and volume factor account for the extra mass and volume required to package replacement lamps. This is in addition to any mass and volume associated with the lamp itself.

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[178] This is generally crop dependent, although the values here provide the range for all ELS crops.

[179] See Table 4-111 for nominal photoperiods of candidate Life Support crops.

[180] This system uses only a bulb in a water jacket. Transmissivity, relative to the baseline case using a coldplate and no barrier, is 0.92. The ratio of total radiation to PAR is 1.6 compared to 2.0 for the baseline. Note: This configuration provided the best overall performance in testing.

[181] This system uses a bulb in a water jacket with a Teflon barrier. Transmissivity, relative to the baseline case using a coldplate and no barrier, is 0.846. The estimated ratio of total radiation to PAR is 1.6 compared to 2.0 for the baseline.

[182] This system uses a coldplate with a glass barrier. Transmissivity, relative to the baseline case using a coldplate and no barrier, is 0.89. The ratio of total radiation to PAR is 1.7 compared to 2.0 for the baseline.

4.14.1.3 *PLANT GROWTH CHAMBER COST FACTORS*

The cost factors for a plant growth chamber have been estimated on a square-meter basis. This addresses the plant growth chamber itself. If crew access is needed, and it generally will be, provision must be made for that access. A reasonable number might be 25 – 50% of the plant canopy area. Lower numbers might be adequate if extensive physical automation is planned. A higher number might be appropriate if most tasks are performed manually. Crew access space would not, however, require the equipment and other "costs" shown here. Crew height will be greater than the height of most plants that have been considered for Life Support crops. Layout of the crops and crew space will depend on issues such as the type of plant lighting. Thus, if natural lighting is to be used, only a single layer of crops might be possible due to the diffuseness of light on Mars. In this case, the limiting height would be the taller of the crew and the plants. Table 4-88 (Drysdale, 1999b) presents preliminary values for an optimized biomass production chamber based on projecting current NASA growth chambers to flight configurations.

From a power perspective, most research has focused on more efficient lighting and progress has been make. Integrated plant growth chambers also need power for blowers, pumps, *etc*. Reference values for biomass production per unit energy range from 1.6 g/kWh (based on JSC's VPGC) to 10 g/kWh (based on a mixed crop in South Pole Food Growth Chamber). Note that lamp and ballast values in Table 4-88 have not been updated based on modern LED lighting.

Table 4-88 Plant Growth Chamber Equivalent System Mass per Growing Area

Component	Mass [kg/m^2]	Volume [m^3/m^2]	Power [kW/m^2]	Thermal Control [kW/m^2]	Crew-time [CM-h /m^2·y]	Logistics [kg /m^2·y]	Reference
Crops	20.0	–	–	–	13.0		From Drysdale (1999b)
Shoot Zone	3.6	0.67	0.3 [183]	0.3 [183]	–	–	
Root Zone Water and Nutrients	36.8	0.11	0.14	0.14	TBD	TBD	
Lamps	22.9	0.25	2.1	2.1	0.027	0.57	
Ballasts	8.4	TBD	0.075	0.075	0.032	3.24	
Mechanization Systems	4.1	TBD	TBD	TBD	TBD	TBD	
Secondary Structure	5.7	–	–	–	–	–	
Total	**101.5**	**1.03**	**2.6**	**2.6**	**13.1**	**3.81**	

4.14.1.4 *PLANT GROWTH*

4.14.1.4.1 TIME-AVERAGED VALUES DESCRIBING PLANT GROWTH

Plant growth rates depend on the type of plant (species and cultivar) and the growth conditions. Table 4-89 lists nominal environmental conditions for each crop and provide design values for candidate ELS crops (Behrend and Henninger, 1998).

Table 4-90 presents overall life-cycle growth rates in terms of grams of biomass per square meter per day. The dry mass (dw) fresh mass (fw) [184]and water content for both edible and inedible biomass are given. The harvest

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[183] Power consumption and thermal control within the shoot zone reflect fans for gas movement.

[184] Historically, "dw" and "fw" denote "dry weight" and "fresh weight," respectively. Scientifically, these quantities are masses and not weights. Weight is a force derived from the gravitational attraction between a body and, practically, a much larger body such as a planet. Thus, a body always has mass, but it has weight only within a planet's gravitational field.

index is the ratio of edible biomass to total biomass. Table 4-91 provides nominal and upper biomass generation rates. The lower rate is zero, and the given upper limit is the highest rate recorded in the literature. This may not be the absolute maximum, however. For example, wheat may well produce higher growth rates with higher light intensities (received from a personal communication from B. Bugbee, 1998). These maximal rates are generally for small chambers under ideal conditions, and they might be difficult to achieve in larger chambers that have been optimized for space flight. The nominal rates are derived from testing within the Biomass Production Chamber (BPC) at Kennedy Space Center (personal communication with R. Wheeler, 2001), and the values presented may be composite or average values from several different tests. These rates are lower partly because of the lower light levels, but a less homogeneous environment, due to the larger scale, may also impact the growth rates. In addition, BPC data are conservative in that they used fixed spacing from germination to harvest. Use of variable spacing or transplanting schemes for widely spaced crops could save up to 15 days on production cycles. For example, the cycle for lettuce is reduced from 28 to ~14 days (Wheeler*, et al.*, 2008). Obviously, seedling nurseries would require some area, but this would be on the order of only 1% to 10% of the area required for mature-plant production. Table 4-91 also presents the biomass chemical composition in terms of carbon and the metabolic reactants and products averaged over the crop life cycle.

Table 4-89 Exploration Life Support Cultivars, Intended Usage, and Environmental Growth Conditions

Crop	ELS Transit Crop (1)	ELS Surface Crop (1)	Photosynthetic Photon Flux [mol/(m^2•d)]	Diurnal Photo-Period [h/d] (3)	Growth Period [185] [dAP]	Temperatures [C] (3)		
						Air during Day	Air during Night	Nutrient Solution
Cabbage	×	×	28 (2)		85 (4)	>25		
Carrot	×	×	28 (2)		75 (4)	16-18		
Chard	×	×	17 (2)	16	45 (3)	23	23	23
Celery			17 (2)		75 (4)			
Dry Bean		×	24 (3)	18	85 (5)	28	24	26
Green Onion			26 (6)		50 (5)	25	25	25
Lettuce	×	×	17 (3)	16	28 (3)	23	23	23
Mushroom			0	0				
Onion	×	×	17		50			
Pea			24 (2)		75 (4)			
Peanut		×	27 (3)	12	104 (3)	26	22	24
Pepper			27 (2)		85 (5)			
Radish	×	×	26 (6)	16	25 (4)	23	23	23
Red Beet			17 (3)	16	40 (3, 7)	23	23	23
Rice		×	33 (3)	12	85 (3)	28	24	24
Snap Bean			24 (2)	18	85 (5)	28	24	26
Soybean		×	28 (3)	12	97 (3)	26	22	24
Spinach	×	×	17 (3)	16	30 (4)	23	23	23
Strawberry			22 (3)	12	100 (4)	20	16	18
Sweet Potato		×	28 (3)	12	85 (5)	26	22	24
Tomato	×	×	27 (3)	12	85 (3)	24	24	24
Wheat		×	115 (4)	20-24	75-90 (3)	20	20	18
White Potato		×	28 (3)	12	132 (8)	20	16	18

References

Information from Drysdale 2001 except as noted.

(1) Behrend and Henninger (1998)
(2) Estimated by similarity to other crops.
(3) Wheeler, *et al.* (2003)
(4) Personal communication with. Wheeler (2001)
(5) Ball, *et al.* (2001) and EDIS (2001)
(6) Richards, *et al.* (2005, 2006)
(7) for small tap roots and greens (Wheeler)
(8) Wheeler, R.M. 2006

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[185] Growth period is measured here in terms of "days after planting," [dAP].

Table 4-90 Overall Physical Properties at Maturity for Nominal Crops [186]

			Edible Biomass Productivity			Inedible Biomass Productivity		
Crop	**Mature Plant Height [m]**	**Harvest Index [%]**	**Dry Basis $[\mathrm{g_{dw}/m^2 \cdot d}]$**	**Fresh Basis $[\mathrm{g_{fw}/m^2 \cdot d}]$**	**Fresh Basis Water Content [%]**	**Dry Basis $[\mathrm{g_{dw}/m^2 \cdot d}]$**	**Fresh Basis $[\mathrm{g_{fw}/m^2 \cdot d}]$**	**Fresh Basis Water Content [%]**
Cabbage	0.35	90	6.06 (2)	75.78	92	0.67	6.74	90
Carrot	0.25	60	8.98 (2)	74.83	88	5.99	59.87	90
Chard	0.45 (1)	65 (1)	7.00 (1)	87.50	92	3.77	37.69	90
Celery	0.25	90	10.33 (2)	103.27	90	1.15	11.47	90
Dry Bean	0.50 (1)	40 (1)	10.00 (3)	11.11	10	15.00	150.00	90
Green Onion	0.25	90	9.00 (3)	81.82	89	1.00	10.00	90
Lettuce	0.25 (1)	90 (1)	6.57 (1)	131.35	95	0.73	7.30	90
Mushroom		90			90			90
Onion	0.25	80	9.00	81.82	89	2.25	22.50	90
Pea	0.50	40	10.73 (2)	12.20	12	16.10	161.00	90
Peanut	0.65 (1)	25 (1)	5.63 (1)	5.96	5.6	16.88	168.75	90
Pepper	0.40	45	10.43 (3)	148.94	93	12.74	127.43	90
Radish	0.20 (1)	50 (1)	5.50 (3)	91.67	94 (3)	5.50	55.00	90
Red Beet	0.45 (1)	65 (1)	6.50	32.50	80	3.50	35.00	90
Rice	0.80 (1)	30 (1)	9.07 (1)	10.30	12	21.16	211.58	90
Snap Bean	0.50	40	11.88 (2)	148.50	92 (3)	17.82	178.20	90
Soybean	0.55 (1)	40 (1)	4.54 (1)	5.04	10	6.80	68.04	90
Spinach	0.25 (1)	90 (1)	6.57 (3)	72.97	91	0.73	7.30	90
Strawberry	0.25 (1)	35 (1)	7.79 (2)	77.88	90	14.46	144.46	90
Sweet Potato	0.65 (1)	60 (4)	24.7 (3,4)	51.72	71	16.5 (3,4)	225.00	90
Tomato	0.40 (1)	45 (1)	10.43 (1)	173.76	94	12.74	127.43	90
Wheat	0.50 (1)	40 (1)	20.00 (3)	22.73	12	30.00	300.00	90
White Potato	0.65 (1)	70 (1)	21.06 (1)	105.30	80	9.03	90.25	90

References

Information from Drysdale 2001 except as noted.

(1) Wheeler, *et al.* (2003)

(2) Ball, *et al.* (2001) and EDIS (2001)

(3) Personal communication with Wheeler (2001)

(4) Hill, *et al.* (1992)

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[186] Productivities could increase for most species by ~10 to 15% by use of transplanting schemes for more efficient spacing according to Wheeler, *et al.* (2006).

Table 4-91 Nominal and Highest Biomass Production, Composition, and Metabolic Products [187]

Crop	Total Biomass (Edible + Inedible), Dry Basis $[g_{dw}/m^2 \cdot d]$		Carbon Content [%]	Metabolic Reactants and Products		
	Nominal	High		Oxygen (O_2) Production $[g/m^2 \cdot d]$	Carbon Dioxide (CO_2) Uptake $[g/m^2 \cdot d]$	Average Water (H_2O) Uptake / Transpiration $[kg/m^2 \cdot d]$
Cabbage	6.74	10.0	40	7.19	9.88	1.77
Carrot	14.97	16.7	41	16.36	22.50	1.77
Chard	10.77		40	11.49	15.79	1.77
Celery	11.47		40	12.24	16.83	1.24
Dry Bean	25.00		40	30.67	42.17	2.53
Green Onion	10.00		40	10.67	14.67	1.74
Lettuce	7.30	7.9	40 (1)	7.78	10.70	2.10
Onion	11.25		40	12.00	16.50	1.74
Pea	26.83		40 (3)	32.92	45.26	2.46
Peanut	22.50	36.0	60 (2)	35.84	49.28	2.77
Pepper	23.17		40	24.71	33.98	2.77
Radish	11.00		40 (2)	11.86	16.31	1.77
Red Beet	10.00		41	7.11	9.77	1.77
Rice	30.23	39.0	42	36.55	50.26	3.43
Snap Bean	29.70		40	36.43	50.09	2.46
Soybean	11.34	20.0	46 (1)	13.91	19.13	4.70
Spinach	7.30		40	7.78	10.70	1.77
Strawberry	22.25		43 (2)	25.32	34.82	2.22
Sweet Potato	37.50	51.3	41 (2)	41.12	56.54	2.88
Tomato	23.17	37.8	43 (2)	26.36	36.24	2.77
Wheat	50.00	150.0	42 (1)	56.00	77.00	11.79
White Potato	30.08	50.0	41 (1)	32.23	45.23	4.00

References

Information from Drysdale 2001 except as noted.

(1) Wheeler, *et al.* (1995)

(2) Calculated

(3) Orcun and Wheeler (2003)

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[187] Productivities & transpiration rates could increase for most species by ~10-15% with transplanting schemes for more efficient spacing according to Wheeler, *et al.* (2008).

Plant environmental demands differ compared to the crew's requirements. For example, the optimum partial pressure of carbon dioxide for plant growth is roughly 0.10 to 0.20 kPa (Wheeler, *et al.*, 1993); below this, productivities decrease. Sensitivity may vary from species to species, but plants do appear to have reduced productivity at very high partial pressures of carbon dioxide that are considered within the normal range for crew (up to about 1.0 kPa). Similarly, plants require higher relative humidity – about 75% – to avoid water stress and minimize nutrient solution usage. Such humidity levels are at the high end for crew comfort. Further, some key plants, such as wheat and potatoes, are most productive at temperatures below the standard crew comfort zone. Finally, at nominal Earth ambient carbon dioxide partial pressures (p [CO_2] = 0.04 kPa), plants grow better under atmospheres with reduced partial pressures of oxygen (p [O_2] less than 21 kPa). If the partial pressure of carbon dioxide is elevated to 0.1 to 0.2 kPa, the benefits of reduced oxygen partial pressure are negligible. However, because human beings live with plants on Earth, plants and crew can live in a common atmosphere as demonstrated in the bioregenerative lifr support systems experiment in Lunar Palace 1 (Fu, *et al.*, 2016).

Table 4-92enumerates growing areas and fresh weight inedible biomass production associated with the ELS Project diets presented in Section 4.5.7. The edible biomass values are the nominal values listed in Table 4-92. The total inedible biomass production is based on the edible biomass production and the harvest index and does not include any waste associated with uneaten portions or the material removed during food preparation.

Table 4-92 Inedible Biomass Generation for Exploration Life Support Diets Based on Fresh Weight

				Diet Using Only ELS Salad Crops		Diet Using Salad and Carbohydrate Crops		Diet Using All ELS Crops	
Crop	**ELS Crop**	**Edible Biomass [g/m^2·d]**	**Inedible Biomass [g/m^2·d]**	**Diet Growing Area [m^2/CM]**	**Total Inedible Biomass [kg/CM-d]**	**Diet Growing Area [m^2/CM]**	**Total Inedible Biomass [kg/CM-d]**	**Diet Growing Area [m^2/CM]**	**Total Inedible Biomass [kg/CM-d]**
Cabbage	×	75.78	6.74	0.256	0.002	0.033	0.000	n/a	n/a
Carrot	×	74.83	59.87	0.488	0.029	0.535	0.032	0.536	0.032
Chard	×	87.50	37.69	n/a	n/a	n/a	n/a	n/a	n/a
Celery		103.27	11.47	n/a	n/a	0.073	0.001	n/a	n/a
Dry Bean	×	11.11	150.00	n/a	n/a	1.170	0.176	1.926	0.289
Green Onion		81.82	10.00	0.055	0.001	0.416	0.004	0.276	0.003
Lettuce	×	131.35	7.30	0.119	0.001	0.160	0.001	0.057	0.000
Mushroom				n/a	n/a	TBD	0.0013	n/a	n/a
Onion	×	81.82	22.50	n/a	n/a	n/a	n/a	n/a	n/a
Pea		12.20	161.00	n/a	n/a	0.311	0.050	n/a	n/a
Peanut	×	5.96	168.75	n/a	n/a	n/a	n/a	4.832	0.815
Pepper		148.94	127.43	n/a	n/a	0.208	0.027	n/a	n/a
Radish	×	91.67	55.00	0.098	0.005	n/a	n/a	0.164	0.008
Red Beet		32.50	35.00	n/a	n/a	n/a	n/a	n/a	n/a
Rice	×	10.30	211.58	n/a	n/a	n/a	n/a	2.078	0.440
Snap Bean		148.50	178.20	n/a	n/a	0.067	0.012	n/a	n/a
Soybean	×	5.04	68.04	n/a	n/a	n/a	n/a	46.429	3.159
Spinach	×	72.97	7.30	0.066	0.000	0.548	0.004	0.635	0.005
Strawberry		77.88	144.46	n/a	n/a	n/a	n/a	n/a	n/a
Sweet Potato	×	51.72	225.00	n/a	n/a	3.480	0.783	1.485	0.334
Tomato	×	173.76	127.43	0.265	0.034	1.209	0.154	1.642	0.209
Wheat	×	22.73	300.00	n/a	n/a	9.679	2.904	4.237	1.271
White Potato	×	105.30	90.25	n/a	n/a	1.614	0.146	0.994	0.090
Total				**1.35**	**0.07**	**19.50**	**4.29**	**65.29**	**6.66**

4.14.1.4.2 HYDROPONIC PLANT GROWTH SUPPORT

Table 4-93 presents some details about plant growth with current hydroponic technology, providing water and nutrient use necessary to keep the plants healthy. Luxuriant nutrient levels were provided, so lower levels of nutrients might also suffice. The nutrient solution shown was formulated to require only acid addition for pH control. However, alternative formulations might require less active pH control (and thus fewer consumables to maintain the pH). Finally, plant productivity varies from one cropping cycle to the next even under controlled conditions, so the values here should be viewed as typical. Actual productivity from any real cropping cycle might vary.

Table 4-93 Plant Growth and Support Requirements per Dry Biomass

	Units	Soybean	Wheat	Potato	Lettuce	Reference
Water Usage per Dry Biomass	L/g_{dw}	0.32	0.13	0.15	0.34	From Wheeler, *et al.* (1999).
Stock Usage per Dry Biomass	L/g_{dw}	0.026	0.021	0.022	0.034	
Acid Usage per Dry Biomass [188]	g_{acid}/g_{dw}	0.0548	0.0744	0.0428	0.0618	

Table 4-94 and Table 4-95 describe the major ionic components of the nutrient solutions used for studies within the Biomass Production Chamber at Kennedy Space Center as determined from Wheeler, *et al.* (1996) and Wheeler, *et al.* (1997). As indicated, the initial stock solution, which is at the desired concentration to support plant growth, is more dilute than the mixture of two replenishment solutions that are added incrementally, as necessary, to replace nutrient used by plants or otherwise lost. For this facility, replenishment solution is added in a fixed concentration as a function of electrical conductivity regardless of which ions are depleted. Each salt primarily contributes one important element, as noted. The elemental concentrations, then, are with respect to the listed important element. Note that because pH is controlled by adding nitric acid (HNO_3), the nitrogen content of the acid must be considered in calculating the total nitrogen provided to the plants. In addition, minerals might be lost to the plants through uptake by microorganisms and by precipitation from solution. Some nitrogen may leave nutrient solution via volatilization as nitrogen gas or as nitrogen oxides as a result of microbial metabolism. Finally, to inhibit ionic build-up within the nutrient solution due to the procedures outlined here, especially sodium or boron; the nutrient solution is often replaced at regular intervals.

Projections of total fertilizer needs (based on Table 4-93) to supply all the dietary calories for human life support (2500 kcal person-1 day-1) suggest that 90 to 100 kg of fertilizer salt might be required per person per year (Lunn, *et al.*, 2017). But > 50% of these nutrients could be recycled from inedible biomass from the crops, using processing like stirred tank reactors or composting (Strayer, *et al.*, 2002). In addition, recycled wastewater, especially wastewater containing processed urine, could further close the mass loop for nutrients required to grow crops.

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[188] For nitrate-based formulations. Acid is provided as 0.4 M HNO_3. One mole of nitric acid (HNO_3) contains 63.013 grams of solute.

Table 4-94 Composition of Initial Nutrient Solution

						Content		
Initial Ionic Component	**Important Element**	**Elemental Atomic Weight**	**Concentration [meq/L]** [189]	**Ion Molecular Weight**	**Valence**	**g/L (element)**	**g/L (ion)**	**Reference**
Nitrate, NO_3^{-}	Nitrogen, N	14.01	7.5	62.00	–1	0.1051	0.465	Wheeler, *et al.* (1996)
Phosphate, PO_4^{3-}	Phosphorous, P	30.97	0.5	94.97	–3	0.0465	0.142	
Potassium, K^{+}	Potassium, K	39.10	3	39.10	+1	0.1173	0.117	
Calcium, Ca^{2+}	Calcium, Ca	40.08	2.5	40.08	+2	0.2004	0.200	
Magnesium, Mg^{2+}	Magnesium, Mg	24.31	1	24.31	+2	0.0486	0.049	
Sulfate, SO_4^{2-}	Sulfur, S	32.06	1	96.06	–2	0.0641	0.192	
Total							**1.166**	

Table 4-95 Composition of Replenishment Nutrient Solution

						Content		
Replenishment Ionic Component	**Important Element**	**Elemental Atomic Weight**	**Concentration [meq/L]** [189]	**Ion Molecular Weight**	**Valence**	**g/L (element)**	**g/L (ion)**	**Reference**
Nitrate, NO_3^{-}	Nitrogen, N	14.01	75	62.00	–1	1.051	4.650	Wheeler, *et al.* (1997)
Phosphate, PO_4^{3-}	Phosphorous, P	30.97	7.5	94.97	–3	0.697	2.137	
Potassium, K^{+}	Potassium, K	39.10	68	39.10	+1	2.659	2.659	
Calcium, Ca^{2+}	Calcium, Ca	40.08	7.5	40.08	+2	0.601	0.601	
Magnesium, Mg^{2+}	Magnesium, Mg	24.31	9.8	24.31	+2	0.476	0.476	
Sulfate, SO_4^{2-}	Sulfur, S	32.06	9.8	96.06	–2	0.628	1.883	
Total							**12.406**	

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[189] Here the units, [meq/L], denote milli-equivalent weights of the ionic component per liter of solution. An equivalent weight is the ion’s molecular weight divided by the absolute value of the ion’s valence.

4.14.1.5 *PLANETARY REGOLITH FOR PLANT GROWTH*

Much of these discussions have concerned the hydroponic growth of plants for food production whereby a nutrient solution with appropriate composition (nitrates, phosphates, sulfates, and minerals) as well as appropriate pH is formulated and used to supplement plant growth for crew consumption. As discussed in the previous sections, the required fertilizer salts can result in substantial up-mass (90 – 100 kg of fertilizer salt per crewmember per year (Lynn*, et al.*, 2017)) in order to sustain plant growth to meet the caloric requirements of the crew. Nutrients from inedible biomass may be recycled in order to reduce the fertilizer requirements for the nutrient solutions.

Another strategy is to utilize the inherent nutrition present in the planetary regolith in order to solely sustain plant growth or as a supplement to current hydroponic strategies. Table 4-96 shows an analysis of Earth, Moon, and Mars soil simulants with their respective elemental compositions (Wamelink*, et al.* (2014). However, because these simulants are derived from Earth soils to mimic each planetary system's mineral composition, the analysis is not truly representative of the planetary surface. In particular, the Mars surface contains no organic content; however, the analyses found a substantial amount of it present in the simulant which may be due to the harvesting process. The moon regolith simulant was determined to be quite nutrient poor, though it does contain some nitrates and ammonium; however, its elevated pH relative both the Earth and Mars simulants may be problematic for plant growth.

In their study, Wamelink*, et al.* compared germination and biomass production of various plants (carrot, rye, tomato, *etc*.) and found Mars soil simulant to perform equally well or better compared to the Earth soil, albeit a nutrient poor Earth soil sample. Of crop plants, after the 50-day growth period, Mars soil simulant germinated and sustained > 80% of crop seeds/plants. This study highlights the viability in using planetary regolith, although this is highly variable on location (latitude and longitude) and other factors of the planetary surface (sunlight, climate, *etc*.). Sunlight from electrical sources, water supply, nutrient supplementation, and plant growth architecture (potted or in-ground) are additional points of concern which will greatly affect the potential for plant growth. This discussion doesn't favor one method over another, hydroponics versus using regolith, rather it indicates other strategies available to alleviate up-mass of required nutrients for plant growth.

Table 4-96 Analysis of Earth, Moon, and Mars Soil Simulants: Average Nutrient Composition[190]

Element	Unit	Simulant Type		
		Earth	Moon	Mars
Nt	g/kg	0.0	0.0	2.6
Pt	mg/kg	57.3	1003.0	2487.0
Al	mg/kg	0.0	0.5	0.0
Fe	mg/kg	0.0	0.0	0.0
K	mg/kg	4.7	27.0	138.0
Cr	μg/kg	2.0	0.0	0.0
N (NH_4)	mg/kg	0.5	0.3	3.9
N ($NO_3 + NO_2$)	mg/kg	4.2	4.2	2.1
P (PO_4)	mg/kg	0.0	0.2	0.0
pH (20 ± 1 °C)	--	8.3	9.6	7.3
C-elementary	g/kg	3.2	3.0	30.1
N-elementary	g/kg	0.0	0.0	2.5

4.14.1.6 *MODIFIED ENERGY CASCADE MODELS FOR CROP GROWTH*

Cavazzoni (2001) presents a package of models appropriate for use in system-level modeling. These Modified Energy Cascade (MEC) models build upon the earlier work of Volk, *et al.* (1995) and benefit from studies by Monje (1998), Monje and Bugbee, (1998), and Jones and Cavazzoni (2000) [191].

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[190] Adapted from Wamelink *et al*. (2014)

[191] Jones and Cavazzoni present the Top-Level Energy Cascade models. Though the Modified Energy Cascade equations and the Top-Level Energy Cascade equations share some ideas, the Top-Level Energy Cascade equations provide models for quantities that are input parameters for the Modified Energy Cascade equations. Further, the Modified Energy Cascade equations include models to compute biomass oxygen generation.

The MEC models calculate biomass production, on a dry-mass basis, as a function of photosynthetic photo flux, PPF, and the atmospheric carbon dioxide concentration, $[CO_2]$.[192] The atmospheric temperatures, one for light periods and a second for dark periods, and the photoperiod are constant, and the plant growth is not limited by water or nutrients. These models accommodate daily variations in PPF and $[CO_2]$, but weighted values of PPF and $[CO_2]$ should be used to estimate time for canopy closure, t_A. The models generally apply over a range of PPF from 200 to 1,000 µmol/m²·s[193] and a range of $[CO_2]$ from 330 to 1,300 µmol/mol. For rice and wheat, these models apply up to 2,000 µmol/m²·s. The PPF range for lettuce is limited to 200 to 500 µmol/m²·s, because a light integral of only 17 mol/m²·d is recommended to prevent leaf tip burn. See, for example, Hopper, *et al.* (1997), for recommended PPF requirements for crop growth.

4.14.1.7 *MODIFIED ENERGY CASCADE MODELS FOR CROP BIOMASS PRODUCTION*

The following material outlines the top-level MEC models developed by Cavazzoni (2001) in detail. The various parameters depend upon the crop cultivar and growing conditions. Parameters for nominal conditions of lighting, temperature, and atmospheric composition are presented in Section 4.14.1.8.1.

The fraction of PPF absorbed by the plant canopy, A, is a function of time, t, in terms of days after emergence $[d_{AE}]$, and the time for canopy closure, t_A $[d_{AE}]$ by the following relationship:

$$A = A_{MAX}\left(\frac{t}{t_A}\right)^n \qquad \text{for } t < t_A$$

$$A = A_{MAX} \qquad \text{for } t \geq t_A \qquad \text{Equation 4-14}$$

where A_{MAX} is 0.93 and n is enumerated for various crops in Table 4-97 below. The parameter, t_A, is computed as a function of PPF and $[CO_2]$ for each crop. This function is presented below with appropriate coefficients.

Table 4-97 Values for the Exponent n in MEC Models

Crop	n
Wheat	1.0
Rice, Soybean, Sweet Potato	1.5
Dry Bean, Peanut, White Potato	2.0
Lettuce, Tomato	2.5

The canopy quantum yield, CQY, $[\mu mol_{\text{Carbon Fixed}}/\mu mol_{\text{Absorbed PPF}}]$ is defined by:

$$CQY = CQY_{MAX} \qquad \text{for } t \leq t_Q$$

$$CQY = CQY_{MAX} - (CQY_{MAX} - CQY_{MIN})\frac{(t - t_Q)}{(t_M - t_Q)} \qquad \text{for } t_Q < t \leq t_M \qquad \text{Equation 4-15}$$

where t_M is time at crop harvest or maturity $[d_{AE}]$, and t_Q is the time at onset of canopy senescence $[d_{AE}]$. t_M and t_Q are model constants. CQY_{MAX} is a crop-specific function of PPF and $[CO_2]$, as noted below, while CQY_{MIN} is a crop-specific constant.

Carbon use efficiency (CUE) is defined as the amount of carbon incorporated into plant biomass divided by the total amount of carbon fixed during gross photosynthesis, thus accounting for losses of carbon due to respiration (Monje and Bugbee, 1998). The 24-hour carbon use efficiency, CUE_{24}, a fraction, is constant for most

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[192] Other environmental and physiological factors may also vary. See Cavazzoni (2001) for complete details on this model.

[193] Photosynthetic photon flux (PPF) is commonly expressed in units of either µmol/(m²·s), as listed here, or mol/(m²·d). The units for PPF are related by the expression:

PPF [µmol/(m²•s)] = PPF [mol/(m²·d)] × 1/H × (1 h/3600 s) × (10^6 µmol/1 mol)

where H is photoperiod [h/d]. See Table 4-111for nominal values of H, which are designated H_O. Because units for PPF depend upon the duration during which crops receive photosynthetic irradiation, the conversion to a “per day” basis depends on the diurnal photoperiod per day.

crops. In such cases, a single value is listed under CUE_{MAX} in the tables below. For legumes, CUE_{24} is described by:

$$CUE_{24} = CUE_{MAX} \qquad \text{for } t \leq t_Q$$
$$CUE_{24} = CUE_{MAX} - (CUE_{MAX} - CUE_{MIN}) \frac{(t - t_Q)}{(t_M - t_Q)} \qquad \text{for } t_Q < t \leq t_M \qquad \text{Equation 4-16}$$

where CUE_{MAX} and CUE_{MIN} are model inputs unique to each crop.

The daily carbon gain, DCG, $[mol_{Carbon}/m^2 \cdot d]$ is computed from:

$$DCG = 0.0036 \frac{s}{h} \frac{mol}{\mu mol} \times H \times CUE_{24} \times A \times CQY \times PPF \qquad \text{Equation 4-17}$$

where H is the photoperiod [h/d], a crop-specific model input. Photoperiod may vary daily. See Cavazzoni (2001) for the assumptions involved.

The daily oxygen production, DOP, $[mol_{O_2}/m^2 \cdot d]$ may be computed using:

$$DOP = OPF \times DCG \qquad \text{Equation 4-18}$$

where OPF is the oxygen production fraction $[mol_{O_2}/mol_{Carbon}]$, which is a crop specific parameter.

The crop growth rate, CGR $[g/m^2 \cdot d]$, is related to DCG by:

$$CGR = MW_C \frac{DCG}{BCF} \qquad \text{Equation 4-19}$$

where MW_C is the molecular weight of carbon, 12.011 g/mol, and BCF is the biomass carbon fraction, another crop-specific constant.

The total crop biomass, on a dry basis, TCB $[g/m^2]$, is determined by integrating CGR, from $t = 0$ to the time of interest, such as harvest, t_M. Or:

$$TCB = \int_0^{t_M} CGR \, dt \qquad \text{Equation 4-20}$$

Total edible biomass, on a dry basis, TEB $[g/m^2]$, may be estimated by integrating the product of CGR and the fraction of daily carbon gain allocated to edible biomass, XFRT, from time storage organs begin to form, t_E $[d_{AE}]$. Both XFRT and t_E are tabulated below. Thus:

$$TEB = XFRT \int_{t_E}^{t_M} CGR \, dt \qquad \text{Equation 4-21}$$

Inedible biomass is the difference between TCB and TEB.

Table 4-98 Summary of Modified Energy Cascade Model Variables for Biomass Production

Variable	Units	Description	Reference/Value
A	--	fraction of PPF absorbed by the plant canopy	Equation 4-14
A_{MAX}	--	maximum value for A	0.93
BCF	--	biomass carbon fraction	Table 4-113
CGR	$\frac{g}{m^2 \cdot d}$	crop growth rate	Equation 4-19
C_i	varies	coefficients in functions describing t_A and CQY_{MAX}	Table 4-100
$[CO_2]$	$\frac{\mu mol_{CO2}}{mol_{air}}$	atmospheric concentration of carbon dioxide; model variable	none
CQY	$\frac{\mu mol_{C.\ Fixed}}{\mu mol_{Ab.\ PPF}}$	canopy quantum yield	Equation 4-15
CQY_{MAX}	$\frac{\mu mol_{C.\ Fixed}}{\mu mol_{Ab.\ PPF}}$	maximum value for CQY that applies until t_Q	Table 4-23
CQY_{MIN}	$\frac{\mu mol_{C.\ Fixed}}{\mu mol_{Ab.\ PPF}}$	minimum value for CQY at t_M	Table 4-99
CUE_{24}	--	24-hour carbon use efficiency; a fraction	Equation 4-16
CUE_{MAX}	--	maximum value for CUE_{24} that applies until t_Q	Table 4-99
CUE_{MIN}	--	minimum value for CUE_{24} at t_M	Table 4-99
DCG	$\frac{mol_{Carbon}}{m^2 \cdot d}$	daily carbon gain	Equation 4-17
DOP	$\frac{mol_{O2}}{m^2 \cdot d}$	daily oxygen production	Equation 4-18
H	h/d	Photoperiod	Table 4-111
MW_C	g/mol	molecular weight of carbon	12.011
n	--	an exponent	Table 4-97
OPF	$\frac{mol_{O2}}{mol_{Carbon}}$	oxygen production fraction	Table 4-113
PPF	$\frac{\mu mol_{photon}}{m^2 \cdot s}$	photosynthetic photon flux; model variable	none
TCB	g/m²	total crop biomass, on a dry basis	Equation 4-20
TEB	g/m²	total edible biomass, on a dry basis	Equation 4-21
t	d_{AE}	time; model variable	none
t_A	d_{AE}	time until canopy closure	Equation 4-30
t_E	d_{AE}	time at onset of organ formation	Table 4-112
t_M	d_{AE}	time at harvest or crop maturity	Table 4-112
t_Q	d_{AE}	time until onset of canopy senescence	Table 4-112
XFRT	--	fraction of daily carbon gain allocated to edible biomass after t_E	Table 4-112

The environmentally dependent parameters for these models are provided in the sections below. The MEC variables for biomass production models are summarized in Table 4-98. General model constants, which depend only on the crop cultivar and not on environmental conditions, are listed in Table 4-100.

Table 4-99 Biomass Production Model Constants [194]

Crop	Specific Cultivar	CQY_{MIN} [$\mu mol_{C\ Fixed}/\mu mol_{Ab.\ PPF}$]	CUE_{MAX}	CUE_{MIN}
Dry Bean	*Meso Amer. Hab. 1 – Determinate*	0.02	0.65	0.50 [195]
Lettuce	*Waldmann's Green*	n/a	0.625	n/a
Peanut	*Pronto*	0.02	0.65	0.30
Rice	*Early maturing types*	0.01	0.64	n/a
Soybean	*Hoyt*	0.02	0.65	0.30
Sweet Potato	*TU-82-155 (Tuskegee University)*	n/a	0.625	n/a
Tomato	*Reinmann Philippe 75/59*	0.01	0.65	n/a
Wheat	*Veery 10*	0.01	0.64	n/a
White Potato	*Norland or Denali*	0.02	0.625	n/a

Based on multivariable polynomial regression, the functions for maximum canopy quantum yield, CQY_{MAX} [$\mu mol_{\text{Carbon Fixed}}/\mu mol_{\text{Absorbed PPF}}$], have the general form:

$$
\begin{aligned}
CQY_{MAX}(PPF, [CO_2]) = {} & C_1 \frac{1}{PPF}\frac{1}{[CO_2]} + C_2 \frac{1}{PPF} + C_3 \frac{[CO_2]}{PPF} + C_4 \frac{[CO_2]^2}{PPF} \\
& + C_5 \frac{[CO_2]^3}{PPF} + C_6 \frac{1}{[CO_2]} + \text{Constant} + C_8 [CO_2] + C_9 [CO_2]^2 + C_{10} [CO_2]^3 + C_{11} \frac{PPF}{[CO_2]} \\
& + C_{12} PPF + C_{13} PPF [CO_2] + C_{14} PPF [CO_2]^2 + C_{15} PPF [CO_2]^3 + C_{16} \frac{PPF^2}{[CO_2]} + C_{17} PPF^2 \\
& + C_{18} PPF^2 [CO_2] + C_{19} PPF^2 [CO_2]^2 + C_{20} PPF^2 [CO_2]^3 + C_{21} \frac{PPF^3}{[CO_2]} + C_{22} PPF^3 \\
& + C_{23} PPF^3 [CO_2] + C_{24} PPF^3 [CO_2]^2 + C_{25} PPF^3 [CO_2]^3
\end{aligned}
$$

Equation 4-22

where C_1 through C_{25} again denote coefficients. PPF is designated in [µmol/m²·s], while $[CO_2]$ is measured in $\left[\frac{\mu mol_{CO_2}}{mol_{Air}}\right]$. To simplify the presentation of these functions, Table 4-101; through Table 4-109 present the coefficient values for each crop in a matrix of the form presented in Table 4-100.

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[194] The parameters in this table apply independent of temperature regime, photoperiod, or planting density.

[195] This suggested value is based on Wheeler (2001a) whereby growth costs are less for dry bean than for soybean and peanut.

Table 4-100 Format for Tables of Coefficients for Equations Employing Multivariable Polynominal Regression Fits

	1/PPF	**1**	**PPF**	**PPF^2**	**PPF^3**
$1/[CO_2]$	$1/PPF \times 1/[CO_2]$ or C_1	$1/[CO_2]$ or C_6	$PPF/[CO_2]$ or C_{11}	$PPF^2/[CO_2]$ or C_{16}	$PPF^3/[CO_2]$ or C_{21}
1	$1/PPF$ or C_2	Constant Term	PPF or C_{12}	PPF^2 or C_{17}	PPF^3 or C_{22}
$[CO_2]$	$[CO_2]/PPF$ or C_3	$[CO_2]$ or C_8	$PPF\ [CO_2]$ or C_{13}	$PPF^2\ [CO_2]$ or C_{18}	$PPF^3\ [CO_2]$ or C_{23}
$[CO_2]^2$	$[CO_2]^2/PPF$ or C_4	$[CO_2]^2$ or C_9	$PPF\ [CO_2]^2$ or C_{14}	$PPF^2\ [CO_2]^2$ or C_{19}	$PPF^3\ [CO_2]^2$ or C_{24}
$[CO_2]^3$	$[CO_2]^3/PPF$ or C_5	$[CO_2]^3$ or C_{10}	$PPF\ [CO_2]^3$ or C_{15}	$PPF^2\ [CO_2]^3$ or C_{20}	$PPF^3\ [CO_2]^3$ or C_{25}

The coefficients for CQY_{MAX} are independent of photoperiod and planting density and are only a weak function of temperature regime. Thus, for life support crop-growth scenarios, the CQY_{MAX} coefficients are essentially functions of the crop cultivar alone. See Cavazzoni (2001) for applicability under extreme temperature ranges.

Table 4-101 Maximum Canopy Quantum Yield, CQY_{MAX}, Coefficients for Dry Bean

	1/PPF	**1**	**PPF**	**PPF^2**	**PPF^3**
$1/[CO_2]$	0	0	0	0	0
1	0	4.191×10^{-2}	-1.238×10^{-5}	0	0
$[CO_2]$	0	5.3852×10^{-5}	0	-1.544×10^{-11}	0
$[CO_2]^2$	0	-2.1275×10^{-8}	0	6.469×10^{-15}	0
$[CO_2]^3$	0	0	0	0	0

Table 4-102 Maximum Canopy Quantum Yield, CQY_{MAX}, Coefficients for Lettuce

	1/PPF	**1**	**PPF**	**PPF^2**	**PPF^3**
$1/[CO_2]$	0	0	0	0	0
1	0	4.4763×10^{-2}	-1.1701×10^{-5}	0	0
$[CO_2]$	0	5.163×10^{-5}	0	-1.9731×10^{-11}	0
$[CO_2]^2$	0	-2.075×10^{-8}	0	8.9265×10^{-15}	0
$[CO_2]^3$	0	0	0	0	0

Table 4-103 Maximum Canopy Quantum Yield, CQY_{MAX}, Coefficients for Peanut

	1/PPF	**1**	**PPF**	**PPF^2**	**PPF^3**
$1/[CO_2]$	0	0	0	0	0
1	0	4.1513×10^{-2}	0	-2.1582×10^{-8}	0
$[CO_2]$	0	5.1157×10^{-5}	4.0864×10^{-8}	-1.0468×10^{-10}	4.8541×10^{-14}
$[CO_2]^2$	0	-2.0992×10^{-8}	0	0	0
$[CO_2]^3$	0	0	0	0	3.9259×10^{-21}

Table 4-104 Maximum Canopy Quantum Yield, CQY_{MAX}, Coefficients for Rice

	1/PPF	**1**	**PPF**	**PPF^2**	**PPF^3**
$1/[CO_2]$	0	0	0	0	0
1	0	3.6186×10^{-2}	0	-2.6712×10^{-9}	0
$[CO_2]$	0	6.1457×10^{-5}	-9.1477×10^{-9}	0	0
$[CO_2]^2$	0	-2.4322×10^{-8}	3.889×10^{-12}	0	0
$[CO_2]^3$	0	0	0	0	0

Table 4-105 Maximum Canopy Quantum Yield, CQY_{MAX}, Coefficients for Soybean

	1/PPF	**1**	**PPF**	**PPF^2**	**PPF^3**
$1/[CO_2]$	0	0	0	0	0
1	0	4.1513×10^{-2}	0	-2.1582×10^{-8}	0
$[CO_2]$	0	5.1157×10^{-5}	4.0864×10^{-8}	-1.0468×10^{-10}	4.8541×10^{-14}
$[CO_2]^2$	0	-2.0992×10^{-8}	0	0	0
$[CO_2]^3$	0	0	0	0	3.9259×10^{-21}

Note: The function for soybean here is identical to the function for peanut.

Table 4-106 Maximum Canopy Quantum Yield, CQY_{MAX}, Coefficients for Sweet Potato

	1/PPF	**1**	**PPF**	**PPF^2**	**PPF^3**
$1/[CO_2]$	0	0	0	0	0
1	0	3.9317×10^{-2}	-1.3836×10^{-5}	0	0
$[CO_2]$	0	5.6741×10^{-5}	-6.3397×10^{-9}	-1.3464×10^{-11}	0
$[CO_2]^2$	0	-2.1797×10^{-8}	0	7.7362×10^{-15}	0
$[CO_2]^3$	0	0	0	0	0

Table 4-107 Maximum Canopy Quantum Yield, CQY_{MAX}, Coefficients for Tomato

	1/PPF	**1**	**PPF**	**PPF^2**	**PPF^3**
$1/[CO_2]$	0	0	0	0	0
1	0	4.0061×10^{-2}	0	-7.1241×10^{-9}	0
$[CO_2]$	0	5.688×10^{-5}	-1.182×10^{-8}	0	0
$[CO_2]^2$	0	-2.2598×10^{-8}	5.0264×10^{-12}	0	0
$[CO_2]^3$	0	0	0	0	0

Table 4-108 Maximum Canopy Quantum Yield, CQY_{MAX}, Coefficients for Wheat

	1/PPF	**1**	**PPF**	**PPF^2**	**PPF^3**
$1/[CO_2]$	0	0	0	0	0
1	0	4.4793×10^{-2}	-5.1946×10^{-6}	0	0
$[CO_2]$	0	5.1583×10^{-5}	0	-4.9303×10^{-12}	0
$[CO_2]^2$	0	-2.0724×10^{-8}	0	2.2255×10^{-15}	0
$[CO_2]^3$	0	0	0	0	0

Table 4-109 Maximum Canopy Quantum Yield, CQY_{MAX}, Coefficients for White Potato

	1/PPF	**1**	**PPF**	**PPF^2**	**PPF^3**
$1/[CO_2]$	0	0	0	0	0
1	0	4.6929×10^{-2}	0	0	-1.9602×10^{-11}
$[CO_2]$	0	5.0910×10^{-5}	0	-1.5272×10^{-11}	0
$[CO_2]^2$	0	-2.1878×10^{-8}	0	0	0
$[CO_2]^3$	0	0	4.3976×10^{-15}	0	0

4.14.1.8 *MODIFIED ENERGY CASCADE MODELS FOR CROP TRANSPIRATION*

Following the approach in Section 4.14.1.7 for biomass production, this section focuses on a similar model to predict crop canopy transpiration. In fact, the crop transpiration model employs many of the parameters computed by the algorithm above. The model in this section was adapted from Monje (1998).

The vapor pressure deficit, VPD [kPa], is the difference between the saturated vapor pressure for air at the mean atmospheric temperature, VP_{SAT} [kPa], and the actual vapor pressure for the atmosphere, VP_{AIR} [kPa]. Or:

$$VP_{SAT} = 0.611 \ e^{\left[\frac{17.4 \, T_{LIGHT}}{T_{LIGHT} + 239}\right]}$$

$$VP_{AIR} = VP_{SAT} \times RH$$

$$VPD = VP_{SAT} - VP_{AIR} \qquad \text{Equation 4-23}$$

where T_{LIGHT} [C] is the mean atmospheric temperature during the crop's light cycle and RH is the mean atmospheric relative humidity as a fraction bounded between 0 and 1, inclusive. Calculation of VP_{SAT} assumes that the temperature of the canopy leaves, from which transpiration originates, is equal to the mean light-cycle air temperature, T_{LIGHT}.

The gross canopy photosynthesis, P_{GROSS} [$\mu mol_{Carbon}/m^2 \cdot s$], may be expressed in terms of previously defined values as:

$$P_{GROSS} = A \times CQY \times PPF \qquad \text{Equation 4-24}$$

The net canopy photosynthesis, P_{NET} [$\mu mol_{Carbon}/m^2 \cdot s$], may be expressed as:

$$P_{NET} = \left[\frac{D_{PG} - H}{D_{PG}} + \frac{H \times CUE_{24}}{D_{PG}}\right] P_{GROSS} \qquad \text{Equation 4-25}$$

where D_{PG} [h/d] is the length of the plant growth chamber's diurnal cycle. During development of these models, Cavazzoni (2001) assumed a value of 24.0 h/d for D_{PG}, which is consistent with ground-based data gathered to date.

Table 4-110 Summary of Modified Energy Cascade Model Variables for Canopy Transpiration

Variable	Units	Description	Reference/Value
A	--	fraction of PPF absorbed by the plant canopy	Equation 4-14
$[CO_2]$	$\frac{\mu mol_{CO_2}}{mol_{Air}}$	atmospheric concentration of carbon dioxide; model variable	none
CQY	$\frac{\mu mol_{Carbon}}{\mu mol_{Photon}}$	canopy quantum yield	Equation 4-15
CUE_{24}	--	24-hour carbon use efficiency; a fraction	Equation 4-16
D_{PG}	h/d	plant growth diurnal cycle	24 [196]
DTR	$L_{Water}/m^2 \cdot d$	daily canopy transpiration rate	Equation 4-29
g_A	$mol_{Water}/m^2 \cdot s$	atmospheric aerodynamic conductance	Equation 4-27 and Equation 4-28
g_C	$mol_{Water}/m^2 \cdot s$	canopy surface conductance	Equation 4-26
g_S	$mol_{Water}/m^2 \cdot s$	canopy stomatal conductance	Equation 4-27 and Equation 4-28
H	h/d	photoperiod; model variable	none [197]
H_O	h/d	nominal photoperiod	Table 4-111
MW_W	g/mol	molecular weight of water	18.015
P_{ATM}	kPa	total atmospheric pressure; model variable	none
P_{GROSS}	$\frac{\mu mol_{Carbon}}{m^2 \cdot s}$	gross canopy photosynthesis	Equation 4-24
P_{NET}	$\frac{\mu mol_{Carbon}}{m^2 \cdot s}$	net canopy photosynthesis	Equation 4-25
PPF	$\frac{\mu mol_{Photon}}{m^2 \cdot s}$	photosynthetic photon flux; model variable	none
PPF_E	$\frac{\mu mol_{Photon}}{m^2 \cdot s}$	effective photosynthetic photon flux	Equation 4-31
RH	--	atmospheric relative humidity; model variable	none
T_{LIGHT}	C	atmospheric temperature during crop's light cycle	Table 4-111
VP_{AIR}	kPa	actual moisture vapor pressure	Equation 4-23
VP_{SAT}	kPa	saturated moisture vapor pressure	Equation 4-23
VPD	kPa	vapor pressure deficit	Equation 4-23
ρ_W	g/L	density of water	998.23

The canopy surface conductance, g_C [$mol_{Water}/m^2 \cdot s$], is based on the canopy stomatal conductance, g_S [$mol_{Water}/m^2 \cdot s$], and the atmospheric aerodynamic conductance, g_A [$mol_{Water}/m^2 \cdot s$].

$$g_C = \frac{g_A \times g_S}{g_A + g_S} \qquad \text{Equation 4-26}$$

The following models for g_S and values for g_A were derived from the experimental conditions studied by Monje (1998).

With planophile-type canopies, such as for dry bean, lettuce, peanut, soybean, sweet potato, tomato, and white potato, g_S and g_A are computed as:

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[196] This value applies to data used to date from terrestrial test facilities. More generally, it's the length of a local sol.

[197] For the nominal case, assume the photoperiod, H, equals the nominal photoperiod, H_O, which is listed in Table 4-111.

$$g_S = \left(1.717\ T_{LIGHT} - 19.96 - 10.54\ VPD\right)\left(\frac{P_{NET}}{[CO_2]}\right)$$

$$g_A = 2.5 \qquad \text{Equation 4-27}$$

With erectophile canopies, such as for rice and wheat, g_S and g_A have the form:

$$g_S = 0.1389 + 15.32\ RH\left(\frac{P_{NET}}{[CO_2]}\right)$$

$$g_A = 5.5 \qquad \text{Equation 4-28}$$

The daily canopy transpiration rate, DTR [$L_{Water}/m^2 \cdot d$], is:

$$DTR = 3600\ \frac{s}{h}\ H\left(\frac{MW_W}{\rho_W}\right) g_C \left(\frac{VPD}{P_{ATM}}\right) \qquad \text{Equation 4-29}$$

where P_{ATM} [kPa] is the total atmospheric pressure, MW_W is the molecular weight of water, 18.015 g/mol, and ρ_W is the density of water, 998.23 g/L at 20 °C. The parameters for the transpiration model are provided in the sections below and the variables are summarized in Table 4-110.

4.14.1.8.1 MODIFIED ENERGY CASCADE MODEL CONSTANTS FOR NOMINAL TEMPERATURE REGIMES AND PHOTOPERIODS

For nominal temperature regimes and photoperiods, MEC model constants are provided here for the parameters in Section 4.14.1.7 and Section 4.14.1.8.

Note: Some values in Table 4-111 differ from the corresponding values listed in Table 4-89.

Table 4-111 Nominal Temperature Regimes, Planting Densities, and Photoperiods for the Plant Growth and Transpiration Models

Crop	Nominal Photoperiod H_O [h/d]	Planting Density[198] [plants/m²]	Light Cycle Temperature, T_{LIGHT} [°C]	Dark Cycle Temperature, T_{DARK}[199] [°C]
Dry Bean	12	7.0	26	22
Lettuce	16	19.2	23	23
Peanut	12	7.0	26	22
Rice	12	200	29	21
Soybean	12	35	26	22
Sweet Potato	18	16	28	22
Tomato	12	6.3	26	22
Wheat	20	720	23	23
White Potato	12	6.4	20	16

---

[198] Planting density affects the time to canopy closure, t_A, even though an explicit functionality is not apparent.

[199] The MEC models do not explicitly use the dark cycle temperature, but because the dark cycle temperature affects a crop's development, these values are assumed implicitly for this set of parameters.

Table 4-112 Biomass Production Model Time Constants for Nominal Temperature Regime and Photoperiod

Crop	Fraction of Edible Biomass After t_E XFRT	Time at Onset of Edible Biomass Formation, t_E [d_{AE}]	Time at Onset of Canopy Senescence, t_Q [d_{AE}]	Time at Harvest, t_M [d_{AE}]
Dry Bean	0.97	40	42	63
Lettuce	0.95	1	n/a [200]	30
Peanut	0.49	49	65	110
Rice	0.98	57	61	88
Soybean	0.95	46	48	86
Sweet Potato	1.00	33	n/a [200]	120
Tomato	0.70	41	56	80
Wheat	1.00	34	33	62
White Potato	1.00	45	75	138 [201]

Table 4-113 Biomass Carbon and Oxygen Production Fractions for Nominal Temperature Regime and Photoperiod

Crop	Biomass Carbon Fraction, BCF	Oxygen Production Fraction, OPF [mol O_2/mol C]
Dry Bean	0.45	1.10
Lettuce	0.40	1.08
Peanut	0.50	1.19
Rice	0.44	1.08
Soybean	0.46	1.16
Sweet Potato	0.44	1.02
Tomato	0.42	1.09
Wheat	0.44	1.07
White Potato	0.41	1.02

The functions for the canopy closure time, t_A [d_{AE}], have the general form:

$$
\begin{aligned}
t_A(\mathrm{PPF_E}, [\mathrm{CO_2}]) = {} & C_1 \frac{1}{\mathrm{PPF_E}} \frac{1}{[\mathrm{CO_2}]} + C_2 \frac{1}{\mathrm{PPF_E}} + C_3 \frac{[\mathrm{CO_2}]}{\mathrm{PPF_E}} + C_4 \frac{[\mathrm{CO_2}]^2}{\mathrm{PPF_E}} + C_5 \frac{[\mathrm{CO_2}]^3}{\mathrm{PPF_E}} \\
& + C_6 \frac{1}{[\mathrm{CO_2}]} + \mathrm{Constant} + C_8 [\mathrm{CO_2}] + C_9 [\mathrm{CO_2}]^2 + C_{10} [\mathrm{CO_2}]^3 + C_{11} \frac{\mathrm{PPF_E}}{[\mathrm{CO_2}]} + C_{12} \mathrm{PPF_E} \\
& + C_{13} \mathrm{PPF_E} [\mathrm{CO_2}] + C_{14} \mathrm{PPF_E} [\mathrm{CO_2}]^2 + C_{15} \mathrm{PPF_E} [\mathrm{CO_2}]^3 + C_{16} \frac{\mathrm{PPF_E}^2}{[\mathrm{CO_2}]} + C_{17} \mathrm{PPF_E}^2 \\
& + C_{18} \mathrm{PPF_E}^2 [\mathrm{CO_2}] + C_{19} \mathrm{PPF_E}^2 [\mathrm{CO_2}]^2 + C_{20} \mathrm{PPF_E}^2 [\mathrm{CO_2}]^3 + C_{21} \frac{\mathrm{PPF_E}^3}{[\mathrm{CO_2}]} + C_{22} \mathrm{PPF_E}^3 \\
& + C_{23} \mathrm{PPF_E}^3 [\mathrm{CO_2}] + C_{24} \mathrm{PPF_E}^3 [\mathrm{CO_2}]^2 + C_{25} \mathrm{PPF_E}^3 [\mathrm{CO_2}]^3
\end{aligned}
$$

Equation 4-30

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[200] This crop is harvested before the canopy reaches senescence.

[201] White potato plants are harvested at t = 105 d_{AE}, but t_M = 138 d_{AE} is used for the models.

where C_1 through C_{25} denote coefficients. PPF_E is expressed in [µmol/m²·s], while $[CO_2]$ is measured in $\left[\frac{\mu mol_{CO_2}}{mol_{Air}}\right]$. To simplify the presentation of these functions, Table 4-114 through Table 4-122 present the coefficient values for each crop in a matrix using the form of Table 4-100 above.

The effective photosynthetic photon flux, PPF_E [µmol/m²·s], (Rodriguez and Bell, 2004) is:

$$PPF_E = PPF\left(\frac{H}{H_O}\right) \qquad \text{Equation 4-31}$$

where values for nominal photoperiod, H_O [h/d], are tabulated in Table 4-111

Table 4-114 Canopy Closure Time, t_A, Coefficients for Dry Bean with Nominal Conditions

	$1/PPF_E$	**1**	**PPF_E**	**$PPF_E{}^2$**	**$PPF_E{}^3$**
$1/[CO_2]$	2.9041×10^5	0	0	0	0
1	1.5594×10^3	15.840	6.1120×10^{-3}	0	0
$[CO_2]$	0	0	0	-3.7409×10^{-9}	0
$[CO_2]^2$	0	0	0	0	0
$[CO_2]^3$	0	0	0	0	9.6484×10^{-19}

Table 4-115 Canopy Closure Time, t_A, Coefficients for Lettuce with Nominal Conditions

	$1/PPF_E$	**1**	**PPF_E**	**$PPF_E{}^2$**	**$PPF_E{}^3$**
$1/[CO_2]$	0	0	1.8760	0	0
1	1.0289×10^4	1.7571	0	0	0
$[CO_2]$	-3.7018	0	0	0	0
$[CO_2]^2$	0	2.3127×10^{-6}	0	0	0
$[CO_2]^3$	3.6648×10^{-7}	0	0	0	0

Table 4-116 Canopy Closure Time, t_A, Coefficients for Peanut with Nominal Conditions

	$1/PPF_E$	**1**	**PPF_E**	**$PPF_E{}^2$**	**$PPF_E{}^3$**
$1/[CO_2]$	3.7487×10^6	-1.8840×10^4	51.256	-0.05963	2.5969×10^{-5}
1	2.9200×10^3	23.912	0	5.5180×10^{-6}	0
$[CO_2]$	0	0	0	0	0
$[CO_2]^2$	0	0	0	0	0
$[CO_2]^3$	9.4008×10^{-8}	0	0	0	0

Table 4-117 Canopy Closure Time, t_A, Coefficients for Rice with Nominal Conditions

	$1/PPF_E$	**1**	**PPF_E**	**$PPF_E{}^2$**	**$PPF_E{}^3$**
$1/[CO_2]$	6.5914×10^6	-3.748×10^3	0	0	0
1	2.5776×10^4	0	0	4.5207×10^{-6}	0
$[CO_2]$	0	-0.043378	4.562×10^{-5}	-1.4936×10^{-8}	0
$[CO_2]^2$	6.4532×10^{-3}	0	0	0	0
$[CO_2]^3$	0	0	0	0	0

Table 4-118 Canopy Closure Time, t_A, Coefficients for Soybean with Nominal Conditions

	$1/PPF_E$	**1**	**PPF_E**	**$PPF_E{}^2$**	**$PPF_E{}^3$**
$1/[CO_2]$	6.7978×10^6	-4.326×10^4	112.63	- 0.13637	6.6918×10^{-5}
1	-4.3658×10^3	33.959	0	0	-2.1367×10^{-8}
$[CO_2]$	1.5573	0	0	0	1.5467×10^{-11}
$[CO_2]^2$	0	0	-4.911×10^{-9}	0	0
$[CO_2]^3$	0	0	0	0	0

Table 4-119 Canopy Closure Time, t_A, Coefficients for Sweet Potato with Nominal Conditions

	$1/PPF_E$	**1**	**PPF_E**	**$PPF_E{}^2$**	**$PPF_E{}^3$**
$1/[CO_2]$	1.2070×10^6	0	0	0	4.0109×10^{-7}
1	4.9484×10^3	4.2978	0	0	0
$[CO_2]$	0	0	0	0	2.0193×10^{-12}
$[CO_2]^2$	0	0	0	0	0
$[CO_2]^3$	0	0	0	0	0

Table 4-120 Canopy Closure Time, t_A, Coefficients for Tomato with Nominal Conditions

	$1/PPF_E$	**1**	**PPF_E**	**$PPF_E{}^2$**	**$PPF_E{}^3$**
$1/[CO_2]$	6.2774×10^5	0	0.44686	0	0
1	3.1724×10^3	24.281	5.6276×10^{-3}	-3.0690×10^{-6}	0
$[CO_2]$	0	0	0	0	0
$[CO_2]^2$	0	0	0	0	0
$[CO_2]^3$	0	0	0	0	0

Table 4-121 Canopy Closure Time, t_A, Coefficients for Wheat with Nominal Conditions

	$1/PPF_E$	**1**	**PPF_E**	**$PPF_E{}^2$**	**$PPF_E{}^3$**
$1/[CO_2]$	9.5488×10^4	0	0.3419	-1.9076×10^{-4}	0
1	1.0686×10^3	15.977	1.9733×10^{-4}	0	0
$[CO_2]$	0	0	0	0	0
$[CO_2]^2$	0	0	0	0	0
$[CO_2]^3$	0	0	0	0	0

Table 4-122 Canopy Closure Time, t_A, Coefficients for White Potato with Nominal Conditions

	$1/PPF_E$	**1**	**PPF_E**	**$PPF_E{}^2$**	**$PPF_E{}^3$**
$1/[CO_2]$	6.5773×10^5	0	0	0	0
1	8.5626×10^3	0	0.042749	-1.7905×10^{-5}	0
$[CO_2]$	0	0	8.8437×10^{-7}	0	0
$[CO_2]^2$	0	0	0	0	0
$[CO_2]^3$	0	0	0	0	0

For certain crops under low-lighting conditions, the relationships above for t_A and A_{MAX} require modification. Physically, the canopy does not close under low light, so A_{MAX} does not reach 0.93, for the nominal photoperiod and planting densities listed in Table 4-111. Thus, to use the models above under such conditions and obtain reasonably accurate results, modified values for the time at canopy closure, t_A, and the maximum fraction of PPF absorbed by the plant canopy, A_{MAX}, are required. Table 4-123 provides modified values for the conditions listed, where t_A is the time until the listed A_{MAX} is attained. The nominal photoperiods and planting densities associated with these values are also given for reference, and they are consistent with values provided in Table 4-111 above.

Table 4-123 MEC Model Parameters for Low-Light Conditions, Nominal Temperature Regimes

Crop	Photo-period [h/d]	Planting Density [plants/m²]	PPF [µmol/m²·s]	[CO_2] [µmol/mol]	t_A [d_{AE}]	A_{MAX}
Lettuce	16	19.2	200	330	32	0.18
				660	32	0.35
				990	32	0.46
				1,320	32	0.49
			300	330	32	0.75
Rice	12	200	200	330	45	0.13
				660	45	0.21
				990	45	0.26
				1,320	45	0.28
			300	330	50	0.33
				660	50	0.50
				990	50	0.59
				1,320	50	0.62
			400	330	50	0.57
				660	50	0.75
				990	50	0.82
				1,320	50	0.83
Sweet Potato	18	16	200	330	30	0.58
				660	30	0.76
				990	30	0.84
				1,320	30	0.86
			300	330	31	0.90
White Potato	12	6.4	200	330	36	0.34
				660	38	0.49
				990	38	0.58
				1,320	39	0.60
			300	330	40	0.80
				660	42	0.90

MEC model constants for additional temperature regimes are reported in Cavazzoni (2001).

4.15 PLANETARY PROTECTION

4.15.1 WHAT DESIGNS DECREASE THE PROBABILITY OF CONTAMINATING MARS AND EARTH?

NASA possesses several policy documents describing necessary constraints on missions traveling to and from extraterrestrial bodies that either may harbor indigenous life or could support terrestrial life. Two documents (NPD 8020.7G, 2013, and NPR 8020.12D, 2011) describe the processes NASA uses to comply with international agreements (UN, 1967, and COSPAR, 2005) to ensure that robotic probes do not contaminate potentially sensitive extraterrestrial destinations that may support their own indigenous life and to ensure that any samples returned from those targets do not release extraterrestrial life forms to Earth. Two documents (NPD 8900.5B, 2011, and NPR 8900.1A, 2012) describe how crew members are to be protected while operating in an extraterrestrial environment where extraterrestrial life forms may be present.

What is missing, however, are NASA-approved and published guidance to address potential planetary protection for vehicles carrying human crews. The NASA Planetary Protection Officer is developing appropriate procedures and requirements to govern missions with human crews to Mars and other sensitive extraterrestrial destinations. Spry (2013) provides some preliminary material that may become part of the final NASA documents. Spry (2013) begins with four general principles:

1. *"Safeguarding the Earth from potential back contamination is the highest planetary protection priority in Mars exploration."*

2. *"The greater capability of human explorers can contribute to the astrobiological exploration of Mars only if human-associated contamination is controlled and understood."*

3. *"For a landed mission conducting surface operations, it will not be possible for all human associated processes and mission operations to be conducted within entirely closed systems."*

4. *"Crewmembers exploring Mars, or their support systems, will inevitably be exposed to martian materials."*

Spry (2013) also provides several implementation guidelines, with those applicable to the present discussion being:

1. *"Human missions will carry microbial populations that will vary in both kind and quantity, and it will not be practicable to specify all aspects of an allowable microbial population or potential contaminants at launch. Once any baseline conditions for launch are established and met, continued monitoring and evaluation of microbes carried by human missions will be required to address both forward and backward contamination concerns."*

2. *"A quarantine capability for both the entire crew and for individual crewmembers shall be provided during and after the mission, in case potential contact with a martian life-form occurs."*

3. *"A comprehensive planetary protection protocol for human missions should be developed that encompasses both forward and backward contamination concerns and addresses the combined human and robotic aspects of the mission, including subsurface exploration, sample handling, and the return of the samples and crew to Earth."*

4. *"Neither robotic systems nor human activities should contaminate "Special Regions"* [202] *on Mars, as defined by this [Committee on Space Research (COSPAR)]* [203] *policy."*

5. *"An onboard crewmember should be given primary responsibility for the implementation of planetary protection provisions affecting the crew during the mission."*

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[202] Special regions are defined by COSPAR as domains that may either support extraterrestrial life or terrestrial life (COSPAR, 2005). Beaty, *et al.* (2006) define special regions quantitatively for NASA, to comply with COSPAR (2005), as a region where the temperature rises above –20 °C and the water activity is 0.5 or above.

[203] COSPAR is an international body that, among other functions, defines protocols to comply with the Outer Space Treaty (UN, 1967). COSPAR's planetary protection requirements are detailed in COSPAR (2005).

6. *"Planetary protection requirements for initial human missions should be based on a conservative approach consistent with a lack of knowledge of martian environments and possible life, as well as the performance of human support systems in those environments. Planetary protection requirements for later missions should not be relaxed without scientific review, justification, and consensus."*

Spry (2013) recommends the following approach regarding introduction of ECLSS waste streams to the Martian environment:

> *"On the specific issue of waste streams, presuming that they are identified as having biologic or organic components (that could confound [planetary protection] efforts if released in an uncontrolled fashion), they should be filtered or otherwise processed prior to release/disposal (e.g., maybe [high-efficiency particulate air] filter of gases, autoclaving of solid/liquid wastes)."*

4.15.2 BACKWARD CONTAMINATION

The general principles and implementation guidelines above can be reduced to a few points in the context of ECLSS architecture and preventing backward contamination.

4.15.2.1 *SAFEGUARD EARTH*

Safeguarding Earth from any type of backward contamination is the principle of greatest importance. No unconstrained extraterrestrial life forms should be allowed to reach Earth either in returned samples or as an infection to the crew.

4.15.2.2 *HUMAN SURFACE SYSTEMS WILL NOT BE COMPLETELY CLOSED*

As currently envisioned, human surface systems will not be completely closed because in order for human beings to investigate the martian surface they must leave their habitat to conduct EVAs. This mechanism of departing the surface habitat enables a process by which the crew and/or the habitat are either intentionally or unintentionally exposed to martian materials in an uncontrolled manner.

4.15.2.3 *PROVIDE A QUARANTINE CAPABILITY*

When crewmembers are exposed to martian materials and, possibly, to martian life forms, a quarantine capability is necessary to segregate the affected crewmembers from the rest of the crew while determining the severity and effects of the exposure.

4.15.2.4 *USE CONSERVATIVE APPROACHES INITIALLY*

The initial approaches for all surface habitat systems, including the ECLSS architecture, should be conservative. While future missions could potentially use more relaxed protocols once the martian surface is determined to be biologically benign based upon thorough scientific examination, the overall ECLSS architecture is likely to remain mostly unchanged except as necessary to correct any design or operational deficiencies.

4.15.3 FORWARD CONTAMINATION

In like manner, the general principles and implementation guidelines provide some guidance on preventing forward contamination of the Martian environment via the ECLSS architecture.

4.15.3.1 *CONTROL AND UNDERSTAND HUMAN-ASSOCIATED CONTAMINATION*

Terrestrial biomarkers released on the martian surface may confound any planetary science, so such events are to be avoided to preserve the integrity of planetary science. Historically, some Lunar samples collected by Project Apollo contained water with the same elemental isotopes as terrestrial water. Because the Apollo heat rejection technologies for both the Lunar Module and the EVA space suit used vaporization of water to reject thermal loads, a possible explanation for the Lunar water is that Apollo mission elements deposited it upon the samples before collection (Glavin, *et al.*, 2010). Another possible explanation is that the same mechanism that delivered water to Earth also provided the water found in the Lunar samples. However, because Apollo surface assets potentially provided the observed water, a contamination scenario cannot be rejected without reasonable doubt remaining, so the mission elements themselves unintentionally confounded the planetary science.

Microbial terrestrial biomarkers are an intimate and vital part of any healthy human being. Indeed, separating the symbiotic microorganisms from the human being will eventually kill that human being. Because the symbiotic microorganisms cannot be removed from a human being, they are part of the potential terrestrial load that is part of any human crew. For a robotic probe, COSPAR (2005) requires prior to launch a detailed catalog of all substances comprising components of the probe that are intended to reach the Martian surface. Further, the microbial loading for a probe going to the Martian surface is to be significantly reduced, with the level of reduction dependent upon the intent of the mission and its expected interaction with potentially sensitive regions of Mars (COSPAR, 2005). Similar restrictions are impractical for a human crew because human beings cannot be segregated from their symbiotic microorganisms and because biological creatures are much harder to definitively catalog for constitutive compounds compared with mechanical structures. Further, the composition of a living human being changes with time on much shorter timescales and in a less predictable manner than for a mechanical structure that may exhibit oxidation and similar surface degradation due to chemical interactions with the environment. In summary, human-associated contamination varies more widely than probe-associated contamination and understanding this contribution from a human crew is essential for guarding and interpreting planetary science while using human beings as direct investigators on the Martian surface.

4.15.3.2 *HUMAN SURFACE SYSTEMS WILL NOT BE COMPLETELY CLOSED*

Human surface systems, if based upon or are similar to current technology, are unlikely to be completely closed, so terrestrial biomarkers could have an avenue to escape from the interior of human surface systems. Terrestrial biomarkers include living or recent deceased terrestrial microorganisms and any organic compounds produced by or incorporated within a terrestrial organism. As noted above, deposition of terrestrial biomarkers may confound Martian planetary science. Thus, even without complete isolation of human surface systems from the Martian environment, it is essential to inhibit the transfer of terrestrial biomarkers into areas of the Martian environment where those biomarkers may contaminate potential samples used to understand the evolution of the Martian environment. Therefore, as specifically recommended by Spry (2013), any discharge streams should be filtered to contain any terrestrial biomarkers within the human-occupied volume.

4.15.3.3 *DO NOT AFFECT "SPECIAL REGIONS"*

As noted above, special regions are those areas of Mars that may either be a haven for terrestrial life, if released into the Martian environment, or they may support indigenous Martian life.[204] To truly maximize planetary science, terrestrial biomarkers must not be allowed to contaminate these areas prior to investigating them thoroughly. If Martian life is discovered, such areas may remain perpetually excluded from willful terrestrial contamination. Current approaches within Mars DRA 5.0 (Drake, 2009a) envision using sterilized robotic assistants for initial exploration of any special regions near a human landing site both to ensure the planetary science and to reduce the likelihood of accidental human exposure to Martian life forms.

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[204] Though far from a certainty, the underlying assumption is that Martian life will require similar conditions to those required by terrestrial life. Certainly, for terrestrial life to flourish on Mars, the conditions must be sufficient to support that life. That Martian life will flourish only under similar conditions as those required for terrestrial life remains an active area of research.

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6 APPENDICES

6.1 APPENDIX A - ACRONYMS AND ABBREVIATIONS [205]

Symbol	Definition
ACY	Russian acronym for its urinal system aboard the ISS
AES	Advanced Exploration Systems
ALS	Advanced Life Support
ALS RD	ALS Requirements Document
ATCS	active thermal control system
ATV	Automated Transfer Vehicle
BDB	Bioastronautics Data Book
BIO-Plex	Bioregenerative Planetary Life Support Systems Test Complex
BOB	bulk overwrap bag
BPA	Brine Processor Assembly
BPC	Biomass Production Chamber at KSC
BVAD	Baseline Values and Assumptions Document (This document)
BGI	bubble growth index
CI	controlled inorganic (compound)
CM	number of crew or crew members
CO2	carbon dioxide
COPS	overall system thermodynamic coefficient of performance
CQ	Crew quarters
CTMP	crewtime-mass-penalty [kg/CM-h]
CTSD	Crew and Thermal Systems Division
CxP	Constellation Program
DDCU	direct-current-to-direct-current conversion unit
dw	dry mass (dry “weight”)
EATCS	external active thermal control system
ECLS	Environmental Control and Life Support
ECLSS	Environmental Control and Life Support System
EER	estimated energy requirement
ELS	Exploration Life Support (Project)
EMC	Environmental Monitoring and Control (Interface)
EMU	extravehicular mobility unit (space suit)
ESCG	Engineering and Sciences Contract Group
ESM	equivalent system mass
ESM GD	ESM Guidelines Document
ETCS	external thermal control system
EVA	extravehicular activity
ffm	frozen food mass
fw	fresh mass (fresh “weight”)
GSC	grab sample containers
HPS	high pressure sodium, a type of lamp
HTV	H-II Transfer Vehicle

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[205] Symbols specific to the crop models in Section 4.14.1.7 are defined in

Table 4-98 and Table 4-110

Symbol	Definition
ISRU	in-situ resource utilization
ISS	International Space Station
IST	Invariantly-Scheduled Time
ITCS	internal thermal control system
IUPAC	International Union of Pure and Applied Chemistry
IVA	intravehicular activity
JCPC	Joint Crew Provisioning Catalog
JSC	Johnson Space Center
KSC	Kennedy Space Center
IBD	Individual breathing device
I/X	ion exchange
LAT	Lunar Architecture Team
LL	Lunar Lander
LMLSTP	Lunar Mars Life Support Test Program (integrated test)
LO	Lunar Orbiter
LR	Logistics Reduction
MAG	Maximum Absorbency Garment (for EMU)
MCA	Major Constituents Analyzer
MEC	Modified Energy Cascade models
MMOD	Micrometeorids and Orbital Debris
MORD	Medical Operation Requirements Document
MSIS	Man-Systems Integration Standards
MTBF	Mean Time Between Failures
MMS	Mutch Memorial Station
MW	molecular weight or Megawatt if used as a unit (See below.)
n/a	not applicable
NASA	National Aeronautics and Space Administration
NextSTEP	Next Space Technologies for Exploration Partnerships
NIOSH	National Institute for Occupational Safety and Health
NRC	National Research Council
O2	oxygen
OGA	Oxygen Generation Assembly
OGS	Oxygen Generation System
OSHA	Occupational Safety and Health Administration
ppCO2	partial pressure of CO2
p[gas]	partial pressure exerted by gas
PAR	photosynthetically active radiation
pH	potential of hydrogen
PLSS	portable life support system
PPF	photosynthetic photon flux
PSR	permanently shadowed region
PV	photovoltaic
RBD	reliability block diagram
RDA	recommended dietary allowance
RMD	Reference Missions Document
RS	system composite thermal resistance
SI	Système Internationale d'Unités (Metric System)

Symbol	Definition
SIMA	Systems Integration, Modeling, and Analysis (element of ELS Project)
SMAC	spacecraft maximum allowable concentration
SODB	Shuttle Operational Data Book
SP100	type of nuclear reactor
STS	Space Transportation System (or Shuttle)
SVCHp	solar vapor-compression heat pump
SWEG	Spacecraft Water Exposure Guidelines
TBD	to be determined
TRRJ	thermal radiator rotary joint
VO2 max	maximal rate of oxygen uptake by the whole-body during exercise
VOC	Volatile organic compound
VST	Variably-Scheduled Time
UPA	Urine Processor Assembly
USOS	United States Operating Segment
UWMS	Universal Waste Management System
w/	With
w/o	without
$\hat{W}_{RF}$	specific power consumption for a cooled volume within a cabinet
WHC	Waste and Hygiene Compartment
WPA	Water Processor Assembly
WRS	Water Recovery System

6.2 APPENDIX B - ABBREVIATIONS FOR UNITS

Symbol	Actual Unit	Physical Correspondence
Btu	British thermal unit	energy (English)
°C	degrees Centigrade	temperature
CM	Crewmember	person
CM-d	crewmember-day	crewtime
CM-h	crewmember-hour	crewtime
CM-wk	crewmember-week	crewtime
CM-℘	crewmember-menstrual period	crewtime
c	centi-	prefix
d	Day	time
°F	degrees Fahrenheit	temperature (English)
ft	Foot	length (English)
g	Gram	mass
H Ht	Hour Height	Time length
IU	International Unit	see specific usage
J	Joule	energy
K	Kelvin	absolute temperature
k	kilo-	prefix
kW	Kilowatt	power
kW_e	kilowatt electric	electric power
kW_{th}	kilowatt thermal	thermal heat
L	Liter	volume
lb_m	pounds (mass)	mass (English)
M	mega-	prefix
MW_e	megawatt electric	electric power
m	Meter	length
m^2	square meter	area
m^3	cubic meter	volume
m	milli-	prefix
meq/L	milli-equivalents per liter	concentration
min	Minute	time
mol	Mole	mole
N	Newton	force
Pa	Pascal	pressure
ppm	parts per million	concentration
psia	pounds (force) per square inch, absolute	absolute pressure (English)
S	Siemens	conductivity
s	Second	time
W	Watt	power
wk	Week	time
y	Year	time
μ	micro-	Prefix