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Advanced Life Support Baseline Values and Assumptions Document

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PREPARED BY:	*Original Signed by:* A. J. Hanford, SIMA Deputy
APPROVED BY:	*Original Signed by:* M. K. Ewert, SIMA Element Lead
APPROVED BY:	*Original Signed by:* D. L. Henninger, ALS Project Manager
APPROVED BY:	
APPROVED BY:	
APPROVED BY:	

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Advanced Life Support
Baseline Values and Assumptions Document

Editor:

Anthony J. Hanford, Ph.D.
Lockheed Martin Space Operations
Houston, Texas 77058

Responsible National Aeronautics and Space Administration Official:

Michael K. Ewert
Johnson Space Center
Houston, TX 77058

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1 Introduction

The Advanced Life Support (ALS) Baseline Values and Assumptions Document (BVAD) provides analysts and modelers as well as other ALS researchers with a common set of initial values and assumptions, or baseline. This baseline, in turn, provides a common point of origin from which all Systems Integration, Modeling, and Analysis (SIMA) Element studies will depart.

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 plus 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.

For example, the direct solar irradiation for vehicles orbiting around Luna varies between 1,323 W/m² and 1,414 W/m² with a mean value of 1,367 W/m² (K&K, 1998). Thus, the solar constant at Luna naturally varies by 91 W/m² (6.7 %). Williams (1997) lists a mean value of 1,380 W/m² for the solar constant at Luna. While any value from 1,323 W/m² to 1,414 W/m² might be selected for the solar constant in a study sited in Luna orbit, a mean value of 1,370 W/m² might be defined as the baseline solar flux at Luna. Thus, all studies would use a consistent value of 1,370 W/m² unless they were specifically exploring the effect of varying the solar constant.

This example is well bounded. Some life support assumptions are similarly well bounded. Others, such as the growth rate for plants, are not well bounded. For these, 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.

Values for this document were taken from a variety of sources and several SIMA researchers, in addition to the authors, helped to prepare the manuscript that follows. As part of the process of assigning values to each of the life support quantities, the writers evaluated and debated each entry to produce a set of mutually agreeable values with corresponding limits. Ultimately comments from all readers are welcome and encouraged. To allow the BVAD to truly maintain its utility as a store of modeling and analysis information, the BVAD is a living document that will be updated as necessary to reflect new technology and/or scientific discoveries.

The ALS Project controls the BVAD, while SIMA maintains and updates the BVAD. Subsequent releases will be made as required. Please send comments to:

Mr. M. K. Ewert
Lead, Systems Integration, Modeling, and Analysis Element
National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
2101 NASA Road One, Mail Code EC2
Houston, Texas 77058
E-mail: Michael.k.ewert1@jsc.nasa.gov

1.2 Advantages

Aside from the advantages implied 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.
- Each study can now benefit from the "best" available input values and assumptions by drawing upon information collected by a group of researchers rather than just from one person's files. Further, such values reflect the combined expertise of the group as a whole rather than just those from 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 to any previous work because each study's assumptions 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 Systems Integration, Modeling, and Analysis Element

SIMA is the element within the ALS Project responsible for maintaining this document. One objective of the SIMA Element is to encourage and improve communication between the various modelers within the ALS Project.

1.4 Acknowledgement [1]

- Many researchers contributed information or insights to make this current draft possible. Thus, the BVAD editor would like to specifically acknowledge the following individuals for their contributions: Charles Bourland, Ph.D., Juan M. Castillo (Lockheed Martin), James Cavazzoni, Ph.D. (Rutgers, The State University of New Jersey), Katherine R. Daues (NASA/JSC), Alan E. Drysdale, Ph.D. (The Boeing Company), Bruce E. Duffield (Lockheed Martin), Michael K. Ewert (NASA/JSC), David R. Fletcher (NASA/JSC), James R. Geffre (NASA/JSC), Jean B. Hunter, Ph.D. (Cornell University), Frank F. Jeng (Lockheed Martin), Kevin E. Lange, Ph.D. (Lockheed Martin), Wen-Ching Lee (Hernandez Engineering), Julie A. Levri (NASA/ARC), Sabrina Maxwell (The Boeing Company), Michele Perchonok, Ph.D. (National Space Biomedical Research Institute), Jay L. Perry (NASA/MSFC), Karen D. Pickering (NASA/JSC), Susan D. Ramsey (NASA/JSC), Michael Rouen (NASA/JSC), Kathy Ruminsky, David A. Vaccari, Ph.D. (Stevens Institute of Technology), Yael Vodovotz, Ph.D., Raymond Wheeler, Ph.D. (NASA/KSC), and Kristina R. Wines (NASA/JSC).

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[1] The National Aeronautics and Space Administration (NASA) Centers abbreviated below are Ames Research Center (ARC), Lyndon B. Johnson Space Center (JSC), John F. Kennedy Space Center (KSC), and George C. Marshall Space Flight Center (MSFC).

2 Approach

The assumptions here arise from various sources and they have been 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 static and dynamic models of life support systems. Where numerical values are given, and an attempt has been made to focus on quantitative data, an attempt has been made to include upper and lower limits as well as a recommended value. In some cases, the upper and lower limits are definite values set by the physics or biology of the situation. For other cases, they are representative values that will not often be exceeded in a real system.

2.2 Context

This document assumes no particular mission, but does focus on long-duration space missions. In some cases, the data may be applicable to only certain missions. The reader is directed to Stafford, *et al.* (2001) for more details on potential mission scenarios.

2.3 Background

2.3.1 Equivalent System Mass Description

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. [2] The primary advantage is to allow comparison of two life support systems with different parameters using a single scale. This 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, for example, the power system can yield an appropriate power-mass penalty by dividing the average power plant output by the total mass of the generating power system. Thus, for a nuclear power system on an independent lander that, on average, delivers 100 kW of electrical power and has an overall mass of 8,708 kg (Mason, *et al.*, 1992) [3] the power mass penalty is 11.48 W/kg. This power-mass penalty effectively assigns a fraction of the power system mass to a power-using subsystem in place of that subsystem's power requirement. 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 energy management, and crewtime requirements as masses.

2.3.2 Definition of 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 has little impact on the equivalent system mass of a life support system and can thus be safely neglected in this case. Table 2.4.1 and Table 2.4.2 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,

[2] An ESM evaluation is very similar in form to computing a project's net present value. Thus, ESM is a method for ranking a system or subsystem concept relative to other concepts.

[3] 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.

while Section 5 provides additional information about commodity demands to and from the ALS External Interfaces.

2.3.3 Definition of Modeling

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

2.3.4 Units and Values

All numerical assumptions are given using the Système Internationale d'Unités (SI) units. This approach is consistent with the current philosophy within the Crew and Thermal Systems Division (CTSD) that all analysis tasks for advanced systems use SI units. A list of SI units for physical quantities of interest is provided in the Appendices.

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 six, unless otherwise stated.

2.4 Life Support Subsystems Within the Advanced Life Support Project

Hanford (2000) provides a generic description of life support subsystems and subsystem and external interface relationships for the ALS Project. This classification originally arose from a Systems Modeling and Analysis Project [4] workshop in the fall of 1999 and now, after review and revision, is the current standard definition for the ALS Project. [5] Information within the BVAD and future analysis tasks will be organized according to this structure.

As noted above, other formats to describe life support systems exist. This one specifically classifies those disciplines housed within and funded by the ALS Project as subsystems, Table 2.4.1, while those disciplines that interact with life support subsystems, but are not the sole responsibility of the ALS Project, are external life support interfaces, Table 2.4.2. Thus, Air, Biomass, Food, Thermal, Waste, and Water are classified as subsystems, while Crew [6], Cooling, Extravehicular Activity (EVA) Support, Human Accommodations, In-Situ Resource Utilization, Integrated Control, Power, and Radiation Protection are external life support interfaces. The interfaces listed in the last column for each subsystem or external interface are generally inclusive, attempting to account for all possible interactions, even if some of those interactions are highly unlikely.

Please note that within this document the ALS subsystem names, such as "Air Subsystem" and "Biomass 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. This laxness with respect to nomenclature reflects the constantly changing perspective that both ALS 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" often vary according to the current problem definition and often differ for different problems or studies.

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4 Systems Modeling and Analysis Project is the previous name for the Systems Integration, Modeling, and Analysis element.

5 Work on the Bioregenerative Planetary Life Support Systems Test Complex (BIO-Plex) predates this organizational structure, so deviations from Table 2.4.1 and Table 2.4.2 exist for historical documentation from that project.

6 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 external interface here.

Table 2.4.1 Advanced Life Support Subsystem Descriptions and Interfaces

Subsystem	Description	Life Support System Interfaces
Air	The Air Subsystem stores and maintains the vehicle cabin atmospheric gases, including pressure control, overall composition and trace constituents. The Air Subsystem is also responsible for fire detection and suppression and vacuum services.	Biomass, Food, Thermal, Waste, Water, Crew, EVA Support, Human Accommodations, In-Situ Resource Utilization, Integrated Control, Power
Biomass	The Biomass Subsystem produces, stores and provides raw agricultural products to the Food Subsystem while regenerating air and water. This subsystem is not present in a solely physicochemical life support system.	Air, Food, Thermal, Waste, Water, Crew, In-Situ Resource Utilization, Integrated Control, Power
Food	The Food Subsystem receives harvested agricultural products from the Biomass Subsystem, stabilizes them as necessary, and stores raw and stabilized agricultural products, food ingredients, and prepackaged food and beverage items. The Food Subsystem transforms the raw agricultural products into a ready-to-eat form via food processing and meal preparation operations. In the absence of the Biomass Subsystem, this subsystem operates only on prepackaged, stored products.	Air, Biomass, Thermal, Waste, Water, Crew, EVA Support, Human Accommodations, Integrated Control, Power, Radiation Protection
Thermal	The Thermal Subsystem is responsible for maintaining cabin temperature and humidity within appropriate bounds and for rejecting the collected waste heat to the Cooling Interface. Note: Equipment to remove thermal loads from the cabin atmosphere normally provides sufficient air circulation.	Air, Biomass, Food, Waste, Water, Crew, Cooling, EVA Support, Human Accommodations, Integrated Control, Power
Waste	The Waste Subsystem collects and conditions waste material from anywhere in the habitat, including packaging, human wastes, inedible biomass, and brines from other subsystems such as the Water Subsystem. The Waste Subsystem may sterilize and store the waste, or reclaim life support commodities, depending on the life support system closure and/or mission duration.	Air, Biomass, Food, Thermal, Water, Crew, EVA Support, Integrated Control, Human Accommodations, Power, Radiation Protection
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 for crew consumption and hygiene as well as external users.	Air, Biomass, Food, Thermal, Waste, Crew, Cooling, EVA Support, Human Accommodations, In-Situ Resource Utilization, Integrated Control, Power, Radiation Protection

Table 2.4.2 Advanced Life Support External Interfaces Descriptions and Interfaces

External Life Support Interfaces	Description	Life Support System Interfaces
Crew	The Crew Interface interacts with most life support subsystems and external interfaces. Historically, and likely in the near-term, crew-members are the foremost consumers of life support commodities and the primary producers of waste products. Finally, life support technologies are specifically designed to provide for the health, safety, and maximum efficiency of crewmembers.	Air, Biomass, Food, Thermal, Waste, Water, EVA Support, Human Accommodations, In-Situ Resource Utilization, Integrated Control, Power, Radiation Protection.
Cooling	The Cooling Interface rejects vehicle thermal loads, delivered by the Thermal Subsystem, to the external environment.	Thermal, Water, Integrated Control, Power
Extravehicular Activity Support	The Extravehicular Activity Support Interface provides life support consumables for extravehicular activities, including oxygen, water, and food, and carbon dioxide and waste removal.	Air, Food, Thermal, Waste, Water, Crew, Human Accommodations, Integrated Control, Power
Human Accommodations	The Human Accommodations Interface is responsible for the crew cabin layout, crew clothing including laundering, and the crew's interaction with the life support system.	Air, Biomass, Food, Thermal, Waste, Water, Crew, EVA Support, Integrated Control, Power
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, Biomass, Water, Crew, Integrated Control, Power, Radiation Protection
Integrated Control	The Integrated Control Interface provides appropriate control for the life support system.	ALL
Power	The Power Interface provides the necessary energy to support all equipment and functions within the life support system.	ALL
Radiation Protection	The Radiation Protection Interface provides protection from environmental radiation.	Food, Waste, Water, Crew, In-Situ Resource Utilization, Power

2.5 Applicable Documents

The BVAD is intended to provide values for analysis and modeling tasks. Analysis and modeling is 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 spaceflight. 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 within the ALS Project 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 SIMA and provide whatever information could be used to determine values for such omitted quantities.

The following documents are other important references for life support. The latest revision is noted below and will be available electronically at *http://advlife.support.jsc.nasa.gov*. Subsequent releases will be considered in updating this document.

Lange, K. E., and Lin, C. H. (1998) "Advanced Life Support Program: Requirements Definition and Design Consideration," JSC-38571 (CTSD-ADV-245, Revision A) National Aeronautics and Space Administration, Johnson Space Center, Houston, Texas.

Stafford, K. W., Jerng, L. T., Drysdale, A. E., Maxwell, S., Levri, J. A. (2001) "Advanced Life Support Systems Integration, Modeling, and Analysis Reference Missions Document," edited by Ewert, M. K., and Hanford. A. J., JSC-39502, Revision A, National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, Houston, Texas.

Parameters that are non-negotiable, for whatever reason, are considered ALS requirements and are documented within Lange and Lin (1998). Some of the assumptions documented here 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 Stafford, *et al.* (2001), which is a companion document to the BVAD.

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., Mars missions).

3.1.1 Typical Values for Exploration Missions

Primarily, the missions supported here are outlined in the Advanced Life Support Systems Integration, Modeling, and Analysis Reference Missions Document (Stafford, *et al.*, 2001) and focus on near-Earth sites including low-Earth orbit, Luna, near-Earth asteroids, and also Mars. Assumptions are given in Table 3.1.1 for mission parameters associated with missions described within Stafford, *et al.* (2001) and some other possible near-term missions.

Generically, recent NASA exploration mission architectures stipulate separate vehicles for each of three distinct mission phases. The crew travels to and from the vicinity of an extraterrestrial destination in a dedicated transit vehicle. The crew transfers to a waiting descent / ascent lander to travel from orbit to a surface site, landing near a larger prepositioned surface habitat. The crew spends the majority of its surface phase operating from the surface habitat. At the end of the surface phase, the crew transfers back to the waiting transit vehicle using the descent / ascent lander. Table 3.1.1 assumes this generic architecture. [7]

The given volume assumptions in Table 3.1.1 describe unobstructed or free volume per crewmember [8] are specified in terms of tolerable, performance, and optimal for the listed mission segment. For purposes here, performance should be viewed as nominal. Two possible surface missions are mentioned with respect to lunar missions. Per NASA (2001a), nominal possible mission configurations would provide either a 3-day or a 30-day surface phase. Drake (1999) proposes a nominal mission for its descent / ascent vehicle of roughly 7 days, but contingency might stretch this occupancy to 30 days. As a final note, a mission architecture in which multiple crews visit the same surface site and a new crew module is sent with each crew, the actual crew volume will probably increase for later missions because earlier crew modules could be linked together to form a much larger habitable volume.

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7 Though not presented in Stafford, et al. (2001) or mentioned here explicitly, missions to asteroids or comets are possible, and such ventures would probably not need a surface habitat, for example. Rather, the exploration missions here assume a site on a relatively large celestial body with appreciable inherent gravity.

8 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 3.1.1 Mission Assumptions

		Assumptions		
Parameter	**Units**	**lower**	**nominal**	**upper**
Crew Size	people	4 (1)	6 (2)	9 (1)
Visits to One Site	–	1 (2)	3 (2)	7 (4)
Destination: Luna				
Volume: [9]		*Tolerable*	*Performance*	*Optimal*
Transit Phase	m^3/person	1.13 (5)	3.54 (5)	4.25 (5)
Descent / Ascent	m^3/person	1.27 (5)	3.54 (5)	4.39 (5)
Surface, 3 days	m^3/person	1.27 (5)	3.54 (5)	4.39 (5)
Surface, 30 days	m^3/person	2.26 (5)	4.25 (5)	10.62 (5)
Duration: [10]		*Minimum*	*Nominal*	*Maximum*
Transit Phase	d	3 (6)	5 (6)	7 (6)
Descent / Ascent	d	5 (6)	8 (5)	8 (5)
Surface Phase	d	3 (7)	3 or 30 (7) [11]	30 (7)
Destination: Mars				
Volume: [9]		*Tolerable*	*Performance*	*Optimal*
Transit Phase	m^3/person	5.10 (5)	9.91 (5)	18.41 (5)
Descent / Ascent, 7 days	m^3/person	1.13 (5)	3.54 (5)	4.25 (5)
Descent / Ascent, 30 days	m^3/person	2.27 (5)	4.25 (5)	10.62 (5)
Surface Phase	m^3/person	5.10 (5)	9.91 (5)	18.41 (5)
Duration: [10]		*Minimum*	*Nominal*	*Maximum*
Transit Phase	d	110 (2)	180 (2)	180 (2)
Descent / Ascent	d	7 (5)	7 (5)	30 (5)
Surface Phase	d	540 (2)	600 (2)	619 (2)

References

(1) SMAP (1999)
(2) Hoffman & Kaplan (1997)
(3) NASA (1995)
(4) Stafford, *et al.* (2001)
(5) Ramsey (2002)
(6) Geffre (2002)
(7) Fletcher (2001)

3.1.2 Long-Term Extraterrestrial Bases

The Bioregenerative Planetary Life Support Systems Test Complex (BIO-Plex) is planned as a closed-chamber facility comprised of five chambers and an airlock all connected by a tunnel.[12] The BIO-Plex will provide integrated test facilities for technologies that will likely be used for an early human base on Luna or Mars. Each BIO-Plex module is 185.15 m^3 in volume. The tunnel is 263.43 m^3. The airlock volume is 48 m^3. Thus, the total volume is estimated to be 1,237 m^3, or 309 m^3 per crewmember assuming the nominal crew of four people. Internal air pressure will be approximately ambient.

9 The volume here specifically is unobstructed or free volume within the crew cabin.

10 This mission would have an immediate abort-to-orbit option, although not necessarily an immediate return option.

11 The intended nominal surface stay depends on the vehicles provided.

12 *Editor's Note:* At this time, development and activation of the BIO-Plex is suspended until a future date. Further, the final configuration and specifications, when complete, may differ from those listed here. Values here are likely typical of a test facility for bioregenerative research.

The BIO-Plex is nominally designed for four people, but during overlaps for crew rotation, up to eight people may be supported for up to 72 hours (Tri, 2000). While the planned duration for tests is under review, those working on the BIO-Plex have mentioned 120- through 400+-day missions most often. The initial test involving human beings will be 120 days in duration (Tri, 2000). Plant scientists favor tests of 240 days in duration because this allows two complete cropping cycles based on the harvest date for the crops with the longest life cycle.

A facility similar to the BIO-Plex could be built on Luna or Mars, with a similar configuration and constraints. Some likely differences for an actual extraterrestrial base would be mission duration, with a probable minimum duration of 540 days for any mission to Mars (as in Table 3.1.1), and an operational lifetime of up to fifteen years.

3.2 Infrastructure Costs and Equivalencies

Infrastructure costs (mass, volume, power, thermal energy management, and crewtime, for example), are key factors in overall system analysis. They effectively apportion a fraction of the infrastructure mass to the each component of the life support system. It is far easier to decide on reasonable figures for these parameters early in a study than try to objectively determine them at the end of the study. Appropriate infrastructure costs and equivalencies for two possible near-term exploration objectives, Luna and Mars, are provided in Table 3.2.1 and Table 3.2.2. The listed penalties for volume account for primary structure only, including micrometeoroid and orbital debris protection and radiation protection for the crew, if necessary. Table 3.2.7 provides information on secondary structure, including the racks and conditioned volumes such as refrigerated spaces.

The nominal values listed in Table 3.2.1 and Table 3.2.2 correspond to current technology with few improvements or synergistic advantages. Less conservative values, with comments on applicability, are presented in Table 3.2.3, Table 3.2.8, and Table 3.2.9.

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 should use very different values, especially for thermal energy management.

Table 3.2.1 and Table 3.2.2 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, for thermal energy management, is a combined assessment considering hardware from the Thermal Subsystem and the Cooling External Interface. These values are combined here for convenience.

Table 3.2.1 Luna Mission Infrastructure Costs

Parameter	Units	Assumptions lower	nominal	upper
Transit				
Shielded Volume	kg/m³		80.8 [1]	
Unshielded Volume	kg/m³		45.2 [1]	
Power	kg/kW		237 [2]	
Thermal Energy Management: Thermal and Cooling	kg/kW	55 [3]	65 [3]	65 [3]
Crewtime	kg/CM-h		TBD	
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	54 [2]	749 [2]	749 [2]
Thermal Energy Management: Thermal and Cooling	kg/kW	97 [3]	102 [3]	246 [3]
Crewtime	kg/CM-h		TBD	

References
[1] See Table 3.2.3
[2] See Table 3.2.8
[3] See Table 3.2.9

Table 3.2.2 Mars Mission Infrastructure Costs

Parameter	Units	Assumptions lower	nominal	upper
Transit				
Shielded Volume	kg/m³		215.5 [1]	219.7 [1]
Unshielded Volume	kg/m³		9.16 [1]	13.40 [1]
Power	kg/kW		237 [2]	
Thermal Energy Management: Thermal and Cooling	kg/kW		60 [3]	70 [3]
Crewtime	kg/CM-h	1.14 [4]	1.14 [4]	1.54 [4]
Surface				
Shielded Volume	kg/m³		215.5 [1]	219.7 [1]
Unshielded Volume	kg/m³		9.16 [1]	13.40 [1]
Power	kg/kW	54 [2]	228 [2]	338 [2]
Thermal Energy Management: Thermal and Cooling	kg/kW		146 [3]	170 [3]
Crewtime	kg/CM-h	1.25 [4]	1.25 [4]	1.50 [4]

References
[1] See Table 3.2.3
[2] See Table 3.2.8
[3] See Table 3.2.9
[4] See Table 3.3.5

3.2.1 Pressurized Volume or Primary Structure Costs

Pressurized volume houses the crew and crew-accessible systems. Characteristic volume costs are presented in Table 3.2.3. The International Space Station (ISS) common module currently provides pressurized volume in low-Earth orbit. Alternately, an inflatable module could be used. In both cases, the lower value reflects primary structure with protection for micrometeoroids and orbital debris, while the upper value, if known, also includes some dedicated radiation protection.

The aerodynamic crew capsule in Table 3.2.3 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 3.2.3 Cost of Pressurized Volume

	Assumptions [kg/m³]		
Technology/Approach	**lower**	**nominal**	**upper**
Low-Earth Orbit			
ISS Module (shell only)		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) [13]	133.1 (4) [13]	137.3 (4) [14]
Unshielded Inflatable Module		9.16 (2) [15]	13.40 (2) [15]
Martian Mission – Surface [16]			
Shielded Inflatable Module [17]		215.5 (4) [13]	219.7 (4) [14]
Unshielded Inflatable Module		9.16 (2) [15]	13.40 (2) [15]

References
(1) Hanford (1997)
(2) See Table 3.2.5
(3) NASA (2001a)
(4) See Table 3.2.6.

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 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 system 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

13 Estimate based on primary structure plus shielding mass.

14 Estimate based on all listed module masses, including avionics and power management and distribution.

15 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.

16 Transit vehicles for Martian missions are generally larger, based on current concepts, so volume-mass penalties for surface applications would also be suitable for transit applications.

17 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, but the extent of that shielding is unclear.

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 might be located outside the pressurized cabin. While this is unlikely for most life support equipment, the associated volume cost factor would be much less than the lower value, approaching zero.

Leakage is technology dependent. The specification for ISS modules is 83 kg leakage per module per year (0.18% per day), but tests have shown that the actual leakage rate is significantly lower than this specification.

Currently the United States uses the ISS common module to provide pressurized volume. However, this design is more massive and costly than some alternatives. Inflatable modules have been suggested since the Apollo Program. TransHab (Kilbourn, 1998, and NASA, 1999), presented in Table 3.2.4, is a robust inflatable module designed 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 3.2.4 include micrometeoroid protection and a storm shelter for radiation protection in low-Earth orbit against solar particle events. Less substantial inflatable modules could be used on a planetary surface if in-situ resources, such as regolith or caverns, provide meteoroid and radiation protection. 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.

Table 3.2.4 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 [18] (Enclosing 18.8 m^3 and covering 40.1 m^2)	142	
Radiation Protection Media (A 0.0574 m thick Water shield)	2,304	
Initial Inflation System	502	
Avionics and Power Management and Distribution	1,398	
Total Mass	10,663	

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

Based on Table 3.2.4, several cost factors for various configurations of the components presented are possible. See Table 3.2.5. While each configuration is not independently viable, they provide background for other estimates. The applicable volume is 329.4 m³.

Table 3.2.5 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 3.2.4	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	4.24	

Table 3.2.6 presents estimates for masses and volume-mass penalties for several configurations of inflatable modules. The first estimate, based on findings reviewed by Duffield (2001), uses 0.0622 m of hydrogen-impregnated carbon nanofibers to protect the crew quarters from solar particle events. Such a configuration is designed for a lunar mission. The assumed containment mass is 5% of the total shielding material mass. The second estimate assumes 0.0622 m of hydrogen-impregnated carbon nanofibers surround the entire crew cabin. The third estimate assumes 0.100 m of water surround the entire crew cabin for a lunar mission, which is a common “rule of thumb” in some recent design scenarios. Again, this shielding only protects against solar particle events. The containment mass, based on Kilbourn (1998), is 6.2% of the shielding material mass. Finally, the last estimate employs 2.43 m of liquid hydrogen to shield against both solar particle events and galactic cosmic radiation. See Duffield (2001). The assumed containment mass is 50% of the shielding material mass, and this is likely a lower limit.

Table 3.2.6 Estimated Masses for Inflatable Modules

Item (Based on TransHab Architecture)	Mass for Lunar Mission [kg]	Mass for Lunar Mission [kg]	Mass for Lunar Mission [kg]	Mass for Martian Mission [kg]
Primary Structure Mass (Core, Shell) (1) [19]	6,961	6,961	6,961	6,961
Shielding Mass is 0.0622 m of Hydrogen-Impregnated Carbon Nanofibers Around Crew Quarters (2)	5,618			
Tankage (5 %) (3)	281			
Shielding Mass is 0.0622 m of Hydrogen-Impregnated Carbon Nanofibers Around Full Shell (2)		35,119		
Tankage (5 %) (3)		1,756		
Shielding Mass is 0.100 m of Water Around Full Shell			25,094	
Tankage (6.2 %) (4)			1,556	
Shielding Mass is 2.43 m of Liquid Hydrogen Around Full Shell (2)				42,685
Tankage (50 %) (5)				21,342
Total Mass	12,860	43,836	33,611	70,988
Volume-Mass Penalty [kg/m³]		133.1	102.0	215.5
[m³/kg]		0.007514	0.009799	0.004640

References

(1) Kilbourn (1998) and NASA (1999)
(2) Duffield (2001)
(3) Estimated
(4) Computed from Kilbourn (1998)
(5) Assumed (This value is probably a lower limit on the actual tank mass.)

Including the avionics and power management and distribution masses, as listed in Table 3.2.5, 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 9.157 kg/m³ or 0.1092 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.

3.2.2 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 3.2.7 provides estimates for secondary structure masses. Though somewhat simplistic, the volume, power, and thermal energy management 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 energy management, or volume penalties, while a

[19] See the fifth configuration in Table 3.2.5.

100 kg pump mounted to the vehicle floor would have no associated secondary mass, though power, thermal energy management, and volume – to account for primary structure – might still apply.

Table 3.2.7 Secondary Structure Masses

Mounting Configuration	Secondary Structure Mass per Mass of Equipment [$kg_{Secondary\ Structure}$ /$kg_{Equipment}$]	Internal Cargo Volume [m^3]	Reference
Directly to Primary Structure (No Secondary Structure)	0.00	n/a	Information from Green, *et al.* (2000) except as noted. (1) Toups, *et al.* (2001)
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)	

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.

3.2.3 Power Costs

Selection of power systems for a near-term mission to Mars is an important issue. From an engineering perspective, nuclear propulsion and nuclear power for the surface may be essential to provide the required power at an acceptable cost. Table 3.2.8 provides a number of power generation options for various scenarios. Historically in low-Earth orbit, power is either stored in batteries or, alternatively, generated either by non-regenerative fuel cells or via solar photovoltaic (PV) panels with some form of energy storage for periods when the vehicle is in shadow. The first two entries in Table 3.2.8 reflect power generation using International Space Station technology both with and without energy storage, which is provided by batteries. The first value, with energy storage, should be the default power generation option for low-Earth orbit on vehicles of comparable size. The second value applies only for technologies that operate while International Space Station is in sunlight and are not powered while in shadow. For nominal calculations, International Space Station is in shadow for roughly thirty-six minutes of each ninety-two-minute orbit at its median altitude. [20] The third table entry assumes Shuttle non-regenerative fuel cells. These fuel cells use hydrogen and oxygen as reactants, gaining power and water as products. The cost assumes a six-day mission, and the cost for longer missions rises sharply as mission duration increases.

The power system for transit is a hybrid of deployable PV arrays with batteries and fuel cells. The latter provide power during mission phases in which the PV arrays are stowed, such as during an aero-capture maneuver. This system is prototypic of a power system for a small Earth-Luna transit vehicle.

[20] This value corresponds to an orbital altitude of 215 nautical miles at an orbital angle to Sun angle of zero degrees. Note that International Space Station operates completely in sunlight for some orbital angle to Sun angle geometries, so the case here is really a "worst case."

Table 3.2.8 Advanced Mission Power Costs and Equivalencies

Power Cost Options Earth Orbit	**kg/kW(e)**	**kW/kg**	**Comments**
Solar PV Power Generation with Batteries for Power Storage	476 (1)	0.0021	Continuous Power with Deployable PV Cells [21]
Solar PV Power Generation without Power Storage	239 (1)	0.0045	In Sun Power Only with Deployable PV Cells [21]
Non-Regenerative, Hydrogen-Oxygen Fuel Cells	100 (1)	0.010	Shuttle Technology for a Six-day Mission
Transit	**kg/kW(e)**	**kW/kg**	**Comments**
Earth-Luna Transit: Hybrid Solar Array System	237 (2)	0.0042	PV Arrays + Batteries and Fuel Cells.
Surface – Luna	**kg/kW(e)**	**kW/kg**	**Comments**
Solar Photovoltaic (PV) Power Generation at Equatorial Site on Luna			
With Regenerative Fuel Cell Power Storage	749 (3)	0.0013	Tracking PV Arrays
Without Power Storage	62 (3)	0.016	Tracking PV Arrays
	20 (3)	0.050	Horizontal Arrays [22]
Surface – Mars	**kg/kW(e)**	**kW/kg**	**Comments**
Solar Dynamic Power Generation at Equatorial Site on Mars			
With Regenerative Fuel Cell Power Storage	338 (4)	0.0030	
Without Power Storage	149 (4)	0.0067	
Solar Photovoltaic Power Generation at Equatorial Site on Mars			
With Regenerative Fuel Cell Power Storage	178 (5)	0.0056	30% PV Cell Efficiency
	228 (5)	0.0044	20% PV Cell Efficiency
Surface – Site Independent	**kg/kW(e)**	**kW/kg**	**Comments**
Nuclear Power Generation Based on SP100 Program [23]			
On a Mobile Cart	226 (5)	0.0044	100 kW(e) capacity; Shielding Included
On an Independent Lander	87 (5)	0.011	
Emplaced in an Excavated Hole (Excavation Equipment is Included)	54 (5)	0.019	100 kW(e) capacity
	29 (5)	0.035	1 MW(e) capacity.

References

(1) Hanford and Ewert (1996)
(2) NASA (2001a)
(3) Hughes (1995) and Ewert, *et al.* (1996)
(4) NASA (1989)
(5) Cataldo (1998)

21 The value here assumes International Space Station equipment with associated masses and performance.

22 While tracking solar photovoltaic arrays have a fairly constant electrical output when the Sun is above the horizon, the electrical output from a horizontal array varies as the Sun moves across the sky, peaking at noon. A horizontal array is appropriate for systems whose power consumption is proportional to the Sun's position above the local horizon, such as a vapor compression heat pump whose peak thermal energy management load is at local noon.

23 The systems used to develop these infrastructure estimates assume generation of 100 kW(electric) of user power continuously that are sited 1 km from the base. Thus, for scenarios using one or more 100 kW(e) systems, these values are appropriate. Systems delivering considerably less power will have higher power-mass-penalty values, while very large systems, such as a 1 MW nuclear power system, will have a lower power-mass-penalty.

Providing continuous power on Luna using solar PV power generation requires considerable energy storage capacity for any non-polar surface site.[24] The first surface generation entry for Luna in Table 3.2.8 assumes solar PV power generation using tracking arrays with regenerable fuel cells for energy storage. Because most life support equipment requires power almost continuously, compared to the lunar diurnal cycle, this first case is the most common. Users with power profiles that closely approximate the diurnal cycle on Luna can avoid costly energy storage devices as noted in the second and third entries in Table 3.2.8, but such users will likely be exceptions.

Table 3.2.8 lists two solar-driven power generation technologies for Martian surface operations. Solar dynamic systems 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 above, regenerative fuel cells provide energy storage for periods of local darkness.

As on Luna, solar PV power generation on Mars requires very large arrays to provide adequate power during low-light conditions, such as dust storms (Drake, 1998), and these may be costly and difficult to maintain in a dusty environment. Further, solar power generation would be worse for sites located away from the equator. The two options provided in Table 3.2.8 for power generation using PV arrays on the Martian surface assume some advances in PV cell efficiency over current technology, as noted in their entries. They also employ regenerable fuel cells for energy storage during periods of local darkness.

Nuclear generators would provide continuous power regardless of the external environment. The nuclear power options presented in Table 3.2.8 are based on technology developed for the SP100 program and they should be typical of this approach. However, nuclear reactors of this capacity have not yet been developed for use in space. The first nuclear generation option deploys the reactor, using thermoelectric power conversion, on a robotic cart, while the second nuclear generation option deploys the same reactor on an independent lander that has no mobility once it is on the planetary surface. Both options provide complete shielding for the reactor core when placed 1 km from the crew habitat. Further, both of the first two options are ready for operation with little crew interaction. The third nuclear generation option emplaces a reactor, with a more efficient Brayton engine for power conversion, within a hole in the planetary surface, which provides shielding in place of shielding from Earth. The estimate includes equipment for emplacement, and this may even be autonomous. The fourth nuclear generation option employs a much larger reactor core than the previous three options, and so benefits from an economy of scale. It also employs a Stirling engine for power conversion. Because power systems based on nuclear reactors offer the most economical performance, compared to other currently available technologies, especially for systems designed to generate a megawatt or more, under some mission scenarios nuclear power options may be selected.

3.2.4 Thermal Energy Management Costs

Table 3.2.9 presents options for thermal energy management 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. The values in Table 3.2.9 are representative of typical external thermal control system costs for the conditions listed. Lighter, more cost-effective thermal energy management options exist, but the values here provide representative or typical values for most design studies. They assume a traditional thermal energy management system architecture employing both an internal and an external thermal control system.

- ***Note: The cost of a complete thermal energy management system is the sum of the internal thermal control system cost plus the appropriate external thermal control system cost. The external thermal control system costs include the Cooling External Interface costs.***
- ***Note: The inverse thermal-energy-management-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.***

[24] Alternatively, a satellite could beam power to a lunar base with suitable collectors even at night.

Table 3.2.9 Advanced Mission Thermal Energy Management 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	Estimated. Half of the Heat Load is acquired by Coldplates.
External Thermal Control System Cost Options			
Transit or Low-Earth Orbit	**kg/kW**	**kW/kg**	**Comments**
Current Technology, Vehicles: Flow-Through Radiators Only	30.4 [2]	0.0329	Shuttle Technology: Aluminum, Body-Mounted Radiators with Silver Teflon Surface Coating.
Lightweight, Flow-Through Radiators Only	~20	~0.05	Estimated. As above with Composite, Flow-Through Radiators.
Flow-Through Radiators with a Supplemental Expendable Cooling Subsystem	40.0 [2]	0.0250	"Current Technology, Vehicles," with an additional Flash Evaporator Subsystem.
Lightweight, Flow-Through Radiators with a Supplemental Expendable Cooling Subsystem	~30	~0.033	Estimated. As above with Composite, Flow-Through Radiators
Current Technology, Space Stations: International Space Station	323.9 [2]	0.00309	ISS Technology: Aluminum, Anti-Sun Tracking Radiators with Z-93 Surface Coating.
Surface – Luna	**kg/kW**	**kW/kg**	**Comments**
For an Equatorial Site using Horizontal Radiators with Silver Teflon Coating			
Current Technology: Flow-Through Radiators Only	221 [1]	0.0045	Aluminum, Surface-Mounted Radiators
Lightweight, Flow-Through Radiators Only	~190	~0.0053	Estimated. 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	~0.014	Estimated. 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 Only	~145 [3]	~0.0069	Aluminum, Surface-Mounted Radiators
Lightweight, Flow-Through Radiators Only	~121 [3]	~0.0083	As above with Composite Radiators.

References

(1) Hanford and Ewert (1996) and Ewert, *et al.* (1999)
(2) Hanford and Ewert (1996)
(3) Estimated from Hanford and Ewert (1996) and Hanford (1998)

Notes

- The cost of a complete thermal energy management 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 3.2.9 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 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.

3.2.5 Crew Time 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 – producing it, preparing food products, preparing meals, and disposing of waste – the crewtime may be very large. The cost of crewtime is derived from the life support system ESM and the crewtime available. Typical equivalencies vary from about 0.1 to 10 crewmember-hours per kg of ESM. Section 3.3.2 provides additional details.

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.

3.3.1 Crew Metabolic Rate

The metabolic load affects air revitalization, food use, and heat production directly and, to a lesser extent, also affects water use, waste production, and other functions. Lane, *et al.* (1996) lists metabolic energy requirements as shown in Table 3.3.2. The average metabolic rate assumed for a 70 kg crewmember is 11.82 MJ/CM-d (136.8 W/CM), per Lange and Lin (1998) [25]. 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 (1995) defines the crewmember mass range from a 95th percentile American male, with a total body mass of 98.5 kg, to a 5th percentile Japanese female, with a

[25] The section labeled "Nutritional Requirements," from Lange and Lin (1998), provides some insight into the origins of this standard.

total mass of 41.0 kg. (See Table 3.3.1) 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 70 kg male could be as high as 18 MJ/CM-d (208.3 W/CM) of thermal loading on the crew cabin or extravehicular mobility unit. (Metabolic data from Muller and Tobin, 1980.) Thus, EVA, as noted in Section 5.2, 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 Table 3.3.2 account for a moderate level of exercise.

Table 3.3.1 Crewmember Mass Limits

		Limits			
	Units	lower	nominal	upper	Reference
Crewmember Mass	kg	41.0	70.0	98.5	From NASA (1995).

Table 3.3.2 Human Metabolic Rates

Gender	Age [y]	Metabolic Rate [26] [kJ/CM-d]	Reference
Male	18 – 30	1.7 (64.02•*m* + 2,841)	Converted from Lane, *et al.* (1996).
	30 – 60	1.7 (48.53•*m* + 3,678)	
Female	18 – 30	1.6 (61.50•*m* + 2,075)	
	30 – 60	1.6 (36.40•*m* + 3,469)	

3.3.2 Crew Time 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 infrequently replacing expendables. Support for plant growth systems and associated food systems, however, could easily consume a substantial fraction of the crew's time if designed with inadequate automation.

The information here is meant to outline the time available to a crewmember during a standard workweek. Gall (1999) proposes a generic schedule for crewtime on ISS. This is assumed with slight modifications here as shown below in Table 3.3.3.

[26] 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.

Table 3.3.3 Time Allocation for a Nominal Crew Schedule in Micro-gravity [27]

Activity	Weekday [CM-h /CM-d]	Weekend Day [CM-h/CM-d]	Vacation Day [CM-h/CM-d]	
Scheduled Crew Activities	7.75	0.00	0.00	Variably-Scheduled Time
Meals	3.50	3.50	3.50	
Weekly Cleaning	0.00	2.00	0.00	
Ground Coordination and Planning	0.50	0.50	0.00	Invariantly-Scheduled Time
Exercise	2.00	2.00	0.00	
Sleep	8.50	8.50	8.50	
Daily Payload Operations	0.25	0.25	0.25	
Free Time	1.50	7.25	11.75	
Total	**24.00**	**24.00**	**24.00**	

Several of the categories in Table 3.3.3 deserve some additional explanation. The category "scheduled crew activities" includes, among other things, system and vehicle maintenance, according to Gall (1999). Thus, life support system maintenance deducts crewtime from other mission objectives. The category "meals" includes pre-meal preparation and post-meal clean up in addition to actual meal consumption. It is assumed here that the time for meals would not diminish on a vacation day. "Weekly cleaning" 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, or two hours per crewmember per weekend-day. "Exercise" 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 80 minutes total of "daily payload operations" per non-weekday to support experiments that demand tending daily (Gall, 1999). Here the daily payload operations were extended to 90 minutes, or 15 minutes per crewmember per day for a six-member crew, and it is assumed that daily payload operations would be necessary even on a vacation day.

Here, the last five categories in Table 3.3.3, ground coordination and planning, exercise, sleep, daily payload operations, and free time, 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 clean-up, 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 Gall (1999), ISS will operate on a standard week of seven 24-hour days. The standard workweek, for planning purposes, is five days followed by a two-day weekend. Vacation is allotted as eight days per crewmember per year regardless of nationality.

Assuming the standard ISS workweek and vacation schedule, a crewmember will have, on average, 66.3 CM-h/wk of VST and 101.7 CM-h/wk of IST in a microgravity environment. Assuming the exercise time is 0.5 CM-h/d shorter due to working against gravity, a crewmember will have 68.8 CM-h/wk of VST and 99.2 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. 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.

27 From Gall (1999) 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.

Table 3.3.4 Crew Time per Crewmember per Week

Mission Phase	Assumptions [CM-h/wk] lower	nominal	upper [28]
Transit/Microgravity	50 [(1)]	66.3 [(2)]	72.9 [(1)]
Surface/Hypogravity	50 [(1)]	68.8 [(1)]	75.7 [(1)]

References
(1) Estimated (see above)
(2) Gall (1999)

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 3.3.5 provides CTMP values for several mission scenarios computed using Equation 3.3-3. Inputs for these values come from or are based on the Advanced Life Support Research and Technology Development Metric for Fiscal Year 2001 (Drysdale and Hanford, 2002). The mission elements referenced in Table 3.3.5 are detailed in Stafford, *et al.* (2001). Please note that the Advanced Life Support Research and Technology Development Metric for Fiscal Year 2001 used a previous set of infrastructure values than those presented above in Section 3.2. The lower and nominal values in Table 3.3.5 are derived from life support systems using ALS technologies, while the upper values reflect ISS technologies.

Table 3.3.5 Crewtime-Mass Penalty Values Based Upon the Fiscal Year 2001 Advanced Life Support Research and Technology Development Metric

Mission	Assumptions [kg/CM-h] lower	nominal	upper
Low Earth Orbit			
International Space Station, Assembly Complete for United States On-orbit Segment	0.49	0.49	0.65
Mars			
Mars Transit Vehicle	1.14	1.14	1.54
Mars Descent / Ascent Lander	6.01	6.01	8.39
Surface Habitat Lander	1.25	1.25	1.50

Reference
Drysdale and Hanford (2002)

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 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,

[28] 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.

this value is a function of the crewtime required to service and maintain 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:

$$\frac{ESM_{Total}}{t_{MP}} = \frac{ESM_{w/o\ ch}}{t_{MP-LSS}} \qquad \text{Equation 3.3-1}$$

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

$$ESM_{Total} = ESM_{w/o\ ch}\left(\frac{t_{MP}}{t_{MP-LSS}}\right) \qquad \text{Equation 3.3-2}$$

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.

$$CTMP = \frac{ESM_{w/o\ ch}}{t_{MP}} \qquad \text{Equation 3.3-3}$$

3.3.3 Nominal Human Interfaces

Nominal balances of major life support commodities are summarized in Table 3.3.6 for a standard 70 kg crewmember with a respiratory quotient [29] of 0.869 during intravehicular activities. The water loads

[29] Respiratory quotient is defined as moles of carbon dioxide produced divided by moles of oxygen consumed.

include 0.345 kg/CM-d of metabolically generated water. Actual values depend on many factors, including physical workload, diet, and individual metabolism.

Table 3.3.6 Summary of Nominal Human Metabolic Interface Values

Balance [30]	Interface Basis	Units	Nominal Value
	Overall Body Mass	kg	70.0
	Respiratory Quotient		0.869
	Air		
– *m*	Carbon Dioxide Load	kg/CM-d	0.998
+ *m*	Oxygen Consumed	kg/CM-d	0.835
	Food		
+ *m*	Food Consumed; Mass [31]	kg/CM-d	0.617 [32]
+ *E*	Food Consumed; Energy Content	MJ/CM-d	11.82
+ *m*	Potable Water Consumed [33]	kg/CM-d	3.909 (1)
	Thermal		
– *E*	Total Metabolic Heat Load [34]	MJ/CM-d	11.82
	Sensible Metabolic Heat Load	MJ/CM-d	6.31
	Latent Metabolic Heat Load [35]	MJ/CM-d	5.51
	Waste		
– *m*	Fecal Solid Waste (dry basis)	kg/CM-d	0.032
– *m*	Perspiration Solid Waste (dry basis)	kg/CM-d	0.018
– *m*	Urine Solid Waste (dry basis)	kg/CM-d	0.059
	Water [36]		
– *m*	Fecal Water	kg/CM-d	0.091
– *m*	Respiration and Perspiration Water [37]	kg/CM-d	2.277
– *m*	Urine Water	kg/CM-d	1.886 (1)

References

Converted from NASA (1991) unless noted otherwise.

(1) From NASA (1991) and Perchonok (2001)

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.

30 Masses consumed by the crewmember are denoted with a plus, "+ *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*."

31 This assumes a completely dehydrated or dry basis.

32 Dry mass with no water content. Bourland (1998) gives a value of 0.674 kg/CM-d. See Table 4.3.1.

33 This value includes drink water and moisture contained within consumed food. Food is not generally dehydrated.

34 The total metabolic heat load is the summation of the sensible and latent metabolic heat loads.

35 Assuming a latent heat for water of 2,420 kJ/kg.

36 The difference between the water load sum of fecal water, respiration and perspiration water, and urine water, and the potable water consumed, as given above, is metabolic water. Here, metabolic water is 0.345 kg/CM-d. Also, the water values below are consistent with the dry basis waste values above.

37 The respiration and perspiration water corresponds to the latent metabolic heat load above.

4 Life Support Subsystem Assumptions and Values

4.1 Air Subsystem

4.1.1 Design Values for Atmospheric Systems

Air regeneration is one of the more time-critical life support functions. Typical control (steady state) values, are given in Table 4.1.1. Total pressure is an issue. Some generally prefer to use normal sea-level pressure, because that is the condition under which most known data was collected, and because people can live satisfactorily for a long duration under these conditions. Others, however, prefer lower pressures, to reduce the mass of required gas, the mass of the vehicle, and the requirement to pre-breathe with current extravehicular mobility units or "spacesuits." Reduced pressure normally entails increasing the percentage of oxygen, relative to other gases in the cabin atmosphere, which increases the risk of fire. Here a nominal cabin pressure of 70.3 kPa is assumed based on Lin (1997).

The tolerable partial pressure of carbon dioxide, $p(CO_2)$, for humans, is higher than what is accepted as desirable for most plants. The generally accepted optimum for plants is 0.120 kPa (1,200 ppm), but the practical upper limit on carbon dioxide for plant chambers is currently unknown. Separate atmospheric concentrations could be used for crew compartments and plant chambers by regulating inter-chamber gas transfer rates. Earth normal $p(CO_2)$ is 0.035 kPa to 0.040 kPa (350 to 400 ppm).

Table 4.1.1 Typical Steady-State Values for Vehicle Atmospheres

		Assumptions [38]		
Parameter	**Units**	**lower**	**nominal**	**upper**
Carbon Dioxide Generated	kg/CM-d	0.466 (1)	0.998 (2)	2.241 (1)
Oxygen Consumed	kg/CM-d	0.385 (1)	0.835 (2)	1.852 (1)
$p(CO_2)$ for Crew [40]	kPa	0.031 (2)	0.4 (3)	0.71 (2)
$p(CO_2)$ for Plants [40]	kPa	0.04 (4)	0.12 (5)	TBD
$p(O_2)$ for Crew	kPa	17.76 (3)	19.5 - 23.1 (2)	23.1 (2)
Total Cabin Pressure	kPa	59.2 (3) [41]	70.3 (3)	101.3 (2)
Temperature	°C	18.5 (2)	22.0 (2)	26.8 (2)
Relative Humidity	%	25 (6)	60 (6)	75 (6)
Leakage Rate (spaceflight)	%/d	0	0.05 (7)	0.14 (7)
Leakage Rate (test bed)	%/d	1 (8)	5 (8)	10 (8)

References

(1) calculated [39]
(2) Lange and Lin (1998)
(3) Lin (1997)
(4) Earth normal
(5) accepted optimum for plant growth
(6) Lange and Lin (1998), and NASA (1999)
(7) computed from NASA (1998) and Boeing (1994)
(8) Eckart (1996)

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

39 These lower and upper limits are calculated based on metabolic rates.

40 While any contaminant removal technology must, by requirement, maintain that contaminant's concentration below a set value, the nominal concentration likely corresponds to that provided when the technology is operating most efficiently rather than to some specific value (Lange, 1999). Barring other constraints, technology efficiency dictates the nominal carbon dioxide concentration derived from any carbon dioxide removal equipment. However, the values here provide carbon dioxide concentrations for studies that do not explicitly determine such values independently.

41 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 millimeters of mercury), but the crews reported numerous discomforting effects.

In addition to the carbon dioxide load noted above in Table 4.1.1, human beings also emit volatile compounds, products of metabolic processes, on a per crewmember per day basis, as noted in Table 4.1.2, while Table 4.1.3 details emissions from cabin equipment on a per mass of equipment per day basis (Perry, 1998). This model (Perry, 1998) lists trace contaminant emissions accounting for greater than 97 percent of the observed loading during past Shuttle and Spacelab missions, while Perry (1995) gives a complete listing of observed emissions for Shuttle and Spacelab. In addition to the emission rates, Table 4.1.2 and Table 4.1.3 list the compound's International Union of Pure and Applied Chemistry (IUPAC) name [42] in brackets, when it differs from the common name, and the molecular weight (MW). Current spacecraft maximum allowable concentration (SMAC) requirements for these compounds may be found in Lange and Lin (1998). These compounds are historically removed by the trace contaminant control technologies.

To estimate a loading rate for contaminant removal design, Perry (1998) recommends using the mean rate plus one standard deviation. For more conservative designs, the maximum design loading case should be no more than the mean rate plus 1.6 standard deviations.

Table 4.1.2 Model for Trace Contaminant Generation from Human Metabolism [43]

Component	MW	Mean Rate [mg/d-kg]	Standard Deviation [mg/d-kg]
ammonia	17.00	350.0	1.36
methane	16.04	234.0	94.7
hydrogen	2.02	31.3	19.0
carbon monoxide	28.01	13.8	3.74
acetone [2-propanone]	58.08	9.63	9.12
methyl ethyl ketone [2-butanone]	72.11	8.74	2.86
ethane	30.07	4.29	2.41
propane	44.09	3.29	2.10
ethyl alcohol [ethanol]	46.07	2.18	2.08
benzene	78.11	1.18	0.972
isopropyl alcohol [2-propanol]	60.09	1.02	0.671
isoprene [2-methyl-1,3-butadiene]	68.12	0.913	0.643
pentane	72.15	0.765	0.457
toluene [methylbenzene]	92.15	0.462	0.179
n-propyl alcohol [1-propanol]	60.09	0.408	0.168
methyl alcohol [methanol]	32.04	0.396	0.478
n-butyl alcohol [1-butanol]	74.12	0.395	0.122
ethyl acetate [ethanoic acid ethyl ester]	88.11	0.391	0.384
ethylbenzene	106.16	0.373	0.156
hexahydrophenol [cyclohexanol]	100.16	0.370	0.130
acetaldehyde [ethanal]	44.05	0.338	0.258
p-dioxane [1,4-dioxane]	88.11	0.317	0.142
carbolic acid [phenol]	94.11	0.258	0.060
formaldehyde [methanal]	30.03	0.167	0.264
methyl chloroform [1,1,1-trichloroethane]	133.41	0.161	0.249
propionaldehyde [propanal]	58.08	0.154	0.266
butyl acetate [ethanoic acid butyl ester]	116.16	0.132	0.0512
hexamethylene [cyclohexane]	84.16	0.121	0.0512
isobutyl acetate [ethanoic acid isobutyl ester]	116.16	0.0761	0.0301
methyl isobutyl ketone [4-methyl-2-pentanone]	100.16	0.0747	0.0251
methylene chloride [dichloromethane]	84.93	0.0647	0.0245
chlorophene [chlorobenzene]	112.56	0.0497	0.0208
isobutyl alcohol [2-methyl-1-propanol]	74.12	0.0477	0.0827
tetrachloroethylene [tetrachloroethane]	165.83	0.0472	0.0195
o-xylene [1,2-dimethylbenzene]	106.16	0.0323	0.0242
m-xylene [1,3-dimethylbenzene]	106.16	0.0323	0.0242
p-xylene [1,4-dimethylbenzene]	106.16	0.0323	0.0242
propylbenzene	120.20	0.0276	0.0107
propyl acetate [ethanoic acid propyl ester]	102.13	0.00146	0.00252
n-amyl alcohol [1-pentanol]	88.15	0.000866	0.00150

42 The Commission on Nomenclature by The Council of the International Union of Pure and Applied Chemistry (IUPAC) at Paris, 1957, defined IUPAC nomenclature.

43 From Perry (1998).

Table 4.1.3 Model for Trace Contaminant Generation from Cabin Equipment [44]

Component	MW	Mean Rate [mg/d-kg]	Standard Deviation [mg/d-kg]
Freon 113 [1,1,2-trichloro-1,2,2-trifluoroethane]	187.40	0.00864	0.0103
ethyl alcohol [ethanol]	46.07	0.00353	0.00432
methyl ethyl ketone [2-butanone]	72.11	0.00281	0.00320
isopropyl alcohol [2-propanol]	60.09	0.00251	0.00148
n-butyl alcohol [1-butanol]	74.12	0.00227	0.00244
acetone [2-propanone]	58.08	0.00223	0.00139
toluene [methylbenzene]	92.15	0.00153	0.000455
carbon monoxide	28.01	0.00137	0.000658
methylene chloride [dichloromethane]	84.93	0.00112	0.00103
methyl isobutyl ketone [4-methyl-2-pentanone]	100.16	0.000864	0.000546
methyl alcohol [methanol]	32.04	0.000855	0.000418
chlorophene [chlorobenzene]	112.56	0.000784	0.000760
Freon 11 [trichlorofluoromethane]	137.40	0.000771	0.000637
m-xylene [1,3-dimethylbenzene]	106.16	0.000703	0.00132
p-xylene [1,4-dimethylbenzene]	106.16	0.000668	0.000412
methane	16.04	0.000543	0.000096
cellosolve acetate [ethanoic acid 2-ethoxyethyl ester]	132.16	0.000461	0.000285
pimelic ketone [cyclohexanone]	98.14	0.000434	0.000228
isobutyl alcohol [2-methyl-1-propanol]	74.12	0.000414	0.000433
methyl chloroform [1,1,1-trichloromethane]	133.41	0.000414	0.000258
butyl acetate [ethanoic acid butyl ester]	116.16	0.000398	0.000348
tetrachloroethylene [tetrachloroethane]	165.83	0.000380	0.000348
n-butylaldehyde [butanal]	72.10	0.000311	0.000548
o-xylene [1,2-dimethylbenzene]	106.16	0.000307	0.000249
ethyl cellosolve [2-ethoxyethanol]	90.12	0.000281	0.000383
hexahydrophenol [cyclohexanol]	100.16	0.000267	0.000489
octamethylcyclotetraoxosilane	296.62	0.000184	0.000086
propionaldehyde [propanal]	58.08	0.000162	0.000157
carbolic acid [phenol]	94.11	0.000159	0.000324
ethyl acetate [ethanoic acid ethyl ester]	88.11	0.000158	0.000138
hexamethylene [cyclohexane]	84.16	0.000148	0.000231
adipic ketone [cyclopentanone]	84.11	0.000148	0.000322
propyl acetate [ethanoic acid propyl ester]	102.13	0.000118	0.000220
mesityl oxide [4-methyl-3-penten-2-one]	98.14	0.000116	0.000075
hexamethylcyclotrioxosilane	222.40	0.000115	4.65×10^{-5}
n-propyl alcohol [1-propanol]	60.09	0.000111	0.000130
propylbenzene	120.20	9.61×10^{-5}	0.000119
ethylbenzene	106.16	8.38×10^{-5}	6.60×10^{-5}
Halon 1301 [bromotrifluoromethane]	148.90	8.06×10^{-5}	0.000180
trimethylsilanol	90.21	7.89×10^{-5}	8.98×10^{-5}
n-amyl alcohol [1-pentanol]	88.15	7.20×10^{-5}	9.00×10^{-5}
acetaldehyde [ethanal]	44.05	6.86×10^{-5}	3.99×10^{-5}
methyl methacrylate [2-methyl propenoic acid methyl ester]	100.12	6.78×10^{-5}	6.19×10^{-5}
methyl acetate [ethanoic acid methyl ester]	74.08	6.18×10^{-5}	7.91×10^{-5}
isobutyl acetate [ethanoic acid isobutyl ester]	116.16	5.85×10^{-5}	9.32×10^{-5}
p-dioxane [1,4-dioxane]	88.11	5.76×10^{-5}	5.60×10^{-5}
pentane	72.15	4.46×10^{-5}	5.08×10^{-5}
tert-butyl alcohol [2-methyl-2-propanol]	74.12	4.36×10^{-5}	3.02×10^{-5}
ethylene dichloride [1,2-dichloroethane]	98.97	4.24×10^{-5}	3.50×10^{-5}
ammonia	17.00	4.11×10^{-5}	4.35×10^{-5}
decamethylcyclopentaoxosilane	370.64	2.30×10^{-5}	2.66×10^{-5}
benzene	78.11	1.51×10^{-5}	1.00×10^{-5}
Freon 12 [dichlorodifluoromethane]	120.91	6.25×10^{-6}	7.21×10^{-6}
hydrogen	2.02	2.41×10^{-6}	3.50×10^{-6}
propane	44.09	4.27×10^{-7}	4.94×10^{-7}
ethane	30.07	4.07×10^{-7}	7.60×10^{-7}
formaldehyde [methanal]	30.03	1.74×10^{-8}	2.67×10^{-8}

44 From Perry (1998).

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 cost of storage depends on the gas, with the "permanent" gases, such as nitrogen and oxygen, requiring higher pressure and remain 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 energy management 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 4.1.4 for known gas storage tankage masses.

Table 4.1.4 Gas Storage

	Performance [kg of tankage/kg of gas]	
Type of Storage	**Nitrogen**	**Oxygen**
Pressure Vessel	0.556 – 1.70 (1)	0.364 (2)
Cryogenic Storage	0.524 (2)	0.429 (2)

References
(1) Lafuse (2001)
(2) From Ham. Stand. (1970)

4.2 Biomass Subsystem

4.2.1 Plant Growth Chambers

4.2.1.1 Lighting Assumptions

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 uncertainties are the cost of power, and the availability of water locally. The initial assumption, as shown in Table 4.2.1, is that natural lighting cannot be used because Mars is farther from the Sun than the Earth. Significant quantities of dust are always present in the Martian atmosphere and global dust storms occur during Martian spring that often last for as long as a month during which the light levels are reduced significantly.

In addition, fresh food is crucial to crew welfare, and nutritionists generally recommend 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.

Table 4.2.1 Lighting Data

Parameter [Units]	low	nominal	high
Light Conversion Efficiency [$W_{radiation}/W_{electrical}$] [45]	0.18 (1)	0.3 (2)	0.5 (1)
Light Delivery Efficiency [$PPF_{delivered}/PPF_{emitted}$] [46]	0.3 (1)	0.37 (2)	0.7 (1)
Overall Lighting Efficiency	0.05 (1)	0.11 (2)	0.35 (1)

References
(1) Sager (1999)
(2) Ewert (1998)

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

45 Light Conversion Efficiency describes the proportion of lighting system power that eventually becomes PPF.
46 Light Delivery Efficiency describes the proportion of PPF at the lamp surface that is delivered to the canopy.

flux (PPF) is the light absorbed by the plants and used for photosynthesis, and is similar in extent to visible light, but has a different graph of absorption versus wavelength, peaking in the red and blue rather than in the yellow. Incandescent lamps are good because they are red-rich, but the conversion efficiency is low. High-pressure discharge lamps produce more light, but the spectrum is not as good photosynthetically. New lamp types, such as microwave lamps, have good efficiency and spectrum (Sager, 1999). 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, and only achieved a rating of about 30%. Much higher ratings can be achieved, but it is difficult to maintain these high ratings over long time periods.

4.2.1.2 Lighting Equipment Data

Additional assumptions can be made about specific lighting systems. Data for 400 W high-pressure sodium lights (HPS) are shown below.

Table 4.2.2 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/(m²•s)	lamps/m²	1.98 (3) [47]	3.8 (4)	5.56 (3)
Time to Change Out Lamps	CM-h		0.03 (5)	
Photoperiod per Day [48]	h/d	10 (1)	10-24 [49]	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 (4)	
Mass of Coldplate, Water Barrier, Condensing Heat Exchangers per Growing Area	kg/m²	4.43 (7) [50]	7.02 (7) [51]	25.83 (7) [52]
Height of Lighting Assembly	m		0.15 (8)	0.3 (1)
Lamp Resupply Mass Factor	kg/kg		0.8 (9)	
Lamp Resupply Volume Factor	m³/m³		0.5 (1)	

References

(1) Drysdale (1999a)
(2) Hanford (1997)
(3) Sager (1999)
(4) Barta and Ewert (2002)
(5) A rough value from Hunter, J.
(6) Ewert (2001)
(7) Ewert (1998)
(8) BIO-Plex drawings
(9) See Table 3.2.7. This value corresponds to storing lamps within trays.

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.

47 This is a calculated value assuming high efficiency lamps.

48 This is generally crop dependent, although the values here provide the range for all ALS crops.

49 See Table 4.2.6 for nominal photoperiods of candidate ALS crops.

50 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.

51 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.

52 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.

4.2.1.3 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 ALS 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 4.2.3 (Drysdale, 1999b) presents preliminary values for an optimized biomass production chamber based on projecting current NASA growth chambers to flight configurations.

Table 4.2.3 Plant Growth Chamber Equivalent System Mass per Growing Area

Component	Mass [kg/m^2]	Volume [m^3/m^2]	Power [kW/m^2]	Thermal Energy Management [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	0.3	–	–	
Root Zone 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**	

4.2.1.4 Biomass Production Chamber Specifications for BIO-Plex

Barta, *et al.* (1999) presents preliminary physical values for the first BIO-Plex biomass production chamber. [53] See Table 4.2.4. Because many conditions will vary as a function of test goals and each cultivar's needs, nominal values are not generally appropriate. Further, some values, as noted, are controlled for the chamber overall while others may be set for each shelf of crops. Nominally, the total atmospheric pressure is maintained at 101±3 kPa. For the plants alone, the plant chamber atmosphere must be at least 5.0 % oxygen. However, to support human respiration without personal protective equipment, the chamber atmosphere must be 18.5 % oxygen.

Table 4.2.4 Physical Parameters for the First Biomass Production Chamber in BIO-Plex

Parameter	Units	low	high	
Overall Chamber Values:				**Reference**
Oxygen Concentration	%	18.5 (5.0) [54]	23.5	From Barta, *et al.* (1999).
Partial Pressure of Carbon Dioxide	kPa	0.03	1.0	
Values Controlled per Shelf:				
Air Temperature, Dark Cycle	°C	15	25	
Air Temperature, Light Cycle	°C	16	35	
Relative Humidity	%	65	85	
Air Velocity	m/s	0.2	0.7	
Photosynthetic Photon Flux	$\mu mol/m^2 \bullet s$	0	1,500	
Photoperiod	h	0	24	
Nutrient Solution pH [55]	–	3.0	8.0	
Nutrient Solution Conductivity	S/m	0	0.30	
Nutrient Solution Flow Rate /Growth Area	$L/s \bullet m^2$	0	0.1	
Nutrient Solution Depth	m	0.10	0.15	
Shoot Zone Height	m	0.35	0.70	
Root Zone Depth	m	0.10	0.15	

The total growth area within the first BIO-Plex biomass production chamber is 79.6 m^2 (Castillo, 2000). This growing area is arranged in ten shelves stacked in three columns. The center stack contains four shelves while each side stack provides three shelves that conform to the chamber wall profile. Specific shelf dimensions are listed in Table 4.2.5. Aisles between growing area shelves are 0.508 m wide.

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53 *Editor's Note:* At this time, development and activation of the BIO-Plex is suspended until a future date. Further, the final configuration and specifications, when complete, may differ from those listed here. Values here are likely typical of a test facility for bioregenerative research.

54 Nominally, to allow human entry into the biomass production chamber, oxygen concentration will be maintained at or above 18.5%. The lower listed limit will support plant respiration and thus applies if unprotected human beings will not enter the biomass production chamber.

55 Potential of hydrogen (pH)

Table 4.2.5 Growing Area Dimensions for the First BIO-Plex Biomass Production Chamber

Shelf Location [56]	Shelf Width [m]	Shoot Zone Height [m]	Growth Area [m²]
Left Shelving Stack:			
Shelf 1 (top)	0.360	0.440	2.87
Shelf 2 (middle)	0.720	0.700	5.73
Shelf 3 (bottom)	0.360	0.400	2.87
Center Shelving Stack:			
Shelf 1 (top)	1.500	0.500	14.17
Shelf 2	1.500	0.500	14.17
Shelf 3	1.500	0.500	14.17
Shelf 4 (bottom)	1.500	0.500	14.17
Right Shelving Stack:			
Shelf 1 (top)	0.360	0.440	2.87
Shelf 2 (middle)	0.720	0.700	5.73
Shelf 3 (bottom)	0.360	0.400	2.87
Total			**79.6**

4.2.2 Plant Values

4.2.2.1 Static Values Describing Plant Growth

Plant growth rates depend on the type of plant (species and cultivar) and the growth conditions. Table 4.2.6 through Table 4.2.8 provide design values for candidate ALS Project crops (Behrend and Henninger, 1998). Table 4.2.6 lists nominal environmental conditions for each crop. Table 4.2.7 presents overall life-cycle growth rates in terms of grams of biomass per square meter per day. The dry mass (dw), fresh mass (fw) [57], and water content for both edible and inedible biomass are given. The harvest index is the ratio of edible biomass to total biomass. Table 4.2.8 provides nominal and upper biomass generation rates. The lower rate is zero. The given upper limit is the highest rate recorded in the literature. These may not be the absolute maximum, however. For example, wheat may well produce higher growth rates with higher light intensities (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 spaceflight. The nominal rates are derived from testing within the ALS Biomass Production Chamber at Kennedy Space Center (Wheeler, 2001b). 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. Table 4.2.8 also presents the biomass chemical composition in terms of carbon and the metabolic reactants and products averaged over the crop life cycle.

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56 Locations are defined with respect to viewing the biomass production chamber from either end. Shelf numbers are defined such that "1" is the top shelf and shelves below in the same stack are numbered sequentially. From Castillo (2000). Barta, *et al.* (1999) details earlier work for the BIO-Plex biomass production chamber configuration and quotes slightly longer shelves for both the left and right shelving stacks. In both the earlier work and the current configuration the center growing areas are identical.

57 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.

Table 4.2.6 Advanced Life Support Cultivars, Intended Usage, and Environmental Growth Conditions

Crop	ALS Transit Crop [1]	ALS Surface Crop [1]	Photosynthetic Photon Flux [mol /(m²•d)]	Diurnal Photo-Period [h/d] [3]	Growth Period [d]	Temperatures [°C] [3] Air during Day	Air during Night	Nutrient Solution
Cabbage	×	×	17 [2]		85 [4]	>25		
Carrot	×	×	17 [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			17 [2]		50 [5]			
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	×	×	17 [3]	16	25 [4]	23	23	23
Red Beet			17 [3]	16	38 [3]	23	23	23
Rice		×	33 [3]	12	85 [3]	28	24	24
Snap Bean			24 [2]		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	85 [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	79 [3]	20	20	18
White Potato		×	28 [3]	12	132	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.* (2001)

[4] Wheeler (2001b)

[5] Ball, *et al.* (2001) and EDIS (2001)

Table 4.2.7 Overall Physical Properties at Maturity for Nominal Crops

			Edible Biomass Productivity			Inedible Biomass Productivity		
Crop	Mature Plant Height [m]	Harvest Index [%]	Dry Basis [g_{dw} /m²•d]	Fresh Basis [g_{fw} /m²•d]	Fresh Basis Water Content [%]	Dry Basis [g_{dw} /m²•d]	Fresh Basis [g_{fw} /m²•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)	40 (1)	15.00 (3)	51.72	71	22.50	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.* (2001)

(2) Ball, *et al.* (2001) and EDIS (2001)

(3) Wheeler (2001b)

Table 4.2.8 Nominal and Highest Biomass Production, Composition, and Metabolic Products

Crop	Total Biomass (Edible + Inedible), Dry Basis [g_{dw}/m²•d]		Carbon Content [%]	Metabolic Reactants and Products		
	nominal	high		Oxygen Production [g/m²•d]	Carbon Dioxide Uptake [g/m²•d]	Water Uptake / Transpiration [kg/m²•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		46	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	1.77
Mushroom						
Onion	11.25		40	12.00	16.50	1.74
Pea	26.83		46	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	45 (2)	36.55	50.26	3.43
Snap Bean	29.70		46	36.43	50.09	2.46
Soybean	11.34	20.0	46 (1)	13.91	19.13	2.88
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	2.88

References

Information from Drysdale (2001) except as noted.

(1) Wheeler, *et al.* (1995)

(2) Calculated

Table 4.2.9 Inedible Biomass Generation for Advanced Life Support Diets

Crop	ALS Crop	Edible Biomass [g/m²•d]	Inedible Biomass [g/m²•d]	Diet Using Only ALS Salad Crops: Diet Growing Area [m²/CM]	Diet Using Only ALS Salad Crops: Total Inedible Biomass [kg/CM-d]	Diet Using Salad and Carbohydrate Crops: Diet Growing Area [m²/CM]	Diet Using Salad and Carbohydrate Crops: Total Inedible Biomass [kg/CM-d]	Diet Using All ALS Crops: Diet Growing Area [m²/CM]	Diet Using All ALS Crops: 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**

Plant environmental demands differ compared to the crew's requirements. For example, the optimum partial pressure of carbon dioxide for plant growth is roughly 0.120 kPa (Wheeler, *et al.*, 1993). Sensitivity may vary from species to species, but plants do appear to have reduced productivity at 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, some evidence indicates that plants might grow better under atmospheres with partial pressures of oxygen below the values associated with nominal conditions on Earth. However, because human beings live with plants on Earth, plants and crew can live in a common atmosphere.

Table 4.2.9 enumerates growing areas and inedible biomass production associated with the ALS Project diets presented in Section 4.3.6. The edible biomass values are the nominal values listed above in Table 4.2.7. 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.

4.2.2.2 Static Values to Support Plant Growth

Table 4.2.10 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 4.2.10 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 [58]	g_{acid}/g_{dw}	0.0548	0.0744	0.0428	0.0618	

Table 4.2.11 and Table 4.2.12 describe the compositions of nutrient solutions used for studies within the ALS 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 must also be considered in calculating the nitrogen provided to the plants. In addition, minerals might be lost to the plants through uptake by microorganisms and by precipitation from solution.

[58] One mole of nitric acid (HNO_3) contains 63.013 grams of solute.

Table 4.2.11 Composition of Initial Nutrient Solution

Initial Ionic Component		Important Element		Elemental Atomic Weight	Concentration [meq/L][59]	Ion Molecular Weight	Valence	Content g/L (element)	Content 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 4.2.12 Composition of Replenishment Nutrient Solution

Replenishment Ionic Component		Important Element		Elemental Atomic Weight	Concentration [meq/L][59]	Ion Molecular Weight	Valence	Content g/L (element)	Content 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**	

59 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.

4.2.3 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) [60].

The MEC models calculate biomass production as a function of photosynthetic photo flux, PPF, and the atmospheric carbon dioxide concentration, [CO_2]. 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 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.

4.2.3.1 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 4.2.3.3.

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:

$$A = A_{MAX}\left(\frac{t}{t_A}\right)^n \quad \text{for } t < t_A$$

$$A = A_{MAX} \quad \text{for } t \geq t_A \qquad \text{Equation 4.2-1}$$

where A_{MAX} is 0.93 and n is enumerated for various crops in Table 4.2.13 below. t_A is computed as a function of PPF and [CO_2] for each crop. This function is presented below with appropriate coefficients.

Table 4.2.13 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:

$$CQY = CQY_{MAX} \quad \text{for } t \leq t_Q$$

$$CQY = CQY_{MAX} - (CQY_{MAX} - CQY_{MIN})\frac{(t - t_Q)}{(t_M - t_Q)} \quad \text{for } t_Q < t \leq t_M \qquad \text{Equation 4.2-2}$$

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.

60 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 24-hour carbon use efficiency, CUE_{24}, a fraction, is constant for most crops. In such cases, a single value is listed under CUE_{MAX} in the tables below. For legumes, CUE_{24} is described by:

$$CUE_{24} = CUE_{MAX} \quad \text{for } t \leq t_Q$$
$$CUE_{24} = CUE_{MAX} - (CUE_{MAX} - CUE_{MIN}) \frac{(t - t_Q)}{(t_M - t_Q)} \quad \text{for } t_Q < t \leq t_M \qquad \text{Equation 4.2-3}$$

where CUE_{MAX} and CUE_{MIN} are model inputs unique to each crop.

The daily carbon gain, DCG, [$mol_{Carbon}/m^2 \bullet d$] is computed from:

$$DCG = 0.0036 \frac{s}{h} \frac{mol}{\mu mol} \times H \times CUE_{24} \times A \times CQY \times PPF \qquad \text{Equation 4.2-4}$$

where H is the photoperiod [h/d], a crop-specific model input. Photoperiod may vary daily, but see Cavazzoni (2001) for the assumptions involved.

The daily oxygen production, DOP, [$mol_{O_2}/m^2 \bullet d$] may be computed using:

$$DOP = OPF \times DCG \qquad \text{Equation 4.2-5}$$

where OPF is the oxygen production fraction [mol_{O_2}/mol_{Carbon}], which is a crop specific parameter.

The crop growth rate, CGR [$g/m^2 \bullet d$], is related to DCG by:

$$CGR = MW_C \frac{DCG}{BCF} \qquad \text{Equation 4.2-6}$$

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, TCB [g/m^2], is determined by integrating CGR, from t = 0 to the time of interest, such as harvest, t_M. Or:

$$TCB = \int_0^{t_M} CGR \, dt \qquad \text{Equation 4.2-7}$$

Total edible biomass, 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:

$$TEB = XFRT \int_{t_E}^{t_M} CGR \, dt \qquad \text{Equation 4.2-8}$$

Inedible biomass is the difference between TCB and TEB.

Table 4.2.14 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 4.2-1
A_{MAX}	--	maximum value for A	0.93
BCF	--	biomass carbon fraction	Table 4.2.29
CGR	g/m²•d	crop growth rate	Equation 4.2-6
C_i	varies	coefficients in functions describing t_A and CQY_{MAX}	Table 4.2.16
$[CO_2]$	$\frac{\mu mol_{CO_2}}{mol_{Air}}$	atmospheric concentration of carbon dioxide; model variable	none
CQY	$\frac{\mu mol_{C.\ Fixed}}{\mu mol_{Ab.\ PPF}}$	canopy quantum yield	Equation 4.2-2
CQY_{MAX}	$\frac{\mu mol_{C.\ Fixed}}{\mu mol_{Ab.\ PPF}}$	maximum value for CQY that applies until t_Q	Equation 4.2-9
CQY_{MIN}	$\frac{\mu mol_{C.\ Fixed}}{\mu mol_{Ab.\ PPF}}$	minimum value for CQY at t_M	Table 4.2.15
CUE_{24}	--	24-hour carbon use efficiency; a fraction	Equation 4.2-3
CUE_{MAX}	--	maximum value for CUE_{24} that applies until t_Q	Table 4.2.15
CUE_{MIN}	--	minimum value for CUE_{24} at t_M	Table 4.2.15
DCG	$mol_{Carbon}/m^2 \bullet d$	daily carbon gain	Equation 4.2-4
DOP	$mol_{O_2}/m^2 \bullet d$	daily oxygen production	Equation 4.2-5
H	h/d	photoperiod	Table 4.2.27
MW_C	g/mol	molecular weight of carbon	12.011
n	--	an exponent	Table 4.2.13
OPF	$\frac{mol_{O_2}}{mol_{Carbon}}$	oxygen production fraction	Table 4.2.29
PPF	$\frac{\mu mol_{Photon}}{m^2 \bullet s}$	photosynthetic photon flux; model variable	none
TCB	g/m²	total crop biomass	Equation 4.2-7
TEB	g/m²	total edible biomass	Equation 4.2-8
t	d_{AE}	time; model variable	none
t_A	d_{AE}	time until canopy closure	Equation 4.2-17
t_E	d_{AE}	time at onset of organ formation	Table 4.2.28
t_M	d_{AE}	time at harvest or crop maturity	Table 4.2.28
t_Q	d_{AE}	time until onset of canopy senescence	Table 4.2.28
XFRT	--	fraction of daily carbon gain allocated to edible biomass after t_E	Table 4.2.28

The environmentally dependent parameters for these models are provided in the sections below. The MEC variables for biomass production models are summarized in Table 4.2.14. General model constants, which depend only on the crop cultivar and not on environmental conditions, are listed in Table 4.2.15.

Table 4.2.15 Biomass Production Model Constants [61]

Crop		CQY_{MIN} [$\mu mol_{C\ Fixed}$ / $\mu mol_{Ab.\ PPF}$]		CUE_{MIN}
Dry Bean	*Meso Amer. Hab. 1 – Determinate*	0.02	0.65	0.50 [62]
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 (MPR), the functions for maximum canopy quantum yield, CQY_{MAX} [$\mu mol_{\text{Carbon Fixed}}/\mu mol_{\text{Absorbed PPF}}$], have the general form:

$$CQY_{MAX}(PPF, [CO_2]) = C_1 \frac{1}{PPF}\frac{1}{[CO_2]} + C_2 \frac{1}{PPF} + C_3 \frac{[CO_2]}{PPF} + C_4 \frac{[CO_2]^2}{PPF} + C_5 \frac{[CO_2]^3}{PPF}$$
$$+ C_6 \frac{1}{[CO_2]} + \text{Constant} + C_8 [CO_2] + C_9 [CO_2]^2 + C_{10} [CO_2]^3 + C_{11} \frac{PPF}{[CO_2]} + C_{12} PPF$$
$$+ C_{13} PPF [CO_2] + C_{14} PPF [CO_2]^2 + C_{15} PPF [CO_2]^3 + C_{16} \frac{PPF^2}{[CO_2]} + C_{17} PPF^2$$
$$+ C_{18} PPF^2 [CO_2] + C_{19} PPF^2 [CO_2]^2 + C_{20} PPF^2 [CO_2]^3 + C_{21} \frac{PPF^3}{[CO_2]} + C_{22} PPF^3$$
$$+ C_{23} PPF^3 [CO_2] + C_{24} PPF^3 [CO_2]^2 + C_{25} PPF^3 [CO_2]^3$$

Equation 4.2-9

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 4.2.17 through Table 4.2.25 present the coefficient values for each crop in a matrix of the form presented in Table 4.2.16.

61 The parameters in this table apply independent of temperature regime, photoperiod, or planting density.

62 This suggested value is based on Wheeler (2001a) whereby growth costs are less for dry bean than for soybean and peanut.

Table 4.2.16 Format for Tables of Coefficients for Equations Employing MPR Fits

	1/PPF	1	PPF	PPF^2	PPF^3
1/[CO_2]	1/PPF × 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 4.2.17 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 4.2.18 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 4.2.19 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 4.2.20 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 4.2.21 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 4.2.22 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 4.2.23 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 4.2.24 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 4.2.25 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

4.2.3.2 Modified Energy Cascade Models for Crop Transpiration

Following the approach in Section 4.2.3.1 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:

$$VP_{SAT} = 0.611\ e^{\left[\frac{17.4\,T_{LIGHT}}{T_{LIGHT}+239}\right]}$$
$$VP_{AIR} = VP_{SAT} \times RH$$
$$VPD = VP_{SAT} - VP_{AIR}$$ Equation 4.2-10

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} [$\mu mol_{Carbon}/m^2 \bullet s$], may be expressed in terms of previously defined values as:

$$P_{GROSS} = A \times CQY \times PPF$$ Equation 4.2-11

The net canopy photosynthesis, P_{NET} [$\mu mol_{Carbon}/m^2 \bullet s$], may be expressed as:

$$P_{NET} = \left[\frac{D_{PG} - H}{D_{PG}} + \frac{H \times CUE_{24}}{D_{PG}}\right] P_{GROSS}$$ Equation 4.2-12

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.

The canopy surface conductance, g_C [$mol_{Water}/m^2 \bullet s$], is based on the canopy stomatal conductance, g_S [$mol_{Water}/m^2 \bullet s$], and the atmospheric aerodynamic conductance, g_A [$mol_{Water}/m^2 \bullet s$].

$$g_C = \frac{g_A \times g_S}{g_A + g_S}$$ Equation 4.2-13

Table 4.2.26 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 4.2-1
$[CO_2]$	$\frac{\mu mol_{CO_2}}{mol_{Air}}$	atmospheric concentration of carbon dioxide; model variable	none
CQY	$\frac{\mu mol_{Carbon}}{\mu mol_{Photon}}$	canopy quantum yield	Equation 4.2-2
CUE_{24}	--	24-hour carbon use efficiency; a fraction	Equation 4.2-3
D_{PG}	h/d	plant growth diurnal cycle	24 [63]
DTR	$L_{Water}/m^2 \bullet d$	daily canopy transpiration rate	Equation 4.2-16
g_A	$mol_{Water}/m^2 \bullet s$	atmospheric aerodynamic conductance	Equation 4.2-14 and Equation 4.2-15
g_C	$mol_{Water}/m^2 \bullet s$	canopy surface conductance	Equation 4.2-13
g_S	$mol_{Water}/m^2 \bullet s$	canopy stomatal conductance	Equation 4.2-14 and Equation 4.2-15
H	h/d	photoperiod	Table 4.2.27
MW_W	g/mol	molecular weight of water	18.015
P_{ATM}	kPa	total atmospheric pressure; model variable	none
P_{GROSS}	$\frac{\mu mol_{Carbon}}{m^2 \bullet s}$	gross canopy photosynthesis	Equation 4.2-11
P_{NET}	$\frac{\mu mol_{Carbon}}{m^2 \bullet s}$	net canopy photosynthesis	Equation 4.2-12
PPF	$\frac{\mu mol_{Photon}}{m^2 \bullet s}$	photosynthetic photon flux; model variable	none
RH	--	atmospheric relative humidity; model variable	none
T_{LIGHT}	°C	atmospheric temperature during crop's light cycle	Table 4.2.27
VP_{AIR}	kPa	actual moisture vapor pressure	Equation 4.2-10
VP_{SAT}	kPa	saturated moisture vapor pressure	Equation 4.2-10
VPD	kPa	vapor pressure deficit	Equation 4.2-10
ρ_W	g/L	density of water	998.23

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:

$$g_S = (1.717\ T_{LIGHT} - 19.96 - 10.54\ VPD)\left(\frac{P_{NET}}{[CO_2]}\right)$$

$$g_A = 2.5 \qquad \text{Equation 4.2-14}$$

63 This value applies to data used to date from terrestrial test facilities. More generally, it's the length of a local sol.

With erectophile canopies, such as for rice and wheat, g_S and g_A have the form:

$$g_S = 0.1389 + 15.32\ RH \left(\frac{P_{NET}}{[CO_2]} \right)$$

$$g_A = 5.5 \qquad \text{Equation 4.2-15}$$

The daily canopy transpiration rate, DTR [$L_{Water}/m^2 \bullet d$], is:

$$DTR = 3600 \frac{s}{h}\ H \left(\frac{MW_W}{\rho_W} \right) g_C \left(\frac{VPD}{P_{ATM}} \right) \qquad \text{Equation 4.2-16}$$

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 4.2.26.

4.2.3.3 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 4.2.3.1 and Section 4.2.3.2.

Table 4.2.27 Nominal Temperature Regimes, Planting Densities, and Photoperiods for the Plant Growth and Transpiration Models

Crop	Photoperiod H [h/d]	Planting Density [64] [plants/m²]	Light Cycle Temperature, T_{LIGHT} [°C]	Dark Cycle Temperature, T_{DARK} [°C] [65]
Dry Bean	12	7	26	22
Lettuce	16	19.2	23	23
Peanut	12	7	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

64 Planting density affects the time to canopy closure, t_A, even though an explicit functionality is not apparent.

65 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 4.2.28 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 [66]	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 [66]	120
Tomato	0.70	41	56	80
Wheat	1.00	34	33	62
White Potato	1.00	45	75	138 [67]

Table 4.2.29 Biomass Carbon and Oxygen Production Fractions for Nominal Temperature Regime and Photoperiod

Crop	Biomass Carbon Fraction, BCF	Oxygen Production Fraction, OPF [mol_O/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

Crop	Biomass Carbon Fraction, BCF	Oxygen Production Fraction, OPF [mol_O/mol_C]
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:

$$
\begin{aligned}
t_A(\text{PPF}, [CO_2]) = {} & C_1 \frac{1}{\text{PPF}} \frac{1}{[CO_2]} + C_2 \frac{1}{\text{PPF}} + C_3 \frac{[CO_2]}{\text{PPF}} + C_4 \frac{[CO_2]^2}{\text{PPF}} + C_5 \frac{[CO_2]^3}{\text{PPF}} \\
& + C_6 \frac{1}{[CO_2]} + \text{Constant} + C_8 [CO_2] + C_9 [CO_2]^2 + C_{10} [CO_2]^3 + C_{11} \frac{\text{PPF}}{[CO_2]} + C_{12}\,\text{PPF} \\
& + C_{13}\,\text{PPF}\,[CO_2] + C_{14}\,\text{PPF}\,[CO_2]^2 + C_{15}\,\text{PPF}\,[CO_2]^3 + C_{16} \frac{\text{PPF}^2}{[CO_2]} + C_{17}\,\text{PPF}^2 \\
& + C_{18}\,\text{PPF}^2 [CO_2] + C_{19}\,\text{PPF}^2 [CO_2]^2 + C_{20}\,\text{PPF}^2 [CO_2]^3 + C_{21} \frac{\text{PPF}^3}{[CO_2]} + C_{22}\,\text{PPF}^3 \\
& + C_{23}\,\text{PPF}^3 [CO_2] + C_{24}\,\text{PPF}^3 [CO_2]^2 + C_{25}\,\text{PPF}^3 [CO_2]^3
\end{aligned}
$$

Equation 4.2-17

66 This crop is harvested before the canopy reaches senescence.

67 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 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 4.2.30 through Table 4.2.38 present the coefficient values for each crop in a matrix as illustrated by Table 4.2.16 above. These functions apply for the nominal photoperiods, planting densities, and temperature regimes given in Table 4.2.27.

Table 4.2.30 Canopy Closure Time, t_A, Coefficients for Dry Bean with Nominal Conditions

	1/PPF	1	PPF	PPF^2	PPF^3
1/[CO_2]	2.9041×10^5	0	0	0	0
	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 4.2.31 Canopy Closure Time, t_A, Coefficients for Lettuce with Nominal Conditions

	1/PPF	1	PPF	PPF^2	PPF^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 4.2.32 Canopy Closure Time, t_A, Coefficients for Peanut with Nominal Conditions

	1/PPF	1	PPF	PPF^2	PPF^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]	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 4.2.33 Canopy Closure Time, t_A, Coefficients for Rice with Nominal Conditions

	1/PPF	1	PPF	PPF^2	
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]	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 4.2.34 Canopy Closure Time, t_A, Coefficients for Soybean with Nominal Conditions

	1/PPF	1	PPF	PPF^2	PPF^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 4.2.35 Canopy Closure Time, t_A, Coefficients for Sweet Potato with Nominal Conditions

	1/PPF	1	PPF	PPF^2	PPF^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 4.2.36 Canopy Closure Time, t_A, Coefficients for Tomato with Nominal Conditions

	1/PPF	1	PPF	PPF^2	PPF^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 4.2.37 Canopy Closure Time, t_A, Coefficients for Wheat with Nominal Conditions

	1/PPF	1	PPF	PPF^2	PPF^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 4.2.38 Canopy Closure Time, t_A, Coefficients for White Potato with Nominal Conditions

	1/PPF	1	PPF	PPF^2	PPF^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 4.2.27. 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 4.2.39 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 4.2.27 above.

Table 4.2.39 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).

4.3 Food Subsystem

Food, though historically omitted from life support analysis, has significant impacts on closure and the cost of crew support. In particular, 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.

4.3.1 Physical Parameters for Historical Flight Food Systems

The crew food energy requirement will depend on the crew themselves, their lean body mass in particular, and the amount of physical work they perform. Extravehicular activity (EVA), for example, requires additional food energy compared with crews conducting only intravehicular activities (IVA) because more physical work is typically associated with an EVA. Unless specified otherwise, this document assumes an average body mass of 70 kg, and an intravehicular metabolic requirement of 11.82 MJ/CM-d, which are consistent with Lange and Lin (1998).

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 a food system 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. For example, a greater mass of protein is required if it is of inferior 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. 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 3.2.2 provides estimates for supporting secondary structure for food systems. Analysis of Table 4.3.1, which presents estimates of associated food packaging masses from historical systems, indicates that an additional ~15 % mass penalty, based on fresh food mass, is appropriate for individually packaged meals. Note that the values presented in Table 4.3.1 are historical or predicted averages for the indicated programs and, therefore, may or may not provide 11.82 MJ/CM-d of metabolic energy.

Table 4.3.1 Historical and Near-Term Food System Masses

Parameter	Mass [kg/CM-d]	Volume [m³/CM-d]	Comments	Water Content [%]	References
IVA Food, dw	0.674		A Reference Value	0	From Bourland (1998), Vodovotz (1999), and Perchonok, *et al.* (2002).
Space Transportation Food System					
STS Food [68]	0.8	0.002558	Dehydrated	20	
	1.591		As-Shipped, No Packaging	58	
	0.227 [69]		Packaging Alone		
	1.818	0.004045	Packaged, As-Consumed		
International Space Station Food Systems					
Phase II [70]	1.83	TBD	Packaged, As-Shipped, with Food Locker	TBD	
Phase III [71]	1.955		As-Shipped, No Packaging	66	
	0.345 [72]		Packaging Alone		
	2.3	0.006570	Packaged, As-Consumed		

Packaging masses are available for Shuttle and ISS Assembly Complete, which are two "ready to eat" food systems. Bourland (1999) reports 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 (Bourland, 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.

Perchonok, *et al.* (2002) reports that a loaded ISS food locker for 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 locker masses vary according to individual crew entrée preferences and nutritional requirements, and the lockers themselves are placed in racks, incurring a secondary structure penalty not included in the masses above.

4.3.2 Physical Parameters of Refrigeration Equipment

Table 4.3.2 presents characteristics for the ISS refrigerator / freezer technology. These units are designed, but ISS Program deferred launching them along with 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.

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68 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 microgravity diet.) These food systems do not use any refrigeration.

69 The packaging for this food system is 14.3 %, by mass, of the mass of fresh food it contains.

70 International Space Station (ISS) Assembly Phase food system. This system is shelf stable.

71 International Space Station (ISS) Assembly Complete food system. This food is provided as 50% frozen products. For a 540 CM-d (six crew for 90 d) food supply, 1.84 m³ of refrigerated storage is required.

72 The packaging for this food system is 17.6 %, by mass, of the mass of fresh food it contains.

Each ISS refrigerator / freezer fits within one ISS rack and has four cold volume compartments, each with a dedicated thermoelectric thermal energy management system. An ISS refrigerator / freezer may 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 ISS unit has an operational lifetime of 10 y, with servicing provided on the ground once a year.

Table 4.3.2 International Space Station Refrigerator / Freezer Properties

	Units	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 Energy Management	kW	0.297 (4)	0.228 (4)
Crew Time	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) [73]

References

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

More generally, Table 4.3.3 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 spaceflight requirements, especially with respect to microgravity and acoustics (Ewert, 2002a).

As described in Ewert (2002b) and presented in Equation 4.3-1, the specific power consumption for a cooled volume within a cabinet, $\hat{W}_{RF}$ [kW/kg_{ffm}], may be expressed as an empirical function of two system-level values, the composite thermal resistance, R_S [m²•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 assumed air temperature within the cooled volume is – 22 °C, while the ambient external cabin temperature is 23 °C.

$$\hat{W}_{RF} = 1.028\left(\frac{1}{R_S}\right)\left(\frac{1}{COP_S}\right)$$

Equation 4.3-1

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

Table 4.3.3 Frozen Food Storage on a Property per Frozen-Food-Mass Basis

Characteristic	Units	Assumptions low	nominal	high
$1/COP_S$	$kW_{electrical}/kW_{thermal}$	0.5 [1]	1.0 [1]	9.2 [1]
$1/R_S$	$kW/m^2 \bullet K \times 10^{-3}$	0.28 [1]	0.32 [1]	0.32 [1]
Mass [74]	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 Energy Management	kW	0.053 [1]	0.106 [1]	0.297 [1]
	$kW/kg_{ffm} \times 10^{-3}$	0.18	0.36	1.01
Crew Time	CM-h/y	0.0	0.0	0.0
	$CM\text{-}h/(y \bullet kg_{ffm})$	0.0	0.0	0.0
Logistics	kg/y	0.0	0.0	321 [2]
	$kg/(y \bullet kg_{ffm})$	0.0	0.0	1.09

References

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

4.3.3 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 is 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.

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 9 CM-h/d, or 2.25 CM-h/CM-d because the LMLSTP Phase III test supported a crew of four.

4.3.4 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

74 Including the freezer mass and rack but excluding the secondary structure.

to packaging and due to plate wastage. Waste model values are noted below in Section 4.5 for both historical pre-packaged food systems and projected food systems based on crops from bioregenerative life support systems.

4.3.5 Overall Food Subsystem Parameters

Typical values from the literature for food-related masses are shown in Table 4.3.4. However, the food mass values here do not reflect as great a range as is associated with the metabolic gas exchange values in Table 4.1.1. The listed food masses in Table 4.3.4 are "as shipped" and before addition of any hydration fluid and reflect historical pre-packaged food systems, although the upper value for crewtime is associated with a food system using crop products derived from a biomass production chamber.

Table 4.3.4 Food Quantity and Packaging

		Assumptions		
Parameter	**Units**	**lower**	**nominal**	**upper**
IVA Food, dry mass [75]	kg/CM-d	0.54 [(1)]	0.617 [(1)]	0.674 [(2)]
IVA Human Metabolic Water Production	kg/CM-d		0.345 [(1)]	
IVA Energy	MJ/CM-d		11.82 [(1)]	
IVA Potable Water Consumption	kg/CM-d		3.909 [(3)]	
EVA Food, dry mass, added [76]	kg/CM-h		+ 0.026 [(4)]	
EVA Metabolic Water Production added [76]	kg/CM-h		+ 0.016 [(4)]	
EVA Energy added [76]	MJ/CM-h		+ 0.570 [(5)]	
EVA Potable Water Consumption	kg/CM-h		0.24 [(1)]	
Packaging [77]	kg/kg		+ 15 %	
Crewtime	CM-h/d	1 – 1.5 [(6)]	1.5 [(6)]	9 [(7)]

References

(1) Lange and Lin (1998)
(2) Bourland (1998)
(3) Perchonok (2001) and NASA (1991)
(4) derived, Lange and Lin (1998)
(5) Rouen (2001)
(6) NASA (1996)
(7) Kloeris, *et al.* (1998)

4.3.6 Food Systems Based on Biomass Production Systems

The ALS Project assumes that crops within a biomass production chamber will 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 4.3.5 provides wet or fresh masses for the dietary components, as received from the biomass production system, while Table 4.3.6 provides the corresponding nutritional information.

In all cases, the menus given in Table 4.3.5 and Table 4.3.6 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 without post-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 Assembly Complete food system.

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75 On a dry mass (dw) basis.
76 EVA requirements are in addition to any IVA requirements.
77 Packaging accounts for individual food packages only. Secondary structure, lockers, and trays are additional.

Table 4.3.5 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 Only ALS Salad Crops [78]**	**Diet Using Salad and Carbohydrate Crops [79]**	**Diet Using All ALS Crops [80]**
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 [81]	1.1581	2.1	0.6053
Resupplied Food Stuffs	1.168 [82]	0.5 [82, 83]	0.0944
Total	**2.462**	**3.6**	**1.70**
Potable Water [84]	2.0	2.0	2.0
Food Processing Waste	TBD	TBD	0.094

78 From Hall, Vodovotz, and Peterson (2000). This diet assumes a 10-day cycle.

79 From Hall and Vodovotz (1999). This diet assumes a 20-day cycle.

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

81 Water for hydration, cooking, and food preparation only. Water for clean-up is not included. Water tankage is not included.

82 Resupplied food is a combination of STS and ISS foodstuffs.

83 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.

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

Table 4.3.6 Nutritional Content of Diets Using Advanced Life Support Crops and Resupplied Foods

Dietary Component	Units	Goal	Diet Using Only ALS Salad Crops [78]	Diet Using Salad and Carbohydrate Crops [79]	Diet Using All ALS Crops [80]
Energy	MJ/CM-d	11.82 [85]	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 [86]	925.557	812	545
Iron, Fe	mg/CM-d	≤ 10 [86]	19.2385	21.5	17.23
Magnesium, Mg	mg/CM-d	350 [86]	294.687	386	376.48
Phosphorous, P	mg/CM-d	≤ 1.5 Ca intake [86]	1,440.68	1,356	1,079.52
Potassium, K	mg/CM-d	~ 3,500 [86]	3,316.57	3,723	3,179.86
Sodium, Na	mg/CM-d	1,500 – 3,500 [86]	3,909.56	3,600	3,205.96
Zinc, Zn	mg/CM-d	15 [86]	12.8077	10	7.5
Dietary Fiber	g/CM-d	10 – 25 [86]	25.1129	33.3	28.5
Percentage of Energy Contributed to Diet					
Carbohydrate	%	50 – 55 [86]	55.5	61	68.1
Fat	%	30 – 35 [86]	28.7	27	22.4
Protein	%	12 – 15 [86]	16.2	12	12

The Diet Using Only ALS Salad Crops (Hall, Vodovotz, and Peterson, 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 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 ALS 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 ALS crop variety is limited, resupply items provide necessary nutrients that are not available in sufficient quantities within the grown biomass.

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. 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 rehydrated food mass adheres to the inside of the food packaging.

85 From Lange and Lin (1998).
86 From Lane, *et al.* (1996).

Table 4.3.7 presents mass and volume properties for three study food systems, as formulated by Levri, *et al.* (2001), which are modified from the standard Shuttle Training Menu. 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.[87] Some sources, such as the National Research Council (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. See Section 4.3.2. Locker and freezer volumes are computed with respect to external dimensions.

Table 4.3.7 Properties of Early Mars Diets for Intravehicular Activities Using Resupplied Foods

	Units	Modified Shuttle Training Menu [88]	Low Moisture Content Menu [88]	Menu Containing Some Frozen Food [88]
IVA Food Properties, No Packaging				
Food, Dry Mass	kg/CM-d	0.66	0.66	0.66
Food "As-Shipped"	kg/CM-d	1.15	0.92	1.37
Moisture Content of Food "As-Shipped"	%	42	28	52
Food "As-Consumed," with Rehydration	kg/CM-d	2.40	2.20	2.38
Additional Drinking Water	kg/CM-d	1.132	1.322	1.153
IVA Food Packaging Properties				
Packaging Mass	kg/CM-d	0.26	0.27	0.24
IVA Food Locker Properties [89]				
Locker Mass	kg/CM-d	0.35	0.32	0.25
Locker Volume	m^3/CM-d	0.00482	0.00452	0.00354
IVA Food Freezer Properties				
Freezer Mass	kg/CM-d	n/a	n/a	0.808
Freezer Volume	m^3/CM-d	n/a	n/a	0.00231
IVA Food and Packaging Waste				
Trash Mass	kg/CM-d	0.33	0.32	0.29

87 Alternately, this guideline may be formulated as 1.0 milliliters of water per kilocalorie of food energy consumed.
88 From Levri (2002). The values here include material that normally clings to food packaging and is discarded.
89 Food maintained at ambient conditions is stored in lockers aboard ISS.

Table 4.3.8 provides the nutritional analysis for the food systems presented in Table 4.3.7. However, unlike Table 4.3.7, 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 4.3.8 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.

Table 4.3.8 Nutritional Content of Early Mars Diets for Intravehicular Activities Using Resupplied Foods

Dietary Component	Units	Modified Shuttle Training Menu [90]	Low Moisture Content Menu [90]	Menu Containing Some Frozen Food [90]
Energy	MJ/CM-d	11.82	11.82	11.82
Carbohydrate	g/CM-d	376	382	371
Fat	g/CM-d	97	93	97
Protein	g/CM-d	113	115	116
Dietary Fiber	g/CM-d	33	33	37
Ash	g/CM-d	27	25	30
Water in Food [91]	g/CM-d	466	248	690
Rehydration Water	g/CM-d	1,227	1,255	982
Additional Drinking Water [92]	g/CM-d	1,132	1,322	1,153
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 ALS salad crops and resupplied food systems are presented in Table 4.3.9. 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 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 prepackaged food item will adhere to the packaging.

90 From Levri (2002). The values here are based on food “as consumed” by a crewmember, excluding material that normally clings to the food packaging.

91 Moisture, or water, held in the food as shipped before rehydration.

92 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 4.3.7 because losses were not measured or assumed.

Table 4.3.9 Menu Masses for Diets Using Advanced Life Support Crops and Resupplied Foods

Crop	Average Production Based on Consumption, Fresh Mass [kg/CM-d]			
	Diet Using Shuttle Training Menu and ALS Salad Crops [93]	Diet Using Low Moisture Content Menu and ALS Salad Crops [93]	Diet Using ISS Assembly Complete Menu with Some Frozen Food and ALS Salad Crops [93]	Diet Using Shuttle Training Menu and ALS Salad Crops plus Potato [93]
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	0.3032
Crop Sub Total	**0.0953**	**0.0953**	**0.0953**	**0.3985**
Rehydration Water [94]	1.2173	1.2455	0.9744	1.1914
Resupplied Food Stuffs [95]	1.1030	0.8831	1.3200	1.0688
Total	**2.4154**	**2.2239**	**2.3897**	**2.6587**
Drinking Water [96]	1.058	1.246	1.079	1.038
Food Processing Waste [97]	0.0371	0.0303	0.0438	0.0454

93 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.

94 Water for rehydration only. Water for clean-up is not included. Water tankage is not included.

95 Masses are for food "as shipped," without packaging, storage lockers, or water for hydration.

96 Again, this listing excludes packaging/tankage.

97 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 4.3.10 provides the nutritional analysis for the food systems presented in Table 4.3.9. As above, values in Table 4.3.10 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 4.3.10 Nutritional Content of Diets Using Advanced Life Support Crops and Resupplied Foods

Dietary Component	Units	Diet Using Shuttle Training Menu and ALS Salad Crops [98]	Diet Using Low Moisture Content Menu and ALS Salad Crops [98]	Diet Using ISS Assembly Complete Menu with Some Frozen Food and ALS Salad Crops [98]	Diet Using Shuttle Training Menu and ALS Salad Crops plus Potato [98]
Energy	MJ/CM-d	11.82	11.82	11.82	11.82
Carbohydrate	g/CM-d	376	383	372	385
Fat	g/CM-d	96	93	97	93
Protein	g/CM-d	114	115	116	111
Dietary Fiber	g/CM-d	35	35	39	36
Ash	g/CM-d	28	26	31	28
Water in Food [99]	g/CM-d	550	333	772	595
Percentage of Energy Contributed to Diet					
Carbohydrate	%	53	54	53	54
Fat	%	31	30	31	30
Protein	%	16	16	16	16

The four diets presented in Table 4.3.9 and Table 4.3.10 are derived from the standard Shuttle Training Menu and work by Levri, *et al.* (2001). The first and fourth diets included prepackaged items from the Modified Shuttle Training Menu. See Table 4.3.7 and Table 4.3.8. 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 is planned for ISS when that facility is completely assembled.

Perchonok, *et al.* (2002) provides estimates for salad servings based on preliminary menus for early BIO-Plex testing. [100] This overall approach assumes a prepackaged food system augmented with salad crops grown within BIO-Plex. Thus, this diet is analogous to the Diet Using Only ALS Salad Crops from Hall, Vodovotz, and Peterson (2000). Note that Table 4.3.11 provides inputs only for the dietary contributions derived directly from BIO-Plex biomass production. The supporting prepackaged food items are not included.

98 From Levri (2002). The values here are based on food "as consumed" by a crewmember, excluding edible material that normally clings to food packaging or serving dishes.

99 Moisture, or water, held in the food as shipped before rehydration.

100 *Editor's Note:* At this time, development and activation of the BIO-Plex is suspended until a future date. Further, the final configuration and specifications, when complete, may differ from those listed here. Values here are likely typical of a test facility for bioregenerative research.

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 4.3.12 provides overall values for locally grown crops for this diet.

Table 4.3.11 Updated ALS Salad Crop Only Dietary Contributions

Menu Item	Vegetable	Serving Size [101] [g]	Number per Week	Serving Rate [102] [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	0.009

Table 4.3.12 Overall Crops Masses for Updated Salad Crop Only Diet

Vegetable	Serving Rate [102] [kg/CM-d]
Cabbage	0.009
Carrot	0.03542
Lettuce	0.00971
Radish	0.01143
Spinach	0.01872
Tomato (Cherry)	0.01429
Total	**0.09857**

4.3.7 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 the BIO-Plex, from outside the facility), and prepared to provide food.

BIO-Plex [103] planning assumes 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 BIO-Plex test equipment will likely differ. Thus, the value here is a suitable "placeholder" until more definitive values are available.

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101 Mass "as prepared."

102 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 4.2.7.

103 *Editor's Note:* At this time, development and activation of the BIO-Plex is suspended until a future date. Further, the final configuration and specifications, when complete, may differ from those listed here. Values here are likely typical of a test facility for bioregenerative research.

4.4 Thermal Subsystem

The thermal subsystem provides thermal and humidity conditioning of the vehicle atmosphere, removal of heat from equipment, redistribution of heat from heat sources to heat sinks within the vehicle, and rejection of excess heat to the cooling external interface. Within this manuscript, most Thermal Subsystem masses enter analyses and modeling through use of a thermal-energy-management-mass penalty, appearing as a utility for the other life support systems. Thus, information on Thermal Subsystem equipment may be found under the description of thermal energy management infrastructure in Section 3.2. Notably, some air handling equipment, such as the common cabin air assembly, performs both Air and Thermal Subsystem functions. Here, the common cabin air assembly provides cabin atmosphere humidity control in addition to air circulation for atmospheric composition control.

4.5 Waste Subsystem [104]

The Waste Subsystem is responsible for the collection of wastes from other life support subsystems and interfaces. Wastes accepted by the Waste Subsystem may be collected and stored, prepared for long-term storage, processed to recover resources, or made safe for disposal outside the habitat. Wastes might include crew metabolic wastes, trash, brines, and orbital replacement units from the other subsystems. Other non-recoverable materials generated within the crew cabin may be accepted depending on the mission specific requirements and constraints. The mission specific 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. The wastes might be managed or processed using one or more methods or approaches, including collection, storage, transport, processing, and disposal. Further information related to waste types and characteristics are included below.

Waste tends to be less compact than the stowage it came from. It can be inert or hazardous, such as biologically active or radioactive, depending on its source and previous processing history. On Shuttle missions, most waste is stored and returned to Earth with little or no processing. Waste processing for Shuttle includes exposing fecal material to the vacuum of space to render it biologically inert and releasing excess water to space from the orbiter. Waste from ISS is returned to Earth either via a controlled re-entry aboard the Shuttle, either in the orbiter mid-deck or within a multi-purpose logistics module in the payload bay, or aboard Progress cargo modules. If returned within the Shuttle, these wastes are processed on the ground according to state and federal guidelines. If the wastes are removed from ISS within a Progress module, they are incinerated along with the vehicle during destructive re-entry. During transit to Mars, jettisoning trash might be acceptable, though waste might be used for radiation shielding. However, jettisoning waste on the Martian surface will likely be constrained by exploration planetary protection protocols. Note that organic materials as well as microbial agents could threaten to biologically contaminate the Martian environment.

Vehicle waste includes resources that might provide life support commodities. Extraction of life support resources from vehicle waste could be more cost effective than from in-situ resources. However, there are situations where this is not true, and costs and benefits must be considered.

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104 S. Maxwell (The Boeing Company) identified material for and organized this section.

Waste processing options for future missions can range from collecting and storing wastes for eventual return to Earth to complete reduction of waste to its elemental components via processes such as oxidation. In a partially closed system, it may be appropriate to store or dispose of excess waste – in equal mass to the mass of stored food consumed – if this can be accomplished within other constraints. This approach would require little technology development, but it would not recover resources contained within the waste. In a completely closed life support system a destructive process, such as oxidation, to reduce waste volume and recover as many resources as possible may be the most cost effective option. However, destructive processes consume other resources. For example, an oxidation process consumes oxygen and produces carbon dioxide and other gases. Providing the reactant oxygen comes at a cost. Whether oxygen is shipped from Earth or produced locally, using physicochemical processes, bioregeneration, and/or from in-situ resources, it is not without some cost.

4.5.1 Design Values for Waste Subsystems

Waste, while ultimately the result of human activity on a vehicle, comes from many different sources, and might be processed by subsystems other than the Waste Subsystem. Examples of possible waste products, with the associated source subsystem, are listed in Table 4.5.1. This table provides waste generation rates as a function of sources, allowing researchers to construct waste models for any mission. Waste generation rates, and actual waste models, from Shuttle and ISS missions are provided in Sections 4.5.2 and 4.5.3, respectively.

Waste streams are highly mission dependent and, as is implied by Table 4.5.1, on other vehicle subsystem configurations. Or, the waste stream is not only mission dependent, but also depends upon the other technologies utilized within the vehicle. However, some waste generation rates, such as human metabolic wastes, though a function of diet and life support system expendables, are well known and can be calculated with high degree of confidence for a given mission scenario. Other wastes complicate defining an absolute waste stream. Such wastes include inedible biomass, which varies based on the diet selection, and EVA wastes, which are mission and technology dependent.

Table 4.5.1 Solid Wastes as a Function of Sources

Subsystem or Interface	Possible Waste Products	Value
Air	filters and beds	Technology and configuration dependent.
Biomass	fresh inedible biomass (fresh mass)	See Table 4.2.7.
Food	plate waste	On average, 10% of all edible biomass provided to the crew at the dining table is wasted (Lee, W. C., 2001). A lower bound for plate waste is 3% (Levri, 2001)
	food preparation waste (fresh mass)	On average, 10% of all edible biomass from salad crops is lost during food preparation. For heavily processed crops, such as soybean, losses from edible biomass can average 30%. (Lee, W. C., 2001)
	food packaging	See Table 4.3.1. Per Lee, W. C. (2001), the water content of the packaging material is 20%.
	uneaten food	Highly mission dependent.
Thermal	filters	Technology and configuration dependent.
Waste	human metabolic waste:	
	feces	See Table 3.3.6. In addition, crewmembers use 3.808 kg/CM-d, or 0.007 m^3/CM-d, in hygiene cleaning supplies. (Rogers, 1999)
	urine	See Table 3.3.6.
Water	filters and beds	Technology and configuration dependent.
	brines	Brines are 3%, by mass, of the total wastewater load (See Table 4.6.1) and are 12% solid, by mass. (Lee, W. C., 2001)
Extravehicular Activity Support	extravehicular mobility unit solid and liquid wastes	Current (Shuttle) Technology: 0.173 kg/(CM•EVA) of solid waste and 0.55 kg/(CM•EVA) wet waste. [105] (Lee, W. C., 2001)
Human Accommodations	sweat solids	0.018 kg_{dw}/CM-d (Lange and Lin, 1998)
	soap, food, and residues on bodies and clothing	0.086 kg_{dw}/CM-d (Lange and Lin, 1998)
	hygiene clothes (towels)	0.063 $kg_{washcloth}$/CM-d and 0.182 $kg_{lintless\ towel}$/CM-d. Individual masses: 0.045 kg per washcloth and 0.13 kg per lintless towel.
	expended clothing	See Table 5.3.1 and Table 5.3.2.
	hygiene wipes [106]	Crewmember usage is 6.0 kg/CM-wk. These wipes are 1.2 kg per bundle.
In General	packing materials	Highly mission dependent.
	expended equipment	Highly mission dependent.

105 Extravehicular activity waste loadings reflect current technology. Thus, the masses account for crew metabolic wastes, feces and urine, and the disposable absorbent garment worn to collect these wastes. Extravehicular mobility unit technology that eliminates the disposable absorbent garment will reduce these masses, as may shorter durations for extravehicular operations.

106 These are listed as “sanitary napkins” in the ISS equipment catalog.

4.5.2 Historical Waste Loads from Space Transportation System Missions

On Shuttle missions, waste is contained and stowed for return to Earth in either "dry" trash bags, or in the volume F "wet" trash. [107] Waste stream characterization and water content studies have been 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. The waste analyses for STS-99 and STS-101 provided data to develop a waste model to support the Waste Subsystem analysis within the ALS Project. Here, Shuttle data provides a baseline to assess ISS waste generation rates, work which is currently ongoing.

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, 1990). 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 4.5.2 and summarized in Table 4.5.3.

Table 4.5.2 Waste Analysis for STS-51D Trash

Trash Item	Mass [kg]	Moisture Content [%]	Fraction of Total Mass [%]	Reference
Food and Food Packaging				Wydeven and Golub (1990)
Plate Waste	4.8	70	9.8	
Plastic Food Containers	10.8	0.2	22.0	
Other Food Containers	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			

Storage of wastes on-orbit during early Shuttle missions of 30 CM-d or less posed no problems for the allotted resources of the Obiter vehicle. However, as Shuttle missions lengthen for Extended Duration Orbiter of 112 CM-d or more, the volume allocated is 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 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 on 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 4.5.3.

[107] 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.

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 m³ (Maxwell, 2000b). Laundry returns to Earth in a mesh laundry bag. Storage, stabilization, and odor control for laundry, some of it wet, will require dedicated facilities on ISS if no change is made to the current storage process. No data was available on life support system expendables for STS-101.

Table 4.5.3 provides the results of the recent waste stream analyses completed for STS-99 and STS-101, as well as historical data from STS-29, STS-30, and STS-51D.

Table 4.5.3 Space Transportation System Crew Provision Wastes from Past Missions

Mission	Duration [CM-d]	Trash (Solids) [kg /CM-d]	Trash (Solids) [m^3 /CM-d]	Water [kg /CM-d]	Water Percent of Total Trash (by mass) [%]
STS-51D [(1)]	49	1.01		0.096	9.61
STS-29 [(2)]	25	1.49	0.0139	0.345	27.35
STS-30 [(2)]	20	1.63	0.0133	0.417	35.35
STS-35 [(3)]	63	1.14	0.0067	0.218	26.80
STS-99 [(4)]	66	1.47	0.0029	0.290	19.75
STS-101 [(5)]	63	1.62	0.0041	0.439	27.09
Average	48	1.39	0.0082	0.301	24.33

References
(1) Wydeven and Golub (1990)
(2) Garcia (1989)
(3) Grounds (1990)
(4) Maxwell (2000a)
(5) Maxwell (2000b)

4.5.3 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 schedule, will benefit from more robust containment options, additional dedicated storage compartments, and resource recovery plans to reduce mission costs. One option might use water recovery technology, such as a drying oven, to recapture water contained in waste followed by compaction of the dried waste. Intermediate storage, before returning the waste to Earth, might hermetically seal the compacted waste in charcoal impregnated storage bags.

ISS solid waste management today 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, which incinerates upon re-entry, or within Shuttle on the middeck or in a multi-purpose logistics module in the orbiter payload bay. Planned additions to the ISS waste processing hardware include only a urine processor scheduled for late in the assembly sequence.

Calculated waste generation rates for ISS Increment Three, based on data made available by the Increment Data Groups (Molinas and Johnson, 2001), are provided in Table 4.5.4. These Increment Three waste generation rate estimates assume a crew of three for 114 days, or 342 CM-d total.

Calculated overall waste generation rates, according to the life support subsystem and external interface categories, using data from ISS human missions through Expedition 3 are provided in Table 4.5.5 and Table 4.5.6, below. Generation rates for both tables are based on manifest data from Shuttle payloads off-loaded to ISS, the multi-purpose logistics module payloads, and Progress cargo ship payloads. See NASA (2001b, 2001c, 2001d, and 2002). Wieland (1998a) and Wieland (1998b) provide additional data. The waste streams are presented "without water recovery" or "including moisture," Table 4.5.5,and "with water recovery" or "with moisture removed," Table 4.5.6. Equipment and resources associated to recover water are not included. Rather, these tables illustrate differences in waste accumulation rates with and without waste stream water recovery for ISS wastes. Because water will become a critical commodity, approaching 50% of the waste mass for platforms in low Earth orbit as mission durations increase, this format allows investigation of current and expected configurations.

Table 4.5.4 International Space Station Increment Three Waste Generation Rates

Waste Category	Overall Rates Mass Rate [kg/d]	Overall Rates Volumetric Rate [m³/d]	Rates per Crewmember Mass Rate [kg/CM-d]	Rates per Crewmember Volumetric Rate [m³/CM-d]	Reference
KTO (Human Waste)	1.500	0.00618	0.500	0.00206	Molinas and Johnson (2001)
Clothing	1.864	0.01274	0.621	0.00425	
Hygiene Components	0.090	0.01049	0.030	0.00350	
Housekeeping Components	0.010	0.00112	0.003	0.00037	
Food Waste	1.864	0.00426	0.621	0.00142	
Life Support System Waste	0.004	0.01019	0.001	0.00340	
Miscellaneous Dry Trash	0.871	0.00163	0.290	0.00054	
Extravehicular Activity Waste	2.700	0.00836	0.900	0.00279	
Batteries	0.195	0.00026	0.065	0.00009	
Medical Waste	0.000	0.00002	0.000	0.00001	
Sharps	0.022	0.00002	0.007	0.00001	
Chemical Waste	0	0	0	0	
Radioactive Waste	0	0	0	0	
Payload Dry Waste	0.002	0.00001	0.0006	0.00000	
Payload Hazardous Waste	0.479	0.00270	0.160	0.00090	
Payload Wet Waste	0.037	0.00021	0.012	0.00007	
Waste Container Mass	0.390	n/a	0.130	n/a	
Oxygen Candles [108]	n/a	n/a	n/a	n/a	
Subtotal (excludes waste water)	**10.03**	**0.0582**	**3.34**	**0.0194**	
EDV (Waste Water)	5.497	0.01166	1.832	0.00389	
Total Rate	**15.53**	**0.0699**	**5.17**	**0.0233**	

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 life support system within 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 such as bathing. In no case did these subsystems/interfaces produce the waste. Rather, the crew produces the wastes. It is difficult to account for all crew-generated wastes when they are divided between, and applied to various subsystems and interfaces, and even more difficult to make assumptions as to percentages accepted by those subsystems and interfaces.

108 Assuming the Elektron oxygen production unit is operational, oxygen candles are not used.

Table 4.5.5 International Space Station Waste Generation Without Water Recovery

Subsystem or Interface	ISS Phase 2 (3 Crewmembers) Mass [kg/d]	ISS Phase 2 (3 Crewmembers) Volume [m³/d]	ISS Phase 3 Assembly Complete (6 Crewmembers) Mass [kg/d]	ISS Phase 3 Assembly Complete (6 Crewmembers) Volume [m³/d]	ISS Phase 3 ALS Configuration (6 Crewmembers) Mass [kg/d]	ISS Phase 3 ALS Configuration (6 Crewmembers) Volume [m³/d]	References
Air	7.56	0.03	7.66	0.03	7.60	0.02	NASA (2001b), NASA (2001c), NASA (2001d), NASA (2002), Wieland (1998a), and Wieland (1998b)
Biomass	0	0	0	0	0	0	
Food	2.48	0	4.95	0.01	4.95	0.01	
Thermal	0	0	0	0	0	0	
Waste	6.14	0.01	12.27	0.02	12.27	0.02	
Water	0.96	0	1.77	0	1.47	0	
Crew	17.66	0.02	35.31	0.03	35.31	0.04	
Cooling	0	0	0	0	0	0	
EVA Support	0.72	0	0.72	0	0.72	0	
Human Accommodations	12.71	0.03	12.71	0.03	56.69	0.08	
In-Situ Resource Utilization	0	0	0	0	0	0	
Integrated Control	0	0	0	0	0	0	
Power	0	0	0	0	0	0	
Radiation Protection	0	0	0	0	0	0	
Total	**48.23**	**0.09**	**75.39**	**0.12**	**119.01**	**0.17**	

Table 4.5.6 International Space Station Waste Generation With Water Recovery

Subsystem or Interface	ISS Phase 2 (3 Crewmembers) Mass [kg/d]	ISS Phase 2 (3 Crewmembers) Volume [m^3/d]	ISS Phase 3 Assembly Complete (6 Crewmembers) Mass [kg/d]	ISS Phase 3 Assembly Complete (6 Crewmembers) Volume [m^3/d]	ISS Phase 3 ALS Configuration (6 Crewmembers) Mass [kg/d]	ISS Phase 3 ALS Configuration (6 Crewmembers) Volume [m^3/d]
Air	7.56	0.03	7.66	0.03	7.60	0.02
Biomass	0	0	0	0	0	0
Food	2.48	0	4.95	0.01	4.95	0.01
Thermal	0	0	0	0	0	0
Waste	6.14	0.01	12.27	0.02	12.27	0.02
Water	0.96	0	1.77	0	1.47	0
Crew	3.45	0	19.80	0	31.66	0.01
Cooling	0	0	0	0	0	0
EVA Support	0.72	0	0.72	0	0.72	0
Human Accommodations	12.71	0.03	12.71	0.03	10.56	0.03
In-Situ Resource Utilization	0	0	0	0	0	0
Integrated Control	0	0	0	0	0	0
Power	0	0	0	0	0	0
Radiation Protection	0	0	0	0	0	0
Total	**34.02**	**0.07**	**59.88**	**0.09**	**69.23**	**0.09**

References

NASA (2001b), NASA (2001c), NASA (2001d), NASA (2002), Wieland (1998a), and Wieland (1998b)

4.5.4 Solid Waste Management for Mars Missions

Waste treatment and removal for Mars missions 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. In addition to accumulation of traditional trash, Mars missions will probably also generate significant amounts of inedible biomass. In later missions, inedible biomass will dominate all other trash sources. See, for example, Table 4.2.9. Finally, depending on the mission protocols, indefinite stable storage for the end products of any waste-processing scheme may be necessary.

Calculated waste generation rates for advanced missions to Mars, assuming life support system configurations as presented in Stafford, *et al.* (2001), are presented in Table 4.5.7 and Table 4.5.8. Using a similar format to that above for the ISS waste streams, the waste model values in Table 4.5.7 assume no water recovery, while values in Table 4.5.8 assume moisture within the waste stream is recovered. These models assume the advanced life support suites, including the water regeneration technologies, as identified in Stafford, *et al.* (2001). The Mars Descent/Ascent Lander is designed for a maximum of 30 days of operation over its entire descent and ascent mission [109] and its life support system is not designed to recover or regenerate water under any current scenario. Wastes are stored on the vehicle without stabilization within the Mars Ascent/Descent Lander. Technologies for the advanced missions need not be the same for each mission phase. For example, the waste compaction is included for the ALS configuration of the Mars Transit Vehicle in Stafford, *et al.* (2001), but waste drying is not. The ALS configuration of the Surface Habitat Lander and the Mars Base includes both the drying and compaction of wastes.

With the addition of bioregeneration and laundering of crew clothing, the water mass required to support a mission increases dramatically. For example, water comprises 146 kg of 178 kg, or 82 %, of the daily waste loading within the ALS configuration of the Mars Base in Stafford, *et al.* (2001). Further, many of the waste loads within these advanced life support system designs are not initially sent directly to the Waste Subsystem. For example, grey water is processed first by the Water Subsystem and only the concentrated brine actually passes to the Waste Subsystem for treatment including either further processing to recover additional commodities or simply for disposal.

[109] This 30 day duration will not be continuous, but rather 30 days total for both descent and ascent both before and after the surface mission segment in the Surface Habitat Lander.

Table 4.5.7 Advanced Mission to Mars Waste Generation Without Water Recovery

Subsystem or Interface	ALS Configuration, Mars Transit Vehicle (6 crewmembers) Mass [kg/d]	ALS Configuration, Mars Transit Vehicle (6 crewmembers) Volume [m^3/d]	Mars Descent / Ascent Lander (6 crewmembers) Mass [kg/d]	Mars Descent / Ascent Lander (6 crewmembers) Volume [m^3/d]	ALS Configuration Surface Habitat Lander (6 crewmembers) Mass [kg/d]	ALS Configuration Surface Habitat Lander (6 crewmembers) Volume [m^3/d]	ALS Configuration Mars Base (6 crewmembers) Mass [kg/d]	ALS Configuration Mars Base (6 crewmembers) Volume [m^3/d]
Air	7.50	0.03	0.37	0	3.98	0.02	0.37	0
Biomass	0.61	0	0	0	1.19	0	1.40	0
Food	4.31	0.01	4.95	0.01	4.31	0.01	78.90	0.09
Thermal	0	0	0	0	0	0	0	0
Waste	2.29	0	5.77	0.01	3.64	0.01	2.29	0
Water	0.98	0	0	0	0	0	0	0
Crew	35.31	0.03	30.32	0.03	35.31	0.03	35.31	0.03
Cooling	0	0	0	0	0	0	0	0
EVA Support	0	0	0	0	7.26	0.03	7.26	0.03
Human Accommodations	52.60	0.07	12.71	0.03	52.60	0.07	52.60	0.07
In-Situ Resource Utilization	0	0	0	0	0	0	0	0
Integrated Control	0	0	0	0	0	0	0	0
Power	0	0	0	0	0	0	0	0
Radiation Protection	0	0	0	0	0	0	0	0
Total	**103.60**	**0.14**	**54.12**	**0.08**	**108.29**	**0.17**	**178.13**	**0.22**

References

Stafford, *et al.* (2001), NASA (2001b), NASA (2001c), NASA (2001d), NASA (2002), Wieland (1998a), and Wieland (1998b)

Table 4.5.8 Advanced Mission to Mars Waste Generation With Water Recovery

	ALS Configuration, Mars Transit Vehicle (6 crewmembers)		ALS Configuration Surface Habitat Lander (6 crewmembers)		ALS Configuration Mars Base (6 crewmembers)		
Subsystem or Interface	**Mass [kg/d]**	**Volume [m^3/d]**	**Mass [kg/d]**	**Volume [m^3/d]**	**Mass [kg/d]**	**Volume [m^3/d]**	**References**
Air	7.50	0.03	3.98	0.02	0.37	0	Stafford, *et al.* (2001), NASA (2001b), NASA (2001c), NASA (2001d), NASA (2002), Wieland (1998a), and Wieland (1998b)
Biomass	0.61	0	1.19	0	1.40	0	
Food	4.31	0.01	4.31	0.01	3.90	0	
Thermal	0	0	0	0	0	0	
Waste	2.29	0	3.64	0.01	2.29	0	
Water	0.98	0	0	0	0	0	
Crew	10.37	0	9.83	0	9.83	0	
Cooling	0	0	0	0	0	0	
EVA Support	0	0	7.26	0.03	7.26	0.03	
Human Accommodations	6.47	0.02	6.47	0.02	6.47	0.02	
In-Situ Resource Utilization	0	0	0	0	0	0	
Integrated Control	0	0	0	0	0	0	
Power	0	0	0	0	0	0	
Radiation Protection	0	0	0	0	0	0	
Total	**32.53**	**0.06**	**36.68**	**0.09**	**31.52**	**0.05**	

4.6 Water Subsystem

Water may not be the most time-critical life support commodity, but water regeneration streams are the most massive. Further, water quality is also of great concern with respect to crew safety. No single technology has proven adequate for water regeneration to date. Instead, a suite of complimentary technologies must be employed. In the past, power use has driven water regeneration. However, other infrastructure costs are also important.

4.6.1 Design Values for Water Reclamation Systems

Clean water is required for drinks, food preparation, personal hygiene, and possibly for cleaning clothes and equipment. Water quality standards will vary, but they might include potable, hygiene, technical, and plant-transpired [110] water. Table 4.6.1 provides anticipated usage rates for several scenarios. The values here are averages during nominal operation of the life support system. Degraded or emergency life support system values may be different.

Table 4.6.1 Typical Steady-State Values for Vehicle Water Usage

Parameter	Units	Assumptions lower	Assumptions nominal	Assumptions upper
Crew Water Allocation assuming Minimal Hygiene Water for a Mission Phase Less Than 30 days	kg/CM-d	2.9 (1)	4.5 (2)	7.7 (2)
Crewmember Water Allotments for Indefinite-Length Scenarios [111]				
Hygiene Water Inputs				
Oral Hygiene Water	kg/CM-d		0.36 (3)	
Hand and Face Wash Water	kg/CM-d		4.08 (3)	
Shower [112]	kg/CM-d		2.72 (3)	
Dish Wash Water	kg/CM-d		5.44 (3)	
Clothes Wash Water	kg/CM-d		12.47 (3)	
Urinal Flush Water	kg/CM-d		0.49 (3)	
Total Hygiene Inputs	kg/CM-d		25.56	
Hygiene Water Outputs				
Oral Hygiene Water	kg/CM-d		0.36 (3)	
Liquid Hygiene Load	kg/CM-d		6.50 (3)	
Latent Hygiene Water Vapor Load	kg/CM-d		0.30 (3)	
Flush Water	kg/CM-d		0.49 (3)	
Machine Wash Water Outputs				
Liquid Laundry Load	kg/CM-d		11.87 (3)	
Latent Laundry Water Vapor Load	kg/CM-d		0.60 (3)	
Dishwashing Load	kg/CM-d		5.41 (3)	
Latent Dishwashing Water Vapor Load	kg/CM-d		0.03 (3)	
Total Water Outputs	kg/CM-d		25.56	
Water Usage in a Biomass Production Chamber [113]	kg/m²•d		4.00	

References

(1) From Apollo Program via Ewert and Drake (2000)
(2) Ewert and Drake (2000)
(3) Lange and Lin (1998) These are Space Station Freedom planning values.

110 Plant transpirate has also been called “agri-clean” water.
111 Water in soaps, detergents, and adhering residues are neglected, and dissolved and entrained solids are listed in the section on the Waste Subsystem. Metabolic water loads are listed Table 3.3.6.
112 Assuming one shower per two days.
113 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.

4.6.2 Wastewater Models Based on Integrated Testing

Advanced life support system test data from NASA Johnson Space Center provides bases for wastewater models for near-term exploration vehicles. Table 4.6.2 presents data from several sources and details wastewater models for an exploration surface habitat and transit vehicle.

Surface habitat data (Sakano, *et al.*, 2002) is based upon analyses of wastewater collected from test subjects during the Lunar-Mars Life Support Project Phase III Test. Hygiene water consisted of shower, hand wash, oral hygiene, and dishwashing grey water streams (Edeen, 2000).

The transit vehicle data is derived from analysis of wastewater collected from many human test subjects over two years during the Integrated Advanced Water Recovery System Test (Pickering, *et al.*, 2002). Hygiene water included shower, hand wash, and oral hygiene streams. The organic carbon content of the hygiene water assumed 12 % of the cleaner mass used for personal hygiene was due to organic carbon. The urine concentration is calculated from the total mass of wastewater, deducting the contributions from the hand wash and humidity condensate. Humidity condensate was simulated during testing.

Table 4.6.2 Wastewater Models Derived from Integrated Testing

Wastewater Stream Component	Units	Surface Habitat	Transit Vehicle
Urine	%	9 [(1)]	13 [(2)]
Hygiene	%	37 [(1)]	67 [(2)]
Humidity Condensate	%	11 [(1)]	20 [(2)]
Laundry	%	43 [(1)]	0 [(2)]
Total	%	100	100
Physical Parameters for Average Composition, Aggregate Wastewater			
Total Organic Carbon	mg/L	247 [(1)]	519 [(2)]
Conductivity	mS/cm	2.35 [(1)]	6.40 [(2)]
pH		8.44 [(1)]	8.89 [(2)]
Alkalinity [114]	meq/L	11.7 [(1)]	46.8 [(2)]
Ammonium-Nitrogen	mg/L	150 [(1)]	663 [(2)]
Total Organic Carbon by Source [mg/L]			
Urine			1,467 [(2)]
Hygiene Wastewater			368 [(2)]
Humidity Condensate			159 [(2)]
Laundry			0 [(2)]

References
(1) Sakano, *et al.* (2002)
(2) Pickering, *et al.* (2002)

Organic carbon by source denotes the concentration of organic carbon present in a particular source.

114 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.

4.6.3 Composition of Wastewater for International Space Station Grey Water and Human Urine

Studies by Carter (1998) and Putnam (1971) provide the data for Table 4.6.3 through Table 4.6.8, which present 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 shower (Table 4.6.5) and hygiene (Table 4.6.6) streams, may be unique to ISS. Likewise, wastes listed for the extravehicular mobility unit (Table 4.6.3) 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 4.6.3 through Table 4.6.8 have a similar format. The first column of each table provides the contaminant name. When the common name differs from 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 [115]. 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 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 4.6.3 details the anticipated aqueous contaminants in the grey water 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.

Table 4.6.3 Waste Water Contaminants in Extravehicular Mobility Unit Stream

Component	CI	SMAC	MW	Percent Carbon [%C]	Loading Density [mg/L]	Percent of Stream [%]
acetone [2-propanone]		×	58.1	62.0	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	12.8	0.0108	14.5
ethylene glycol [1,2-ethandiol]		×	62.1	38.7	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*	*91.2*	*0.0002*	*0.3*
Total					**0.0742**	**100**

Table 4.6.4 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.

115 See Lange and Lin (1998) for CI and SMAC requirements.

Table 4.6.4 Waste Water Contaminants in Crew Latent Condensate

Component	CI	SMAC	MW	Percent Carbon [%C]	Loading Density [mg/L]	Percent of Stream [%]
2-propanol		×	60.1	60.0	46.297	18.6
1,2 propanediol			76.1	47.4	45.234	18.2
bicarbonate			61.0	19.7	33.170	13.3
acetic acid [ethanoic acid]		×	60.1	40.0	14.614	5.9
ammonium	×		18.0	0.0	13.527	5.4
caprolactam			113.2	63.7	11.834	4.8
ethylene glycol [1,2-ethandiol]		×	62.1	38.7	10.224	4.1
glycolic acid [hydroxy acetic acid]			76.1	31.6	10.194	4.1
ethanol		×	46.1	52.1	8.181	3.3
formaldehyde [methanal]		×	30.0	40.0	8.136	3.3
formic acid [methanoic acid]			46.0	26.1	7.239	2.9
propanoic acid			74.1	48.6	3.916	1.6
methanol		×	32.0	37.5	3.737	1.5
lactic acid [2-hydroxy-propanoic acid]			90.1	40.0	3.079	1.2
4-ethyl morpholine			115.2	62.6	2.516	1.0
urea			60.1	20.0	2.415	1.0
chloride	×		35.5	0.0	1.465	0.6
4-hydroxy-4-methyl-2-pentanone			116.2	62.0	1.247	0.5
2-butoxyethoxy-ethanol			162.2	59.2	1.130	0.5
4-acetyl morpholine			129.2	55.8	1.092	0.4
1-butanol		×	74.1	64.8	0.937	0.4
2-butoxyethanol			118.2	61.0	0.803	0.3
carbon disulfide	×	×	76.1	15.8	0.785	0.3
octanoic acid			144.2	66.6	0.665	0.3
zinc	×		65.4	0.0	0.650	0.3
N,N-dimethylformamide [N,N-dimethyl formic acid amide]			73.1	49.3	0.608	0.2
total protein			3,206.3	53.0	0.600	0.2
hexanoic acid			116.2	62.0	0.582	0.2
isocitric acid [1-hydroxy-1,2,3-propanetricarboxylic acid]			192.1	37.5	0.576	0.2
dibutyl amine			129.2	74.3	0.566	0.2
potassium	×		39.1	0.0	0.542	0.2
constituents totaling less than 5%					*9.546*	*3.8*
nitrite	×		*46.0*	*0.0*	*0.517*	*0.2*
2-ethoxyethanol		×	*90.1*	*53.3*	*0.504*	*0.2*
acetone [2-propanone]		×	*58.1*	*62.0*	*0.348*	*0.1*
magnesium	×		*24.3*	*0.0*	*0.282*	*0.1*
phenol		×	*94.1*	*76.6*	*0.204*	*0.1*
silver	×		*107.9*	*0.0*	*0.200*	*0.1*
acetaldehyde [ethanal]		×	*44.1*	*54.5*	*0.098*	*0.0*
cyclohexanone		×	*98.1*	*73.4*	*0.089*	*0.0*
nickel	×		*58.7*	*0.0*	*0.087*	*0.0*
acetophenone		×	*120.2*	*80.0*	*0.083*	*0.0*
calcium	×		*40.1*	*0.0*	*0.060*	*0.0*
sulfate	×		*96.1*	*0.0*	*0.052*	*0.0*
methylene chloride [dichloromethane]	×	×	*84.9*	*14.1*	*0.050*	*0.0*
manganese	×		*54.9*	*0.0*	*0.035*	*0.0*
methyl ethyl ketone [2-butanone]		×	*72.1*	*66.6*	*0.023*	*0.0*
iron	×		*55.9*	*0.0*	*0.008*	*0.0*
tetrachloroethene	×	×	*165.8*	*14.5*	*0.005*	*0.0*
copper	×		*63.6*	*0.0*	*0.004*	*0.0*
isobutyl methyl ketone [4-methyl-2-pentanone]		×	*100.2*	*72.0*	*0.002*	*0.0*
cadmium	×		*112.4*	*0.0*	*0.001*	*0.0*
lead	×		*207.2*	*0.0*	*0.001*	*0.0*
toluene		×	*92.1*	*91.2*	*0.001*	*0.0*
ethyl benzene		×	*106.2*	*90.5*	*trace*	*0.0*
benzene		×	*78.1*	*92.3*	*trace*	*0.0*
chloroform [trichloromethane]	×	×	*119.4*	*10.1*	*trace*	*0.0*
Total					**248.76**	**100**

Table 4.6.5 details the contaminants from the crew shower stream. Depending on the actual cleansing agent employed, actual components in a shower grey water stream may vary. Carter (1998) developed this list based on the International Space Station program.

Table 4.6.5 Waste Water Contaminants in Crew Shower Stream

Component	CI	SMAC	MW	Percent Carbon [%C]	Loading Density [mg/L]	Percent of Stream [%]
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
propionic 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 4.6.6 details the contaminants from the crew hygiene stream derived from hand and oral cleansing operations. Depending on the actual cleansing agent employed, actual components in a hygiene grey water stream may vary. Carter (1998) developed this list based on the International Space Station program.

Table 4.6.6 Waste Water Contaminants in Crew Hygiene Stream

Component	CI	SMAC	MW	Percent Carbon [%C]	Loading Density [mg/L]	Percent of Stream [%]
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
propionic 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 4.6.7 lists the composition of unprocessed urine as derived from the human metabolic process. The reference is Putnam (1971).

Table 4.6.7 Waste Water Contaminants in Crew Urine Stream

Component	CI	SMAC	MW	Percent Carbon [%C]	Loading Density [mg/L]	Percent of Stream [%]
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 asparate	×		*150.1*	*32.0*	*135*	*0.4*
ammonium formate	×		*63.1*	*19.0*	*88*	*0.2*
calcium phosphate	×		*198.0*	*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 4.6.8 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 4.6.8 Waste Water Contaminants in Animal Latent Condensate

Component	CI	SMAC	MW	Percent Carbon [%C]	Loading Density [mg/L]	Percent of Stream [%]
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**

5 Life Support External Interface Assumptions and Values

5.1 Cooling External Interface

The Cooling External Interface takes thermal loads from the Thermal Subsystem and rejects those loads to the environment. Thus, within this manuscript, the cooling masses are treated as infrastructure and enter analyses and modeling through the thermal-energy-management-mass penalty as detailed in Section 3.2.

5.2 Extravehicular Activity Support External Interface [116]

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 planetary surface space suits must be much lighter than current systems. Such new space suits must also be designed for walking, 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 135 kg and is designed for weightless mobility using foot restraints. Table 5.2.1 presents local accelerations due to gravity for planetary bodies and Table 5.2.2 presents historical EMU masses. Finally, Table 5.2.3 presents the weight [117] of an average 70 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 12 % greater than the weight of a nominal, unencumbered crewmember under terrestrial gravity.

- ***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 Luna 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.***

Table 5.2.1 Local Accelerations Due to Gravity

Locale	Mean Acceleration due to Gravity [m/s²]	Fractional Gravity compared to Earth Normal	Reference
Earth	9.807	1.000	Weast and Astle (1979)
Luna	1.620	0.165	
Mars	3.740	0.381	

116 This section on advanced extravehicular activities is from Rouen (2001).

117 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 5.2.2 Historical Extravehicular Activity Masses

Item	Mass [kg]
Nominal Human Being	70 [(1)]
Apollo Program Spacesuit, A7L [118]	83.0 [(2)]
Apollo Program Spacesuit, A7LB [119]	90.7 [(3)]
Shuttle/ISS Program Spacesuit	135 [(4)]

References
(1) See Section 3.3.3
(2) NASA (1969)
(3) Rouen (2002)
(4) Rouen (2001)

Table 5.2.3 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 Unen-cumbered, Earth-Normal Weight [%]
Earth	70.0	686		100
Luna	70.0	113		16.5
Lunar Surface with Apollo A7L EMU	153.0		248	36.1
Lunar Surface with Apollo A7LB EMU	160.7		260	37.9
Lunar Surface with Shuttle EMU	205		332	48.4
Mars	70.0	262		38.2
Martian Surface with Apollo A7L EMU	153.0		572	83.4
Martian Surface with Apollo A7LB EMU	160.7		601	87.5
Martian Surface with Shuttle EMU	205		767	112

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.

5.2.1 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. Thus, the minimum airlock internal volume is about 3.7 m^3. This corresponds to the volume of the current Shuttle airlock.

118 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.

119 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.

5.2.2 Martian Surface Operations

Because the gravity on Mars is about twice that of Luna and about a third of that on Earth, the overall mass of a Mars spacesuit is extremely critical. A likely mission design to mitigate this problem is to reduce the standard EVA duration to 4 hours and plan to recharge the spacesuit consumables at midday. 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 expected number of airlock cycles per year. Each EVA sortie normally requires at least two crewmembers outside.

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/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 would completely 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 energy management 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 m³. During use, the free gas volume within the airlock is 3.7 m³ 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 m³ and a free gas volume of roughly 0.89 m³. 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.

Table 5.2.4 summarizes the estimates above for EVA operations on the surface of Mars. All values are provided by Rouen (2001). Losses in Table 5.2.4 denote mass that leaves the pressurized volume of the spacesuit and, therefore, does not return to the vehicle at the end of EVA operations. Consumption in Table 5.2.5 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. Lange and Lin (1998), based on NASA (1995), provide overall values describing the metabolic loads and inputs for an EVA crewmember. See Table 5.2.5.

Table 5.2.4 Summary of Extravehicular Activity Values for Mars Surface Operations

Value	Units	low	nominal	high	Reference
Human Metabolic Rate During EVA	MJ /CM-h		1.06		Rouen (2001)
	W/CM		295		
EVA Crewmember Hours per Week	CM-h /wk		80	80	
EVA Sorties [120] per Week	Sorties /wk		5 [121] or 10 [122]	5 [121] or 10 [122]	
Cooling Water Losses	kg /CM-h	0	0.19	0.57	
Oxygen Losses	kg /CM-h	0.005 to 0.076	0.15	1.0	
Airlock Volume	m^3	1.02	4.25		
Airlock Free-Gas Volume	m^3	0.89	3.7		
Airlock Cycles per Week	Cycles /wk	0	5 [121] or 10 [122]	5 [121] or 10 [122]	
Airlock Gas Losses per Cycle as a Percentage of Airlock Gas Volume [123]	%	5	10	10	

Table 5.2.5 Extravehicular Activity Metabolic Loads

Parameter	Units	Rate
Oxygen Consumption	kg/CM-h	0.075 [(1)]
Potable Water Consumption [124]	kg/CM-h	0.24 [(1)]
Food Energy Consumption [125]	MJ/CM-h	1.062 [(2)]
Carbon Dioxide Production	kg/CM-h	0.093 [(1)]
Respiration and Perspiration Water Production	kg/CM-h	TBD
Urine Production	kg/CM-h	TBD

References
(1) Lange and Lin (1998) based on NASA (1995)
(2) Rouen (2001)

5.2.3 Lunar Surface Operations

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 Luna, 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.

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120 Each EVA sortie assumes two crewmembers.
121 Assuming 8-hour EVA sorties.
122 Assuming 4-hour, or "half day" EVA sorties.
123 As given, these values are as a percentage of the mass of gas occupying the free airlock volume when depressurization begins.
124 For EVA sorties longer than 3 hours.
125 This is the total energy expended, and thus consumed, per crewmember per hour of extravehicular activity.

5.3 Human Accommodations External Interface

5.3.1 Clothing

Clothes are not traditionally 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 clothes as needed. Alternately, clothes could be cleaned and reused to significantly reduce the mass of clothes allotted per mission.

The main interfaces between the life support subsystems and a traditional laundry would be the mass of water to support a water-based washer and the corresponding water vapor load. 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, the corresponding water-vapor load would be about 1.5 kg/CM-d.

Table 5.3.1 provides a summary of clothing and laundry options. Table 5.3.2 provides values for an aqueous laundry system originally under development for ISS (Lunsford and Grounds, 1993, and ALS Systems Workshop, 1998), while Table 5.3.3 details a recent study of a more efficient washer/dryer prototype unit (Jeng and Ewert, 2002). In this latter study, the authors assumed clothing would have a useful life of 40 laundry cycles.

Table 5.3.1 Clothing and Laundry Options

	Mass [kg]	Mass [kg/CM-d]	Volume [m^3/CM-d]	Power [kW]
ISS Approach (clothes shipped, single use):				
From Rogers (1999)		0.718 (1)	0.0013 (1)	
From Branch (1998)		1.69 (2)	0.00135 (2)	
From Reimers and McDonald (1992)		1.47 (3)	0.00140 (3)	
Using a Laundry:				
clothes		0.267 (3)	0.000351 (3)	
		0.0746 (5a)	0.00044 (5a)	
		0.0373 (5b)	0.00022 (5b)	
		0.0191 (5c)	0.00011 (5c)	
laundry equipment	118 (3)			0.31 (3)
	80 (5)			0.751 (5)
interfaces (water)		12.47 (4) [126]		
		7.33 (5)		

References

(1) Rodgers (1999). This is based on actual clothing "as shipped" to ISS.
(2) Branch (1998)
(3) Reimers and McDonald (1992)
(4) Lange and Lin (1998)
(5) Jeng and Ewert (2002)
(5a) Jeng and Ewert (2002); 90 d mission duration
(5b) Jeng and Ewert (2002); 180 d mission duration
(5c) Jeng and Ewert (2002); 600 d mission duration

[126] The laundry uses clean water and provides a waste stream of grey water to the water recovery system.

Table 5.3.2 Early ISS Laundry Equipment Specifications

Washer Unit	Value	Units	Comments
Mass	118	kg	
Volume	0.66	m^3	
Capacity	2.7	kg/load	
Water Usage	49	kg/load	Effluent is grey water. This unit does not release water vapor.
Crew Time	0.33	CM-h/load	Load, remove, fold, and stow clothes.
Energy	3.3	kWh/load	
Consumables	0.0024	kg/load	Detergent

References

From Lunsford and Grounds (1993) with updates from material presented at the ALS Systems Workshop (1998). This information is based on the laundry originally under development for ISS.

Table 5.3.3 Advanced Washer/Dryer Specifications

Washer Unit	Value	Units	Comments
Mass	80	kg	
Volume	0.264	m^3	
Capacity	4.5	kg/load	Clothes
Water Usage	51.3 [127]	kg/load	Effluent is grey water. This unit does not release water vapor.
Crew Time	0.42	CM-h/load	Load, remove, fold, and stow clothes.
Energy	0.95 [128]	kWh/load	Low setting
Consumables	0.010	kg/load	Detergent (Igepon soap)

Reference

From Jeng and Ewert (2002)

5.4 In-Situ Resource Utilization External Interface

Significant quantities of local resources are available at Mars that might be used for life support. Sridhar, *et al.* (1998) identified some resources that might be needed. (See Table 5.4.1) Drysdale (1998) estimated very roughly the masses required for each resource and the cost leverage that seemed credible from in-situ resource utilization (ISRU) based on data from John Finn (NASA Ames Research Center). (See Table 5.4.3)

Regolith may be used for radiation and meteoroid protection at a long-term base, and would be available for the cost of moving it and bagging it.

Water would be a high leverage item, particularly if bioregeneration is used extensively. It could be available from the atmosphere, despite its dryness, from permafrost that is expected to be extensive a meter or two below the surface, from polar ice, or from subsurface water or ice deposits. It could also be made from atmospheric carbon dioxide, if a source of hydrogen is available. Even if hydrogen had to be shipped from Earth, this would still give a 5 to 1 cost advantage. The cost of acquisition would depend on the cost of extraction and purification. Currently, the abundance and location of water on Mars is undetermined. The atmosphere of Mars carries water vapor in minimal quantities. Likewise, large deposits of water exist at both Martian poles, but accessing that water is complicated by the seasonal deposition of frozen carbon dioxide on top of the ice deposits.

127 A washer using ozone, O_3, for the detergent will use less water. Energy usage, however, increases to support ozone production.

128 Corresponding energy usage values: The washer cycle is 40 minutes at 300 W, and the dryer cycle is 60 minutes at 750 W.

Atmospheric carbon dioxide could support plant growth, particularly if a plant growth unit is set up and started remotely. It could be readily extracted from the atmosphere, which is 95% carbon dioxide, though at a low pressure.

An inert gas would be needed to dilute the cabin oxygen, assuming the base air would not be pure oxygen. This could be extracted from the atmosphere by removing the carbon dioxide and water vapor.

Finally, oxygen, for crew respiration, can be obtained from the atmosphere, either by removing the rest of the gases, or by reaction with the atmospheric carbon dioxide using either a Sabatier/electrolysis or zirconia cell reaction.

A design reference mission (Hoffman and Kaplan, 1997) proposes using local resources to make rocket propellant, liquid methane and liquid oxygen, for the Mars ascent vehicle from the Martian atmosphere. While oxygen is available as a product from splitting carbon dioxide, methane production requires a source of hydrogen. Water provides a readily used source of hydrogen, but as addressed above, it may not be readily available. The design reference mission avoids the issue of water availability by providing liquid hydrogen from Earth for ISRU propellant production.

Similar propellants could be used for power storage, including propelling surface or aerial vehicles, especially if a local source of water is available. In addition, the same chemical processing plant could be used to make life support commodities, such as listed below in Table 5.4.3. Some of these, inert gases, for example, might be made available as by-products at minimal added cost.

Note that shipped commodities will have a negative cost leverage to account for packaging. This can be a significant mass factor, as shown in Table 4.1.4 for permanent gases. This is in addition to any cost factor for the shipping location as identified in Table 3.2.1.

Table 5.4.1 Nitrogen Gas Losses Associated with International Space Station Technology

Parameter	Mass [kg/y]	Comments	Reference
Nitrogen Resupplied	796		Information from Sridhar, *et al.* (1998)
ISS Module Leakage	18 - 44		
Airlock Losses	10%	mass of nitrogen lost per cycle is 1 kg	

Table 5.4.2 Nitrogen Gas Losses for the Mars Design Reference Mission (One Cycle) Using ISS Technologies

Mission Phase	Event	Mass [kg]	per Event	Total Mass Lost [kg]	Calculation Basis	Reference
Transit	Module Leakage	0.1	day	26	260 days transit; both ways	Information from Sridhar, *et al.* (1998)
Surface	Airlock Usage	1	cycle	1,200	2 cycles/day for 619 days	
Surface	Module Leakage	0.1	day	62	619 days	
Total				**1,288**	Gas Mass Excluding Tanks	

Table 5.4.3 Estimation of Cost Leverages from In-Situ Resource Utilization [129]

Commodity	Requirement [kg]	Cost Leverage	Comments / Assumptions	Likelihood [130]
Regolith	620,000	3,100	Assumes a Rover is Available	Always
Water	12,000	310	From Local Permafrost	Unknown to Unlikely
Water	12,000	390	From Local Atmosphere	Unlikely
Water	12,000	5	Produced Using Hydrogen from Earth	Always
Carbon Dioxide	528	47	For 30 days of Plant Growth; Using Local Atmosphere	Always
Inert Gas (Argon/Nitrogen)	508	1.6	From Local Atmosphere	Always
Oxygen	121	19	From Electrolysis of Local Water	Unknown to Unlikely
Hydrogen	system dependent	1.2	From Electrolysis of Local Water	Depends on water availability

Allen and Zubrin (1999) suggest ISRU is also available on Luna, though the variety and source of commodities is more limited. Specifically, oxygen is available as an oxide within the lunar regolith. Further, though very limited in extent, water, as ice, is present in deep craters at both lunar poles.

5.5 Integrated Control External Interface

5.5.1 Sensors

Sensors are critical to life support system operation. However, based on current estimates from the ALS Systems Analysis Workshop of March 1998, the mass will not be significant compared to the overall life support system mass.

Table 5.5.1 Sensor Mass Estimates

Parameter	Assumptions [kg] lower	nominal	upper
low tech	221 [(1)]	TBD	680 [(1)]
high tech	71 [(1)]	TBD	165 [(1)]
highest tech	39 [(1)]	TBD	106 [(1)]

References
(1) Jan (1998)

5.6 Power External 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.

129 From Drysdale (1998) using data from J. Finn (NASA/Ames Research Center). These estimates are very preliminary.

130 Likelihood assesses how likely a particular commodity might be available based on current knowledge of Mars for a typical site. Assessment scale: “Always” implies availability at all sites. “Likely” implies availability at most sites in unlimited quantities. “Unlikely” implies availability at some sites in unlimited quantities, or available at most sites in limited quantities. “Unknown” implies unknown availability.

5.7 Radiation Protection External Interface

Radiation protection, according to Table 2.4.2, may impact numerous systems. While exotic life support designs are possible, it is likely that radiation protection, which is effectively mass between the crew and the external radiant environment, will remain a dedicated mass of material with a high hydrogen content such as polyethylene or, less ideally, even water. Further, vehicle structure, including the primary structure, avionics, and propulsion system can provide varying degrees of protection just due to the nature of their mass. (See Duffield, 2001) However, the most likely interaction for the radiation protection external interface is with the water subsystem and then only as a contingency source.

For operations in near Earth space, hydrogen mass equivalent to roughly 0.10 m of water completely around any safe haven is considered adequate for a vehicle radiation shelter to protect against solar particle events. 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.

For longer duration missions, either for extended operations on Luna or to transit to Mars, the crew cabin must also provide protection versus galactic cosmic radiation. Again this radiation source is, by nature, isotropic. As implied above in the Section 3.2.1 on infrastructure, 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.

Here, radiation protection costs are integrated with the primary structure penalty for volume as noted above in Section 3.2.1.

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7 Appendices

Appendix A: Acronyms and Abbreviations [131]

ALS	Advanced Life Support
BIO-Plex	Bioregenerative Planetary Life Support Systems Test Complex
BPC	Biomass Production Chamber at Kennedy Space Center
BVAD	Baseline Values and Assumptions Document (This Document)
CI	controlled inorganic (compound)
CO_2	carbon dioxide
COP_S	overall system thermodynamic coefficient of performance
CTMP	crewtime-mass-penalty [kg/CM-h]
CTSD	Crew and Thermal Systems Division (at NASA JSC)
dw	dry mass (dry "weight")
EMU	extravehicular mobility unit (space suit)
ESM	equivalent system mass
EVA	extravehicular activity
ffm	frozen food mass
fw	fresh mass (fresh "weight")
HPS	high pressure sodium, a type of lamp
ISRU	in situ resource utilization
ISS	International Space Station
IST	Invariantly-Scheduled Time
IUPAC	International Union of Pure and Applied Chemistry
IVA	intra vehicular activity
JSC	Johnson Space Center
KSC	Kennedy Space Center
LMLSTP	Lunar Mars Life Support Test Program (integrated human life support system test at JSC)
MEC	Modified Energy Cascade models
MPR	multivariable polynomial regression
MSFC	Marshall Space Flight Center
MW	molecular weight or Megawatt if used as a unit
n/a	not applicable
NASA	National Aeronautics and Space Administration
O_2	oxygen
p(gas)	partial pressure exerted by gas
PAR	photosynthetically active radiation
pH	potential of hydrogen
PLSS	portable life support system
PPF	photosynthetic photon flux
PV	photovoltaic
R_S	system composite thermal resistance
SI	Système Internationale d'Unités, or International System of Units (Metric System)
SIMA	Systems Integration, Modeling, and Analysis element (of the ALS Project)
SMAC	spacecraft maximum allowable concentration
SP100	type of nuclear reactor
STS	space transportation system
SVCHp	solar vapor-compression heat pump
TBD	to be determined
VST	Variably-Scheduled Time
$\hat{W}_{RF}$	specific power consumption for a cooled volume within a cabinet

131 Symbols specific to the crop models in Section 4.2.3 are defined in Table 4.2.14 and Table 4.2.26.

Appendix B: Abbreviations for Units

Symbol	Actual Unit	Physical Correspondence
°C	degrees Centigrade	temperature
CM	crewmember	person
CM-d	crewmember-day	crewtime
CM-h	crewmember-hour	crewtime
CM-wk	crewmember-week	crewtime
c	centi-	prefix
d	day	time
g	gram	mass
h	hour	time
J	Joule	energy
k	kilo-	prefix
L	liter	volume
M	mega-	prefix
m	meter	length
m^2	square meter	area
m^3	cubic meter	volume
m	milli-	prefix
meq/L	milli-equivalents per liter	concentration
mol	mole	mole
N	Newton	force
Pa	Pascal	pressure
ppm	parts per million	concentration
S	Siemens	conductivity
s	second	time
W	Watt	power
wk	week	time
y	year	time
μ	micro-	prefix