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Advanced Life Support Baseline Values and Assumptions Document

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August 2004

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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 called a 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). Accordingly, 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 may be selected for the solar constant in a study sited in Luna orbit, a mean value of 1,370 W/m² may be defined as the baseline solar flux at Luna. Consequently, 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. Several SIMA researchers, in addition to the authors, helped to prepare the manuscript. 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 welcomed and encouraged. To allow the BVAD to 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:

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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 instead of a single researcher. Further, such values reflect the combined expertise of the group as a whole rather than one individual.
- The BVAD process identifies those quantities that are not well-defined by current information. Such quantities are primary candidates for parametric studies to determine their importance on modeling and analysis results. Further, this approach identifies values that may require additional experimental input to adequately quantify.
- The BVAD allows researchers from multiple sites to efficiently and quickly compare results from multiple studies. Because each study uses the same baseline, the variations between studies arise from differences in models or the parameters varied rather than a complex combined effect that includes variations in the assumed baseline.
- The BVAD will allow any researcher to conduct a follow-on study to any previous work because assumptions from each study will be clearly available and carefully recorded. Further, researchers can reference the BVAD for their baseline parameter values except those that are unique to their specific study.

1.3 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 Acknowledgments [1]

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[1] The National Aeronautics and Space Administration (NASA) Centers abbreviated here 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 are derived from various sources and are organized into sets of similar data. These assumptions relate to the scenarios, the mission infrastructure, and the various life support subsystems. References are documented—where possible—to provide traceability.

2.1 Development

The baseline values and assumptions are based on experience in developing 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 External Interface can yield an appropriate power-mass penalty by dividing the average power plant output by the total mass of the generating power plant. Thus, for a nuclear power plant on an independent lander that, 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 External Interface mass to a power-using subsystem in place of the power requirement of the subsystem. 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. Please see Levri, et al. (2003) for additional information on ESM.

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 have little impact on the equivalent system mass of a life support system and can therefore 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

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[2] An ESM evaluation is very similar in form to computing the net present value of a project and is a method used 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.

analyses while Section 4.6.3 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 a 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, calculating 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): all analysis tasks for advanced systems shall 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 are based on 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]. Because of this distinction, Air, Biomass, Food, Thermal, Waste, and Water are classified as subsystems. Crew [6], Cooling, Extravehicular Activity (EVA) Support, Human Accommodations, In-Situ Resource Utilization, Integrated Control, Power, and Radiation Protection are classified as external life support interfaces. The interfaces listed in the last column for each subsystem or external interface are generally inclusive in an attempt to account for all possible interactions, even if some of those interactions are highly unlikely.

Please note: within this document, ALS subsystem names such as "Air Subsystem" and "Biomass Subsystem" are proper nouns. 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 of ALS researchers and analysts 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. Consequently, the terms "system" and "subsystem" vary according to the current problem definition and often differ for other problems or studies.

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[4] The Systems Integration, Modeling, and Analysis element was previously named Systems Modeling and Analysis Project.

[5] Work on the Bioregenerative Planetary Life Support Systems Test Complex (BIO-Plex) predates this organizational structure. Deviations from Table 2.4.1 and Table 2.4.2 exist for historical documentation.

[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 are listed as an external interface.

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, storing 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 the 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. Crewmembers have been, and should continue to be, the foremost consumers of life support commodities as well as 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. It also provides for the removal of carbon dioxide and waste.	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. 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 any and all information that 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://advlifesupport.jsc.nasa.gov*. Subsequent releases will be considered in updating this document.

> Duffield, B. E. (2003) "Advanced Life Support Requirements Document," JSC-38571 (CTSD-ADV-245), Revision C, National Aeronautics and Space Administration, Johnson Space Center, Houston, Texas, February, 2003.
>
> 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, November, 2001.

Parameters that are non-negotiable for any reason are considered ALS requirements and are documented within Duffield (2003). Some of the assumptions documented here may in time become requirements while others will be uncertain until NASA embarks on a specific mission. Some possible future missions are documented in Stafford, et al. (2001), 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 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 describing 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. Required by 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 not likely 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

While a goal of ALS is a long-duration facility in an extraterrestrial site, NASA currently has few specifications for such a mission. For now, a long-duration integrated test bed may provide a terrestrial analog for an eventual base. Such an integrated life support test stand is typically a closed-chamber facility comprised of five chambers and an airlock connected by a tunnel. [12] This facility will provide integrated test facilities for technologies that will likely be used for an early human base on Luna or Mars. Each facility module is 185.15 m^3 in volume. The

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[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, the scope and purpose of the integrated test stand to support hardware development within the ALS Project is under review. Because of prior programs such as BIO-Plex, very precise values are available for some earlier facilities. Consequently, the configuration and specifications for the actual ALS integrated testing facility may differ from those listed here. The values listed are likely representative of an integrated bioregenerative research facility and, by analog, to a long-duration extraterrestrial surface facility.

tunnel is 263.43 m^3. The airlock volume is 48 m^3. 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.

This test facility optimally supports 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, past testing concepts have mentioned 120- through 400+- day missions most often. An initial test involving human beings may be 120 days in duration (Tri, 2000). Plant scientists favor tests of 240 days because this would allow two complete cropping cycles based on harvest dates for crops with the longest life cycle.

A facility similar to this test facility could be built on Luna or Mars with 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 (see Table 3.1.1), and an operational lifetime of up to fifteen years.

3.2 Infrastructure Costs and Equivalencies

Infrastructure costs (ex: mass, volume, power, thermal energy management, crewtime) are key factors in overall system analysis. They effectively apportion a fraction of the infrastructure mass to each component of the life support system. It is far easier to decide on reasonable figures for these parameters early in a study than to 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 certain variables, including but not limited to: external mission environment, technologies used, and mission duration. 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 similar 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

		Assumptions		
Parameter	**Units**	**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

		Assumptions		
Parameter	**Units**	**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
(1) 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 can 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 is 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, therefore, referenced nominal values include thermal protection for aerodynamic heating.

Table 3.2.3 Cost of Pressurized Volume

	Assumptions [kg/m^3]		
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 lunar and Martian missions, assume surface sites. The unshielded value reflects 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. 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 External Interface and, therefore, should not also be assessed against the structure mass.

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

The appropriate volume cost factor generally depends on the sensitivity of specific equipment to the external environment or whether the crew must regularly interact with the equipment. As noted above, in radiation intensive environments anywhere beyond the Van Allen Belts, cost factors for shielded volume should be used

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[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.

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 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 massive and more 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, since the ISS common module and TransHab are designed using different design philosophies, 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	

Based on Table 3.2.4, several cost factors for various configurations of the components presented are possible. See 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.

While each configuration is not independently viable, they provide background for other estimates. The applicable volume is 329.4 m^3.

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

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 3.2.5 Estimated Masses and Volume-Mass Penalties for Inflatable Module Configurations

Configuration	Mass [kg]	Volume-Mass Penalty [kg/m³]	Volume-Mass Penalty [m³/kg]
All 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 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/m^3]		133.1	102.0	215.5
[m^3/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.)

The options in Table 3.2.6 differ from each other and reflect different commonly proposed design alternatives. The third option, using 0.100 m of water for a lunar mission, is a reference value because the protection is inferior compared to the other lunar options and it is insufficient to shield the crew cabin versus the expected radiation environment.

If avionics and power management and distribution masses are included, as shown in 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

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[19] See the fifth configuration in 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.

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 3.2.5, this will add an additional 4.24 kg/m^3 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/m^3 or 0.1092 m^3/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 ISS 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 to be 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, but a 100-kg pump mounted to the vehicle floor would have no associated secondary mass even 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 [$\text{kg}_{\text{Secondary Structure}}/\text{kg}_{\text{Equipment}}$]	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 possibilities. Historically, in low-Earth orbit, power is either stored in batteries or, alternatively, generated by non-regenerative fuel cells or 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 ISS technology both with and without energy storage, 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 operating while ISS is in sunlight, not operating while in shadow. For nominal calculations, ISS is in shadow for roughly 36 minutes of each 92 minute orbit at its median altitude. The third table entry assumes Shuttle nonregenerative 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 rised sharply as mission duration increases.

The power system for transit is a hybrid of deployable PV arrays with batteries and fuel cells. The latter provides power during mission phases in which the PV arrays are stowed (such as during an aerocapture maneuver). This system is prototypic of a power system for a small Eearth-Luna transit vehicle.

Providing continuous power on Luna using solar PV power generation requires considerable energy storage capacity for any non-polar surface site. 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 almost continuous power when 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 arrays may be costly and difficult to maintain in a dusty environment. Even more problematic than solar power generation on Mars would be solar power generation on 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, providing 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 certain mission variables, nuclear power options may be selected.

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 [20]	476 (1)	0.0021	Continuous Power with Deployable PV Cells [21]
Solar PV Power Generation without Power Storage [22]	239 (1)	0.0045	In Sun Power Only with Deployable PV Cells [23]
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)

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[20] The value includes significant structures to attach or rotate the solar photovoltaic panel clusters.

[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. 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$_e$ nuclear power system, will have a lower power-mass-penalty.

3.2.4 Thermal Energy Management Costs

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 use an external thermal control system without any evaporative cooling. The external thermal control system value for ISS 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 ISS external thermal control system masses.

Options for cooling habitats at a lunar surface site rely on horizontal radiators. Some options also use a vapor compression heat pump powered by a dedicated solar PV array. While the heat pump is only available as 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 use only radiators sized for the worst environmental conditions expected at an equatorial site—a moderate dust storm—and assume 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 may indicate (see Weaver and Westheimer [2002]). The technologies here are generally available but are far from optimal for specific applications.

- *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.*

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	Half of 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 (4)	~0.05	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 (4)	~0.033	As above with Composite, Flow-Through Radiators
Current Technology, *Space Stations:* ISS [24]	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 (4)	~0.0053	As above with Composite Radiators.
Flow-Through Radiators + Solar Vapor Compression Heat Pump (SVCHp)	77 (1)	0.013	Aluminum, Surface-Mounted Radiators with SVCHp
Lightweight, Flow-Through Radiators with Solar Vapor Compression Heat Pump	~72 (4)	~0.014	As above with Composite Radiators.
Surface – Mars	**kg/kW**	**kW/kg**	**Comments**
For an Equatorial Site using Vertical Radiators with Silver Teflon Coating			
Current Technology: Flow-Through Radiators 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) Estimated from Hanford and Ewert (1996) and Ewert, et al. (1999)

(2) Hanford and Ewert (1996)

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

(4) Estimated.

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.*

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

3.2.5 Crewtime Costs

Life support equipment requires crewtime for operations and maintenance. This crewtime can be small for some systems and large for others. Notably for functions related to food—food production, food product preparation, meal preparation, and waste disposal—the crewtime may be very large. The cost of crewtime is derived from the life support system 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.

3.2.6 Location Factors

Location factors [25] describe the additional resources necessary to move a kilogram of payload from low-Earth orbit to some location elsewhere in space. The additional resources here refer to propulsion assets such as engines, fuel, tankage, and associated propulsion-related structure. [26] Specifically, a location factor represents the additional mass necessary in low-Earth orbit [kg] to push a mass of payload [kg] to a particular destination. Location factors allow comparisons between cases where all payloads do not share the same transportation history. In other words, one payload option may stay entirely aboard one vehicle during the entire mission, while another payload option may jettison mass midway through the mission, reducing its associated propulsion costs for the remainder of the mission. Levri, et al. (2003) details use of location factors within equivalent system mass assessments.

Location factors for two destinations, Luna and Mars, are presented in Table 3.2.10. Estimates for Mars assume the Mars Dual Lander architecture, while estimates for Luna are based on a similar architecture using Luna as the destination. Both sets of estimates assume chemical propulsion and aero-braking when possible, which is current technology for human spaceflight within NASA. [27]

Table 3.2.10 Location Factors for Near-Term Missions

	Location Factor [kg/kg]		
Mission Element (Segment)	**Lower**	**Nominal**	**Upper**
Luna			
Lunar Transfer Vehicle (Full Trip)		7.36 (1)	
Lunar Transfer Vehicle (To Lunar Orbit Only)		5.09 (2)	
Lunar Lander (To Lunar Surface and back to Lunar Orbit)		12.78 (1)	
Lunar Lander (To Lunar Surface Only)		6.98 (1)	
Mars [28]			
Mars Transfer Vehicle (Full Trip)	6.77 (1)	6.77 (1)	11.14 (1)
Mars Transfer Vehicle (To Mars Orbit Only)	3.16 (2)	3.16 (2)	4.37 (2)
Mars Lander (To Martian Surface and back to Martian Orbit)	10.50 (1)	10.50 (1)	15.83 (1)
Mars Lander (To Martian Surface Only)	3.77 (1)	3.77 (1)	5.33 (1)

Reference

(1) Geffre (2003)
(2) Geffre (2004)

Transfer Vehicles travel from low-Earth orbit to either Luna orbit or Mars orbit, then return. The first estimate is for a complete trip to and from the celestial body listed, while the second estimate is for payloads that travel only to the celestial body listed, then remain behind when the Transfer Vehicle returns.

Landers travel from low-Earth orbit to either the Lunar or Martian surface and, in some cases, back to orbit. For example, within the Mars Dual Lander architecture are two landers. The first, the Mars Descent / Ascent Lander, travels to Martian orbit robotically. In orbit, the Mars Transit Vehicle will *rendezvous* with the Mars Descent/Ascent

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

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

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

[28] Mars Dual Lander architecture.

Lander and the crew transfers to the latter vehicle for the trip to the Martian surface. At the end of the surface stay, the Mars Descent / Ascent Lander returns the crew to Martian orbit and the Mars Transit Vehicle for the trip back to Earth. The second lander, the Surface Habitat Lander, travels and lands robotically on Mars. The crew transfers to the Surface Habitat Lander once they are on the surface. Thus, the Mars Descent/Ascent Lander represents a case in which any mass that stays on the vehicle throughout its mission travels all the way to the Martian surface and then back to Martian orbit. The Surface Habitat Lander, however, only travels to the Martian surface. [29]

Per Levri, et al. (2003), location factors multiply the equivalent system masses to which they apply. The location factors given in Table 3.2.10 have units of "kilograms of total vehicle in low-Earth orbit divided by kilograms of life support hardware in low-Earth orbit." Thus, an equivalent system mass corrected for location is the product of the equivalent system mass contributions due to the physical attributes of the hardware and the location factor.

Example: A piece of equipment with an equivalent system mass of 2.0 kg as payload on a Mars Transfer Vehicle would have an equivalent system mass corrected for location of 13.54 kg if it remains on board during the entire mission from Earth, to Mars, and back to Earth. Or, this value may be expressed as an equivalent system mass is 2.0 kg for the payload hardware and other payload equivalencies and an additional 11.54 kg in equivalent system mass for propulsion in low-Earth orbit to move the payload to Mars and back.

Alternatively, location factors in Table 3.2.10 may be expressed as ratios. Thus, the location factor for a full trip to and from Mars aboard a Mars Transfer Vehicle may be expressed as 5.77 kg of additional mass for propulsion in low-Earth orbit for every 1 kg of payload that travels to Mars and back, or, in shorthand notation, 5.77:1. Using this approach yields the same result as the second form in the example above.

3.3 Crew Characteristics

The primary purpose of the life support system is to maintain the crew, and particular 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 NASA (1991) [30]. 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 are 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 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 extended periods, 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 (EMU) (Metabolic data from Muller and Tobin, 1980.). Thus, EVA, as noted in Section 5.2, and exercise protocols can elevate metabolic rate. These data do 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.

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

[30] NASA has used these design values since, or before, the Space Station Freedom program.

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 [31] [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 Crewtime Estimates

Crewtime is an important commodity on any human mission. In fact, wise usage of crewtime is 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 the Biomass Subsystem and the associated Food Subsystem, 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.

Several of the categories in Table 3.3.3 deserve 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 daily attention (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, may 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.

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[31] 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 a Weightless Environment [32]

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	

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 weightless environment. [33] 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.

Table 3.3.4 Crewtime per Crewmember per Week

Mission Phase	Assumptions [CM-h/wk]		
	Lower	Nominal	Upper [34]
Transit/Weightlessness	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

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[32] 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 EVAs.

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

[34] 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.

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 possibilities 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 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 Fiscal Year 2001 Advanced Life Support Research and Technology Development Metric

	Assumptions [kg/CM-h]			
Mission	**Lower**	**Nominal**	**Upper**	**Reference**
Low Earth Orbit				Drysdale and Hanford (2002)
ISS, 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	

The second approach to determine CTMP values assumes 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, this value is a function of 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:

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

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

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

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

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

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 [35] of 0.869 during IVAs. The water loads include 0.345 kg/CM-d of metabolically generated water. Actual values depend on many factors, including physical workload, diet, and individual metabolism.

For a food system based on the Shuttle Training Menu, as detailed above, Levri (2002) lists the properties of the rehydration apparatus and conduction oven collectively as 36.3 kg occupying 0.094 m³ based on the Shuttle galley. During use, the rehydration apparatus consumes up to 0.540 kW to heat water. The conduction oven, when operational, consumes up to 0.360 kW for heaters and 0.060 kW for fans. Thus, the maximum total power load for the galley is 0.960 kW during operation.

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

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

Table 3.3.6 Summary of Nominal Human Metabolic Interface Values

Balance [36]	Interface	Units	Nominal Value
	Basis		
	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 [37]	kg/CM-d	0.617 [38]
+ E	Food Consumed; Energy Content	MJ/CM-d	11.82
+ m	Potable Water Consumed [39]	kg/CM-d	3.909 (1)
	Thermal		
– E	Total Metabolic Heat Load [40]	MJ/CM-d	11.82
	Sensible Metabolic Heat Load	MJ/CM-d	6.31
	Latent Metabolic Heat Load [41]	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 [42]		
– m	Fecal Water	kg/CM-d	0.091
– m	Respiration and Perspiration Water [43]	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)

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[36] Masses consumed by the crewmember are denoted by "+ *m*," while masses rejected by the crewmember are denoted by "- *m*." Likewise, energy entering the crewmember is denoted by "+ *E*," while energy rejected by the crewmember is denoted by "- *E*."

[37] This assumes a completely dehydrated or dry basis.

[38] Dry mass with no water content. Bourland (1998) gives a value of 0.674 kg/CM-d. (See Table 3.2.9).

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

[40] The total metabolic heat load is the summation of the sensible and latent metabolic heat loads.

[41] Assuming a latent heat for water of 2,420 kJ/kg.

[42] 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.

[43] 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 were collected and because people can live satisfactorily for extended periods 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 EMUs 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 [44]		
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 [45]	kPa	0.031 (6)	0.4 (3)	0.71 (6)
$p(CO_2)$ for Plants [47]	kPa	0.04 (4)	0.12 (5)	TBD
$p(O_2)$ for Crew	kPa	18.0 (6)	18.0 - 23.1 (6)	23.1 (6)
Total Cabin Pressure	kPa	48.0 (6) [46]	70.3 (3)	102.7 (6)
Temperature	K	291.5 (6)	295.2 (6)	299.8 (6)
Relative Humidity	%	25 (6)	60 (6)	70 (6)
Perspired Water Vapor	kg/CM-d	0.036 (7)	0.699 (7)	1.973 (7)
Respired Water Vapor	kg/CM-d	0.803 (7)	0.885 (7)	0.975 (7)
Leakage Rate (spaceflight)	%/d	0	0.05 (8)	0.14 (8)
Leakage Rate (test bed)	%/d	1 (9)	5 (9)	10 (9)

References

(1)	calculated based upon lower and upper metabolic rates.
(2)	NASA (1991)
(3)	Lin (1997)
(4)	Earth normal
(5)	accepted optimum for plant growth
(6)	Duffield (2003)
(7)	Boeing (2002)
(8)	computed from NASA (1998) and Boeing (1994)
(9)	Eckart (1996)

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 diem 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 diem basis (Perry, 1998). This

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

[45] 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.

[46] 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.

model (Perry, 1998) lists trace contaminant emissions accounting for greater than 97% 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 International Union of Pure and Applied Chemistry (IUPAC) name [47] of the compound in brackets, when it differs from the common name, along with the molecular weight (MW). Current spacecraft maximum allowable concentration (SMAC) requirements for these compounds may be found in Duffield (2003). 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 [48]

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

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

[48] From Perry (1998).

Table 4.1.3 Model for Trace Contaminant Generation from Cabin Equipment[49]

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}

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[49] 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 since 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. Since shipped fresh foodstuffs from crops are heavier than dehydrated or low-moisture foods due to the significant mass associated with natural moisture, plants will probably be grown on an extraterrestrial body. The proportion of food that will be grown locally versus what proportion will be shipped remains variable.

Table 4.2.1 Lighting Data

Parameter [Units]	**Low**	**Nominal**	**High**
Light Conversion Efficiency [$W_{\text{photosynthetically active radiation}}/W_{\text{electrical}}$] [50]	0.18 (1)	0.3 (2)	0.5 (1)
Light Delivery Efficiency [$PPF_{\text{delivered}}/PPF_{\text{emitted}}$] [51]	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 the necessary lighting. 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. Accordingly, many factors impact photosynthetically active radiation (PAR). Photosynthetic photon 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

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[50] Light Conversion Efficiency describes the proportion of lighting system power that eventually becomes PPF.

[51] Light Delivery Efficiency describes the proportion of PPF at the lamp surface that is delivered to the canopy.

lamps work well because they are red-rich, but the conversion efficiency is low. High-pressure discharge lamps produce more light, but the spectrum is not as photosynthetically efficient. 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 achieved a rating of approximately only 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/(m^2•s)	lamps/m^2	1.43 (3)	4.504 (4)	9.259 (3)
Time to Change Out Lamps	CM-h		0.03 (5)	
Photoperiod per Day [52]	h/d	10 (1)	10-24 [53]	24 (1)
Lamp Volume for Resupply	$m^3 \times 10^{-3}$		0.625 (1)	
Ballast Power	kW/lamp	0.03 (1)	0.06 (2)	0.08 (1)
Ballast Mass	kg/lamp	2.85 (6)	4.76 (1)	9.52 (2)
Ballast Life	10^3 h		88 (7)	
Mass of Coldplate, Water Barrier, Condensing Heat Exchangers per Growing Area	kg/m^2	4.43 (8) [54]	7.02 (8) [55]	25.83 (8) [56]
Height of Lighting Assembly	m		0.15 (9)	0.3 (1)
Lamp Resupply Mass Factor	kg/kg		0.8 (10)	
Lamp Resupply Volume Factor	m^3/m^3		0.5 (1)	

References

(1) Drysdale (1999a)
(2) Hanford (1997)
(3) Hunter and Drysdale (2002) based on Sager (1999)
(4) Hunter and Drysdale (2002) based on Ewert (1998)
(5) A rough value from Hunter, J.
(6) Ewert (2001)
(7) Barta and Ewert (2002)
(8) Ewert (1998)
(9) BIO-Plex drawings
(10) 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.

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

[53] See Table 4.2.6 for nominal photoperiods of candidate ALS crops.

[54] 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.

[55] 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.

[56] 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 may be adequate if extensive physical automation is planned. A higher number may 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. Therefore, 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 [57]	0.3 [59]	–	–	
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 an Integrated Test Facility*

Barta, et al. (1999) presents preliminary physical values for the first biomass production chamber of the now-suspended Bioregenerative Planetary Life Support Systems Test Complex (see Table 4.2.4).[58] 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. Interested readers should also consult Wheeler, et al. (2003) for crop-specific guidance using NASA's envisioned biomass production technologies.

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[57] Power consumption and thermal energy management within the shoot zone reflect fans for gas movement.

[58] *Editor's Note:* At this time, the scope and purpose of the integrated test stand to support hardware development within the ALS Project is under review. Because of prior programs such as the Bioregenerative Planetary Life Support Systems Test Complex (BIO-Plex), very precise values are available for some earlier facilities. The configuration and specifications in the actual ALS integrated testing facility, however, may differ from those listed here. The values here are likely representative of a bioregenerative research facility.

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) [59]	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	μmol/m^2•s	0	1,500	
Photoperiod	h	0	24	
Nutrient Solution pH [60]	–	3.0	8.0	
Nutrient Solution Conductivity	S/m	< 0	0.30	
Nutrient Solution Flow Rate /Growth Area	L/s•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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[59] 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.

[60] Potential of hydrogen (pH)

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

Shelf Location [61]	**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) [62], 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), and the values presented may be composite or average values from several different tests. These rates are lower partly because of the lower light levels, but a less homogeneous environment, due to the larger scale, may also impact the growth rates. 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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[61] 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.

[62] 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. Accordingly, 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 [63] [d_{AP}]	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. (2003)

(4) Wheeler (2001b)

(5) Ball, et al. (2001) and EDIS (2001)

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[63] Growth period is measured here in terms of “days after planting,” [d_{AP}].

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 $_{dw}$ /m^2•d]	Fresh Basis [g $_{fw}$ /m^2•d]	Fresh Basis Water Content [%]	Dry Basis [g $_{dw}$ /m^2•d]	Fresh Basis [g $_{fw}$ /m^2•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. (2003)

(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 [$g_{dw}/m^2 \bullet d$]		Carbon Content [%]	Metabolic Reactants and Products		
	Nominal	High		Oxygen (O_2) Production [$g/m^2 \bullet d$]	Carbon Dioxide (CO_2) Uptake [$g/m^2 \bullet d$]	Water (H_2O) Uptake / Transpiration [$kg/m^2 \bullet d$]
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		40 (3)	32.92	45.26	2.46
Peanut	22.50	36.0	60 (2)	35.84	49.28	2.77
Pepper	23.17		40	24.71	33.98	2.77
Radish	11.00		40 (2)	11.86	16.31	1.77
Red Beet	10.00		41	7.11	9.77	1.77
Rice	30.23	39.0	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

(3) Orcun and Wheeler (2003)

Table 4.2.9 Inedible Biomass Generation for Advanced Life Support Diets

				Diet Using Only ALS Salad Crops		Diet Using Salad and Carbohydrate Crops		Diet Using All ALS Crops	
Crop	**ALS Crop**	**Edible Biomass [g/m^2•d]**	**Inedible Biomass [g/m^2•d]**	**Diet Growing Area [m^2/CM]**	**Total Inedible Biomass [kg/CM-d]**	**Diet Growing Area [m^2/CM]**	**Total Inedible Biomass [kg/CM-d]**	**Diet Growing Area [m^2/CM]**	**Total Inedible Biomass [kg/CM-d]**
Cabbage	×	75.78	6.74	0.256	0.002	0.033	0.000	n/a	n/a
Carrot	×	74.83	59.87	0.488	0.029	0.535	0.032	0.536	0.032
Chard	×	87.50	37.69	n/a	n/a	n/a	n/a	n/a	n/a
Celery		103.27	11.47	n/a	n/a	0.073	0.001	n/a	n/a
Dry Bean	×	11.11	150.00	n/a	n/a	1.170	0.176	1.926	0.289
Green Onion		81.82	10.00	0.055	0.001	0.416	0.004	0.276	0.003
Lettuce	×	131.35	7.30	0.119	0.001	0.160	0.001	0.057	0.000
Mushroom				n/a	n/a	TBD	0.0013	n/a	n/a
Onion	×	81.82	22.50	n/a	n/a	n/a	n/a	n/a	n/a
Pea		12.20	161.00	n/a	n/a	0.311	0.050	n/a	n/a
Peanut	×	5.96	168.75	n/a	n/a	n/a	n/a	4.832	0.815
Pepper		148.94	127.43	n/a	n/a	0.208	0.027	n/a	n/a
Radish	×	91.67	55.00	0.098	0.005	n/a	n/a	0.164	0.008
Red Beet		32.50	35.00	n/a	n/a	n/a	n/a	n/a	n/a
Rice	×	10.30	211.58	n/a	n/a	n/a	n/a	2.078	0.440
Snap Bean		148.50	178.20	n/a	n/a	0.067	0.012	n/a	n/a
Soybean	×	5.04	68.04	n/a	n/a	n/a	n/a	46.429	3.159
Spinach	×	72.97	7.30	0.066	0.000	0.548	0.004	0.635	0.005
Strawberry		77.88	144.46	n/a	n/a	n/a	n/a	n/a	n/a
Sweet Potato	×	51.72	225.00	n/a	n/a	3.480	0.783	1.485	0.334
Tomato	×	173.76	127.43	0.265	0.034	1.209	0.154	1.642	0.209
Wheat	×	22.73	300.00	n/a	n/a	9.679	2.904	4.237	1.271
White Potato	×	105.30	90.25	n/a	n/a	1.614	0.146	0.994	0.090
Total				**1.35**	**0.07**	**19.50**	**4.29**	**65.29**	**6.66**

Plant environmental demands differ compared to the crew's requirements. For example, the optimum $p(CO_2)$ 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 $p(CO_2)$ 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 [64]	g_{acid}/g_{dw}	0.0548	0.0744	0.0428	0.0618	

Table 4.2.11 and Table 4.2.12 describe the major ionic components of the 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. Nitrogen may leave nutrient solution via volatilization as nitrogen gas or as nitrogen oxides. Finally, to inhibit ionic build-up within the nutrient solution due to the procedures outlined here, especially sodium or boron, the nutrient solution is often replaced at regular intervals.

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

Table 4.2.11 Composition of Initial Nutrient Solution

						Content		
Initial Ionic Component	**Important Element**	**Elemental Atomic Weight**	**Concentration [meq/L]** [65]	**Ion Molecular Weight**	**Valence**	**g/L (element)**	**g/L (ion)**	**Reference**
Nitrate, NO_3^{-}	Nitrogen, N	14.01	7.5	62.00	–1	0.1051	0.465	Wheeler, et al. (1996)
Phosphate, PO_4^{3-}	Phosphorous, P	30.97	0.5	94.97	–3	0.0465	0.142	
Potassium, K^{+}	Potassium, K	39.10	3	39.10	+1	0.1173	0.117	
Calcium, Ca^{2+}	Calcium, Ca	40.08	2.5	40.08	+2	0.2004	0.200	
Magnesium, Mg^{2+}	Magnesium, Mg	24.31	1	24.31	+2	0.0486	0.049	
Sulfate, SO_4^{2-}	Sulfur, S	32.06	1	96.06	–2	0.0641	0.192	
Total							**1.166**	

Table 4.2.12 Composition of Replenishment Nutrient Solution

						Content		
Replenishment Ionic Component	**Important Element**	**Elemental Atomic Weight**	**Concentration [meq/L]** [67]	**Ion Molecular Weight**	**Valence**	**g/L (element)**	**g/L (ion)**	**Reference**
Nitrate, NO_3^{-}	Nitrogen, N	14.01	75	62.00	–1	1.051	4.650	Wheeler, et al. (1997)
Phosphate, PO_4^{3-}	Phosphorous, P	30.97	7.5	94.97	–3	0.697	2.137	
Potassium, K^{+}	Potassium, K	39.10	68	39.10	+1	2.659	2.659	
Calcium, Ca^{2+}	Calcium, Ca	40.08	7.5	40.08	+2	0.601	0.601	
Magnesium, Mg^{2+}	Magnesium, Mg	24.31	9.8	24.31	+2	0.476	0.476	
Sulfate, SO_4^{2-}	Sulfur, S	32.06	9.8	96.06	–2	0.628	1.883	
Total							**12.406**	

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[65] 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) [66].

The MEC models calculate biomass production, on a dry-mass basis, as a function of photosynthetic photo flux, PPF, and the atmospheric carbon dioxide concentration, $[CO_2]$. [67] 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 [68] 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:

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

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

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

---

[66] 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.

[67] Other environmental and physiological factors may also vary. See Cavazzoni (2001) for complete details on this model.

[68] Photosynthetic photon flux (PPF) is commonly expressed in units of either µmol/(m²•s), as listed here, or mol/(m²•d), as denoted in Table 4.2.6. The units for PPF are related by the expression:

$$\text{PPF } [\mu\text{mol}/(\text{m}^2\bullet\text{s})] = \text{PPF } [\text{mol}/(\text{m}^2\bullet\text{d})] \times 1/H \times (1\text{ h}/3600\text{ s}) \times (10^6\ \mu\text{mol}/1\text{ mol})$$

where H is photoperiod [h/d]. See Table 4.2.27 for nominal values of H, which are designated H_O. Because units for PPF depend upon the duration during which crops receive photosynthetic irradiation, the conversion to a "per day" basis depends on the diurnal photoperiod per day.

The canopy quantum yield, CQY, [$\mu\text{mol}_{\text{Carbon Fixed}}/\mu\text{mol}_{\text{Absorbed PPF}}$] is defined by:

$$\begin{aligned} CQY &= CQY_{MAX} && \text{for } t \le t_Q \\ CQY &= CQY_{MAX} - (CQY_{MAX} - CQY_{MIN})\frac{(t - t_Q)}{(t_M - t_Q)} && \text{for } t_Q < t \le t_M \end{aligned}$$

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.

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:

$$\begin{aligned} CUE_{24} &= CUE_{MAX} && \text{for } t \le t_Q \\ CUE_{24} &= CUE_{MAX} - (CUE_{MAX} - CUE_{MIN})\frac{(t - t_Q)}{(t_M - t_Q)} && \text{for } t_Q < t \le t_M \end{aligned}$$

Equation 4.2-3

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

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

$$DCG = 0.0036\,\frac{s}{h}\,\frac{\text{mol}}{\mu\text{mol}} \times H \times CUE_{24} \times A \times CQY \times PPF$$

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, [$\text{mol}_{O_2}/\text{m}^2\bullet\text{d}$] may be computed using:

$$DOP = OPF \times DCG$$

Equation 4.2-5

where OPF is the oxygen production fraction [$\text{mol}_{O_2}/\text{mol}_{\text{Carbon}}$], which is a crop specific parameter.

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

$$CGR = MW_C\,\frac{DCG}{BCF}$$

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

$$TCB = \int_0^{t_M} CGR\,dt$$

Equation 4.2-7

Total edible biomass, on a dry basis, TEB [g/m^2], may be estimated by integrating the product of CGR and the fraction of daily carbon gain allocated to edible biomass, XFRT, from time storage organs begin to form, t_E [d_{AE}]. Both XFRT and t_E are tabulated below:

$$TEB = XFRT\int_{t_E}^{t_M} CGR\,dt$$

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}/m²•d	daily carbon gain	Equation 4.2-4
DOP	mol_{O_2} /m²•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, on a dry basis	Equation 4.2-7
TEB	g/m²	total edible biomass, on a dry basis	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 [69]

Crop	**Specific Cultivar**	**CQY_{MIN} [$\mu mol_{C\ Fixed}$ / $\mu mol_{Ab.\ PPF}$]**	**CUE_{MAX}**	**CUE_{MIN}**
Dry Bean	*Meso Amer. Hab. 1 – Determinate*	0.02	0.65	0.50 [70]
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} [$\mu mol_{Carbon\ Fixed}/\mu mol_{Absorbed\ PPF}$], have the general form:

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

Equation 4.2-9

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.

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

[70] 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**
$1/[CO_2]$	$1/PPF \times 1/[CO_2]$ or C_1	$1/[CO_2]$ or C_6	$PPF/[CO_2]$ or C_{11}	$PPF^2/[CO_2]$ or C_{16}	$PPF^3/[CO_2]$ or C_{21}
1	1/PPF or C_2	Constant Term	PPF or C_{12}	PPF^2 or C_{17}	PPF^3 or C_{22}
$[CO_2]$	$[CO_2]/PPF$ or C_3	$[CO_2]$ or C_8	$PPF\ [CO_2]$ or C_{13}	$PPF^2\ [CO_2]$ or C_{18}	$PPF^3\ [CO_2]$ or C_{23}
$[CO_2]^2$	$[CO_2]^2/PPF$ or C_4	$[CO_2]^2$ or C_9	$PPF\ [CO_2]^2$ or C_{14}	$PPF^2\ [CO_2]^2$ or C_{19}	$PPF^3\ [CO_2]^2$ or C_{24}
$[CO_2]^3$	$[CO_2]^3/PPF$ or C_5	$[CO_2]^3$ or C_{10}	$PPF\ [CO_2]^3$ or C_{15}	$PPF^2\ [CO_2]^3$ or C_{20}	$PPF^3\ [CO_2]^3$ or C_{25}

The coefficients for CQY_{MAX} are independent of photoperiod and planting density and are only a weak function of temperature regime. Consequently, 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:

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

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:

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

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

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

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 [$mol_{Water}/m^2\bullet s$].

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

The following models for g_S and values for g_A were derived from the experimental conditions studied by Monje (1998).

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 [71]
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; model variable	none [72]
H_O	h/d	nominal 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
PPF_E	$\frac{\mu mol_{Photon}}{m^2 \bullet s}$	effective photosynthetic photon flux	Equation 4.2-18
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

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

[72] For the nominal case, assume the photoperiod, H, equals the nominal photoperiod, H_O, which is listed in Table 4.2.27.

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:

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

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

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.

Note: Some values in Table 4.2.27 differ from the corresponding values listed in Table 4.2.6.

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

Crop	**Nominal Photoperiod H_O [h/d]**	**Planting Density [73] [plants/m²]**	**Light Cycle Temperature, T_{LIGHT} [°C]**	**Dark Cycle Temperature, T_{DARK} [74] [°C]**
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

---

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

[74] 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[75]	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[77]	120
Tomato	0.70	41	56	80
Wheat	1.00	34	33	62
White Potato	1.00	45	75	138[76]

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

Crop	Biomass Carbon Fraction, BCF	Oxygen Production Fraction $[\text{mol } O_2/\text{mol C}]$
Dry Bean	0.45	1.10
Lettuce	0.40	1.08
Peanut	0.50	1.19
Rice	0.44	1.08
Soybean	0.46	1.16
Sweet Potato	0.44	1.02
Tomato	0.42	1.09
Wheat	0.44	1.07
White Potato	0.41	1.02

The functions for the canopy closure time, t_A $[d_{AE}]$, have the general form:

$$\begin{aligned} t_A(PPF_E, [CO_2]) = {} & C_1 \frac{1}{PPF_E}\frac{1}{[CO_2]} + C_2 \frac{1}{PPF_E} + C_3 \frac{[CO_2]}{PPF_E} + C_4 \frac{[CO_2]^2}{PPF_E} + C_5 \frac{[CO_2]^3}{PPF_E} \\ & + C_6 \frac{1}{[CO_2]} + \text{Constant} + C_8 [CO_2] + C_9 [CO_2]^2 + C_{10} [CO_2]^3 + C_{11} \frac{PPF_E}{[CO_2]} \\ & + C_{12} PPF_E + C_{13} PPF_E [CO_2] + C_{14} PPF_E [CO_2]^2 + C_{15} PPF_E [CO_2]^3 + C_{16} \frac{PPF_E^2}{[CO_2]} \\ & + C_{17} PPF_E^2 + C_{18} PPF_E^2 [CO_2] + C_{19} PPF_E^2 [CO_2]^2 + C_{20} PPF_E^2 [CO_2]^3 + C_{21} \frac{PPF_E^3}{[CO_2]} \\ & + C_{22} PPF_E^3 + C_{23} PPF_E^3 [CO_2] + C_{24} PPF_E^3 [CO_2]^2 + C_{25} PPF_E^3 [CO_2]^3 \end{aligned} \qquad \text{Equation 4.2-17}$$

where C_1 through C_{25} denote coefficients. PPF_E is expressed in [µmol/m²•s], while $[CO_2]$ is measured in $\left[\frac{\mu\text{mol}_{CO_2}}{\text{mol}_{Air}}\right]$. 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 using the form of Table 4.2.16 above.

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[75] This crop is harvested before the canopy reaches senescence.

[76] White potato plants are harvested at $t = 105\ d_{AE}$, but $t_M = 138\ d_{AE}$ is used for the models.

The effective photosynthetic photon flux, PPF_E [μmol/m²•s], (Rodriguez and Bell, 2004) is:

$$PPF_E = PPF\left(\frac{H}{H_O}\right)$$

Equation 4.2-18

where values for nominal photoperiod, H_O [h/d], are tabulated in Table 4.2.27.

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

	$1/PPF_E$	1	PPF_E	PPF_E^2	PPF_E^3
$1/[CO_2]$	2.9041×10^5	0	0	0	0
1	1.5594×10^3	15.840	6.1120×10^{-3}	0	0
$[CO_2]$	0	0	0	-3.7409×10^{-9}	0
$[CO_2]^2$	0	0	0	0	0
$[CO_2]^3$	0	0	0	0	9.6484×10^{-19}

Table 4.2.31 Canopy Closure Time, t_A, Coefficients for Lettuce with Nominal Conditions

	$1/PPF_E$	1	PPF_E	PPF_E^2	PPF_E^3
$1/[CO_2]$	0	0	1.8760	0	0
1	1.0289×10^4	1.7571	0	0	0
$[CO_2]$	-3.7018	0	0	0	0
$[CO_2]^2$	0	2.3127×10^{-6}	0	0	0
$[CO_2]^3$	3.6648×10^{-7}	0	0	0	0

Table 4.2.32 Canopy Closure Time, t_A, Coefficients for Peanut with Nominal Conditions

	$1/PPF_E$	1	PPF_E	PPF_E^2	PPF_E^3
$1/[CO_2]$	3.7487×10^6	-1.8840×10^4	51.256	-0.05963	2.5969×10^{-5}
1	2.9200×10^3	23.912	0	5.5180×10^{-6}	0
$[CO_2]$	0	0	0	0	0
$[CO_2]^2$	0	0	0	0	0
$[CO_2]^3$	9.4008×10^{-8}	0	0	0	0

Table 4.2.33 Canopy Closure Time, t_A, Coefficients for Rice with Nominal Conditions

	$1/PPF_E$	1	PPF_E	PPF_E^2	PPF_E^3
$1/[CO_2]$	6.5914×10^6	-3.748×10^3	0	0	0
1	2.5776×10^4	0	0	4.5207×10^{-6}	0
$[CO_2]$	0	-0.043378	4.562×10^{-5}	-1.4936×10^{-8}	0
$[CO_2]^2$	6.4532×10^{-3}	0	0	0	0
$[CO_2]^3$	0	0	0	0	0

Table 4.2.34 Canopy Closure Time, t_A, Coefficients for Soybean with Nominal Conditions

	$1/PPF_E$	1	PPF_E	$PPF_E^{\ 2}$	$PPF_E^{\ 3}$
$1/[CO_2]$	6.7978×10^{6}	-4.326×10^{4}	112.63	-0.13637	6.6918×10^{-5}
1	-4.3658×10^{3}	33.959	0	0	-2.1367×10^{-8}
$[CO_2]$	1.5573	0	0	0	1.5467×10^{-11}
$[CO_2]^{2}$	0	0	-4.911×10^{-9}	0	0
$[CO_2]^{3}$	0	0	0	0	0

Table 4.2.35 Canopy Closure Time, t_A, Coefficients for Sweet Potato with Nominal Conditions

	$1/PPF_E$	1	PPF_E	$PPF_E^{\ 2}$	$PPF_E^{\ 3}$
$1/[CO_2]$	1.2070×10^{6}	0	0	0	4.0109×10^{-7}
1	4.9484×10^{3}	4.2978	0	0	0
$[CO_2]$	0	0	0	0	2.0193×10^{-12}
$[CO_2]^{2}$	0	0	0	0	0
$[CO_2]^{3}$	0	0	0	0	0

Table 4.2.36 Canopy Closure Time, t_A, Coefficients for Tomato with Nominal Conditions

	$1/PPF_E$	1	PPF_E	$PPF_E^{\ 2}$	$PPF_E^{\ 3}$
$1/[CO_2]$	6.2774×10^{5}	0	0.44686	0	0
1	3.1724×10^{3}	24.281	5.6276×10^{-3}	-3.0690×10^{-6}	0
$[CO_2]$	0	0	0	0	0
$[CO_2]^{2}$	0	0	0	0	0
$[CO_2]^{3}$	0	0	0	0	0

Table 4.2.37 Canopy Closure Time, t_A, Coefficients for Wheat with Nominal Conditions

	$1/PPF_E$	1	PPF_E	$PPF_E^{\ 2}$	$PPF_E^{\ 3}$
$1/[CO_2]$	9.5488×10^{4}	0	0.3419	-1.9076×10^{-4}	0
1	1.0686×10^{3}	15.977	1.9733×10^{-4}	0	0
$[CO_2]$	0	0	0	0	0
$[CO_2]^{2}$	0	0	0	0	0
$[CO_2]^{3}$	0	0	0	0	0

Table 4.2.38 Canopy Closure Time, t_A, Coefficients for White Potato with Nominal Conditions

	$1/PPF_E$	1	PPF_E	$PPF_E^{\ 2}$	$PPF_E^{\ 3}$
$1/[CO_2]$	6.5773×10^{5}	0	0	0	0
1	8.5626×10^{3}	0	0.042749	-1.7905×10^{-5}	0
$[CO_2]$	0	0	8.8437×10^{-7}	0	0
$[CO_2]^{2}$	0	0	0	0	0
$[CO_2]^{3}$	0	0	0	0	0

For certain crops under low-lighting conditions, the relationships above for t_A and A_{MAX} require modification. Physically, the canopy does not close under low light, so A_{MAX} does not reach 0.93, for the nominal photoperiod and planting densities listed in Table 4.2.27. Consequently, 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 Food Flight Systems

The crew food energy requirement will depend on the crew itself, its lean body mass in particular, and the amount of physical work it performs. 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 Duffield (2003) and derived from NASA (1991).

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

Food quality is not specifically discussed here, because this topic is addressed when the Food Subsystem is designed. However, food quality can have a tremendous impact on crew morale and the success of a long-duration mission. The mass of food also depends on food quality. 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 with the Food Subsystem. 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 the values presented in Table 4.3.1 are historical or predicted averages for indicated programs and, therefore, may or may not provide 11.82 MJ/CM-d of metabolic energy.

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

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

Table 4.3.1 Historical and Near-Term Food Subsystem Masses

Parameter	Mass [kg/CM-d]	Volume [m^3/CM-d]	Comments	Water Content [%]	References
IVA Food, dw	0.67 (1)		A Reference Value	0 (1)	Information from Bourland (1998) or Vodovotz (1999), except as noted. (1) NASA (1995), Section 7.2.2.2.3 (2) Levri (2002) (3) Perchonok, et al. (2002)
Space Transportation Food System					
STS Food [77]	0.66 (2)		Food Dehydrated, 11.82 MJ/CM-d	0 (2)	
	1.147 (2)		Food As-Shipped, No Packaging, 11.82 MJ/CM-d	42 (2)	
	0.26 (2)		Packaging Alone (clean)		
	0.35 (2)		Container Mass (ISS “Pantry-style storage”) without secondary structure [78]		
	1.76 (2)	0.0048 (2)	Food As-Shipped, Packaged (ISS “Pantry-style storage”), and within a Container	42 (2)	
International Space Station Food Systems					
Phase II [79]	1.83 (3)	TBD	Food As-Shipped, Packaged with Food Container	TBD	
Phase III [80]	1.955		Food As-Shipped, No Packaging	66	
	0.345		Packaging Alone		
	2.3	0.006570	Food As-Consumed, Packaged		

4.3.2 Physical Parameters of Refrigeration Equipment

Table 4.3.2 presents characteristics for the ISS refrigerator / freezer technology. These units were 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.

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 freezer mode, all four compartments operate as freezers; in refrigerator mode, all four compartments operate as refrigerators; and in refrigerator/freezer mode, two compartments operate as refrigerators while the other two operate as freezers. The overall 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 ground servicing provided once a year.

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[77] Shuttle food systems are provided for reference only. They do not meet nutritional requirements for long-duration space flight. (For example, while this diet meets all minimum nutritional requirements, it exceeds the limit for sodium and iron for a weightless diet.) These food systems do not use any refrigeration.

[78] Historically, Bourland (1999) reports an empty food locker has 6.4-kg mass. Filled, this locker holds up to 42 meals (Perchonok, et al., 2002) (overall filled locker mass: 24.5 kg [Bourland, 1999], equivalent to 0.583 kg/meal, or 1.75 kg/CM-d). The Shuttle food system is shelf-stable without frozen components. Assessments (Levri, 2002) assume ISS pantry-style storage and not Shuttle lockers.

[79] ISS Assembly Phase food system. This system is shelf stable.

[80] 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 m^3 of refrigerated storage is required.

Table 4.3.2 International Space Station Refrigerator/Freezer Properties

	Units	Freezer Mode	Refrig./Freezer Mode
Unit Mass	kg	321.0 (1)	321.0 (1)
Secondary Structure Mass	kg	91 (2)	91 (2)
Volume, Including Rack	m^3	2.00 (3)	2.00 (3)
Volume, Without Rack	m^3	1.16 (3)	1.16 (3)
Power	kW	0.268 (4)	0.205 (4)
Thermal Energy Management	kW	0.297 (4)	0.228 (4)
Crewtime	CM-h/y	0 (1)	0 (1)
Logistics	kg/y	321.0 (1)	321.0 (1)
Internal Load	kg	295 (1)	295 (1)
Internal Volume	m^3	0.614 (1)	0.614 (1) [81]

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 weightlessness and acoustics (Ewert, 2002a).

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

		Assumptions		
Characteristic	**Units**	**Low**	**Nominal**	**High**
$1/COP_S$	$\frac{kW_{electrical}}{kW_{thermal}}$	0.5 (1)	1.0 (1)	9.2 (1)
$1/R_S$	kW/m^2•K × 10^{-3}	0.28 (1)	0.32 (1)	0.32 (1)
Mass [82]	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$_{ffm}$ × 10^{-3}			6.78
External Volume, Excluding Rack	m^3		1.16 (4)	
	m^3/kg$_{ffm}$ × 10^{-3}		3.93	
Power	kW	0.048 (1)	0.096 (1)	0.268 (1)
	kW/kg$_{ffm}$ × 10^{-3}	0.16	0.33	0.91
Thermal Energy Management	kW	0.053 (1)	0.106 (1)	0.297 (1)
	kW/kg$_{ffm}$ × 10^{-3}	0.18	0.36	1.01
Crewtime	CM-h/y	0.0	0.0	0.0
	CM-h/(y•kg$_{ffm}$)	0.0	0.0	0.0
Logistics	kg/y	0.0	0.0	321 (2)
	kg/(y•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)

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

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

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.

$$\hat{W}_{RF} = 1.028\left(\frac{1}{R_S}\right)\left(\frac{1}{COP_S}\right) \qquad \text{Equation 4.3-1}$$

4.3.3 Crewtime for the Food Subsystem

Overall crewtime requirements in the galley depend on the form in which food is shipped and food 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 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 an average of 30 minutes to prepare, a diet based on crops grown on-site would require 5.0 CM-h/d, or 0.83 CM-h/CM-d, assuming a crew of six. Daily meals prepared completely from resupplied foods would require 1.0 CM-h/d, or 0.17 CM-h/CM-d. Assuming five dishes are prepared from crops grown on site and five dishes are prepared from resupplied stocks, daily meal preparation time would be 3.0 CM-h/d or 0.50 CM-h/CM-d.

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

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

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 to its packaging and due to plate wastage. Waste model values are noted below and in Section 4.5.4.7 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 Subsystem 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 [83]	kg/CM-d	0.54 (8)	0.617 (1)	0.66 (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 [84]	kg/CM-h		+ 0.029 (4)	
EVA Metabolic Water Production added [86]	kg/CM-h		+ 0.016 (4)	
EVA Energy added [86]	MJ/CM-h		+ 0.570 (5)	
EVA Potable Water Consumption	kg/CM-h			0.24 (1)
Packaging [85]	kg/kg		+ 15 %	
Crewtime	CM-h/d	1 – 1.5 (6)	1.5 (6)	4.6+ (7)[86]

References

(1) NASA (1991)
(2) Levri (2002)
(3) Perchonok (2001) and NASA (1991)
(4) Derived from McBarron, et al. (1993); metabolic rate of 293 W/CM and a respiratory quotient of 0.9.
(5) Rouen (2001)
(6) NASA (1996)
(7) Kloeris, et al. (1998)
(8) Lange and Lin (1998)

4.3.6 Food Subsystems 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 are available. The three diets presented here assume differing availabilities for crops grown on-site. 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 may include moving small amounts of crops from the list to be grown and into the resupplied mass, especially for those items (such as rice) that are prepared for consumption without post-growth processing operations that will reduce the total edible biomass from the original crop. All diets are comparable in nutritional content to the ISS Assembly Complete food system.

Table 4.3.5 provides wet or fresh masses for the dietary components, as received from the Biomass Subsystem 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 may include moving small amounts of crops from the list to be grown and into the resupplied mass, especially for those items (such as rice) that are prepared for consumption without post-growth processing operations that will reduce the total edible biomass from the original crop. All diets are comparable in nutritional content to the ISS Assembly Complete food system.

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[83] On a dry mass (dw) basis.

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

[85] Packaging accounts for individual food packages only. Secondary structure, lockers, and trays are additional.

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

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** [87]	**Diet Using Salad and Carbohydrate Crops** [88]	**Diet Using All ALS Crops** [89]
Cabbage	0.0194	0.0025	n/a
Carrot	0.0365	0.040	0.0401
Celery	n/a	0.0075	n/a
Dry Bean, incl. 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 [90]	1.1581	2.1	0.6053
Resupplied Foodstuffs	1.168 [91]	0.5 [93, 92]	0.0944
Total	**2.462**	**3.6**	**1.70**
Potable Water [93]	2.0	2.0	2.0
Food Processing Waste	TBD	TBD	0.094

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

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

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

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

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

[92] 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.

[93] 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 [89]	Diet Using Salad and Carbohydrate Crops [90]	Diet Using All ALS Crops [91]
Energy	MJ/CM-d	11.82 [94]	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 [95]	925.557	812	545
Iron, Fe	mg/CM-d	≤ 10 [97]	19.2385	21.5	17.23
Magnesium, Mg	mg/CM-d	350 [97]	294.687	386	376.48
Phosphorous, P	mg/CM-d	≤ 1.5 Ca intake [97]	1,440.68	1,356	1,079.52
Potassium, K	mg/CM-d	~ 3,500 [97]	3,316.57	3,723	3,179.86
Sodium, Na	mg/CM-d	1,500 – 3,500 [97]	3,909.56	3,600	3,205.96
Zinc, Zn	mg/CM-d	15 [97]	12.8077	10	7.5
Dietary Fiber	g/CM-d	10 – 25 [97]	25.1129	33.3	28.5
Percentage of Energy Contributed to Diet					
Carbohydrate	%	50 – 55 [97]	55.5	61	68.1
Fat	%	30 – 35 [97]	28.7	27	22.4
Protein	%	12 – 15 [97]	16.2	12	12

The Diet Using Only ALS Salad Crops (Hall, et al., 2000) is aimed at near-term missions and supplements the 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 the practical minimum wastage rate of resupplied food for situations in which the crew attempts to eat all of the food with which they are supplied is 3 % by mass. This remaining 3 % of the food mass adheres to the inside of the food packaging.

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[94] From NASA (1991).

[95] 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.[96] 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 (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[97]	Low Moisture Content Menu[99]	Menu Containing Some Frozen Food[99]
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[98]				
Locker Mass	kg/CM-d	0.35	0.32	0.25
Locker Volume	m³/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	m³/CM-d	n/a	n/a	0.00231
IVA Food and Packaging Waste				
Trash Mass	kg/CM-d	0.33	0.32	0.29

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

[97] From Levri (2002). The values here include material that normally clings to food packaging and is discarded.

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

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 [99]	Low Moisture Content Menu [101]	Menu Containing Some Frozen Food [101]
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 [100]	g/CM-d	466	248	690
Rehydration Water	g/CM-d	1,227	1,255	982
Additional Drinking Water [101]	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 that 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.

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[99] From Levri (2002). The values here are based on food "as consumed" by a crewmember, excluding material that normally clings to the food packaging.

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

[101] 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 neither measured nor assumed.

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

	Average Production Based on Consumption, Fresh Mass [kg/CM-d]			
Crop	**Diet Using Shuttle Training Menu and ALS Salad Crops** [102]	**Diet Using Low Moisture Content Menu and ALS Salad Crops** [104]	**Diet Using ISS Assembly Complete Menu with Some Frozen Food and ALS Salad Crops** [104]	**Diet Using Shuttle Training Menu and ALS Salad Crops plus Potato** [104]
Cabbage	0.0107	0.0107	0.0107	0.0107
Carrot	0.0357	0.0357	0.0357	0.0357
Celery	n/a	n/a	n/a	n/a
Dry Bean, inc. lentil and pinto	n/a	n/a	n/a	n/a
Green Onion	n/a	n/a	n/a	n/a
Lettuce	0.0097	0.0097	0.0097	0.0097
Mushroom	n/a	n/a	n/a	n/a
Pea	n/a	n/a	n/a	n/a
Peanut	n/a	n/a	n/a	n/a
Peppers	n/a	n/a	n/a	n/a
Radish	0.0114	0.0114	0.0114	0.0114
Rice	n/a	n/a	n/a	n/a
Snap Bean	n/a	n/a	n/a	n/a
Soybean	n/a	n/a	n/a	n/a
Spinach	0.0134	0.0134	0.0134	0.0134
Sweet Potato	n/a	n/a	n/a	n/a
Tomato	0.0143	0.0143	0.0143	0.0143
Wheat	n/a	n/a	n/a	n/a
White Potato	n/a	n/a	n/a	0.0840
Crop Sub Total	**0.0953**	**0.0953**	**0.0953**	**0.1793**
Rehydration Water [103]	1.2173	1.2455	0.9744	1.1822
Resupplied Foodstuffs [104]	1.1030	0.8831	1.3200	1.0703
Total	**2.4154**	**2.2239**	**2.3897**	**2.4319**
Drinking Water [105]	1.058	1.246	1.079	1.050
Food Processing Waste [106]	0.0371	0.0303	0.0438	0.0386

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[102] 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. Crewmembers consume all other masses in this table except for wasted mass.

[103] Water for rehydration only. Water for clean-up is not included. Water tankage is not included.

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

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

[106] 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 [107]	Diet Using Low Moisture Content Menu and ALS Salad Crops [109]	Diet Using ISS Assembly Complete Menu with Some Frozen Food and ALS Salad Crops [109]	Diet Using Shuttle Training Menu and ALS Salad Crops plus Potato [109]
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 [108]	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) provide estimates for salad servings based on preliminary menus for early mission scenario testing. This overall approach assumes a prepackaged food system augmented with grown salad crop, and the diet is analogous to the Diet Using Only ALS Salad Crops from Hall, et al. (2000). Note Table 4.3.11 provides inputs only for the dietary contributions derived directly from the vegetables. The supporting prepackaged food items are not included.

Perchonok, et al. (2002) assumes:

- Salad is served four times per week.
- Raw carrots are served as a snack once per week.
- Steamed carrots are served once per week.
- Steamed or raw spinach is served once per week.
- Bok choy can be served as cole slaw once per week.

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[107] 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.

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

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 [109] [g]	Number per Week	Serving Rate [110] [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 [112] [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 analog testing, from outside the facility), and prepared to provide food.

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

4.4 Thermal Management

Thermal management, in terms of its most direct impact on a spacecraft, maintains temperatures throughout the vehicle. Or, from another perspective, thermal energy, or heat, transfers from regions of high temperature to regions of low temperature. The thermal management hardware regulates when and how thermal energy transfers from regions of high temperature within the spacecraft to regions of low temperature outside of the spacecraft so that all components within the spacecraft are maintained between their prescribed temperature limits. Specifically, thermal management does not directly address heating associated with aerodynamic drag, although aerodynamic heating may impose greater

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[109] Mass "as prepared."

[110] 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.

thermal loads for the thermal management hardware, such as when heat conducts through the vehicle structure and into the crew cabin. Heating generated by aerodynamic drag is managed by the thermal protection system.

4.4.1 Heat Transfer Mechanisms

An outline of underlying mechanisms of heat transfer can be beneficial in understanding heat management technology, so a brief explanation of heat transfer mechanisms is detailed below. However, please see Incropera and DeWitt (1985), the primary reference for this section, for a more thorough discussion.

Physically, heat transfers from high to low temperature via one of three distinct mechanisms. These mechanisms are conduction, convection, and radiation. Heat transfer with a phase change is sometimes discussed separately and may be viewed as a fourth heat transfer mechanism [111].

4.4.1.1 Conduction

Conduction describes the transfer of heat within matter by diffusion, or heat transfer through matter in the absence of macroscopic bulk motion of the matter. An example is heat moving up the shaft of a metal spoon sitting in a heated pot on a stove. The thermal energy, which is expressed as vibrational, rotational, and translational energy on atomic scales, is transferred from more-quickly vibrating atoms closer to the heated surface to less-quickly vibrating atoms further from the heated surface by interactions between adjacent atoms.

4.4.1.2 Convection

Convection describes the transfer of heat in which matter acquires heat, by close molecular interaction, such as is described above for conduction, then bulk motion of that matter carries both the matter and thermal energy away from its location of origin. For example, heat may diffuse from hotter metal to an adjacent cooler moving fluid, then the bulk motion of the moving fluid carries the heat away from its origin. Likewise, the reverse process, that of transferring heat from a hot moving fluid to a cooler solid, is also convection.

4.4.1.3 Radiation

Radiant heat transfer is an exchange of heat between two surfaces without any intervening matter. Specifically, heat transfers from one surface to another surface that it can “see” simply by virtue of a temperature difference between the two surfaces. In a perfect vacuum, which is approximated in free space, no intervening matter is present to convey heat from one surface to another by either conduction or convection, yet heat does transfer from a hotter surface to a cooler surface via electromagnetic waves in the mechanism called radiation. Warm spacecraft reject their thermal loads from relatively hot surfaces to relatively cold space by radiant heat transfer. Please note that while radiation also describes the mechanism by which other forms of energy, such as solar particles and x-rays, pass through a vacuum, thermal radiation merely transfers heat and has no additional mutagenic effect on biological creatures exposed to it. Please note also that while radiant transfer is generally of the greatest importance in a vacuum, radiant transfer occurs in all situations where two surfaces that can “see” each other are at different temperatures, even if, for example, a fluid fills the gap between those two surfaces and heat is transferred to or from the surfaces also by conduction and/or convection. [112]

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[111] As noted below, phase change represents a special case of one of the three heat transfer mechanisms with the additional stipulation that one of the participating materials changes its physical state as a result of gaining or losing heat. However, even though phase change is not a unique mechanism, it is sometimes useful to distinguish heat transfer operations with phase change from other heat transfer operations.

[112] Within a pressurized crew cabin, though all three heat-transfer mechanisms are active, conduction and/or convection usually dominate compared to radiant exchange. Physically, the driving potentials for conduction and convection heat transfer are proportional to the simple difference in temperature while the driving potential for radiant heat transfer is proportional to the difference in temperature to the fourth power. Within the crew cabin, coupled with appropriate transport properties, conduction and convection are greater in magnitude than corresponding radiant exchanges. Thus, within a crew cabin, analysts often neglect radiant exchange with only a minor loss in accuracy. As a cautionary note, there are situations, especially within terrestrial industry, in which radiant exchange is significant or dominates as the preferred heat transfer mechanism even when conduction and/or convection are also viable modes. Please see Incropera and DeWitt (1985) for a more expansive discussion.

4.4.1.4 Heat Transfer with Phase Change

Phase change describes heat transfer when matter accepts or discharges heat and changes its physical state. Though it is mentioned here separately, phase change is really a specialized case of one of the three heat transfer mechanisms in which matter changes state. As an example, when water boils in a stovetop pan, liquid water approaches the bottom of the heated pan and leaves in the form of steam bubbles after accepting heat. This change is really heat transfer by convection with the matter undergoing bulk motion and changing its state from liquid to vapor upon accepting heat from the solid. Likewise, phase change may occur in situations without bulk motion, such as when butter melts between two slices of hot bread, which is an example of conduction with phase change of a participating conducting material.

4.4.2 Thermal Management Organization

Thermal management may be subdivided in several ways. One organization classifies thermal management as either passive or active. Passive thermal management hardware encourages or inhibits heat transfer as the heat passes directly through the hardware and eventually to the external environment, radiating from the vehicle's entire external surface. Active thermal management hardware acquires thermal loads near where the loads are generated and then transports those loads to some other portion of the vehicle before the loads are discharged to the environment by specifically designed radiating surfaces.

4.4.2.1 Passive and Active Thermal Management

Thermal management hardware may be classified as either passive or active. As outlined below, passive thermal management hardware is generally integrated into the vehicle structure and retards the flow of thermal energy either in to or out of the vehicle. Active thermal management hardware acquires thermal loads at or near their point of generation and transports those loads to the exterior of the vehicle for rejection.

4.4.2.1.1 PASSIVE THERMAL MANAGEMENT

Passive thermal management hardware controls heat leakage from the vehicle and maintains cabin walls within prescribed temperature bounds. Passive thermal management hardware is deployed within the vehicle structure and generally takes the form of insulation and resistive heaters. Insulation impedes the transfer of heat either in to and out of the vehicle while resistive heaters allow active control of the wall temperatures when completely passive approaches are inadequate. Because passive thermal management hardware is generally incorporated into the vehicle structure, it is included within mass penalties for the vehicle structure.

4.4.2.1.2 ACTIVE THERMAL MANAGEMENT

Active thermal management hardware removes excess thermal loads from within the vehicle to the environment by physically transporting those loads from their site of generation to an appropriate rejection site. Active thermal management is comprised of three basic processes. These are: acquisition of thermal energy, transport of thermal energy, and rejection of thermal energy. Acquisition hardware is comprised of fans, coldplates, and condensing heat exchangers for primary functionality. Transport hardware can use, theoretically, any mechanism. Historically, for human spacecraft, transport relies on a liquid working fluid constrained within an enclosed flow channel, using the convection heat transfer mechanism to take loads from acquisition devices and to release loads to rejection devices. [113] Using this architecture, transport hardware consists of fluid tubes or pipes, pumps, accumulators, and valves. The working fluid may be two-phase, but NASA has typically employed single-phase working fluids. Finally, rejection hardware may be radiators, devices that reject expendable materials carrying thermal loads, such as a flash evaporator or a sublimator, or phase change devices such as packages containing phase change materials. Thermal management infrastructure penalties generally represent active thermal management hardware.

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[113] It is possible to foresee thermal transport using either conduction or radiant heat transfer. For short distances, relatively small thermal loads, or even highly temperature-tolerant equipment, conduction via solid material pathways to the exterior of the vehicle is possible. In fact, passive thermal management uses conduction as its transport mechanism through the vehicle structure. Radiant transport mechanisms are also possible, but less likely, within a vehicle because convective heat transfer within a working fluid is generally more efficient for relatively small temperature differences associated with temperature variations within a vehicle than is radiant heat transfer.

4.4.2.2 Thermal Subsystem and Cooling External Interface

Active thermal management may be further subdivided into the Thermal Subsystem, an ALS subsystem, and Cooling, which is an external interface to the ALS concept of the life support system.

4.4.2.2.1 THERMAL SUBSYSTEM

The Thermal Subsystem, which is really a subset of active thermal management, acquires waste thermal loads at or near the site of origin and transports those loads to sites where they are rejected. The Thermal Subsystem also redistributes heat for reuse by other processes when necessary as part of the defined life support system. Typical Thermal Subsystem technologies often include heat exchangers, coldplates, pumps and fans, valves, working fluids, accumulators, and fluid lines.

4.4.2.2.2 COOLING EXTERNAL INTERFACE

The Cooling External Interface, which is also a subset of active thermal management, rejects waste thermal loads from the spacecraft. Cooling technologies include rejection hardware such as radiators, phase change devices, and devices that reject expendable materials carrying thermal loads.

4.4.2.3 General Thermal Management Architecture

In addition to dividing active thermal management as a Thermal Subsystem plus a Cooling External Interface, active thermal management may be divided into internal thermal control and external thermal control. In this arrangement, the internal thermal control system (ITCS) [114] initially acquires thermal loads from the crew cabin. The ITCS transports the thermal loads and releases them to a heat exchanger common to both the ITCS and the external thermal control system (ETCS). [115] The ETCS acquires thermal loads from the heat exchanger in common with the ITCS and from heat sources outside the crew cabin. The ETCS transports the combined heat loads to the vehicle heat rejection devices.

This architecture, using an ITCS with an ETCS, allows a non-toxic working fluid to circulate in all thermal management hardware located inside the crew cabin while allowing a more appropriate fluid, from an engineering perspective, to be used in thermal management hardware outside the crew cabin. With recent NASA vehicles, such as the Shuttle Orbiter and ISS, the ITCS working fluid is water, which is non-toxic and has ideal properties for transporting thermal loads, except that it has a relatively high freezing point compared to the external environment in low-Earth orbit. The Shuttle Orbiter and ISS both use more toxic working fluids in their ETCS that have lower freezing point temperatures. The Shuttle Orbiter uses Freon 21 while ISS relies on anhydrous liquid ammonia.

While this architecture, using an ITCS with an ETCS, allows use of more toxic, freeze-resistant working fluids in the ETCS while circulating a non-toxic fluid in the ITCS, this approach carries additional expenses compared with a system using a common loop to both acquire thermal loads from the crew cabin and reject them to the external environment. In particular, a thermal management system using both an ITCS and an ETCS has the added mass of the heat exchanger common to the ITCS and ETCS plus the added mass of an additional pump for the additional loop. Noting that both the Shuttle Orbiter and ISS use two ITCS and two ETCS loops, for redundancy, this arrangement actually adds two extra heat exchangers and two extra pump packages. Further, while the ITCS and ETCS loops are cross-linked or plumbed in a manner that any heat load may be acquired and rejected by either of the two loops serving a particular location in the spacecraft, loss of either an ITCS loop or an ETCS loop degrades the overall heat transport and rejection capabilities of the thermal control system. Consequently, the additional inherent complexity actually reduces overall system reliability.

4.4.2.3.1 INTERNAL THERMAL CONTROL SYSTEM

The internal thermal control system (ITCS) acquires thermal loads from thermal acquisition sites within the crew cabin and transports those loads to a heat exchanger in contact with the ETCS. The ITCS acquires thermal loads through specified interfaces. These interfaces are usually coldplates, where the heat loads are cooled by conduction

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[114] Likewise, this may be designated as the “internal thermal control subsystem.”

[115] At assembly complete, International Space Station also uses the terminology “internal thermal control system” for its corresponding water coolant loops. However, the corresponding International Space Station “external thermal control system” is referred to as the “external active thermal control system” (EATCS). Combined, the ITCS and EATCS are the “active thermal control system” (ATCS).

through the hardware's external structure, or heat exchangers, where the heat loads are initially cooled by convection to a working fluid. In the second case, the most common working fluid within a crew cabin is the enclosed atmosphere because many heat loads release their waste heat to the cabin atmosphere either by convection or radiant transfer. Gas-liquid heat exchangers transfer the atmospheric heat loads to the ITCS.

Cabin atmospheric thermal loads are removed by the gas-liquid heat exchanger through two approaches. Sensible heat is released from cabin atmospheric gases by convection to the gas-liquid heat exchanger. Latent heat is released by condensing water vapor, also called humidity, from the cabin atmospheric gases, removing both humidity and thermal energy by convection with phase change.

Though removal of sensible and latent thermal loads from the cabin atmosphere is a necessary function, because the cabin atmospheric gases and extracted condensate are involved in this process, it is possible that the cabin condensing heat exchanger may organizationally be grouped in whole or in part outside of the Thermal Subsystem even though the underlying processes remove heat. In this document, for completeness, the condensing heat exchanger is grouped with the Thermal Subsystem.

4.4.2.3.2 EXTERNAL THERMAL CONTROL SYSTEM

The external thermal control system (ETCS) acquires thermal loads from the ITCS and from thermal acquisition sites outside of the crew cabin. Because the equipment outside of the crew cabin is almost universally in an unpressurized environment, thermal acquisition interfaces are almost universally coldplates. The ETCS rejects thermal loads to the environment using specified heat rejection devices, such as radiators, phase change devices, and devices that reject expendable materials carrying thermal loads. Mixing warm and cooled working fluid in the return line adjusts the temperature of the ETCS working fluid returning from the heat rejection suite to a prescribed set-point temperature. While the heat-rejection suite thermally cools working fluid, warm working fluid is routed around the heat rejection suite using a flow bypass as necessary to meet the set-point temperature for the ETCS heat acquisition devices.

Figure 4.4.1 illustrates the interrelationship between the various component definitions for the ATCS. The ITCS, denoted in black with plain type, acquires thermal loads within the crew cabin and rejects those thermal loads to the ETCS. The ETCS, denoted in red with italicized type, acquires thermal loads from the ITCS and equipment outside of the crew cabin and rejects those thermal loads to the environment. The Thermal Subsystem hardware is displayed on a green background and includes all ITCS hardware and ETCS hardware not dedicated to heat rejection. Finally, the Cooling External Interface, displayed on a blue background with underlined type, includes ETCS hardware dedicated to heat rejection.

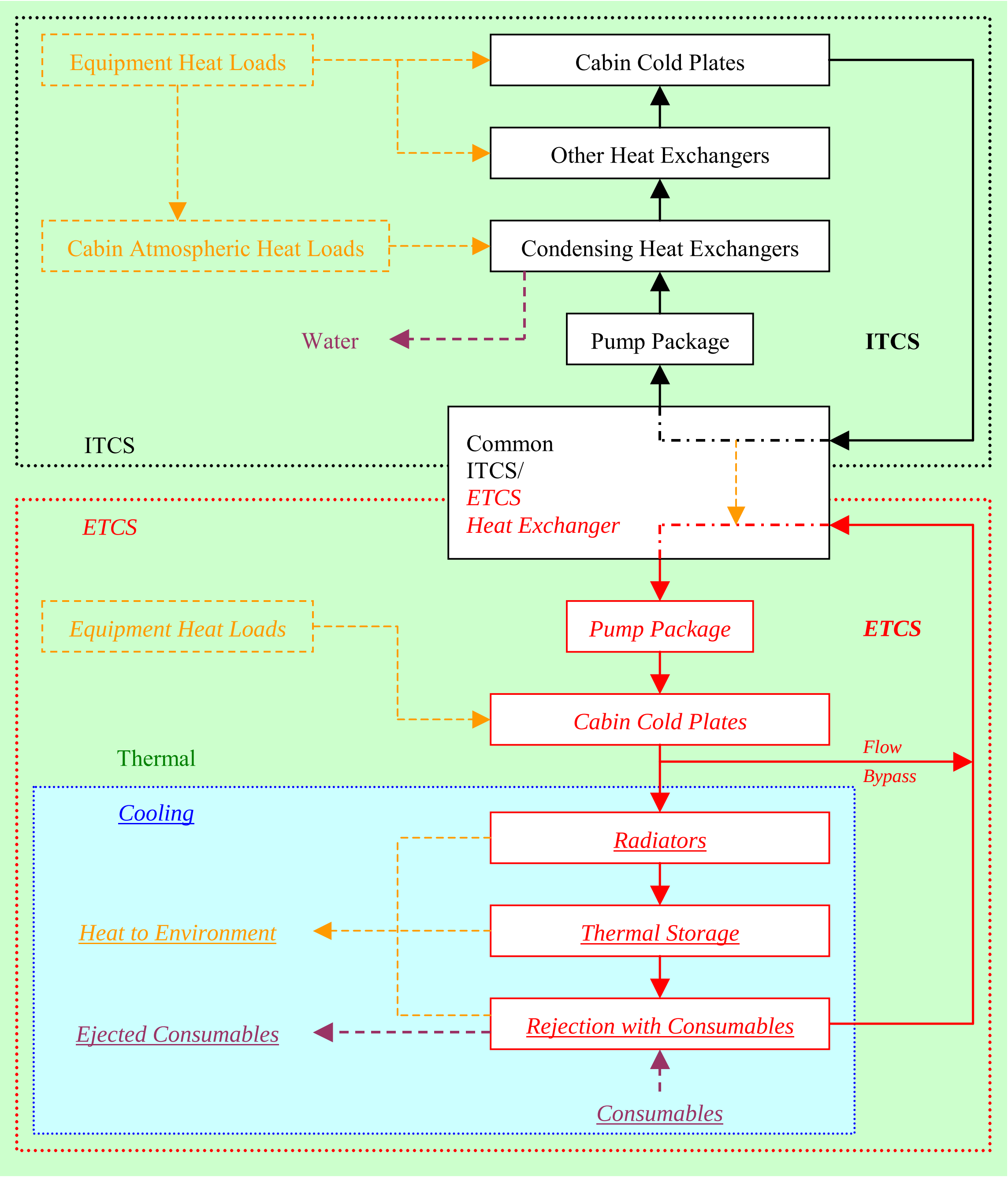

Figure 4.4.1 Active thermal control system component definitions. Internal thermal control system components are designated with black lines and plain type. External thermal control system components are designated with red lines and italicized type. Cooling External Interface hardware is presented on a blue background with underlined type. Thermal Subsystem hardware is presented on a green background without additional adjustments to the type font.

4.4.3 Thermal Management Technology

4.4.3.1 Historical Thermal Management Approaches

While all NASA human-rated vehicles to date have used thermal management hardware to control the crew cabin atmospheric temperature and humidity, recent concerns over safety prohibit all but the most recent designs. In particular, some older spacecraft, such as Apollo, used a mixture of ethylene glycol with water as a working fluid within an active thermal control system loop that entered the crew cabin. Recent flight rules strongly advise against using ethylene glycol in any application within a vehicle in which a crewmember may contact it. Accordingly, the discussion of historical thermal management approaches is limited to designs for the Shuttle Orbiter and the ISS.

4.4.3.1.1 SHUTTLE THERMAL MANAGEMENT

Figure 4.4.2 shows the ordering of components for one of two ETCS loops in a Shuttle Orbiter. A mechanical pump package, with two identical units plumbed in parallel, drives the single-phase Freon 21 working fluid. For this application, one pump is active and the second is a spare. The accumulator sets the low pressure for the fluid loop. When the working fluid contracts, the accumulator adds fluid, and when the working fluid expands, the accumulator stores any excess fluid. Because even liquid material properties are not truly invariant to temperature variations, the accumulator most often compensates for working fluid density variations associated with temperature changes.

The Shuttle was designed to reject heat through several means depending on the mission segment. On the launch pad and after the ground crew can make connections following landing, the ETCS rejects heat to ground facilities through the ground service equipment heat exchanger. On launch, re-entry, and when necessary on-orbit, the flash evaporator allows excess water to evaporate from the outside of the ETCS working fluid line, expelling the vapor, with its waste heat, to space. Upon re-entry, when the external atmospheric pressure is too great to operate the flash evaporator efficiently, the ammonia boiler evaporates anhydrous ammonia to cool the ETCS working fluid lines, again expelling the vapor to the environment. [116] The radiators, which are mounted on the inside of payload bay doors, reject heat by radiant transfer to space while the Shuttle is on-orbit. Shuttle controls the ETCS working fluid temperature from the radiators with a bypass loop as depicted. Varying internal flowrates or expendable fluid consumption rates controls the other heat rejection devices.

Heat is gathered by the ETCS from many sites throughout the vehicle. Those listed as heat exchanger are liquid/liquid devices where the second operating fluid is the coolant for the attached hardware. The water/Freon interchanger is the common ITCS/ETCS heat exchanger, while the oxygen restrictor is a heat exchanger between the ETCS loop and the pressurized cabin oxygen supply.

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[116] In practice, the ammonia boiler is rarely used as designed. Rather, just before the radiators are removed from service by closing the payload bay doors, the Shuttle flies an attitude so that the radiators face deep space. This maneuver fills the radiator panels with chilled Freon 21 and chills the metallic panels as well. Following this maneuver, the radiators are completely bypassed and the flash evaporator rejects the entire vehicle thermal load. When the flash evaporator ceases operations high in the atmosphere, flow through the now-stowed radiators is re-established, releasing the previously cooled working fluid. This approach provides sufficient cooling from when the flash evaporator ceases operations until about 15 minutes after touch down. If all proceeds on schedule, the ground-cooling cart that interfaces with the ground service equipment heat exchanger is operational by 15 minutes after touch down, and the ammonia boiler is not used. The ammonia boiler is provided on each mission as a contingency for heat rejection, and would provide primary cooling if the ground-cooling cart was not available in time or the Shuttle executed a launch abort.

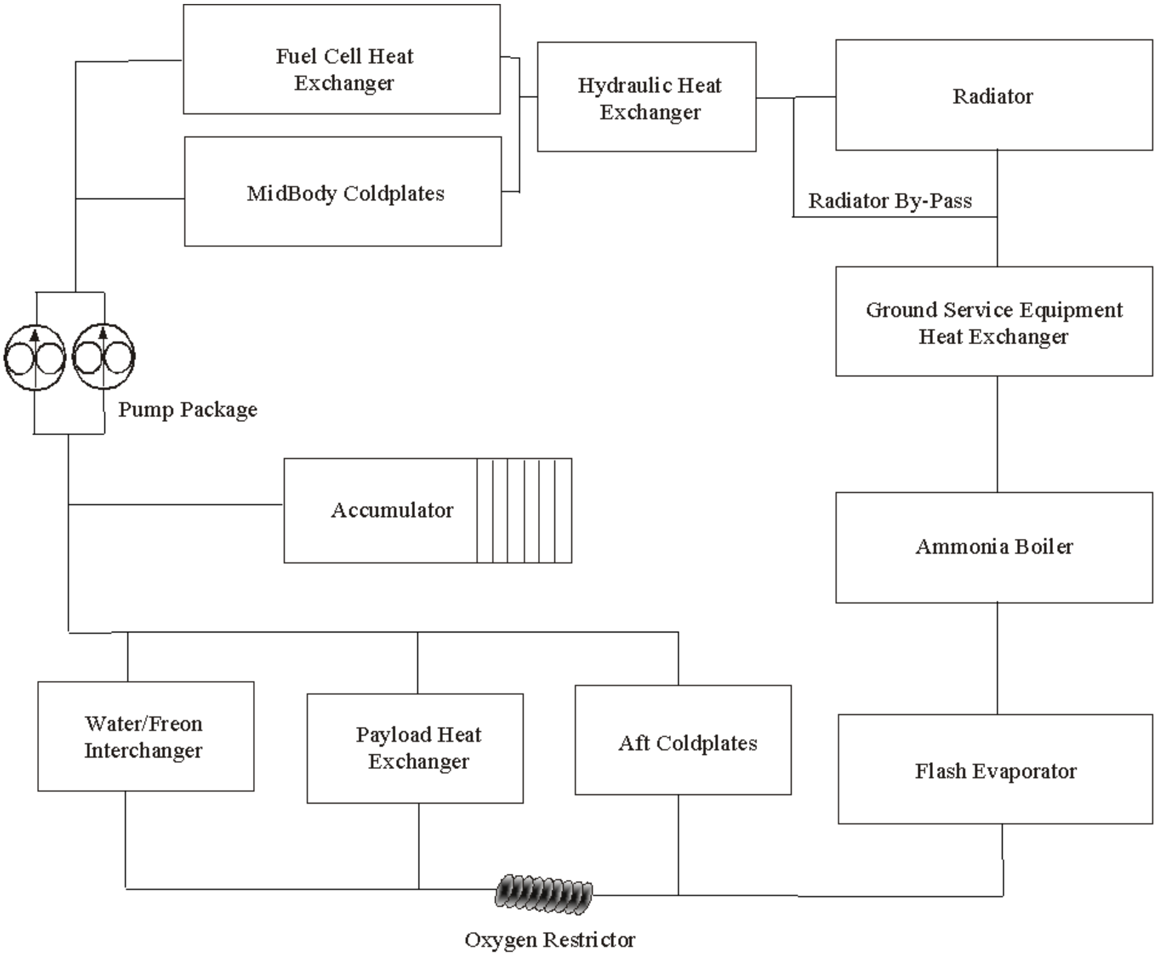

Figure 4.4.2 Active thermal control system hardware for the Shuttle Orbiter. This diagram represents one of two Freon 21 loops in the Shuttle Orbiter ETCS. Coolant flow is clockwise. Because the ETCS loops run through an unpressurized portion of the vehicle, the heat exchangers are integral with the devices they cool. The Water/Freon Interchanger and the Oxygen Restrictor are heat exchangers between the ITCS water loop and the pressurized cabin oxygen supply, respectively. The Accumulator maintains pressure within the flow loop. The Radiator, Ground Service Equipment Heat Exchanger, Ammonia Boiler, and Flash Evaporator are all heat rejection devices.

4.4.3.1.2 *INTERNATIONAL SPACE STATION THERMAL MANAGEMENT*

The external active thermal control system (EATCS) for ISS at Assembly Complete is very similar to the architectures presented above. The ISS EATCS uses single-phase, anhydrous liquid ammonia as its working fluid, although the corresponding ITCS uses water. The radiators are mounted on booms that connect to the P1 and S1 [117] truss segments through a thermal radiator rotary joint (TRRJ). The TRRJs orient the radiator panels so that they display their thinnest face, their “edges,” to the Sun, allowing their radiant face-sheets to be exposed only to relatively cooler environments [118]. While not depicted in Figure 4.4.3, many of the fine details are similar to those in earlier diagrams.

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[117] The ISS truss segments are numbered in ascending order from the center of the vehicle. The S0, “starboard zero,” truss segment forms the base for the other truss segments and connects directly to the other ISS modules through the U. S. Laboratory. The first starboard segment outboard of S0 is S1, while the first port segment outboard is P1, or “port one.”

[118] In rare situations, the TRRJs are not able to completely orient the radiator edges at the Sun, but this case is not common and only occurs for brief periods.

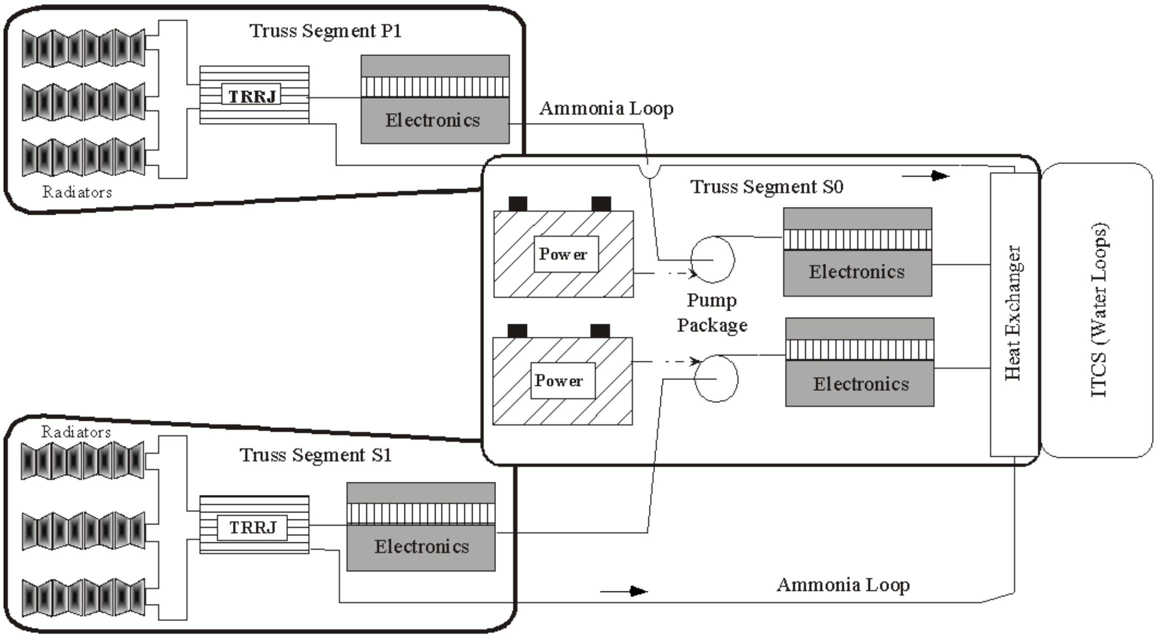

Figure 4.4.3 Active thermal control system hardware for ISS at Assembly Complete. As noted by the arrows, ammonia flows from radiators to the common ITCS/EATCS heat exchanger then to the warmer thermal loads associated with electronics mounted on coldplates. Each Thermal Radiator Rotary Joint (TRRJ) rotates to position the radiator panels so that they face anti-Sun, or "edge-on" to the Sun. The bulk of the EATCS is located on truss segments S0, S1, and P1.

4.4.3.2 Advanced Thermal Management Approaches

There are many concepts to increase the efficiency of thermal management hardware. Several of the more common ideas are summarized in the paragraphs below. Please note, however, this is not an exhaustive discussion and other viable approaches exist.

As noted above, the active thermal control system (ATCS) is the summation of both the ITCS and ETCS [119]. Further, dividing the ATCS into two loops when, physically, only one loop is required, adds inefficiency to the process of removing thermal loads from the vehicle even when there are benefits from this approach. An alternate approach employs only a single ATCS loop in place of each ITCS / ETCS combination. The working fluid requirements are more stringent because the working fluid may not be a significant hazard to the crew if leaked into the crew cabin, nor may it be overly susceptible to freezing when flowing through heat rejection equipment. While not employed currently, such systems are under development and the concept is mentioned here as background.

Another possible advanced concept is a two-phase thermal management working fluid. Thermal management loops using single-phase working fluids rely on the heat capacity of the working fluid to accept and transport thermal loads. However, single-phase working fluids are limiting in practice because acquiring a thermal load raises the temperature of the working fluid, so hardware downstream must reject their thermal loads to a working fluid at a higher temperature than hardware upstream, and this concern can lead to other inefficiencies. Secondly, a single-phase working fluid generally can acquire less heat over its entire liquid temperature range than is required to change the phase of the same mass of working fluid from a liquid to a vapor. If the thermal management working fluid is allowed to vaporize as it acquires thermal loads, the working fluid remains at a constant temperature and actually less fluid mass is required to carry the same thermal load. Issues associated with two-phase flows under non-terrestrial gravitational fields remain as challenges to this approach so far.

Heat pumps also offer promise as advanced thermal management technologies. While terrestrial heat pumps move heat either into or out of a volume, heat pumps as part of an advanced thermal management system move heat from the vehicle to the environment only. Specifically, heat pumps use work, either thermal or mechanical, to raise the temperature of waste heat loads so as to increase the ease of rejecting those loads by radiant heat transfer. While heat pumps add hardware and use power, the increased temperature of the heat load for radiant emission from the vehicle

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[119] Or the "external active thermal control system" (EATCS) when using International Space Station nomenclature.

decreases the required radiator size so that the overall system may be less massive than a thermal management system without a heat pump.

4.4.4 Radiant Energy Balance

Heat transfer is a broad topic and any in depth treatment is beyond the scope of this document. Reference a heat transfer text such as Incropera and DeWitt (1985) for a more complete introduction. However, several definitions and assumptions are common when analyzing radiant heat transfer for space applications within NASA. Except as specifically noted, the development below follows Incropera and DeWitt (1985).

In general, heat emitted by a perfectly black body, q_{bb} [W], may be described by the Stefan-Boltzmann equation.

$$q_{bb} = \sigma A T^4 \qquad \text{Equation 4.4-1}$$

where σ is the Stefan-Boltzmann constant with a value of 5.67×10^{-8} W/(m²•K⁴), A is the body's surface area [m²], and T is the body's absolute temperature [K]. A black body is a perfect emitter and its emittance is a function only of its temperature once its geometry is fixed.

In practice, most real surfaces are not perfect emitters, and their surface emittance may be described as some fraction of the emittance from a perfectly black body. For a non-ideal body whose emittance fraction is constant, a slightly modified relation applies.

$$q_e = \sigma \varepsilon A T^4 \qquad \text{Equation 4.4-2}$$

where q_e is emittance [W], and ε is the emissivity or the fraction of the surface's actual emittance compared to its ideal or black body emittance at its current absolute temperature, T. Alternately, ε is unity only for an ideal or black body.

As noted earlier, radiant exchange of thermal energy does not depend on intervening matter for transfer. Rather, radiant exchange is possible between any two surfaces with a view of each other. Physically, according to one theory, thermal energy transfers between the surfaces via electromagnetic waves. [120] According to classic physics, thermal radiation, which is a subset of a broader phenomenon know as electromagnetic radiation, varies between wavelengths of 0.1 and 100 μm. Visible light, according to the human eye, is confined to a range varying from 0.40 to 0.70 μm. In addition to visible radiation, classic physics defines thermal radiation at wavelengths less than 0.40 μm is also ultraviolet radiation, and thermal radiation at wavelengths greater than 0.70 μm is also infrared radiation. As context, electromagnetic radiation at wavelengths less than 0.1 μm is classified, depending on its wavelength, as ultraviolet radiation [121], x-rays, or gamma rays. Electromagnetic radiation at wavelengths immediately greater than 100 μm is classified as microwaves.

When thermal radiation strikes a solid object, it may be absorbed, reflected from the surface, or transmitted through the object. If the surface is opaque to the incident radiation, transmittance is zero and only absorbance or reflectance is possible.

$$\alpha + \rho = 1 \qquad \text{Equation 4.4-3}$$

where α is the absorptivity and ρ is the reflectivity. For an ideal or black body, reflectivity is zero and absorptivity is unity.

At any given wavelength, λ, according to Kirchhoff's Law, absorptivity and emissivity are equal for a particular surface if (1) the incident irradiation is invariant with respect to direction, or diffuse, and (2) the surface properties are invariant with respect to direction, or diffuse.

$$\alpha_\lambda = \varepsilon_\lambda \qquad \text{Equation 4.4-4}$$

Additionally, if (3) the incident irradiation is diffuse and if (4) the surface properties, the absorptivity and emissivity, are independent of wavelength, λ, the surface is called a gray surface.

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[120] Alternate theories describe the transfer via photons or quanta, but the image of an electromagnetic wave is most applicable to the current discussion.

[121] Ultraviolet radiation varies from 0.01 to 0.40 μm, and so overlaps the range classified as thermal radiation.

$$\alpha = \varepsilon \qquad \text{Equation 4.4-5}$$

While most real surfaces do not abide by this final requirement to qualify as gray surfaces, many are effectively gray over some subset of the range of thermal radiation. At Johnson Space Center, two thermal radiation sub ranges are often defined for radiant transfer calculations (Conger and Clark, 1997). Thermal irradiation between 0.25 µm and 2.5 µm, inclusive, is designated as solar thermal radiation (AZ Technology, 1993), while thermal irradiation above 2.5 µm is designated as infrared thermal radiation. Over each of these sub ranges, material surface properties are assumed gray.

$$\alpha_s = \varepsilon_s$$
$$\alpha_{ir} = \varepsilon_{ir} \qquad \text{Equation 4.4-6}$$

where the subscript "s" denotes surface properties over the range of solar thermal radiation and the subscript "ir" denotes surface properties over the range of infrared thermal radiation. This does not imply that α_s equals α_{ir} or that ε_s is equal to ε_{ir}. This approach effectively considers Equation 4.4-5 applicable in a piecewise manner over two sub ranges for thermal radiation.

Physically, except during re-entry or similar operations with extremely high aerodynamic drag, the surface temperatures of spacecraft in space do not approach the range where surfaces emit in the solar range. So, surface emissions from spacecraft, planetary surfaces, and other non-glowing physical bodies have surface properties as defined by the second relation in Equation 4.4-6. Irradiation coming from the Sun, or reflected irradiation that originated from the Sun, however, emit in the solar range. Because of this, incident or reflected irradiation from the Sun uses surface properties as defined by the first relation in Equation 4.4-6.

From the perspective of a spacecraft, which emits infrared thermal radiation but likewise absorbs incident solar thermal radiation, it is meaningful to define the ε_{ir}, for both infrared thermal emittance and absorptivity, and α_s, for solar thermal absorptivity.

4.4.5 Thermal Management Values

This section provides values necessary to estimate heat transfer both within a spacecraft and between a spacecraft and its environment. Thermal exchange with the environment is more correctly identified as Cooling, but to ease use of this material, all similar values are grouped below. In fact, many values below may apply both to thermal management within a spacecraft as well as to heat rejection from the spacecraft.

Table 4.1.1 presents solar absorptivities and infrared emissivities for several common aerospace structural materials. The end-of-life properties reflect changes associated with external usage in near-Earth space and are not applicable within the crew cabin. While surfaces within the crew cabin certainly wear, aging mechanisms differ from those in the vacuum of space or even on the Martian surface. Accordingly, as a first approximation, emissivities for new materials apply even for a used interior.

Within the crew cabin, thermal considerations are dictated by two concerns. The first is crew comfort and maintaining equipment within its thermal bounds. The second concern is to maintain humidity within an acceptable range. If the overall cabin atmospheric temperature drops below the local dew-point temperature, allowing water vapor to condense. Because liquid water poses a significant hazard to electronics especially in weightless situations, maintaining cabin atmospheric and humidity within prescribed limits is important.

Table 4.4.2 presents applicable thermal limits from current ALS requirements (Duffield, 2003).

Table 4.4.1 Surface Optical Properties for Common Exterior Space Material

	New		End-of-Life [122]	
Material	α_s	ε_{ir}	α_s	ε_{ir}
Silverized Teflon	0.07	0.80	0.14	0.80
Aluminized Teflon	0.12	0.80	0.20	0.80
Ortho Fabric [123]	0.18	0.84		
Beta Cloth	0.26	0.90		
A276 White Paint	0.28	0.87	0.36	0.90
Clear Anodized Aluminum	0.38	0.83	0.58	0.79
Gold Anodized Aluminum	0.55	0.81	0.63	0.81
Black Anodized Aluminum	0.81	0.88	0.84	0.79
Alodine Aluminum	0.45	0.35		
Bare Stainless Steel	0.42	0.11		
Sand-Blasted Stainless Steel	0.58	0.38		
Bare Titanium	0.52	0.12		
Tiodized Titanium	0.82	0.51		

References

From Conger and Clark (1997) unless otherwise noted.

Table 4.4.2 Crew Cabin Thermal Ranges

		Assumptions		
Parameter	**Units**	**Lower**	**Nominal**	**Upper**
Air Temperature [124]	K	291.5		299.8
Dew-Point Temperature	K	277.6		288.7
Relative Humidity	%	25		70
Ventilation	m/s	0.076		0.347

References

From Duffield (2003) unless otherwise noted

Transport properties for several common thermal management working fluids are tabulated in Table 4.4.3 at likely operating temperatures. These values support basic thermal loop energy balances.

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[122] These values apply to external applications only because aging and wear mechanisms within the crew cabin differ considerably from external aging and wear mechanisms. As a first approximation, surface properties for materials within the crew cabin do not change with time.

[123] The exterior fabric on the EMU.

[124] The cabin "dry bulb" atmospheric temperature.

Table 4.4.3 Transport Properties for Common Thermal Management Loop Working Fluids

		Temperature = 280.0 K			**Temperature = 297.0 K**			**Temperature = 300.0 K**			
Fluid	**Hazards**	**Density [kg/m^3]**	**Specific Heat [kJ/kg•K]**	**Viscosity [kg/m•s]**	**Density [kg/m^3]**	**Specific Heat [kJ/kg•K]**	**Viscosity [kg/m•s]**	**Density [kg/m^3]**	**Specific Heat [kJ/kg•K]**	**Viscosity [kg/m•s]**	**References**
Water		1,002.08	4.204	0.00148				998.35	4.187	0.00083	From Schoppa (1997) unless noted otherwise.
30 % Ethylene Glycol/70 % Water	Irritant	1,042.15	3.741	0.00311				1,033.34	3.788	0.00176	
60 % Ethylene Glycol/40 % Water	Irritant	1,083.84	3.130	0.00796				1,071.70	3.216	0.00417	
30 % Propylene Glycol/70 % Water		1,027.79	3.800	0.00542				1,018.36	3.861	0.00212	
60 % Propylene Glycol/40 % Water		1,050.18	3.264	0.02090				1,036.12	3.369	0.00710	
30 % Glycerin /70 % Water					1,072	3.656	0.00223				
60 % Glycerin /40 % Water					1,147	3.176	0.00819				
Potassium Acetate/Water					1,196	3.300	0.00270				
Fluorinert 72		1,722.12	1.025	0.00117				1,669.92	1.056	0.00092	
Hydrofluoroether HFE-7100		1,522.76	1.147	0.00088				1,477.38	1.187	0.00071	
Ammonia (liquid)	Toxic	628.20	4.679	0.000232				600.46	4.854	0.00021	
D Limonene	Flammable				847.5	2.05	0.00091				

Table 4.4.4 and Table 4.4.5 provide appropriate thermodynamic values to compute energy balances of phase-change materials for representative materials. Of the materials available, both here and more generally, water requires the greatest heat input for the least mass and is the "best" phase-change material available (although the temperatures at which it transitions from one phase to the next sometimes prohibits its use.) While the temperature at which a liquid boils varies directly with pressure, melting point temperatures are effectively invariant with pressure for applications likely to see use in spaceflight.

Table 4.4.4 Thermodynamic Properties of Common Thermal Management Phase-Change Materials for Liquid-Vapor Transitions

Material	Formula	Liquid Density [kg/m³]	Saturation Pressure [kPa]	Saturation Temperature [K]	Heat of Vaporization [kJ/kg]	Reference
Ammonia	NH_3	702.2 (1)	40.7 (1)	223.2 (1)	1,425.8 (1)	(1) Howell and Buckius (1987)
		690.1 (1)	71.6 (1)	233.2 (1)	1,392.5 (1)	
		677.5 (1)	119.5 (1)	243.2 (1)	1,361.1 (1)	
Water	H_2O	1,000 (1)	0.61 (1)	273.2 (1)	2,500.0 (1)	
		1,000 (1)	1.23 (1)	283.2 (1)	2,478.4 (1)	
		998 (1)	2.34 (1)	293.2 (1)	2,455.0 (1)	

Table 4.4.5 Thermodynamic Properties of Common Thermal Management Phase-Change Materials for Solid-Liquid Transitions

Material	Formula	Solid Density [kg/m³]	Liquid Density at 20°C [kg/m³]	Melting Temperature [K]	Heat of Fusion [kJ/kg]	References
Water	H_2O	920 (1)	998 (2)	273.2 (3)	333.5 (3)	(1) Incropera and DeWitt (1985) (2) Howell and Buckius (1987) (3) Weast and Astle (1979) (4) Humphries and Griggs (1977)
Waxes (Paraffin)						
n-Dodecane	$C_{12}H_{26}$		748.7 (3)	263.6 (4)	210.5 (4)	
n-Tetradecane	$C_{14}H_{30}$		762.8 (3)	279.1 (4)	229.9 (4)	
n-Hexadecane	$C_{16}H_{34}$		773.3 (3)	291.4 (4)	228.9 (4)	
n-Octadecane [125]	$C_{18}H_{38}$		776.8 (3)	301.4 (4)	243.5 (4)	

4.5 Waste Subsystem

The Waste Subsystem collects waste materials from life support subsystems and interfaces. Commonly, wastes are perceived as materials with no further utility. However, because ALS focuses on increased material loop closure, "wastes" encompass a variety of materials with varying degrees of possible future utility. Wastes might include crew metabolic wastes, food packaging, wasted food, paper, tape, soiled clothing, brines, inedible biomass, expended hygiene supplies, and equipment replacement parts from the other subsystems. The traditional definition of a waste within ALS and within this document excludes most gases, depending on the system configuration. For example, crew-expelled carbon dioxide might not be recycled within a given life support system architecture. In such a case, although carbon dioxide is technically a waste material, the Air Subsystem typically assumes the responsibility for waste gases. However, the Waste Subsystem might ultimately collect the expended carbon dioxide scrubbing materials and trapped gases if those gases are not vented. To further complicate subsystem definitions, a waste-processing device might incorporate trace contaminant control hardware which is usually an Air Subsystem function, to control the release of potentially harmful gases. Further information related to waste types and characteristics is included below.

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[125] The liquid density for n-octadecane is evaluated at 28°C.

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

Current NASA spacecraft waste-handling approaches essentially rely on dumping and storage. On Shuttle missions, most waste is stored and returned to Earth with little or no processing. Consequently, the volume of wastes can be significant. Waste processing on Shuttle includes drying fecal material by exposure to the vacuum of space. 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 the wastes are removed from ISS using a Progress module, they are incinerated along with the vehicle during destructive re-entry. Wastewater, excess fuel cell product water, urine, and condensate are dumped, as necessary, from Shuttle according to the mission schedule.

In future long-duration missions, wastes may be disposed directly, or they may be processed. For example, during transit to Mars, jettisoning trash might be acceptable, though waste might be retained for radiation shielding or resource recovery. However, jettisoning waste on the Martian surface may be constrained by planetary protection protocols for exploration missions. Organic materials and microbial agents could threaten to biologically contaminate the Martian environment. Wastes may be processed to recover useful resources, such as water and carbon dioxide. Wastes might also be processed in preparation for long-term storage or disposal, for example, microbial inactivation/elimination. Specific waste processing operations depend upon the mission scenario and the system-level costs versus the system-level benefits.

4.5.1 Historical Data on Skylab

The first NASA medium-duration missions were performed aboard Skylab. Prior to Skylab, the longest duration missions were Gemini 7, 14 days, and Apollo 17, 13 days. Within the Gemini and Apollo programs, wastes were either returned to Earth in the vehicle, or dumped, most notably on the Lunar surface. On Skylab, the Saturn S-IVB [126] oxygen tank was used for waste disposal. The tank was vented to space through non-propulsive vents. Wastes were placed in the tank through an airlock and off gassed to space. This eliminated the possibility of contamination of the crew areas through off-gassing and stored the wastes in a safe manner for an indefinite time. However, off-gassing may have contaminated the Skylab's exterior surfaces.

4.5.2 Historical Waste Loads from Shuttle 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. [127] 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.

In 1985, wastes for STS-51D were analyzed at NASA Ames Research Center to determine the chemical composition of wastes and characterize the trash (Wydeven and Golub, 1991). This study found that for 49.2 kg of total waste, 27.8 kg was food-related trash. Approximately 22 %, or 10.8 kg, of the trash recovered was comprised of food-related plastic packaging materials. Another 12.2 kg of other plastics and paper brought the total for packaging materials within the trash to almost 47 %. These data are presented in Table 4.5.1 and summarized in Table 4.5.2. STS-51D supported seven crewmembers for seven days, [128] which is equivalent to 49 CM-d.

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

[127] 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.

[128] Officially, the mission duration for STS-51D is six days, 23 hours, 55 minutes, and 23 seconds. See http://www-pao.ksc.nasa.gov/kscpao/chron/sts51-d.htm

Table 4.5.1 Waste Analysis for STS-51D Trash

Trash Item	Mass [kg]	Moisture Content [%]	Fraction of Total Mass [%]	Reference
Food and Food Packaging				Wydeven and Golub (1991)
Plate Waste	4.8	70	9.8	
Plastic Food Containers	10.8	0.2	22.0	
Uneaten Food and Beverages [129]	12.2	0.2	24.7	
Biomedical	6.4		13.0	
Aluminum and Tape				
Grey Duct Tape	1.6		3.3	
Aluminum Cans	1.2	2	2.4	
Plastic and Paper				
Paper (mixed)	6.4	10.2	13.0	
Plastic Bags	3.2	0.2	6.5	
Miscellaneous Plastic	2.6	0.2	5.3	
Total	49.2		100.0	

Storage of wastes on-orbit during early Shuttle missions of 30 CM-d or less posed no challenge for the allotted resources of the 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, not boxes, for beverages, and carried a prototype trash compactor (Grounds, 1990). Subsequently, there is a marked decrease in the volume of trash from STS-35 compared with the previous missions, probably in large part due to the change in drink packaging. This reduction in volume was consistent with data collected for STS-99 and STS-101 (Maxwell, 2000a and 2000b). The data from these missions are summarized in Table 4.5.2.

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

Table 4.5.2 summarizes waste stream analyses completed for STS-99 and STS-101, as well as historical data from STS-29, STS-30, and STS-51D.

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

Table 4.5.2 Shuttle Crew Provision Wastes from Past Missions

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

References

(1) Garcia (1989)
(2) Grounds (1990)
(3) Wydeven and Golub (1991)
(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, with a 90-day resupply schedule, ISS may benefit from more robust containment options, additional dedicated storage compartments, and resource recovery plans to reduce mission costs.

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 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 4.5.3 (for reference missions associated with ISS) and Table 4.5.4 (for reference missions associated with near-term exploration missions to Mars using the Mars Dual Lander Architecture). Stafford, et al. (2001) details the assumed reference missions. Some data here are inferred, such as air filters. These tables present generation of storable or disposable wastes based on the assumed configurations. A common list of hardware is used for all vehicles. In cases where particular hardware is not part of the configuration for a specific reference mission, the location within the table is marked with an "×." When hardware is present, but a storable or disposable waste is not produced, a "☑"appears. When hardware is present and a storable or disposable waste is produced, a rate, in terms of mass per crewmember per day, is listed. These tables list only wastes delivered from the hardware or elements for disposal or storage listed, including any containers. Thus, wastes should not be counted more than once.

The technology suite for segments or vehicles in Table 4.5.3 and Table 4.5.4 are denoted by prefixes. Vehicles or segments with a prefix of "ISS" assume a hardware suite using primarily technologies listed in Carrasquillo, et al. (1997) for ISS. Vehicles or segments with a prefix of "ALS" use advanced and current technologies, as appropriate. Segments listed as Russian On-Orbit Segments of ISS use Russian ISS hardware and are provided as a reference. See Stafford, et al. (2001) for details.

Possible types of waste are virtually unbounded, so Table 4.5.3 and Table 4.5.4 do not encompass all possible types of waste within a space mission. Further, the waste types are organized according to the subsystems and external interfaces defined in Section 2.4 and detailed in Stafford, et al. (2001). The configurations are not unique, nor are they necessarily complete. However, they provide a documented baseline.

The crew contribution to the waste stream can enter more than one subsystem or interface. For example, the crew respiration and perspiration load is first received by the 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. Consequently, 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 calculate percentages accepted by those subsystems and interfaces.

Table 4.5.3 International Space Station Reference Mission Vehicle Wastes

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

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

Table 4.5.3 International Space Station Reference Mission Vehicle Wastes (continued)

	Assumptions [kg/CM-d]					
Component	**Russian On-Orbit Segment, Phase 2**	**Russian On-Orbit Segment, Phase 3**	**ISS United States On-Orbit Segment, Phase 3**	**ALS United States On-Orbit Segment, Post-Phase 2**	**ALS United States On-Orbit Segment, Phase 3**	**Notes**
Waste Subsystem Interfaces						
Air Subsystem	0.13 (4)	0.13 (4)	0.13 (4)	0.13 (4)	0.13 (4)	Based on ISS data at Assembly Complete. Reflects spares for the Air Subsystem.
Biomass Subsystem						
Inedible Biomass	×	×	×	×	×	
EVA Support External Interface Wastes	0.02 (5)	0.02 (5)	0.02 (5)	0.02 (5)	0.02 (5)	The difference in values reflects variations in EVA workload.
Food Subsystem Wastes	0.32 (5)	0.32 (5)	0.32 (5)	0.32 (5)	0.28 (5)	Assumption: Biomass production reduces prepackaged food mass slightly.
Human Accommodations External Interface Wastes						
Expended Clothing	0.82 (5)	0.82 (5)	0.82 (5)	0.82 (5)	0.02 (5)	Clothing mass reduced by a factor of 40 with laundry. Assumption: 50% initial water content.
Hygiene Wipes	0.23 (5)	0.23 (5)	0.23 (5)	0.23 (5)	0.15 (5)	
Thermal Subsystem Wastes	0.03 (4)	0.03 (4)	0.03 (4)	0.03 (4)	0.03 (4)	Based on ISS data for Assembly Complete.
Waste Subsystem to Environment						
Urine to Earth	1.83 (1)	0.16 (1)	×	×	×	Assumption: Stowage in EDV.
Solid Waste to Earth	☑	☑	☑	☑	☑	
Vacuum Vent (Lyophilizer)	×	×	×	×	×	Mass losses for Air and Water to be determined.
Subtotal	**3.38**	**1.71**	**1.55**	**1.55**	**0.63**	

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

Table 4.5.3 International Space Station Reference Mission Vehicle Wastes (concluded)

	Assumptions [kg/CM-d]					
Component	**Russian On-Orbit Segment, Phase 2**	**Russian On-Orbit Segment, Phase 3**	**ISS United States On-Orbit Segment, Phase 3**	**ALS United States On-Orbit Segment, Post-Phase 2**	**ALS United States On-Orbit Segment, Phase 3**	**Notes**
Water Subsystem						
Air Evaporator Wicks	✗	✗	✗	0.08 (6)	0.04 (6)	This value includes air evaporator wicks and urine solids. Assumption: Cases with a biological water processor are 50% less massive.
Flush Water	0.00 (2)	0.00 (2)	0.00 (2)	0.00 (2)	0.00 (2)	None identified to date.
Greywater from Dryer to Water Subsystem	✗	✗	✗	✗		
Urine Processing System Brine to Waste Subsystem	✗	☑	☑	✗	✗	
Urine to Water Subsystem	✗	☑	☑	☑	☑	
Urine Processor	✗	☑	0.33 (1,7)	☑	☑	This entry based on vapor compression distillation performance. Brine is stored in an EDV (Russian wastewater container).
Water Processor Spares	0.33 (4)	0.33 (4)	0.33 (4)	TBD	TBD	
Miscellaneous	0.89 (5)	0.89 (5)	0.89 (5)	0.89 (5)	0.89 (5)	Based on ISS data for Assembly Complete.
Subtotal	**1.22**	**1.22**	**1.55**	**0.97**	**0.93**	
Overall Total	**5.14**	**3.47**	**3.61**	**3.03**	**1.69**	

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

Table 4.5.4 Advanced Mars Exploration Reference Mission Vehicle Wastes

	Assumptions [kg/CM-d]					
Component	**ISS Mars Transit Vehicle**	**ISS Surface Habitat Lander**	**ISS Mars Decent / Ascent Lander**	**ALS Mars Transit Vehicle**	**ALS Surface Habitat Lander**	**Notes**
Waste Subsystem Hardware						
Compactor	☑	☑	✗	☑	☑	Compactors reduce waste volume and waste storage containment mass
Commode	☑	☑	☑	☑	☑	
Dryer	✗	✗	✗	✗	☑	
Fecal Storage	0.50 (1)	0.50 (1)	0.50 (1)	0.50 (1)	0.13 (1)	This entry includes the Russian KBO (Russian solid waste container). Usage is based on mass of waste. Mass of waste depends on moisture content, which varies between options.
Lyophilization	✗	✗	✗	✗	☑	This technology yields a dry, stable solid waste and a separate greywater component.
Solid Waste Storage	☑	☑	☑	☑	☑	
Urinal	☑	☑	☑	☑	☑	
Urine Pretreatment	0.01 (2)	0.01 (2)	0.01 (2)	0.01 (2)	✗ (3)	This entry reflects chemical pretreatment, whether Russian or U.S. This is the mass of pretreatment chemicals only.
Subtotal	**0.51**	**0.51**	**0.51**	**0.51**	**0.13**	

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

Table 4.5.4 Advanced Mars Exploration Reference Mission Vehicle Wastes (continued)

	Assumptions [kg/CM-d]					
Component	**ISS Mars Transit Vehicle**	**ISS Surface Habitat Lander**	**ISS Mars Decent / Ascent Lander**	**ALS Mars Transit Vehicle**	**ALS Surface Habitat Lander**	**Notes**
Waste Subsystem Interfaces						
Air Subsystem	0.13 (4)	0.13 (4)	0.13 (4)	0.13 (4)	0.13 (4)	Based on ISS data at Assembly Complete. Reflects spares for the Air Subsystem.
Biomass Subsystem						
Inedible Biomass	✗	✗	✗	0.01	0.01	Estimates assume 1 m² of growing area producing 0.1 kg/d fresh biomass with at 90% harvest index and 90% moisture content.
EVA Support External Interface Wastes	✗	0.25 (5)	0.25 (5)	✗	0.25 (5)	The difference in values reflects variations in EVA workload.
Food Subsystem Wastes	0.32 (5)	0.32 (5)	0.32 (5)	0.32 (5)	0.28 (5)	Assumption: Biomass production reduces prepackaged food mass slightly.
Human Accommodations External Interface Wastes						
Expended Clothing	0.82 (5)	0.82 (5)	0.82 (5)	0.02 (5)	0.02 (5)	Clothing mass reduced by a factor of 40 with laundry. Assumption: 50% initial water content.
Hygiene Wipes	0.23 (5)	0.23 (5)	0.23 (5)	0.23 (5)	0.15 (5)	
Thermal Subsystem Wastes	0.03 (4)	0.03 (4)	0.03 (4)	0.03 (4)	0.03 (4)	Based on ISS data for Assembly Complete.
Waste Subsystem to Environment						
Urine to Earth	✗	✗	✗	✗	✗	Assumption: Stowage in EDV.
Solid Waste to Earth	✗	✗	✗	✗	✗	
Vacuum Vent (Lyophilizer)	✗	✗	✗	✗	☑	Mass losses for Air and Water to be determined.
Subtotal	**1.53**	**1.78**	**1.78**	**0.74**	**0.87**	

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

Table 4.5.4 Advanced Mars Exploration Reference Mission Vehicle Wastes (concluded)

	Assumptions [kg/CM-d]					
Component	**ISS Mars Transit Vehicle**	**ISS Surface Habitat Lander**	**ISS Mars Decent / Ascent Lander**	**ALS Mars Transit Vehicle**	**ALS Surface Habitat Lander**	**Notes**
Water Subsystem						
Air Evaporator Wicks	✗	✗	✗	0.08 (6)	0.04 (6)	This value includes air evaporator wicks and urine solids. Assumption: Cases with a biological water processor are 50% less massive.
Flush Water	0.00 (2)	0.00 (2)	0.00 (2)	0.00 (2)	0.00 (2)	None identified to date.
Greywater from Dryer to Water Subsystem	✗	✗	✗	✗	☑	
Urine Processing System Brine to Waste Subsystem	☑	☑	✗	✗	✗	
Urine to Water Subsystem	☑	☑	☑	☑	☑	
Urine Processor	0.33 (1,7)	0.33 (1,7)	✗	0.33 (1,7)	☑	This entry based on vapor compression distillation performance. Brine is stored in an EDV (Russian wastewater container).
Water Processor Spares	TBD	TBD	TBD	TBD	TBD	
Miscellaneous	0.89 (5)	0.89 (5)	0.89 (5)	0.89 (5)	0.89 (5)	Based on ISS data for Assembly Complete.
Subtotal	**1.22**	**1.22**	**0.89**	**1.30**	**0.93**	
Overall Total	**3.26**	**3.51**	**3.18**	**2.55**	**1.93**	

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

The overall waste generation rates, including both Russian and United States On-Orbit Segments, listed in Table 4.5.3 include all currently known waste streams. This table should be close to actual waste loads for future long-duration missions. There are, however, significant gaps in the data, and the total will be greater than what is listed here.

4.5.4 Solid Waste Management for Future Long-Duration Missions

Waste treatment and removal for missions to Mars and other likely near-term destinations will be more challenging due to the longer mission duration, regardless of complications from the environment. Waste management for such missions may employ more efficient versions of technologies developed for Shuttle and ISS—or, completely different approaches may be more cost effective. Future missions may also generate significant amounts of inedible biomass. In later or far-term missions, inedible biomass may dominate all other trash sources (see 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.

Wastes generated during human spaceflight are materials with no further utility, yet require storage at least until the mission is complete. However, advanced Waste Subsystems may reclaim valuable resources from input wastes to allow greater closure within the overall life support system.

The following tables provide mass data for various waste products, organized by references. Though unavailable here, waste volumes can be significant. Further, although wastes are listed separately below, some wastes may be contained in or associated with other wastes. For example, feces may adhere to toilet paper, wasted food may adhere to corresponding food packaging, and miscellaneous body wastes may adhere to hygiene wipes and dissolve or suspend in hygiene water. Also, various degrees of source separation are possible. For example, contaminated toilet paper might be collected in a container separate from the feces collector, or contaminated food packages might be collected separately from wasted food.

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

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

The tables present several mass values for some wastes. In such cases, an asterisk denotes the “preferred” or suggested value for waste models if there is an appropriate entry for that particular waste with other important defining factors about the waste being unknown. The suggested values are also summarized in Table 4.5.5. The variability between sources is somewhat indicative of the variability in data collection methods. When known, the data variability is provided below. Additionally, when known, variation of waste mass and composition with particular environmental parameters are noted, allowing for customization of waste characteristics for a specific purpose. The degree of confidence in data values is highly variable and often unknown. In some cases, data have not been diligently collected, and mass estimates are included. In other cases, the values are contingent upon environmental variables. Finally, the original or earliest data source available for a particular value is listed first, followed by other sources that reference the earliest source.

Table 4.5.5 Summary Information on Wastes for Developing Waste Models for Future Long-Duration Missions

	Assumptions [g/CM-d]		
Waste	**Lower**	**Nominal**	**Upper**
Equipment Wastes		TBD (1)	
Experiment Wastes		TBD (1)	
Extravehicular Activity Maximum Absorption Garments (MAGs) [130]		173 (1) [132]	
Feminine Wastes: [131]			
Menstrual Hygiene Products		104 (2) [133]	
Menses		113.4 (2) [133]	
Food Packaging and Adhered Food		324 (3)	
Gloves		7 (4)	
Grey or Duct Tape		33 (5)	
Greywater		TBD (6)	
Greywater Brine		TBD (6)	
Human Detritus:			
Finger and Toe Nails		0.01 (7)	
Hair		0.33 (7)	
Mucus		0.4 (7)	
Saliva Solids		0.01 (7)	
Skin Cells		3 (7)	
Skin Oils		4 (7)	
Sweat Solids		8 (7)	
Hygiene Products, Miscellaneous		TBD (5)	
Inedible Biomass and Wasted Crop Materials		TBD (3)	
Laundry: Clothing, Towels and Wash Cloths		TBD (5)	
Medical Wastes		TBD (1)	
Metabolic Wastes:			
Feces		123 (8)	
Urine		1,562 (9)	
Paper		77 (5)	
Wipes:			
Toilet Paper		28 (10)	
Wipes, Detergent		58 (4)	
Wipes, Disinfectant		56 (4)	
Wipes, Dry		13 (4)	
Wipes, Wet		51 (4)	

References

(1) See Table 4.5.14.
(2) See Table 4.5.8
(3) See Table 4.5.12
(4) See Table 4.5.11
(5) See Table 4.5.13
(6) See Section 4.5.4.9
(7) See Table 4.5.10
(8) See Table 4.5.6
(9) See Table 4.5.7
(10) See Table 4.5.9

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[130] Units for this category: grams per crewmember per EVA event [g/CM-EVA].

[131] The waste production rates in this category exist only for a woman during her menstrual period. Units for this category are: grams per crewmember per menstrual period [g/CM-℘].

4.5.4.1 Feces

The mass and composition of feces varies with the quantity and composition of consumed food, among other factors. Additional fiber in the diet is known to increase daily stool mass (Tucker, et al., 1981). Wydeven and Golub (1990) provide general detailed estimates of dry human feces. Hawk (1965) states "…the amount of fecal discharge varies with the individual and diet. Various authorities claim that on an ordinary mixed diet the daily excretion by an adult male will aggregate 110-170g with a solid content ranging between 25 and 45g; the fecal discharge of such an individual on a vegetable diet will be much greater and may even be as great as 350 g and possess a solid content of 75g."

NASA (1995) states that the fecal collection system shall have the capacity to accommodate fecal matter of 400g/CM-d by mass and 300 mL/CM-d by volume and a maximum bolus length of 330mm. NASA (1995) also states that the fecal collection device shall have the capacity to accommodate a maximum of 1000mL of diarrhea discharge.

Finally, depending on the post-defecation cleansing methods, portions of feces may adhere to toilet paper or wipes. Table 4.5.6 summarizes information on feces.

Table 4.5.6 Information on Feces

Waste	Units	Value	Comments
Feces	g/CM-d	* 123 (1)	Composition: 32g/CM-d solids and 91g/CM-d water. Metabolic Energy: 11.82 MJ/CM-d. Ingested Food Composition: not available.
	g/CM-d	114 (2)	Composition: 32g/CM-d "dehydrated residue" (4.5g/CM-d fat, 4.5g/CM-d protein, 1.8g/CM-d cellulose, 9.5g/CM-d inorganic matter, 11.4g/CM-d bound water) and 82g/CM-d water. Metabolic Energy: not available. Ingested Food Composition: not available.
	g/CM-d	120 (3,4)	Composition: 20g/CM-d solids and 100g/CM-d water. Metabolic Energy: 11.82 MJ/CM-d (assumed). Ingested Food Composition: not available.
	g/CM-d	95.5 (5,6)	Composition: 20.5g/CM-d solids (19.5g/CM-d standard deviation) and 75g/CM-d water. Metabolic Energy: not available. Ingested Food Composition: "relatively low fiber diet, not unlike that eaten while in space." Note: 24 h mean sample; standard deviation of 95.7g/CM-d.
	g/CM-d	132 (7)	Composition: 21g/CM-d solids and 111g/CM-d water. Metabolic Energy: not available. Ingested Food Composition: not available.
	g/CM-d	30 (8)	Composition: 30g/CM-d solids. Metabolic Energy: not available. Ingested Food Composition: not available. Note: Dry mass only. Wet mass unavailable.

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

4.5.4.2 Urine

The mass and composition of urine varies with the individual, with the quantity and composition of water and food consumed, as well as with other factors. Wydeven and Golub (1990) provide general detailed estimates of human urine.

NASA (1995) states the urine collection devices shall have the capacity to accommodate a maximum urine output volume of 4,000 mL/CM-d and a discharge up to 800 mL in a single urination event at a delivery rate of 50 mL/s.

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* An asterisk denotes a suggested value. If a particular waste component is essential for a waste model, but details on the waste component's generation are unknown, the suggested value is recommended.

Depending on the post-urination-event cleansing methods, urine may adhere to toilet paper or wipes. Depending on the life support system configuration, urine may or may not be included with greywater. Table 4.5.7 summarizes information on urine.

Table 4.5.7 Information on Urine

Waste	Units	Value	Comments
Urine	g/CM-d	* 1,562 (1-4)	Composition: 59g/CM-d solids and 1,503g/CM-d water. Ingested Food Composition: not available.
	g/CM-d	1,700 (5)	Composition: 70g/CM-d solids and 1,630g/CM-d water. Ingested Food Composition: not available.
	g/CM-d	1,470 (6)	Composition: 70g/CM-d solids and 1,400g/CM-d water. Ingested Food Composition: not available.
	g/CM-d	2,107 (7,8)	Composition: not available. Ingested Food Composition: not available. Note: 24 h mean sample; standard deviation of 1,259g/CM-d. [132] The wet mass was calculated from urine volumes assuming a density of 1.02g/mL.
	g/CM-d	1,390 (9)	Composition: not available. Ingested Food Composition: not available. Note: The wet mass was calculated from urine volumes assuming a density of 1.02g/mL.

Table References: (1) Parker and West (1973), (2) NASA (1991), (3) Wydeven and Golub (1990), (4) Schubert, et al. (1984), (5) NASA (1995), (6) LSDB (1962), (7) Parker and Gallagher (1988), (8) Diem and Lentner (1970), (9) Leach (1983).

4.5.4.3 Menstruation

Normally, adult female human beings menstruate once every 26 to 34 days for a duration of 4 to 6 days (NASA, 1995). These excretion products provide another possible waste generation mechanism. Menstrual flow is highly variable between individuals. Consequently, menstrual pad and tampon use is also highly variable between individuals. Female crewmembers on ISS use medication before flight to prevent menstruation for up to six months during flight. This approach, for many reasons, may not be acceptable for longer duration flights. Depending on the menstruation management and cleansing method used, menses may adhere to tampons, menstrual pads, toilet paper, or wipes. Table 4.5.8 summarizes information on menstruation using units of grams per crewmember per menstrual cycle [g/CM-℘].

Table 4.5.8 Information on Menstruation

Waste	Units	Value	Comments
Menses	g/CM-℘	* 113.4 (1)	Composition: 80% is released during the first 3 d of menstruation. Note: Menstrual period duration is 4 to 6 d every 26 to 34 d.
	g/CM-℘	28 (2,3)	Composition: 10 g/CM-℘ solids (estimated).
Menstrual Pads and Tampons	g/CM-℘	104 (3)	Note: Mean estimated tampon or menstrual pad usage is 16.2 products/CM-℘. The average menstrual product (menstrual pads or tampons) is 6.4 g/product (clean).

Table References: (1) NASA (1995), (2) Hallberg and Nilsson (1964), (3) Parker and Gallagher (1992).

4.5.4.4 Toilet Paper

Toilet paper usage varies with production rates and consistency of metabolic waste excretions. For all crewmembers, toilet paper is an important cleansing agent following a bowel movement. Additionally, female

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[132] 78% of the variation in urine output could be explained by variations in fluid consumed.

* An asterisk denotes a suggested value. If a particular waste component is essential for a waste model, but details on the waste component's generation are unknown, the suggested value is recommended.

crewmembers use toilet paper following urination events and menstrual discharges. Because of relatively frequent resupply, toilet paper usage on current human missions, such as ISS, may not be as frugal as necessary for longer-duration missions with limited or no resupply. The value provided in Table 4.5.9 may be an upper limit.

NASA (1995) states, "In microgravity, [133] many more tissues are needed for cleansing the anal areas after defecation, because gravitational forces are not present to aid in separation of the feces from the body."

If used as a means for post-defecation, post-urination and menstruation cleansing, toilet paper may contain feces, urine, and menses. Table 4.5.9 summarizes information on toilet paper usage.

Table 4.5.9 Information on Toilet Paper

Waste	Units	Value	Comments
Toilet Paper	g/CM-d	* 28 (1) [134]	
	g/CM-d	5.1 (2,3)	Note: Value computed assuming 6.0 g per bowel movement and 0.86 bowel movements/CM-d based on statistical data. Additionally, for female crewmembers, add 36 g/CM-d to support post-urination cleansing following each of 6 urinations/CM-d.

Table References: (1) Maxwell (2001a), (2) Parker and Gallagher (1992), (3) Wydeven and Golub (1990).

4.5.4.5 Miscellaneous Body Wastes

In addition to metabolic excretions, human beings also shed various wastes from the exposed surfaces of their bodies. These include sweat solids, dead skin cells and associated oils, hair, saliva solids, mucus, fingernails, and toe nails. Estimates and data for these waste stream components are detailed in Table 4.5.10.

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

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

Finally, skin oils, hair, saliva solids, and mucus may adhere to clothing, hygiene wipes, towels, washcloths, or suspend in hygiene greywater. Estimated generation rates for all these human byproducts are provided in Table 4.5.10.

Table 4.5.10 Information on Miscellaneous Body Wastes

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

Table References: (1) NASA (1991), (2) LSDB (1962), (3) NASA (1995).

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[133] See Footnote 33.

[134] Charmin (2002) claims "the average person uses 57 sheets [of toilet paper] per day," or 23 g/CM-d.

* An asterisk denotes a suggested value. If a particular waste component is essential for a waste model, but details on the waste component's generation are unknown, the suggested value is recommended.

4.5.4.6 *Consumable Hygiene Products*

Aboard ISS, crewmembers use a variety of wipes and gloves for various housekeeping and hygiene tasks. Maxwell (2001a) estimates consumption rates for these items based on ISS usage.

Though confirmed only verbally, gloves are used at a rate of one glove per day to clean the toilet after defecation. These gloves are non-powdered, medium, latex laboratory gloves. Following use, human metabolic wastes, such as feces or urine, may adhere to the gloves.

Wipes are essential to many tasks aboard ISS and the estimated consumption rates here are based on ISS usage. Four types of wipes are listed below, though detergent and disinfectant wipes are the same as wet wipes with a commercial detergent or disinfectant solution applied to them. Because of relatively frequent resupply, wipe usage on current human missions, such as ISS, may not be as frugal as necessary for longer-duration missions with limited or no resupply. The values provided in Table 4.5.11 may be an upper limit.

Table 4.5.11 Information on Consumable Hygiene Products

Waste	Units	Value	Comments
Gloves	g/CM-d	7 (1)	Usage: 1 glove/CM-d to clean the toilet following defecation.
Wipes			
Dry	g/CM-d	13 (1)	Usage: This is equivalent to 3 Kimwipe® brand, low-lint 29.2 cm by 30.5 cm wipes/CM-d.
Wet	g/CM-d	51 (1)	Usage: This is equivalent to 4.7 Huggies® brand wet baby wipes/CM-d. Clark (2003) states that Huggies® wet baby wipes at 75% moisture have a mass of 10.9 g/wipe.
Detergent	g/CM-d	58 (1)	
Disinfectant	g/CM-d	56 (1)	

Table Reference: (1) Maxwell (2001a).

4.5.4.7 *Food Packaging, Inedible Biomass, and Wasted Food*

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

The first estimate in Table 4.5.12 provides an estimate of the minimal waste stream from a prepackaged-food system. Levri, et al. (2001) assumed ambient-stored, prepackaged food, similar in nature to the Shuttle Training Menu. Further, each crewmember requires metabolic energy from food of 11.82 MJ/CM-d and only 3% of all prepackaged food and rehydration water is wasted. This is a lower practical wastage limit to estimate the material wasted if the crew attempted to eat all of the food in every package that is opened. The food wastage represents approximately 3% of prepackaged food and rehydration water adheres to the sides of the packaging. Additionally, this study assumed that a small salad crop provides less than 1% of the crew's food energy needs.

The second estimate, from Maxwell (2001b), an unpublished source to date, studied actual ISS food usage rates. This study collected information on the preferred menus of three ISS occupants during one expedition and computed the daily average per crewmember usage rates for food, packaging, and rehydration water. This study additionally assumed that 15% of all food packages shipped to ISS were unopened and discarded and that 5% of all opened food with any rehydration water was discarded while adhered to the food packaging. The actual values in Table 4.5.12 assume modified packaging numbers to reflect more recent food packaging mass data as presented in Levri, et al. (2001). Further, because actual crewmembers are not nominal crewmembers, the nominal metabolic energy of 11.82 MJ/CM-d does not apply to these data. Lastly, food wastage assumptions for future long-duration missions are usually more conservative than ISS usage values because resupply may be more limited or completely nonexistent.

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

* An asterisk denotes a suggested value. If a particular waste component is essential for a waste model, but details on the waste component's generation are unknown, the suggested value is recommended.

Table 4.5.12 summarizes information on food packaging, inedible biomass, and wasted food.

Table 4.5.12 Information on Food Packaging, Inedible Biomass, and Wasted Food

Waste	Units	Value	Comments
Food Packaging and Adhered Food	g/CM-d	* 324 (1)	Composition: 62g/CM-d adhered food (~73% moisture content, including beverages) and 262g/CM-d plastic packaging. Metabolic Energy: 11.82 MJ/CM-d. Ingested Food Composition: ambient-stored, prepackaged food system.
	g/CM-d	508 (2)	Composition: 206g/CM-d unopened food (175 g/CM-d food and 31 g/CM-d plastic packaging) and 302g/CM-d adhered food and packaging waste (58 g/CM-d food, 176g/CM-d plastic packaging, and 68g/CM-d rehydration water). Metabolic Energy: not available. Ingested Food Composition: ambient-stored, prepackaged food system.
Inedible Biomass and Wasted Crop Materials	g/CM-d	TBD	Note: Highly mission dependent. See Table 4.2.7 for inedible biomass productivity under typical crop growth chamber conditions. See Table 4.2.6 for suggested application based on the mission. See Table 4.2.9 for examples of diets using crops.

Table References: (1) Levri, et al. (2001), (2) Maxwell (2001b).

4.5.4.8 Paper, Tape, Miscellaneous Hygiene Products, and Clothing

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

ISS uses paper for documentation and the data point in Table 4.5.13 is based on ISS usage rates. Waste paper generation rates can vary significantly between ISS increments and may not be closely correlated to the number of crewmembers. It is theorized that the relatively frequent upload and download of supplies to ISS is strongly related to the somewhat high rate of waste paper generation from documentation. Much lower waste paper generation rates for documentation are likely on longer-duration missions with little or no resupply.

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

As noted in Table 4.5.13, waste generation rates associated with personal hygiene products can be significant. The data here are based on ISS usage rates. These values may include items such as dental floss, toothbrushes, containers for toothpaste, shave cream, razors, mouthwash, shampoo, moisturizing lotion, deodorant, sun block, chap stick, makeup, and similar personal hygiene products. The value here should probably be considered a historical point, and future long-duration missions with little or no resupply will be much lower. Theoretically, the relatively frequent resupply schedule for ISS is strongly correlated to the surprisingly high rate of miscellaneous hygiene product waste generation.

Clothing usage and associated dirty clothing generation rates are also significant historically, as documented in Table 5.3.1 for ISS. Actual expended clothing generation rates are strongly correlated to how long clothing may be used before it is sufficiently worn or dirty and no longer fit for use. A laundry can increase clothing life, reducing waste generation rates associated with discarded clothing, at a cost of other vehicle resources such as power, crewtime, and water usage.

As a simplifying assumption, clothing is comprised of 100% cotton and has 8.5% moisture content when clean and dry, an industry standard for cotton. Actual clothing may be comprised of other materials that are more efficient and fire retardant, but historically, crewmembers preferred clothing with higher cotton content. Clothing will likely not be discarded in clean form. Rather: clothing, towels, and washcloths will likely contain skin cells, sweat solids, skin oil, hair, and other miscellaneous body wastes. Towels and washcloths will likely also contain

* An asterisk denotes a suggested value. If a particular waste component is essential for a waste model, but details on the waste component's generation are unknown, the suggested value is recommended.

moisture from sweat and bathing. McGlothlin (2000) reports that the average 49-g Class III [135] Shuttle washcloth, measuring 30.5 cm by 30.5 cm and comprised of 100% cotton, retains up to 202g of water when completely soaked.

Table 4.5.13 summarizes information on waste streams from paper, tape, miscellaneous hygiene products, and clothing.

Table 4.5.13 Information on Paper, Tape, Miscellaneous Hygiene Products, and Clothing

Waste	Units	Value	Comments
Paper	g/CM-d	77 (1)	Composition: 6% moisture content.
Grey or Duct Tape	g/CM-d	33 (2)	Note: This value is highly design contingent. The value here represents ISS usage.
Misc. Hygiene Products	g/CM-d	781 (1)	Note: This value is highly design contingent. The value here represents ISS usage. Future missions may allow much lower waste generation rates from miscellaneous hygiene products.
Clothing, Towels, and Wash-cloths	g/CM-d	TBD	Composition: 100% cotton solids, with 8.5% moisture content (clean and dry). Note: See Table 5.3.1 for expended clothing generation rates.

Table References: (1) Maxwell (2001b), (2) Wydeven, et al. (1989).

4.5.4.9 Greywater and Brine

Wastewater and brines, though historically processed by the Water Subsystem, may initially or post-processing pass to the Waste Subsystem. Section 4.6 lists wastewater generation rates and stream compositions. However, these tables do not provide greywater generation data for configurations with crop production or food processing. Greywater production from such activities depends on the crops produced, the growing techniques, the crop processing approaches following harvest, the food processing technology, and the processing equipment and crop cleansing approaches. Finally, greywater may also include urine.

In general, greywater production rates and, more importantly here, the rate of wastewater transfer to the Waste Subsystem, are highly dependent upon the vehicle design. The individual greywater production rates are variable, and decisions about how the wastewater streams are managed significantly influence the wastewater and brine loads passed to the Waste Subsystem.

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

4.5.4.10 Other Waste Streams

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

Extravehicular activities (EVA) supply waste streams to the life support system. While some wastes are gaseous, others are solid wastes. Most significantly, crewmembers are provided with a maximum absorption garment (MAG) to catch metabolic wastes. A used garment may be contaminated with urine, feces, and other wastes associated with exposure to human skin. The data in Table 4.5.14 are based on ISS equipment and production rates in terms of grams per crewmember per EVA sortie [g/CM-EVA]. Data on other likely EVA wastes, such as food sticks, drink pouches, and batteries, were unavailable. EVA consumption rates for consumables are given in Table 5.2.5, although these values do not reflect solid waste production rates.

Equipment wastes are highly variable with the overall vehicle design. Equipment wastes include supplies for life support hardware, such as filters and plastic bags. Generally, the Waste Subsystem design varies with the life support system architecture, including the degree of resource recovery and containment for pre-processing storage, post-processing storage, and disposal. For example, a system in which there is no recovery from solid wastes, such

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

* An asterisk denotes a suggested value. If a particular waste component is essential for a waste model, but details on the waste component's generation are unknown, the suggested value is recommended.

as on ISS, may require more Waste Subsystem resupply items than a system that reuses or recovers resources. Regarding storage options, some equipment wastes might be returned to its original stowage volumes, although cleaning may be required before such an approach is acceptable. For example, contaminated membranes from the Water Subsystem might be cleaned to remove water wastes and then stowed in the original stowage volume for membranes.

Experimental wastes are highly variable in experimental procedures and mission objectives. Some waste materials may be hazardous.

Medical wastes are also highly variable with medical protocol. These waste loads could be very sporadic and may require special handling. Some waste product materials may even be biohazardous.

Table 4.5.14 summarizes information on EVA, equipment, experiment, and medical waste streams.

Table 4.5.14 Information on Other Waste Streams

Waste	Units	Value	Comments
EVA Wastes	g/CM-EVA	173 (1)	Note: This value represents the maximum absorption garment (clean and dry)
Equipment Wastes	g/CM-d	TBD	Note: Highly variable and dependent on vehicle design.
Experiment Wastes	g/CM-d	TBD	Note: Highly variable and dependent on mission design. Waste streams delegated to the Waste Subsystem will depend on mission protocols. Some wastes may be hazardous.
Medical Wastes	g/CM-d	TBD	Note: Highly variable and dependent on mission medical protocol. Waste streams delegated to the Waste Subsystem will depend on mission protocols. Some wastes may be biohazards.

Table Reference: (1) EDCC (1998).

* An asterisk denotes a suggested value. If a particular waste component is essential for a waste model, but details on the waste component's generation are unknown, the suggested value is recommended.

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 complementary 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 Subsystems

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 water. The tables here provide anticipated usage rates for several possibilities. 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 lists steady-state water usage estimates for missions of 30 days or less. Table 4.6.2 lists steady-state water usage estimates for longer duration missions. More importantly here, Table 4.6.3 details anticipated wastewater generation rates to be processed by the Water Subsystem for long-duration missions. Please note the water usage rates and wastewater generation rates sometimes differ, as a quick comparison of Table 4.6.2 to Table 4.6.3 confirms. In some cases, either the water usage or wastewater generation rates are unknown. In other cases, water usage does not correspond to wastewater generated and sent to the Water Subsystem, varying with the configuration of the system using the water.

The mission scenarios are defined as: assembly complete ISS, assumed as lacking a waste and hygiene compartment; a transit mission, currently assumed to have similar hygiene capabilities as ISS; Early Planetary Base, assumed to have the capability for limited hygiene water use; and Mature Planetary Base, assumed to have the capability for full hygiene water use as well as a biomass production chamber for food cultivation.

Table 4.6.1 Steady-State Values for Vehicle Water Usage for Short-Duration Missions [136]

		Assumptions			
Parameter	**Units**	**Lower**	**Nominal**	**Upper**	**References**
Crew Water Allocation, assuming Minimal Hygiene Water for a Mission Less Than 30 days	kg/CM-d	2.9 (1)	4.5 (2)	7.7 (2)	(1) From Apollo Program via Ewert and Drake (2000) (2) Ewert and Drake (2000)

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[136] For information only.

Table 4.6.2 Typical Steady-State Water Usage Rates for Various Missions [137]

Parameter	Units	International Space Station	Transit Vehicle	Early Planetary Base	Mature Planetary Base
Crew Drinks	kg/CM-d	2.00 (2)	2.00 (2)	2.00 (2)	2.00 (2)
Total Metabolic and Related Consumption	*kg/CM-d*	*2.00*	*2.00*	*2.00*	*2.00*
Urinal Flush	kg/CM-d	0.30 (1)	0.30 (1)	0.50 (2)	0.50 (2)
Oral Hygiene	kg/CM-d	0.37 (2)	0.37 (2)	0.37 (2)	0.37 (2)
Hand Wash	kg/CM-d	n/a	n/a	4.08 (2)	4.08 (2)
Shower [138]	kg/CM-d	n/a	n/a	2.72 (2)	2.72 (2)
Laundry	kg/CM-d	n/a	n/a	n/a	12.47 (2)
Dish Wash	kg/CM-d	n/a	n/a	n/a	5.44 (2)
Food Processing and Preparation	kg/CM-d	TBD	TBD	TBD	TBD
Total Hygiene Consumption	*kg/CM-d*	*0.67*	*0.67*	*7.67*	*25.58*
Payload	kg/CM-d	2.18 (1)	TBD (3)	TBD (3)	TBD (3)
Total Payload Consumption	*kg/CM-d*	*2.18*			
Total Water Consumption	***kg/CM-d***	***4.85***	***2.67***	***9.67***	***27.58***
Biomass Production Water Consumption [139]	kg/m^2•d	n/a	n/a	n/a	4.00

References

(1) NASA (2004)
(2) NASA (1991)
(3) Architecture dependent.

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[137] For information only.

[138] Assuming one shower per two days.

[139] 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.

Table 4.6.3 Typical Steady-State Wastewater Generation Rates for Various Missions

Parameter	Units	International Space Station	Transit Vehicle	Early Planetary Base	Mature Planetary Base
Urine	kg/CM-d	1.20 (1)	1.50 (2)	1.50 (2)	1.50 (2)
Urinal Flush	kg/CM-d	0.30 (1)	0.30 (1)	0.50 (2)	0.50 (2)
Total Urine Wastewater Load	*kg/CM-d*	*1.80*	*1.80*	*2.00*	*2.00*
Oral Hygiene	kg/CM-d	n/a	n/a	0.37 (2)	0.37 (2)
Hand Wash	kg/CM-d	n/a	n/a	4.08 (2)	4.08 (2)
Shower [140]	kg/CM-d	n/a	n/a	2.72 (2)	2.72 (2)
Laundry	kg/CM-d	n/a	n/a	n/a	11.87 (2)
Dish Wash	kg/CM-d	n/a	n/a	n/a	5.41 (2)
Food Preparation and Processing	kg/CM-d	n/a	n/a	n/a	TBD
Total Hygiene Wastewater Load	*kg/CM-d*	*0.00*	*0.00*	*7.17*	*24.45+*
Crew Latent Humidity Condensate	kg/CM-d	2.27 (2)	2.27 (2)	2.27 (2)	2.90 (2)
Animal Latent Humidity Condensate	kg/CM-d	n/a	n/a	TBD	TBD
Total Latent Wastewater Load	*kg/CM-d*	*2.27*	*2.27*	*2.27+*	*2.90+*
Payload	kg/CM-d	n/a	n/a	TBD (3)	TBD (3)
Total Payload Wastewater Load	*kg/CM-d*	*0.00*	*0.00*	*0.00+*	*0.00+*
Total Wastewater Load	***kg/CM-d***	***4.07***	***4.07***	***11.44+***	***29.35+***
Biomass Production Wastewater [141]	kg/m^2•d	n/a	n/a	n/a	TBD

References

(1) NASA (2004)
(2) NASA (1991)
(3) Architecture dependent.

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[140] Assuming one shower per two days.

[141] 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 Component Contaminant Loading

Studies by Carter (1998) and Putnam (1971) provide the data for Table 4.6.4 through Table 4.6.9, 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. Consequently, some contaminants, especially those associated with ISS cleansing agents in the shower (Table 4.6.6) and hygiene (Table 4.6.7) streams, may be unique to ISS. Likewise, wastes listed for the EMU (Table 4.6.4) 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 4.6.4 through Table 4.6.9 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 [142]. 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 4.6.4 details the anticipated aqueous contaminants in the greywater stream from an EMU. This stream reflects Shuttle or ISS program technology, so a similar stream for an advanced spacesuit may differ. Carter (1998) developed this list based on the ISS program.

Table 4.6.4 Wastewater 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 4.6.5 lists the anticipated contaminants from the latent condensate derived from the crew cabin. Carter (1998) developed this list based on the ISS program.

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[142] See Duffield (2003) for CI and SMAC requirements.

Table 4.6.5 Wastewater 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 4.6.6 details the contaminants from the crew shower stream. Subject to the cleansing agent employed, actual components in a shower greywater stream may vary. Carter (1998) developed this list based on the ISS program. Verostko, et al. (1989) and Wydeven and Golub (1990) also provide crew shower greywater models.

Table 4.6.6 Wastewater 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
propanoic acid			74.1	48.6	30.00	3.2
lactic acid [2-hydroxy-propanoic acid]			90.1	40.0	24.16	2.6
potassium	×		39.1	0.0	17.50	1.9
ammonium	×		18.0	0.0	16.80	1.8
sulfate	×		96.1	0.0	12.33	1.3
constituents totaling less than 5%					*32.39*	*3.4*
ethanol		×	*46.1*	*52.1*	*3.08*	*0.3*
ethylene glycol [1,2-ethandiol]		×	*62.1*	*38.7*	*2.51*	*0.3*
methanol		×	*32.0*	*37.5*	*0.90*	*0.1*
phenol		×	*94.1*	*76.6*	*0.37*	*0.0*
acetone [2-propanone]		×	*58.1*	*62.0*	*0.21*	*0.0*
formaldehyde [methanal]		×	*30.0*	*40.0*	*0.10*	*0.0*
propionaldehyde [propanal]		×	*58.1*	*62.0*	*0.09*	*0.0*
Total					**945.2**	**100**

Table 4.6.7 details the contaminants from the crew hygiene stream derived from hand and oral cleansing operations. Subject to the cleansing agent employed, actual components in a hygiene greywater stream may vary. Carter (1998) developed this list based on the ISS program. Wydeven and Golub (1990) also provides a crew hygiene greywater model.

Table 4.6.7 Wastewater 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
propanoic acid			74.1	48.6	9.56	0.9
ethanol		×	46.1	52.1	8.57	0.8
phosphate			95.0	0.0	7.20	0.7
constituents totaling less than 5%					*32.09*	*3.2*
methanol		×	*32.0*	*37.5*	*6.36*	*0.6*
ammonium	×		*18.0*	*0.0*	*5.81*	*0.6*
ethylene glycol [1,2-ethandiol]		×	*62.1*	*38.7*	*1.58*	*0.2*
1-propanol		×	*60.1*	*60.0*	*0.58*	*0.1*
2-propanol		×	*60.1*	*60.0*	*0.26*	*0.0*
phenol		×	*94.1*	*76.6*	*0.16*	*0.0*
dimethyl disulfide	×		*94.2*	*25.5*	*0.13*	*0.0*
acetone [2-propanone]		×	*58.1*	*62.0*	*0.09*	*0.0*
pentane		×	*72.2*	*83.2*	*0.09*	*0.0*
formaldehyde [methanal]		×	*30.0*	*40.0*	*0.07*	*0.0*
propionaldehyde [propanal]		×	*58.1*	*62.0*	*0.05*	*0.0*
1-butanol		×	*74.1*	*64.8*	*0.05*	*0.0*
dimethyl sulfide	×	×	*62.1*	*38.7*	*0.05*	*0.0*
carbon disulfide	×	×	*76.1*	*15.8*	*0.02*	*0.0*
Total					**1,018.0**	**100**

Table 4.6.8 lists the composition of unprocessed urine as derived from the human metabolic process. The reference is Putnam (1971).

Table 4.6.8 Wastewater 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 aspartate	×		*150.1*	*32.0*	*135*	*0.4*
ammonium formate	×		*63.1*	*19.0*	*88*	*0.2*
calcium phosphate	×		*310.2*	*0.0*	*62*	*0.2*
ammonium pyruvate	×		*105.1*	*34.3*	*44*	*0.1*
ammonium oxalate	×		*124.1*	*19.4*	*37*	*0.1*
Total					**37,057**	**100**

Table 4.6.9 lists anticipated contaminants from the latent condensate derived from experimental animals. Carter (1998) developed this list based on the ISS program.

Table 4.6.9 Wastewater 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**

4.6.3 Wastewater and Intermediate Water System Solution Formulations for Testing

The following formulations provide standardized feed solutions for developmental hardware. Please see Verostko, et al. (2004) for additional details. Sections 4.6.3.1 and 4.6.3.2 present projected input wastewater streams from the crew cabin for a transit vehicle and an early planetary base, respectively. The concentrations and volumes for the transit mission wastewater stream are originate in literature describing wastewater for ISS. The wastewater volumes for the early planetary base originate from flowrates measured during the Advanced Water Recovery System test. These formulations provide researchers with two different feed wastewater streams for testing developmental water processing hardware. For completeness, both streams should be considered.

Sections 4.6.3.3, 4.6.3.4, and 4.6.3.5 detail product streams from the biological water processor (BWP), a reverse osmosis (RO) system, and the air evaporation subsystem (AES), respectively, to provide authentic pre-processed input streams for downstream hardware. These formulations of hardware product streams are based on data taken at Johnson Space Center during an Integrated Advanced Water Recovery Systems test. The tested configuration included a BWP coupled with a RO system. The BWP included a packed-bed denitrification reactor and a tubular nitrification reactor. An AES dewatered brine from the RO system. Though not represented in the data below, the dewatered brine and RO-system permeate were post-processed during testing with a mixed-media ion exchange bed and a series of ultraviolet-light lamps. Because water quality from actual water processing hardware may vary, nominal and worst-case formulations are listed for both the RO permeate and the AES condensate. The BWP effluent is an appropriate feed stream for developmental secondary processors while the RO permeate and the AES condensate formulations provide appropriate feed streams for developmental post-processors.

4.6.3.1 Transit Mission Wastewater Ersatz

4.6.3.1.1 TRANSIT MISSION WASTEWATER ERSATZ CONCENTRATE CONSTITUENT TABLES

Table 4.6.10 through Table 4.6.14 describe the components of the transit mission (TM) wastewater ersatz. The state of each constituent is indicated by its measured value. For solid constituents, a mass is listed. For liquid constituents, a volume is listed. In all cases, when applicable, the constituent purity or concentration is noted in the first column following the constituent name. When not otherwise noted, all constituent purities are greater than 99%. Final solution properties are listed in Table 4.6.15. The preparation instructions are presented in Section 4.6.3.1.2. For the original source, see Verostko, et al. (2004)

Table 4.6.10 Concentrate 1: Urine 1 – Organic Compounds for TM Wastewater Ersatz (C1) [143]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
urea	NH_2CONH_2	60.06	52.021	-
creatinine (98%)	$C_4H_7N_3O$	113.10	5.221	-
histidine, soluble (98%)	$C_6H_9N_3O_2$	155.20	0.958	-
taurine	$C_2H_5NSO_3$	125.10	0.556	-
glutamic acid	$C_5H_9NO_4$	147.10	1.660	-
glucose (96%)	$C_6H_{12}O_6$	390.40	2.636	-
ammonium citrate (99%)	$(NH_4)_2C_6H_5O_7$	226.20	12.340	-
ammonium formate (97%)	NH_4HCO_2	63.10	1.466	-
ammonium oxalate monohydrate	$(NH_4)_2C_2O_4$	142.10	0.665	-

Table 4.6.11 Concentrate 2: Urine 2 – Inorganic Compounds for TM Wastewater Ersatz (C2) [144]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
sodium chloride	$NaCl$	58.40	23.126	-
magnesium chloride hexahydrate	$MgCl_2 \bullet 6H_2O$	203.31	5.483	-
potassium bicarbonate	$KHCO_3$	100.10	2.197	-
potassium carbonate	K_2CO_3	138.21	0.474	-
potassium monobasic phosphate	KH_2PO_4	136.09	1.069	-
potassium chloride	KCl	74.60	5.436	-
potassium sulfate	K_2SO_4	174.29	7.424	-
calcium chloride	$CaCl_2$	110.99	0.221	-
sodium sulfate	Na_2SO_4	142.00	4.144	-

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[143] This solution is 10 times more concentrated than will be its constituents in the final TM wastewater ersatz.

[144] This solution is 10 times more concentrated than will be its constituents in the final TM wastewater ersatz.

Table 4.6.12 Concentrate 3: Humidity Condensate for TM Wastewater Ersatz (C3) [145]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
acetic acid	CH_3CO_2H	60.05	-	0.441
benzoic acid	$C_6H_5CO_2H$	122.20	0.046	-
benzyl alcohol	$C_6H_5CH_2OH$	108.14	-	0.259
ethanol	C_2H_6O	46.07	-	1.506
acetone	CH_3COCH_3	58.08	-	0.030
caprolactam	$C_6H_{11}NO$	113.16	0.191	-
phenol	C_6H_5OH	94.11	0.027	-
N,N-dimethylformamide	$HCON(CH_3)_2$	73.10	-	0.035
ethylene glycol	$HOCH_2CH_2OH$	62.07	-	0.157
4-ethyl morpholine	$C_6H_{13}NO$	115.18	-	0.072
formaldehyde (37%)	$HCHO$	30.03	-	0.461
formic acid (96%)	HCO_2H	46.03	-	0.208
lactic acid	$CH_3CH(OH)CO_2H$	90.08	-	0.187
methanol	CH_3OH	32.04	-	0.218
1,2-propanediol	$C_3H_8O_2$	76.09	-	0.013
2-propanol	$(CH_3)_2CHOH$	60.10	-	0.042
propionic acid	$CH_3CH_2CO_2H$	74.08	-	0.042
urea	NH_2CONH_2	60.06	0.101	-

Table 4.6.13 Concentrate 4: Sabatier Product Water for TM Wastewater Ersatz (C4)

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
ammonium bicarbonate	NH_4HCO_3	79.06	2.611	-

Table 4.6.14 US Urine Pretreatment (per liter of wastewater) for TM Wastewater Ersatz

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
oxone	$2KHSO_5 \bullet KHSO_4 \bullet K_2SO_4$	614.80	1.671	-
potassium benzoate	$C_7H_5KO_2$	160.22	0.334	-
sulfuric acid, concentrated (96%, 36 Normal)	H_2SO_4	98.08	-	0.615

4.6.3.1.2 TRANSIT MISSION WASTEWATER ERSATZ FORMULATION PROCEDURE

1) Concentrate Preparation:
   - Label four (4) 1-liter flasks “C1,” “C2,” “C3,” and “C4.” Add 750 mL of deionized water to each.
   - For each concentrate, add the constituents listed in Table 4.6.10 through Table 4.6.14 above, one at a time and in the order listed. Mix thoroughly between constituents until each dissolves.
   - Dilute each flask to 1 liter with deionized water and mix thoroughly to complete preparation of the concentrate mixes.
   - Cap all concentrates and store under ambient conditions. (In other words, **DO NOT REFRIGERATE**.)

   NOTE: DO NOT MAKE a Urine Pretreatment concentrate. (These constituents are added directly to the 1-Liter Working Solution in Step 3)

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[145] This solution is 10 times more concentrated than will be its constituents in the final TM wastewater ersatz.

2) 1-Liter Working Solution Preparation:
   - Add 300 mL deionized water, 100 mL of solution C1, and 100 mL of solution C2 to a 1-liter flask, dilute to 500 mL with deionized water, and mix thoroughly.
3) 1-Liter Working Solution Preparation (continued):
   - Add 1.671g oxone and 0.334 g potassium benzoate, and mix thoroughly.
   - Slowly add 0.615 mL concentrated sulfuric acid. Mix thoroughly.
   - The solution pH should be less than 2.4.
4) 1-Liter Working Solution (concluded):
   - Now add 100 mL of solution C3, and 50 mL of solution C4.
   - Dilute with deionized water to 1 liter and mix thoroughly.
5) Verification:
   - Analyze working solution for cation, anion, pH, conductivity, total organic carbon (TOC), and total inorganic carbon (TIC).
   - Target values for these solution properties are listed in Table 4.6.15.

Table 4.6.15 Average Solution Properties for Transit Mission Wastewater Ersatz

Property or Concentration	Formula	Units	Average Value	Standard Deviation	Reference
potential of hydrogen	pH		2.6	± 0.2	Verostko, et al. (2004)
Conductivity		µS	12,352	± 1,853	
total organic carbon	TOC	mg/L	2,209	± 221	
total inorganic carbon	TIC	mg/L	-	-	
Chloride	Cl^-	mg/L	1,870	± 281	
Nitrite	NO_2^-	mg-N/L	-	-	
Nitrate	NO_3^-	mg-N/L	-	-	
Phosphate	PO_4^{-3}	mg/L	75	± 11	
Sulfate	SO_4^{-2}	mg/L	2,864	± 430	
Sodium	Na^+	mg/L	1,045	± 157	
Ammonium	NH_4^+	mg-N/L	221	± 33	
potassium	K^+	mg/L	1,387	± 208	
calcium	Ca^{+2}	mg/L	7.95	± 1.2	
magnesium	Mg^{+2}	mg/L	64.0	± 10	

4.6.3.2 Early Planetary Base Wastewater Ersatz

4.6.3.2.1 EARLY PLANETARY BASE WASTEWATER ERSATZ CONCENTRATE CONSTITUENT TABLES

Table 4.6.16 through Table 4.6.21 describe the components of the early planetary base (EPB) wastewater ersatz. The state of each constituent is indicated by its measured value. For solid constituents, a mass is listed. For liquid constituents, a volume is listed. In all cases, when applicable, the constituent purity or concentration is noted in the first column following the constituent name. When not otherwise noted, all constituent purities are greater than 99%. Final solution properties are listed in Table 4.6.22. The preparation instructions are presented in Section 4.6.3.2.2. For the original source, see Verostko, et al. (2004)

Table 4.6.16 Concentrate 1: Inorganic Compounds 1 for EPB Wastewater Ersatz (C1) [146]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
ammonium bicarbonate	NH_4HCO_3	79.06	23.002	-
sodium bicarbonate	$NaHCO_3$	84.01	2.118	-
potassium bicarbonate	$KHCO_3$	100.10	0.462	-

Table 4.6.17 Concentrate 2: Inorganic Compounds 2 for EPB Wastewater Ersatz (C2) [147]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
potassium chloride	KCl	74.60	1.968	-
sodium chloride	$NaCl$	58.40	6.942	-
potassium monobasic phosphate	KH_2PO_4	136.09	1.661	-
potassium sulfate	K_2SO_4	174.29	1.595	-
ammonium hydroxide, concentrated (29.34%)	NH_4OH	35.05	-	10.000

Table 4.6.18 Concentrate 3: Humidity Condensate for EPB Wastewater Ersatz (C3) [148]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
acetic acid	CH_3CO_2H	60.05	-	0.927
benzoic acid	$C_6H_5CO_2H$	122.20	0.096	-
benzyl alcohol	$C_6H_5CH_2OH$	108.14	-	0.542
ethanol	C_2H_6O	46.07	-	3.164
acetone	CH_3COCH_3	58.08	-	0.039
caprolactam	$C_6H_{11}NO$	113.16	0.401	-
phenol	C_6H_5OH	94.11	0.057	-
N,N-dimethylformamide	$HCON(CH_3)_2$	73.10	-	0.073
ethylene glycol	$HOCH_2CH_2OH$	62.07	-	0.330
4-ethyl morpholine	$C_6H_{13}NO$	115.18	-	0.150
formaldehyde (37%)	$HCHO$	30.03	-	0.967
formic acid (96%)	HCO_2H	46.03	-	0.438
lactic acid	$CH_3CH(OH)CO_2H$	90.08	-	0.393
methanol	CH_3OH	32.04	-	0.457
1,2-propanediol	$C_3H_8O_2$	76.09	-	1.980
2-propanol	$(CH_3)_2CHOH$	60.10	-	0.195
propionic acid	$CH_3CH_2CO_2H$	74.08	-	0.236
urea	NH_2CONH_2	60.06	0.290	-

Table 4.6.19 Concentrate 4: Sabatier Product Water for EPB Wastewater Ersatz (C4) [149]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
ammonium bicarbonate	NH_4HCO_3	79.06	0.389	-

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[146] This solution is 10 times more concentrated than will be its constituents in the final EPB wastewater ersatz.

[147] This solution is 10 times more concentrated than will be its constituents in the final EPB wastewater ersatz.

[148] This solution is 100 times more concentrated than will be its constituents in the final EPB wastewater ersatz.

[149] This solution is 10 times more concentrated than will be its constituents in the final EPB wastewater ersatz.

Table 4.6.20 Concentrate 5: Hygiene Water for EPB Wastewater Ersatz (C5) [150]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
NASA Whole Body Shower Soap (40%) [151]	-		30.076	-
acetic acid	CH_3CO_2H	60.05	-	0.681
urea	NH_2CONH_2	60.06	0.180	-
ethanol	C_2H_6O	46.07	-	0.130
lactic acid	$CH_3CH(OH)CO_2H$	90.08	1.627	-
methanol	CH_3OH	32.04	-	0.060
propionic acid	$CH_3CH_2CO_2H$	74.08	-	0.246

Table 4.6.21 Concentrate 6: Urine Organics for EPB Wastewater Ersatz (C6) [152]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
urea	NH_2CONH_2	60.06	1.595	-
creatinine (98%)	$C_4H_7N_3O$	113.10	1.585	-
histidine, soluble (98%)	$C_6H_9N_3O_2$	155.20	0.291	-
taurine	$C_2H_5NSO_3$	125.10	0.170	-
glutamic acid	$C_5H_9NO_4$	147.10	0.509	-
glucose (96%)	$C_6H_{12}O_6$	390.40	0.783	-
ammonium citrate (99%)	$(NH_4)_2C_6H_5O_7$	226.20	3.712	-
ammonium formate (97%)	NH_4HCO_2	63.10	0.445	-
ammonium oxalate monohydrate	$(NH_4)_2C_2O_4$	142.10	0.182	-

4.6.3.2.2 EARLY PLANETARY BASE WASTEWATER ERSATZ FORMULATION PROCEDURE

1) Concentrate Preparation:
    - Label six (6) 1-liter flasks “C1,” “C2,” “C3,” “C4,” “C5,” and “C6.” Add 750 mL of deionized water to each.
    - For each concentrate, add the constituents listed in Table 4.6.16 through Table 4.6.21 above, one at a time in the order listed, and mix thoroughly between constituents until each dissolves.
    - Dilute each flask to 1 liter with deionized water and mix thoroughly to complete preparation of the concentrate mixes.
    - Cap all concentrates and store under ambient conditions. (In other words, **DO NOT REFRIGERATE**.)
2) Working Solution:

    <u>NOTE:</u> DO NOT ADD solution C1 now. See Step 3 below.
    - Add 300 mL deionized water, 100 mL of solution C2, 10 mL of solution C3, 100 mL of solution C4, 50 mL of solution C5, and 100 mL of solution C6 to a 1-liter flask.
    - Dilute to 850 mL with deionized water and mix thoroughly.
3) Working Solution (continued):
    - Now slowly add 100 mL of solution C1. NOTE: Be sure to add C1 last to prevent TIC loss.

    <u>NOTE:</u> Be sure to add solution C1 last to prevent loss of total inorganic carbon (TIC).
4) pH Adjustment:
    - If required, adjust pH to 8.9 ± 0.2 with 1.5 Normal ammonium hydroxide (NH_4OH), using less than 7 mL.
    - Add deionized water to make 1 liter and mix.

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[150] This solution is 20 times more concentrated than will be its constituents in the final EPB wastewater ersatz.

[151] “Geropon TC-42,” formerly “Igepon TC-42,” is manufactured by Rhodia North American Chemicals and is approximately 60% water. See Ecolab (1998).

[152] This solution is 10 times more concentrated than will be its constituents in the final EPB wastewater ersatz.

5) Verification:
   - Analyze working solution for cation, anion, pH, conductivity, total organic carbon (TOC), and total inorganic carbon (TIC).
   - Target values for these solution properties are listed in Table 4.6.22.

Table 4.6.22 Average Solution Properties for Early Planetary Base Wastewater Ersatz

Property or Concentration	Formula	Units	Average Value	Standard Deviation	Reference
potential of hydrogen	pH		8.9	± 0.2	Verostko, et al. (2004)
conductivity		µS	6,869	± 1,030	
total organic carbon	TOC	mg/L	631	± 63	
total inorganic carbon	TIC	mg/L	391	± 59	
chloride	Cl^-	mg/L	514	± 77	
nitrite	NO_2^-	mg-N/L	-	-	
nitrate	NO_3^-	mg-N/L	-	-	
phosphate	PO_4^{-3}	mg/L	116	± 17	
sulfate	SO_4^{-2}	mg/L	88	± 13	
sodium	Na^+	mg/L	331	± 50	
ammonium	NH_4^+	mg-N/L	852	± 128	
potassium	K^+	mg/L	240	± 36	
calcium	Ca^{+2}	mg/L	-	-	
magnesium	Mg^{+2}	mg/L	-	-	

4.6.3.3 *Biological Water Processor Effluent Ersatz*

4.6.3.3.1 BIOLOGICAL WATER PROCESSOR EFFLUENT ERSATZ CONCENTRATE CONSTITUENT TABLES

Table 4.6.23 through Table 4.6.27 describe the components of the biological water processor (BWP) effluent ersatz. The state of each constituent is indicated by its measured value. For solid constituents, a mass is listed. For liquid constituents, a volume is listed. In all cases, when applicable, the constituent purity or concentration is noted in the first column following the constituent name. When not otherwise noted, all constituent purities are greater than 99%. Final solution properties are listed in Table 4.6.28. The preparation instructions are presented in Section 4.6.3.3.2. For the original source, see Verostko, et al. (2004)

Table 4.6.23 Concentrate 1: Inorganic Compounds 1 for BWP Effluent Ersatz (C1) [153]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
ammonium bicarbonate	NH_4HCO_3	79.06	36.214	-

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[153] This solution is 50 times more concentrated than will be its constituents in the final BWP effluent ersatz.

Table 4.6.24 Concentrate 2: Inorganic Compounds 2 for BWP Effluent Ersatz (C2) [154]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
ammonium chloride	NH_4Cl	53.49	5.001	-
sodium chloride	NaCl	58.40	31.614	-
sodium nitrite	$NaNO_2$	69.00	1.230	-
sodium nitrate	$NaNO_3$	84.99	14.271	-
potassium monobasic phosphate	KH_2PO_4	136.09	8.591	-
potassium bisulfate	$KHSO_4$	136.20	8.286	-
potassium chloride	KCl	74.60	13.681	-
hydrochloric acid (concentrated, 37%)	HCl	36.46	-	7.900

Table 4.6.25 Concentrate 3: Soluble Organic Compounds for BWP Effluent Ersatz (C3) [155]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
dextran	$(C_6H_{10}O_5)_n$	(15k-20k)	27.220	-
glucuronic acid	$C_6H_{10}O_7$	194.10	2.690	-
creatinine (98%)	$C_4H_7N_3O$	113.10	2.350	-
urea	NH_2CONH_2	60.06	2.500	-

Table 4.6.26 Concentrate 4: Insoluble Organic Compounds for BWP Effluent Ersatz (C4) [156]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
fructan (xanthan gum)	-	-	0.450	-
tyrosine	$C_9H_{11}NO_3$	181.20	0.596	-
ibuprofen	$C_{13}H_{18}O_2$	206.30	0.757	-
bis-2-ethylhexyl phathalate	$C_{24}H_{38}O_4$	390.60	0.736	-
ethyl morpholine	$C_6H_{13}NO$	115.17	0.626	-

Table 4.6.27 Concentrate 5: Volatile Organic Carbon Compounds for BWP Effluent Ersatz (C5) [157]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
acetic acid	CH_3CO_2H	60.05	-	2.390
lactic acid	$CH_3CH(OH)CO_2H$	90.08	-	2.360
2-propanol	$(CH_3)_2CHOH$	60.10	-	2.140
acetone	CH_3COCH_3	58.08	-	2.060
ethanol	C_2H_6O	46.07	-	2.850

4.6.3.3.2 BIOLOGICAL WATER PROCESSOR EFFLUENT ERSATZ FORMULATION PROCEDURE

1) Concentrate Preparation:
   - Label five (5) 1-liter flasks “C1,” “C2,” “C3,” “C4,” and “C5.” Add 750 mL of deionized water to each.
   - For each concentrate, add the constituents listed in Table 4.6.23 through Table 4.6.27 above, one at a time in the order listed, and mix thoroughly among constituents until each dissolves, except as noted below.

   NOTE: The constituents of solution C4 ***WILL NOT DISSOLVE*** *completely.*

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[154] This solution is 50 times more concentrated than will be its constituents in the final BWP effluent ersatz.

[155] This solution is 1,000 times more concentrated than will be its constituents in the final BWP effluent ersatz.

[156] This solution has variable concentration based on the solubility of its constituents. This solution is more concentrated than will be its constituents in the final BWP effluent ersatz.

[157] This solution is 100 times more concentrated than will be its constituents in the final BWP effluent ersatz.

- Dilute each flask to 1 liter with deionized water and mix thoroughly to complete preparation of the concentrate mixes.
- Cap all concentrates and store under ambient conditions. (In other words, **DO NOT REFRIGERATE**.)

2) Working Solution:

   NOTE: DO NOT ADD solution C1 now. See Step 3 below.

   - Add, to a 1-liter flask, 300 mL deionized water, 20 mL of solution C2, and 3.6 mL of solution C3
   - Add, to the solution above, 10.22 mL of solution C4 filtered through a #4 Whatman filter paper.
   - Add, to the solution above, 0.094 mL of solution C5.
   - Dilute to 950 mL with deionized water and mix thoroughly.

3) Working Solution (continued):

   - Now slowly add 20 mL of solution C1.

   NOTE: Be sure to add solution C1 last to prevent loss of total inorganic carbon (TIC).

4) pH Adjustment:

   - If required, adjust pH to 6.6 ± 0.2 with 1.5 Normal ammonium hydroxide (NH_4OH), using less than 500 µL.
   - Add deionized water to make 1 liter and mix.

5) Verification:

   - Analyze working solution for cation, anion, pH, conductivity, total organic carbon (TOC), and total inorganic carbon (TIC).
   - Target values for these solution properties are listed in Table 4.6.28.

Table 4.6.28 Average Solution Properties for Biological Water Processor Effluent Ersatz

Property or Concentration	Formula	Units	Average Value	Standard Deviation	Reference
potential of hydrogen	pH		6.6	± 0.2	Verostko, et al. (2004)
conductivity		µS	3,802	± 570	
total organic carbon	TOC	mg/L	51	± 5.1	
total inorganic carbon	TIC	mg/L	110	± 17	
chloride	Cl^-	mg/L	608	± 91	
nitrite	NO_2^-	mg-N/L	5.0	± 0.7	
nitrate	NO_3^-	mg-N/L	47	± 7.1	
phosphate	PO_4^{-3}	mg/L	120	± 18	
sulfate	SO_4^{-2}	mg/L	117	± 18	
sodium	Na^+	mg/L	334	± 50	
ammonium	NH_4^+	mg-N/L	154	± 23	
potassium	K^+	mg/L	240	± 36	
calcium	Ca^{+2}	mg/L	-	-	
magnesium	Mg^{+2}	mg/L	-	-	

4.6.3.4 Reverse Osmosis Subsystem Permeate Ersatz

The reverse osmosis subsystem permeate ersatz is presented for both nominal and worst-case possibilities.

4.6.3.4.1 REVERSE OSMOSIS PERMEATE (NOMINAL) ERSATZ CONCENTRATE CONSTITUENT TABLES

Table 4.6.29 through Table 4.6.33 describe the components of the nominal reverse osmosis (RO) permeate ersatz. The state of each constituent is indicated by its measured value. For solid constituents, a mass is listed. For liquid constituents, a volume is listed. In all cases, when applicable, the constituent purity or concentration is noted in the first column following the constituent name. When not otherwise noted, all constituent purities are greater than 99%. Final solution properties are listed in Table 4.6.34. The preparation instructions are presented in Section 4.6.3.4.2. For the original source, see Verostko, et al. (2004)

Table 4.6.29 Concentrate 1: Inorganic Compounds 1 for RO Permeate (Nominal) Ersatz (C1) [158]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
ammonium bicarbonate	NH_4HCO_3	79.06	9.221	-

Table 4.6.30 Concentrate 2: Inorganic Compounds 2 for RO Permeate (Nominal) Ersatz (C2) [159]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
sodium nitrite	$NaNO_2$	69.00	0.896	-
magnesium sulfate	$MgSO_4$	120.40	0.005	-
potassium sulfate	K_2SO_4	174.29	0.449	-
sodium chloride	NaCl	58.40	3.857	-
potassium monobasic phosphate	KH_2PO_4	136.09	0.152	-
calcium chloride	$CaCl_2$	110.99	0.031	-
potassium nitrate	KNO_3	101.10	3.142	-
nitric acid (0.1 Normal)	HNO_3	63.01	-	51.140
hydrochloric acid (concentrated, 37%)	HCl	36.46	-	1.500

Table 4.6.31 Concentrate 3: Soluble Organic Compounds for RO Permeate (Nominal) Ersatz (C3) [160]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
dextran	$(C_6H_{10}O_5)_n$	(15k-20k)	27.220	-
glucuronic acid	$C_6H_{10}O_7$	194.10	2.690	-
creatinine (98%)	$C_4H_7N_3O$	113.10	2.350	-
urea	NH_2CONH_2	60.06	2.500	-

Table 4.6.32 Concentrate 4: Insoluble Organic Compounds for RO Permeate (Nominal) Ersatz (C4) [161]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
fructan (xanthan gum)	-	-	0.450	-
tyrosine	$C_9H_{11}NO_3$	181.20	0.596	-
ibuprofen	$C_{13}H_{18}O_2$	206.30	0.757	-
bis-2-ethylhexyl phathalate	$C_{24}H_{38}O_4$	390.60	0.736	-
ethyl morpholine	$C_6H_{13}NO$	115.17	0.626	-

Table 4.6.33 Concentrate 5: Volatile Organic Compounds for RO Permeate (Nominal) Ersatz (C5) [162]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
acetic acid	CH_3CO_2H	60.05	-	2.390
lactic acid	$CH_3CH(OH)CO_2H$	90.08	-	2.360
2-propanol	$(CH_3)_2CHOH$	60.10	-	2.140
acetone	CH_3COCH_3	58.08	-	2.060
ethanol	C_2H_6O	46.07	-	2.850

---

[158] This solution is 100 times more concentrated than will be its constituents in the final nominal RO permeate ersatz.

[159] This solution is 100 times more concentrated than will be its constituents in the final nominal RO permeate ersatz.

[160] This solution is 1,000 times more concentrated than will be its constituents in the final nominal RO permeate ersatz.

[161] This solution has variable concentration based on the solubility of its constituents. This solution is more concentrated than will be its constituents in the final nominal RO permeate ersatz.

[162] This solution is 1,000 times more concentrated than will be its constituents in the final nominal RO permeate ersatz.

4.6.3.4.2 REVERSE OSMOSIS PERMEATE (NOMINAL) ERSATZ FORMULATION PROCEDURE

1) Concentrate Preparation:
   - Label five (5) 1-liter flasks "C1," "C2," "C3," "C4," and "C5." Add 750 mL of deionized water to each.
   - For each concentrate, add the constituents listed in Table 4.6.29 through Table 4.6.33 above, one at a time in the order listed, and mix thoroughly between constituents until each dissolves, except as noted below.

   NOTE: The constituents of solution C4 ***WILL NOT DISSOLVE*** *completely.*

   - Dilute each flask to 1 liter with deionized water and mix thoroughly to complete preparation of the concentrate mixes.
   - Cap all concentrates and store under ambient conditions. (In other words, **DO NOT REFRIGERATE**.)
2) Working Solution:

   NOTE: DO NOT ADD solution C1 now. See Step 3 below.

   - Add, to a 1-liter flask, 300 mL deionized water, 10 mL of solution C2, and 0.040 mL of solution C3.
   - Add, to the solution above, 1.023 mL of solution C4 filtered through a #4 Whatman filter paper.
   - Add, to the solution above, 0.070 mL of solution C5.
   - Dilute to 950 mL with deionized water and mix thoroughly.
3) Working Solution (continued):
   - Now slowly add 10 mL of solution C1.

   NOTE: Be sure to add solution C1 last to prevent loss of total inorganic carbon (TIC).
4) pH Adjustment:
   - If required, adjust pH to 6.6 ± 0.2 with 0.14 Normal hydrochloric acid (HCl), using less than 300 µL.
   - Add deionized water to make 1 liter and mix.
5) Verification:
   - Analyze working solution for cation, anion, pH, conductivity, total organic carbon (TOC), and total inorganic carbon (TIC).
   - Target values for these solution properties are listed in Table 4.6.34.

Table 4.6.34 Average Solution Properties for Reverse Osmosis Permeate (Nominal) Ersatz

Property or Concentration	Formula	Units	Average Value	Standard Deviation	Reference
potential of hydrogen	pH		6.6	± 0.2	Verostko, et al. (2004)
conductivity		µS	285	± 43	
total organic carbon	TOC	mg/L	1.4	± 0.5	
total inorganic carbon	TIC	mg/L	14	± 2.1	
chloride	Cl^-	mg/L	32	± 4.8	
nitrite	NO_2^-	mg-N/L	1.8	± 0.3	
nitrate	NO_3^-	mg-N/L	5.1	± 0.8	
phosphate	PO_4^{-3}	mg/L	1.06	± 0.2	
sulfate	SO_4^{-2}	mg/L	2.5	± 0.4	
sodium	Na^+	mg/L	18	± 2.7	
ammonium	NH_4^+	mg-N/L	16	± 2.5	
potassium	K^+	mg/L	14	± 2.0	
calcium	Ca^{+2}	mg/L	-	-	
magnesium	Mg^{+2}	mg/L	-	-	

4.6.3.4.3 REVERSE OSMOSIS PERMEATE (WORST-CASE) ERSATZ CONCENTRATE CONSTITUENT TABLES

Table 4.6.35 through Table 4.6.39 describe components of the worst-case reverse osmosis (RO) permeate ersatz. The state of each constituent is indicated by its measured value. For solid constituents, a mass is listed. For liquid constituents, a volume is listed. In all cases, when applicable, the constituent purity or concentration is noted in the first column following the constituent name. When not otherwise noted, all constituent purities are greater than 99%. Final solution properties are listed in Table 4.6.40. The preparation instructions are presented in Section 4.6.3.4.4. For the original source, see Verostko, et al. (2004)

Table 4.6.35 Concentrate 1: Inorganic Compounds 1 for RO Permeate (Worst-case) Ersatz (C1) [163]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
ammonium bicarbonate	NH_4HCO_3	79.06	11.878	-

Table 4.6.36 Concentrate 2: Inorganic Compounds 2 for RO Permeate (Worst-case) Ersatz (C2) [164]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
sodium nitrite	$NaNO_2$	69.00	1.364	**-**
sodium chloride	$NaCl$	58.40	5.373	**-**
magnesium sulfate	$MgSO_4$	120.40	0.130	**-**
potassium nitrate	KNO_3	101.10	4.136	**-**
potassium sulfate	K_2SO_4	174.29	0.456	**-**
calcium chloride	$CaCl_2$	110.99	0.146	**-**
potassium monobasic phosphate	KH_2PO_4	136.09	0.188	**-**
nitric acid (0.1 Normal)	HNO_3	63.01	-	**63.520**
ammonium hydroxide (1.5 Normal)	NH_4OH	35.05	-	**46.000**
hydrochloric acid (concentrated, 37%)	HCl	36.46	-	**6.500**

Table 4.6.37 Concentrate 3: Soluble Organic Compounds for RO Permeate (Worst-case) Ersatz (C3) [165]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
dextran	$(C_6H_{10}O_5)_n$	(15k-20k)	27.220	-
glucuronic acid	$C_6H_{10}O_7$	194.10	2.690	-
creatinine (98%)	$C_4H_7N_3O$	113.10	2.350	-
urea	NH_2CONH_2	60.06	2.50	-

Table 4.6.38 Concentrate 4: Insoluble Organic Compounds for RO Permeate (Worst-case) Ersatz (C4) [166]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
fructan (xanthan gum)	-	-	0.450	-
tyrosine	$C_9H_{11}NO_3$	181.20	0.596	-
ibuprofen	$C_{13}H_{18}O_2$	206.30	0.757	-
bis-2-ethylhexyl phathalate	$C_{24}H_{38}O_4$	390.60	0.736	-
ethyl morpholine	$C_6H_{13}NO$	115.17	0.626	-

---

[163] This solution is 100 times more concentrated than will be its constituents in the final worst-case RO permeate ersatz.

[164] This solution is 100 times more concentrated than will be its constituents in the final worst-case RO permeate ersatz.

[165] This solution is 1,000 times more concentrated than will be its constituents in the final worst-case RO permeate ersatz.

[166] This solution has variable concentration based on the solubility of its constituents. This solution is more concentrated than will be its constituents in the final worst-case RO permeate ersatz.

Table 4.6.39 Concentrate 5: Volatile Organic Compounds for RO Permeate (Worst-case) Ersatz (C5) [167]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
acetic acid	CH_3CO_2H	60.05	-	2.390
lactic acid	$CH_3CH(OH)CO_2H$	90.08	-	2.360
2-propanol	$(CH_3)_2CHOH$	60.10	-	2.140
acetone	CH_3COCH_3	58.08	-	2.060
ethanol	C_2H_6O	46.07	-	2.850

4.6.3.4.4 REVERSE OSMOSIS PERMEATE (WORST-CASE) ERSATZ FORMULATION PROCEDURE

1) Concentrate Preparation:
   - Label five (5) 1-liter flasks “C1,” “C2,” “C3,” “C4,” and “C5.” Add 750 mL of deionized water to each.
   - For each concentrate, add the constituents listed in Table 4.6.35 through Table 4.6.39 above, one at a time in the order listed, and mix thoroughly between constituents until each dissolves, except as noted below.

   NOTE: The constituents of solution C4 ***WILL NOT DISSOLVE*** *completely.*
   - Dilute each flask to 1 liter with deionized water and mix thoroughly to complete preparation of the concentrate mixes.
   - Cap all concentrates and store under ambient conditions. (In other words, **DO NOT REFRIGERATE**.)
2) Working Solution:

   NOTE: DO NOT ADD solution C1 now. See Step 3 below.
   - Add, to a 1-liter flask, 300 mL deionized water, 10 mL of solution C2, and 0.30 mL of solution C3.
   - Add, to the solution above, 1.53 mL of solution C4 filtered through a #4 Whatman filter paper.
   - Add, to the solution above, 0.094 mL of solution C5.
   - Dilute to 950 mL with deionized water and mix thoroughly.
3) Working Solution (continued):
   - Now slowly add 10 mL of solution C1.

   NOTE: Be sure to add solution C1 last to prevent loss of total inorganic carbon (TIC).
4) pH Adjustment:
   - If required, adjust pH to 7.3 ± 0.2 with 1.5 Normal ammonium hydroxide (NH_4OH), using less than 30 µL. Add deionized water to make 1 liter and mix.
5) Verification:
   - Analyze working solution for cation, anion, pH, conductivity, total organic carbon (TOC), and total inorganic carbon (TIC).
   - Target values for these solution properties are listed in Table 4.6.40.

---

[167] This solution is 1,000 times more concentrated than will be its constituents in the final worst-case RO permeate ersatz.

Table 4.6.40 Average Solution Properties for Reverse Osmosis Permeate (Worst-case) Ersatz

Property or Concentration	Formula	Units	Average Value	Standard Deviation	Reference
potential of hydrogen	pH		7.3	± 0.2	Verostko, et al. (2004)
conductivity		µS	382	± 57	
total organic carbon	TOC	mg/L	5	± 1.5	
total inorganic carbon	TIC	mg/L	17.9	± 2.7	
chloride	Cl^-	mg/L	62	± 9.3	
nitrite	NO_2^-	mg-N/L	2.8	± 0.4	
nitrate	NO_3^-	mg-N/L	6.6	± 1.0	
phosphate	PO_4^{-3}	mg/L	1.32	± 0.2	
sulfate	SO_4^{-2}	mg/L	3.6	± 0.5	
sodium	Na^+	mg/L	26	± 3.8	
ammonium	NH_4^+	mg-N/L	26	± 4.0	
potassium	K^+	mg/L	17.5	± 2.6	
calcium	Ca^{+2}	mg/L	-	-	
magnesium	Mg^{+2}	mg/L	-	-	

4.6.3.5 Air Evaporation Subsystem Condensate Ersatz

The air evaporation subsystem condensate ersatz is presented for both nominal and worst-case possibilities.

4.6.3.5.1 AIR EVAPORATION CONDENSATE (NOMINAL) ERSATZ CONCENTRATE CONSTITUENT TABLES

Table 4.6.41 through Table 4.6.44 describe the components of the nominal air evaporation condensate subsystem (AES) ersatz. The state of each constituent is indicated by its measured value. For solid constituents, a mass is listed. For liquid constituents, a volume is listed. In all cases, when applicable, the constituent purity or concentration is noted in the first column following the constituent name. When not otherwise noted, all constituent purities are greater than 99%. Final solution properties are listed in Table 4.6.45. The preparation instructions are presented in Section 4.6.3.5.2. For the original source, see Verostko, et al. (2004)

Table 4.6.41 Concentrate 1: Inorganic Compounds for AES Condensate (Nominal) Ersatz (C1) [168]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
ammonium bicarbonate	NH_4HCO_3	79.06	34.308	-
ammonium hydroxide, concentrated (29.34%)	NH_4OH	35.05	-	1.000

Table 4.6.42 Concentrate 3: Soluble Organic Compounds for AES Condensate (Nominal) Ersatz (C3) [169]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
dextran	$(C_6H_{10}O_5)_n$	(15k-20k)	27.222	-
glucuronic acid	$C_6H_{10}O_7$	194.10	2.694	-
creatinine (98%)	$C_4H_7N_3O$	113.10	2.354	-
urea	NH_2CONH_2	60.06	2.500	-

---

[168] This solution is 100 times more concentrated than will be its constituents in the final nominal AES condensate ersatz.

[169] This solution is 1,000 times more concentrated than will be its constituents in the final nominal AES condensate ersatz.

Table 4.6.43 Concentrate 4: Insoluble Organic Compounds for AES Condensate (Nominal) Ersatz C4) [170]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
fructan (xanthan gum)	-	-	0.450	-
tyrosine	$C_9H_{11}NO_3$	181.20	0.596	-
ibuprofen	$C_{13}H_{18}O_2$	206.30	0.757	-
bis-2-ethylhexyl phathalate	$C_{24}H_{38}O_4$	390.60	0.736	-
ethyl morpholine	$C_6H_{13}NO$	115.17	0.626	-

Table 4.6.44 Concentrate 5: Volatile Organic Compounds for AES Condensate (Nominal) Ersatz (C5) [171]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
acetic acid	CH_3CO_2H	60.05	-	2.390
lactic acid	$CH_3CH(OH)CO_2H$	90.08	-	2.360
2-propanol	$(CH_3)_2CHOH$	60.10	-	2.140
acetone	CH_3COCH_3	58.08	-	2.060
ethanol	C_2H_6O	46.07	-	2.850

4.6.3.5.2 AIR EVAPORATION CONDENSATE (NOMINAL) ERSATZ FORMULATION PROCEDURE

1) Concentrate Preparation:
   - Label four 1-liter flasks “C1,” “C3,” “C4,” and “C5.” Add 750 mL of deionized water to each.
   - For each concentrate, add the constituents listed in Table 4.6.41 through Table 4.6.44 above, one at a time in the order listed, and mix thoroughly between constituents until each dissolves, except as noted below.

   <u>NOTE:</u> *The constituents of solution C4* ***WILL NOT DISSOLVE*** *completely.*

   - Dilute each flask to 1 liter with deionized water and mix thoroughly to complete preparation of the concentrate mixes.
   - Cap all concentrates and store under ambient conditions. (In other words, **DO NOT REFRIGERATE**.)
2) Working Solution:
   - Add, to a 1-liter flask, 300 mL deionized water, 10 mL of solution C1, and 0.24 mL of solution C3.
   - Add, to the solution above, 2.04 mL of solution C4 filtered through a #4 Whatman filter paper.
   - Add, to the solution above, 0.094 mL of solution C5.
   - Dilute to 980 mL with deionized water and mix thoroughly.
3) pH Adjustment:
   - If required, adjust pH to 8.1 ± 0.2 with 1.5 Normal ammonium hydroxide (NH_4OH), using less than 250 µL.
   - Add deionized water to make 1 liter and mix.
4) Verification:
   - Analyze working solution for cation, anion, pH, conductivity, total organic carbon (TOC), and total inorganic carbon (TIC).
   - Target values for these solution properties are listed in Table 4.6.45.

---

[170] This solution has variable concentration based on the solubility of its constituents. This solution is more concentrated than will be its constituents in the final nominal AES condensate ersatz.

[171] This solution is 1,000 times more concentrated than will be its constituents in the final nominal AES condensate ersatz.

Table 4.6.45 Average Solution Properties for Air Evaporation Condensate (Nominal) Ersatz

Property or Concentration	Formula	Units	Average Value	Standard Deviation	Reference
potential of hydrogen	pH		8.0	± 0.2	Verostko, et al. (2004)
conductivity		µS	507	± 76	
total organic carbon	TOC	mg/L	4.5	± 1.5	
total inorganic carbon	TIC	mg/L	52	± 7.8	
chloride	Cl -	mg/L	-	-	
nitrite	NO2 -	mg-N/L	-	-	
nitrate	NO3 -	mg-N/L	-	-	
phosphate	PO4 -3	mg/L	-	-	
sulfate	SO4 -2	mg/L	-	-	
sodium	Na +	mg/L	-	-	
ammonium	NH4 +	mg-N/L	64.0	± 9.6	
potassium	K +	mg/L	-	-	
calcium	Ca +2	mg/L	-	-	
magnesium	Mg +2	mg/L	-	-	

4.6.3.5.3 *AIR EVAPORATION CONDENSATE (WORST-CASE) ERSATZ CONCENTRATE CONSTITUENT TABLES*

Table 4.6.46 through Table 4.6.49 describe the components of the worst-case air evaporation subsystem (AES) condensate ersatz. The state of each constituent is indicated by its measured value. For solid constituents, a mass is listed. For liquid constituents, a volume is listed. In all cases, when applicable, the constituent purity or concentration is noted in the first column following the constituent name. When not otherwise noted, all constituent purities are greater than 99%. Final solution properties are listed in Table 4.6.50. The preparation instructions are presented in Section 4.6.3.5.4. For the original source, see Verostko, et al. (2004)

Table 4.6.46 Concentrate 1: Inorganic Compounds for AES Condensate (Worst-case) Ersatz (C1) [172]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
ammonium carbonate	$(NH_4)_2CO_3$	96.09	12.501	-
ammonium hydroxide, concentrated (29.34%)	NH_4OH	35.05	-	10.000

Table 4.6.47 Concentrate 3: Effluent Soluble Organic Compounds for AES Condensate (Worst-case) Ersatz (C3) [173]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
dextran	$(C_6H_{10}O_5)_n$	(15k-20k)	27.222	-
glucuronic acid	$C_6H_{10}O_7$	194.10	2.694	-
creatinine (98%)	$C_4H_7N_3O$	113.10	2.354	-
urea	NH_2CONH_2	60.06	2.500	-

---

[172] This solution is 100 times more concentrated than will be its constituents in the final worst-case AES condensate ersatz.

[173] This solution is 1,000 times more concentrated than will be its constituents in the final worst-case AES condensate ersatz.

Table 4.6.48 Concentrate 4: Insoluble Organic Compounds for AES Condensate (Worst-case) Ersatz (C4) [174]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
fructan (xanthan gum)	-	-	0.450	-
tyrosine	$C_9H_{11}NO_3$	181.20	0.596	-
ibuprofen	$C_{13}H_{18}O_2$	206.30	0.757	-
bis-2-ethylhexyl phathalate	$C_{24}H_{38}O_4$	390.60	0.736	-
ethyl morpholine	$C_6H_{13}NO$	115.17	0.626	-

Table 4.6.49 Concentrate 5: Volatile Organic Compounds for AES Condensate (Worst-case) Ersatz (C5) [175]

Constituent	Chemical Formula	Molecular Weight	Constituent Mass [g]	Constituent Volume [mL]
acetic acid	CH_3CO_2H	60.05	-	2.390
lactic acid	$CH_3CH(OH)CO_2H$	90.08	-	2.360
2-propanol	$(CH_3)_2CHOH$	60.10	-	2.140
acetone	CH_3COCH_3	58.08	-	2.060
ethanol	C_2H_6O	46.07	-	2.850

4.6.3.5.4 AIR EVAPORATION CONDENSATE (WORST-CASE) ERSATZ FORMULATION PROCEDURE

1) Concentrate Preparation:

- Label four (4) 1-liter flasks “C1,” “C3,” “C4,” and “C5.” Add 750 mL of deionized water to each.
- For each concentrate, add the constituents listed in Table 4.6.46 through Table 4.6.49 above, one at a time in the order listed, and mix thoroughly between constituents until each dissolves, except as noted below.

NOTE: The constituents of solution C4 ***WILL NOT DISSOLVE*** *completely.*

- Dilute each flask to 1 liter with deionized water and mix thoroughly to complete preparation of the concentrate mixes.
- Cap all concentrates and store under ambient conditions. (In other words, **DO NOT REFRIGERATE**.)

2) Working Solution:

- Add, to a 1-liter flask, 300 mL deionized water, 60 mL of solution C1, and 0.56 mL of solution C3.
- Add, to the solution above, 4.09 mL of solution C4 filtered through a #4 Whatman filter paper.
- Add, to the solution above, 0.094 mL of solution C5.
- Dilute to 980 mL with deionized water and mix thoroughly.

3) pH Adjustment:

- If required, adjust pH to 9.4 ± 0.2 with 1.5 Normal ammonium hydroxide (NH_4OH), using less than 6 mL. Add deionized water to make 1 liter and mix.

4) Verification:

- Analyze working solution for cation, anion, pH, conductivity, total organic carbon (TOC), and total inorganic carbon (TIC).
- Target values for these solution properties are listed in Table 4.6.50.

---

[174] This solution has variable concentration based on the solubility of its constituents. This solution is more concentrated than will be its constituents in the final worst-case AES condensate ersatz.

[175] This solution is 1,000 times more concentrated than will be its constituents in the final worst-case AES condensate ersatz.

Table 4.6.50 Average Solution Properties for Air Evaporation Condensate (Worst-case) Ersatz

Property or Concentration	Formula	Units	Average Value	Standard Deviation	Reference
potential of hydrogen	pH		9.4	± 0.2	Verostko, et al. (2004)
conductivity		µS	1,286	± 193	
total organic carbon	TOC	mg/L	9.5	± 3.0	
total inorganic carbon	TIC	mg/L	94	± 14	
chloride	Cl^-	mg/L	-	-	
nitrite	NO_2^-	mg-N/L	-	-	
nitrate	NO_3^-	mg-N/L	-	-	
phosphate	PO_4^{-3}	mg/L	-	-	
sulfate	SO_4^{-2}	mg/L	-	-	
sodium	Na^+	mg/L	-	-	
ammonium	NH_4^+	mg-N/L	636	± 95	
potassium	K^+	mg/L	-	-	
calcium	Ca^{+2}	mg/L	-	-	
magnesium	Mg^{+2}	mg/L	-	-	

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. Accordingly, within this manuscript, the Cooling External Interface masses are treated as infrastructure. Detailed analyses and modeling through the thermal-energy-management-mass penalty are outlined in Section 3.2. Additional values related to the Cooling External Interface may be found in Section 4.4 Thermal Management.

5.2 Extravehicular Activity Support External Interface [176]

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 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 [177] 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	

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[176] This section on advanced extravehicular activities is from Rouen (2001).

[177] 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 [178]	83.0 (2)
Apollo Program Spacesuit, A7LB [179]	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 Unencumbered, 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, requiring technology development. The final design solution depends upon the mission architecture as well as the success of development efforts. Several possibilities 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 with minimal intrusions into the crew habitat. 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. Accordingly, the minimum airlock internal volume is about 3.7 m^3. This corresponds to the volume of the current Shuttle airlock.

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[178] The value here corresponds to the Apollo A7L EMU 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.

[179] The value here corresponds to the Apollo A7LB EMU 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. Therefore, 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 to the environment via radiator and vaporizes 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 providing 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. Since 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 used 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. McBarron, et al. (1993) provide overall values describing the metabolic loads and inputs for an EVA crewmember assuming an average metabolic rate of 1,055 kJ/CM-h (293 W) and a respiratory quotient of 0.90. 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 [180] per Week	Sorties /wk		5 [181] or 10 [182]	5 [183] or 10 [184]	
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 [183] or 10 [184]	5 [183] or 10 [184]	
Airlock Gas Losses per Cycle as a Percentage of Airlock Gas Volume [183]	%	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 [184]	kg/CM-h	0.24 (1, 2)
Food Energy Consumption [185]	MJ/CM-h	1.062 (3)
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) McBarron, et al. (1993); metabolic rate of 293 W/CM and a respiratory quotient of 0.9.

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

(3) 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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[180] Each EVA sortie assumes two crewmembers.

[181] Assuming 8-hour EVA sorties.

[182] Assuming 4-hour, or “half day” EVA sorties.

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

[184] For EVA sorties longer than 3 hours.

[185] This is the total energy expended, and as 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 an aqueous 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 1.5kg/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 Chaput (2003)		0.343 (1) [186]		
From Rogers (1999)		0.718 (2)	0.0013 (2)	
From Branch (1998)		1.69 (3)	0.00135 (3)	
From Reimers and McDonald (1992)		1.47 (4)	0.00140 (4)	
Using a Laundry:				
Clothes		0.267 (4)	0.000351 (4)	
		0.0746 (6a)	0.00044 (6a)	
		0.0373 (6b)	0.00022 (6b)	
		0.0191 (6c)	0.00011 (6c)	
Laundry Equipment	118 (4)			0.31 (4)
	80 (6)			0.751 (6)
Interfaces (Water)		12.47 (5) [187]		
		7.33 (6)		

References

(1) Chaput (2003). Based on clothing allocation “as planned” for ISS
(2) Rodgers (1999). Based on clothing “as planned” for ISS.
(3) Branch (1998)
(4) Reimers and McDonald (1992)
(5) NASA (1990)
(6) Jeng and Ewert (2002)
(6a) Jeng and Ewert (2002); 90 d mission duration
(6b) Jeng and Ewert (2002); 180 d mission duration
(6c) Jeng and Ewert (2002); 600 d mission duration

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[186] Chaput (2003) gives ISS planning values for clothing of 10.3 kg per crewmember per 30 days.

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

Table 5.3.2 Early ISS Laundry Equipment Specifications

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

Table 5.3.3 Advanced Washer/Dryer Specifications

Washer Unit	Value	Units	Comments	Reference
Mass	80	kg		From Jeng and Ewert (2002)
Volume	0.264	m^3		
Capacity	4.5	kg/load	Clothes	
Water Usage	51.3 [188]	kg/load	Effluent is greywater. This unit does not release water vapor.	
Crewtime	0.42	CM-h/load	Load, remove, fold, and stow clothes.	
Energy	0.95 [189]	kWh/load	Low setting	
Consumables	0.010	kg/load	Detergent (Igepon soap)	

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 at 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.

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.

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

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

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[190]

Commodity	Requirement [kg]	Cost Leverage	Comments / Assumptions	Likelihood[191]
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)

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

[191] 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.

5.6 Power External Interface

Within this manuscript, power enters analyses and modeling through use of a power-mass penalty. Information on power systems is provided under the description of infrastructure in Section 3.2.

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, 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 (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, as detailed in Table 3.2.6, in and 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. 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 be transported with the spacecraft. On a planetary surface, local resources, such as regolith packed into “sandbags” or underground caverns may 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 External Interface costs are integrated with the primary structure penalty for volume as noted above in Section 3.2.1.

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7 Appendices

7.1 Appendix A: Acronyms and Abbreviations

AES	air evaporation subsystem
ALS	Advanced Life Support
ARC	Ames Research Center
ATCS	active thermal control system
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)
BWP	biological water processor
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”)
EATCS	external active thermal control system
EMU	extravehicular mobility unit (space suit)
EPB	early planetary base
ESM	equivalent system mass
ETCS	external thermal control system
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
ITCS	internal thermal control system
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)
MAG	Maximum Absorption Garment (for the EMU)
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
RO	reverse osmosis (system)
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
TIC	total inorganic carbon
TM	transit mission
TOC	total organic carbon
TRRJ	thermal radiator rotary joint
VST	Variably-Scheduled Time
$\hat{W}_{RF}$	specific power consumption for a cooled volume within a cabinet

Note: Symbols specific to the crop models in Section 4.2.3 are defined in Table 4.2.14 and The canopy surface conductance, gC [molWater/m^2•s], is based on the canopy stomatal conductance, gS [molWater/m^2•s], and the atmospheric aerodynamic conductance, gA [molWater/m^2•s].

7.2 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
CM-$\wp$	crewmember-menstrual period	crewtime
c	centi-	prefix
d	day	time
g	gram	mass
h	hour	time
J	Joule	energy
k	kilo-	prefix
kW	kilowatt	power
kW_e	kilowatt electric	electric power
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

7.3 Appendix C: Life Support Equipment Parameters from the Advanced Life Support Database [192]

7.3.1 International Space Station

Table 7.3.1 International Space Station Atmosphere Control and Supply

Assembly or Component	Mass [kg]	Volume $[m^3]$	Length [m]	Width or Diameter [m]	Height [m]	Peak Power [W]	Operational Average Power [W]	MTBF [h]	CMMTTR [h]	Life Limit [y]	No.
Cabin Pressure Sensor [193]	0.3316 (1)	0.000369 (2)	0.0444 (1)	0.0762 (1)	0.1092 (1)						1
Manual Pressurization Equalization Valve (MPEV) [194]	1.0795 (1)	0.002394 (2)	0.1143 (1)	0.1676 (1)	0.1249 (1)						9
MPEV with Muffler [196]	0.1134 (1)	0.000151 (2)	0.0355 (1)	0.0762 (1)	0.0558 (1)						1
Negative Pressure Relief Valve [195]	0.9343 (1)	0.002836 (2)	0.163 (1)	0.163 (1)	0.1066 (1)						6
Nitrogen / Oxygen Manual Isolation Valve [196]	3.928 (3)										1
Nitrogen Manual Isolation Valve	1.0432 (3)	0.002548 (7)	0.1905 (4)	0.0355 (4)	0.08 (4)			1.0×10^{6}	0.5		1
Oxygen Manual Isolation Valve	0.9616 (3)	0.002548 (7)						1.0×10^{6}	0.5		3
Nitrogen / Oxygen Pressure Restrictor [196]	0.9071 (4)	0.000189 (2)		0.0355 (4)	0.1905 (4)						1
Nitrogen / Oxygen Pressure Sensor [195]	0.8436 (3)	0.002548 (3)		0.0317 (4)	0.1778 (4)						4
Nitrogen / Oxygen Pressure Vessel [197]	108.8616 (4)			0.9804 (4)	1.397 (4)						1
Nitrogen / Oxygen Regulator / Relief Valve Assembly [197]	7.8										1
Low Pressure Nitrogen Regulator / Relief Valve Assembly	1.9504 (4)	0.002548 (3)	0.2095 (4)	0.1333 (4)	0.0889 (4)			300,000 (3)	0.52 (3)		1 (3)
Low Pressure Oxygen Regulator / Relief Valve Assembly	1.9504 (4)	0.002548 (3)	0.2095 (4)	0.1333 (4)	0.0889 (4)			300,000 (3)	0.92 (3)		2 (3)
Medium Pressure Oxygen Regulator / Relief Valve Assembly	1.9504 (4)	0.002548 (4)	0.2095 (4)	0.1333 (4)	0.0889 (4)			300,000 (3)	0.92 (3)		1 (7)
Oxygen / Nitrogen Latching Motor Valve [198]	4.9 (3)										1
Nitrogen Latching Motor Valves	1.6329 (3)	0.004531 (3)	0.2032 (4)	0.1841 (4)	0.1196 (4)			500,000	0.84		1
Oxygen Latching Motor Valves	1.6329 (3)	0.004531 (3)	0.2032 (4)	0.1841 (4)	0.1196 (4)			500,000	0.95		2

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[192] See Database (2002)

[193] Function: atmospheric pressure monitoring

[194] Function: pressure equalization

[195] Function: pressure relief

[196] Function: nitrogen and oxygen flow distribution

[197] Function: nitrogen and oxygen storage

References: (1) de Vera (1999); (2) Calculation; (3) MADS (2001); (4) de Vera (1998b); (5) NASA (2001b); (6) Niehuss (2001); (7) NASA (2001c); (8) de Vera (1998a).
Note: Hardware entries in *italics* are components of assembly entries in **bold** type.

Table 7.3.1 International Space Station Atmosphere Control and Supply (continued)

Assembly or Component	Mass [kg]	Volume [m³]	Length [m]	Width or Diameter [m]	Height [m]	Peak Power [W]	Operational Average Power [W]	MTBF [h]	CMMTTR [h]	Life Limit [y]	No.
Oxygen Generation Assembly [198]	446										1
Hydrogen	161.6176 (6)	0.146697 (6)	0.7874 (6)	0.4318 (6)	0.4318 (6)			27,156 (6)	1.1 (6)	2.38 (6)	1 (6)
Hydrogen Sensor	4.3545 (6)	0.003398 (6)	0.1778 (6)	0.1524 (6)	0.127 (6)			61,845.6 (6)	0.6 (6)	0.25 (6)	1 (6)
Inlet Deionizing Bed	28.6675 (6)	0.029452 (6)	0.6146 (6)	0.2362 (6)	0.2032 (6)			296,701.2 (6)	0.233 (6)	6 (6)	1 (6)
Nitrogen Purge ORU	34.2468 (6)							138,408 (6)			1 (6)
Oxygen Outlet	48.1723 (6)	0.031152 (6)	0.3556 (6)	0.3175 (6)	0.2768 (6)			98,112 (6)	0.65 (6)	10 (6)	1 (6)
Power Supply Module	42.6384 (6)	0.064852 (6)	0.6096 (6)	0.381 (6)	0.2794 (6)			47,479.2 (6)	0.583 (6)	4.17 (6)	1 (6)
Process Controller	47.0836 (6)	0.083827 (6)	0.7213 (6)	0.4445 (6)	0.2616 (6)			103,280.4 (6)	1.05 (6)	7.72 (6)	1 (6)
Pump	17.9625 (6)	0.010152 (6)	0.2794 (6)	0.2286 (6)	0.1574 (6)			144,540 (6)	0.583 (6)	1 (6)	1 (6)
Water	61.0545 (6)	0.075614 (6)	0.4572 (6)	0.4521 (6)	0.3657 (6)			33,288 (6)	0.966 (6)	2.92 (6)	1 (6)
Oxygen Relief Valve Assembly [199]	1.9504 (4)	0.000849 (3)	0.1524 (4)	0.2189 (4)	0.0533 (4)						1
Portable Breathing Apparatus Quick Disconnect [200]	0.1514 (1)		0.0177 (1)	0.019 (1)	0.0508 (1)						1
Positive Pressure Relief Valve [201]	1.3607 (1)		0.179 (1)	0.1143 (1)	0.1524 (1)						1
Pressure Control Panel [201]	22.68 (5)	0.035116 (3)	0.4826 (3)	0.3149 (3)	0.2311 (3)						1
Firmware Controller	4.8897 (8)	0.005608 (8)	0.2057 (8)	0.1651 (8)	0.1651 (8)	15 (8)	12 (8)				1
Nitrogen Isolation Valve	1.2927 (8)	0.000849 (8)		0.0095 (8)		50 (8)	38 (8)				1
Oxygen Isolation Valve	1.2927 (8)	0.000849 (8)		0.0095 (8)		50 (8)	38 (8)				1
Vent and Relief Valve [201]	5.4432 (8)	0.01416 (8)		0.0558 (8)		30 (8)					1
Vent and Relief Control Valve (VRCV)				0.0558 (8)							1
Vent and Relief Isolation (VRIV)				0.0558 (8)							1

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[198] Function: oxygen generation

[199] Function: pressure relief

[200] Function: emergency equipment

[201] Function: atmospheric pressure control

References: (1) de Vera (1999); (2) Calculation; (3) MADS (2001); (4) de Vera (1998b); (5) NASA (2001b); (6) Niehuss (2001); (7) NASA (2001c); (8) de Vera (1998a).
Note: Hardware entries in *italics* are components of assembly entries in **bold** type.

Table 7.3.2 International Space Station Atmosphere Revitalization Subsystem

Assembly or Component	Mass [kg]	Volume [m³]	Length [m]	Width or Diameter [m]	Height [m]	Peak Power [W]	Operational Average Power [W]	MTBF [h]	CMMTTR [h]	Life Limit [y]	No.
3-way Sample Valve[202]	1.9731 (1)	0.002322 (1)	0.1778 (1)	0.1143 (1)	0.1143 (1)						1
Carbon Dioxide Removal Assembly[203]	195.3793 (8)	0.387984 (8)				1,487 (8)	860 (8)				1
Air Pump, Two-Stage, ORU	10.8861 (8)	0.004531 (3)	0.084 (3)	0.234 (3)	0.234 (3)	245 (8)	23 (8)	156,200 (3)	1.53 (3)	15.29 (3)	1 (3)
Blower	5.5792 (8)	0.025488	0.61 (3)	0.203 (3)	0.203 (3)	170 (8)	170 (8)	129,700 (3)	1.67 (3)	10 (3)	1
Check Valves	39.9159 (8)	0.178416 (8)				960 (8)	346 (8)				1
Desiccant Beds	42.6384 (3)	0.08496 (3)	1.0922 (3)	0.3048 (3)	0.254 (3)			77,100 (3)	2.28 (3)		2
Heat Controller	3.3112 (8)	0.008496 (3)	0.178 (3)	0.142 (3)	0.216 (3)	32 (8)	19 (8)	242,700 (3)	0.55 (3)		2 (3)
Precooler	5.5792 (8)	0.025488	0.61 (3)	0.203 (3)	0.203 (3)			129,700 (3)	1.67 (3)	10 (3)	1
Pump Fan Motor Controller	2.7215 (8)	0.005664 (3)	0.14 (3)	0.089 (3)	0.165 (3)	20 (8)	2 (8)	2.272×10^{6} (3)	0.52 (3)		2 (3)
Selector Valves	3.039 (8)	0.001699 (8)	0.155 (3)	0.109 (3)	0.109 (3)	60 (8)	1 (8)	117,000 (3)	0.94 (3)	10.61 (3)	6 (3)
Sorbent Beds (Zeolite)	42.6384 (3)	0.08496 (3)	1.0922 (3)	0.3048 (3)	0.254 (3)			77,100 (3)	2.28 (3)		2
Catalyst Element Assembly[204]	5.2616 (1)	0.004729 (1)	0.0939 (1)	0.6604 (1)	0.0762 (1)						4
Major Constituent Analyzer[205]	54.7483 (8)	0.43896 (8)					87.6 (8)				1
ORU 1-Data and Control Assembly	8.0196 (3)	0.013214 (3)	0.1905 (3)	0.2844 (3)	0.2438 (3)		34.9 (8)	43,500 (3)	0.84 (3)	10 (3)	1 (5)
ORU 2-Mass Spectrometry Assembly	13.304 (3)	0.023794 (3)	0.254 (3)	0.4191 (3)	0.2235 (3)		31.8 (8)	8,180 (3)	0.8 (3)	4.5 (3)	1
ORU 4-Low Voltage Power Supply Assembly	5.67 (3)	0.005333 (3)	0.1574 (3)	0.1778 (3)	0.1905 (3)		30.8 (8)	199,000 (3)	0.82 (3)		1 (3)
ORU 5-Series Sample Pump Assembly	3.1298 (3)	0.004961 (3)	0.2209 (3)	0.1016 (3)	0.1981 (3)		4 (8)	11,900 (3)	0.71 (3)	2 (3)	1 (5)
ORU 6-Sample Distribution Assembly	2.1092 (3)	0.003613 (3)	0.16 (3)	0.127 (3)	0.1778 (3)		0.1 (8)	70,900 (3)	0.71 (3)	15 (3)	1 (5)
ORU 7-EMI Filter Assembly	1.4515 (3)	0.001699 (3)	0.1752 (3)	0.0744 (3)	0.1303 (3)		1.8 (8)	1.16×10^{6} (3)	0.71 (3)		1 (3)
ORU 8-Verification Gas Assembly	5.7607 (3)	0.013722 (3)	0.3098 (3)	0.1981 (3)	0.2235 (3)		0.1 (8)	52,100 (3)	0.74 (3)	1.5 (8)	1 (3)
Manual Sample Valve[204]	0.2267 (1)	0.000589 (1)	0.1016 (1)	0.0762 (1)	0.0762 (1)						1
Sample Distribution Assembly[204]											1
Trace Contaminant Control Subsystem[206]	79.8318 (8)	0.271866 (2)	0.6461 (8)	0.4508 (8)	0.9331 (8)	250 (8)	180 (8)				1
Activated Charcoal Bed	36.65 (8)	0.075699 (8)	0.8255 (3)	0.3886 (3)	0.3505 (3)			215,000 (3)	0.7 (3)		1 (3)
Blower	2.9392 (8)	0.005899 (8)				51.75 (8)	34.5 (8)	121,500 (3)	0.38 (3)	5 (3)	1
Catalytic Oxidizer	11.0449 (8)	0.024312 (8)	0.2413 (3)	0.2463 (3)	0.4089 (3)	168 (8)	120.96 (8)	89,500 (3)	0.6 (3)		1 (3)
Electronic Interface Assembly	3.4201 (3)	0.003749 (3)	0.254 (3)	0.2235 (3)	0.066 (3)	7.64 (8)	7.64 (8)	483,000 (3)	0.59 (3)		1 (3)
Flowmeter	1.0886 (8)	0.000196 (8)	0.1778 (3)	0.0635 (3)	0.1651 (3)	11.5 (8)	11.5 (8)	936,000 (3)	0.35 (3)		1 (3)
Lithium Hydroxide Sorbent Bed	4.1049 (8)	0.007823 (8)	0.3759 (3)	0.16 (3)	0.2082 (3)			241,000 (3)	0.59 (3)		1

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[202] Function: air sampling

[203] Function: carbon dioxide control

[204] Function: control gaseous contaminants

[205] Function: monitor atmospheric partial pressure

[206] Function: control gaseous contaminants

References: (1) de Vera (1999); (2) Calculation; (3) MADS (2001); (4) de Vera (1998b); (5) NASA (2001b); (6) Niehuss (2001); (7) NASA (2001c); (8) de Vera (1998a).
Note: Hardware entries in *italics* are components of assembly entries in **bold** type.

Table 7.3.3 International Space Station Temperature and Humidity Control

Assembly or Component	Mass [kg]	Volume [m³]	Length [m]	Width or Diameter [m]	Height [m]	Peak Power [W]	Operational Average Power [W]	MTBF [h]	CMMTTR [h]	Life Limit [y]	No.
Avionics Air Assembly [207]	12.519 (3)	0.033134 (3)	0.5969 (3)	0.2794 (3)	0.1981 (3)		175 (8)				1
Bacteria Filter Assembly [208]	26.36 (5)	0.018781 (5)	0.785 (5)	0.145 (5)	0.165 (5)						1
Bacteria Filter Element	2.0275 (3)	0.009062 (3)	0.7112 (3)	0.1016 (3)	0.127 (3)			2.0×10^{8} (3)	0.1 (3)		13
Cabin Diffuser Assembly [209]	0.82 (5)	0.003398 (3)	0.0635 (3)	0.1676 (3)	0.3175 (3)						6
Charcoal Catalytic Filter Element [210]	4.46	0.00921	0.711	0.102	0.127						1
Common Cabin Air Assembly [210]	96.161 (8)					705 (8)	469 (8)				1
Condensing Heat Exchanger	49.71 (5)	0.393293 (5)	1.016 (5)	0.762 (5)	0.508 (5)			832,600 (3)	1.56 (3)		1
Electronic Interface Box (EIB)	4.037 (3)	0.017275 (3)	0.3302 (3)	0.2286 (3)	0.2286 (3)			2.3506×10^{6} (3)	0.83 (3)		2
Fan Delta Pressure Sensor	0.4535 (8)	0.000163 (8)	0.0558 (3)	0.0406 (3)	0.1473 (3)		0.24 (8)	1.25×10^{6} (3)	0.94 (3)		1
Heat Exchanger Liquid Sensor	0.635 (8)	0.000566 (8)	0.098 (3)	0.0546 (3)	0.0995 (3)		0.009 (8)	1.1363×10^{6} (3)	0.47 (3)		2
Inlet ORU	25.31 (5)	0.130875 (3)	0.5905 (8)	0.4826 (8)	0.4889 (8)	469 (8)		332,900	0.39		1
Pressure Transducer	0.4762 (3)	0.000283 (3)	0.1524 (3)	0.0406 (3)	0.0406 (3)		0.24 (8)	1.25×10^{6} (3)	0.92 (3)	15	1
Temperature Control Check Valve (TCCV)	7.4526 (3)	0.00708 (3)	0.381 (3)	0.1905 (3)	0.0965 (3)			32,880 (3)	0.44 (3)		2
Temperature Sensor	0.263 (3)	0.001416 (3)	0.1046 (3)	0.1206 (3)	0.1016 (3)			3.7594×10^{7} (3)	0.53 (3)		4
Water Separator	11.93 (3)	0.058285 (3)	0.371 (3)	0.356 (3)	0.434 (3)			130,800 (3)	0.79 (3)	5	2
Water Separator Liquid Sensor	0.635 (8)	0.000566 (8)					0.009 (8)				1
Damper Valve Assembly [211]	2.7215 (1)	0.006125 (1)	0.1682 (1)	0.1574 (1)	0.2311 (1)						4
Intermodule Ventilation Muffler [213]		0.000237 (1)	0.0762 (1)	0.0558 (1)	0.0558 (1)						9
Intermodule Ventilation Caps [213]	1.9										1
IMV cap	0.635 (1)	0.00192 (1)	0.1587 (1)	0.1587 (1)	0.0762 (1)						1
IMV Cap Flange Saver	0.4989 (1)	0.00192 (2)	0.1587 (1)	0.1587 (1)	0.0762 (1)						1
IMV Leak Check Cap	0.7257 (1)	0.00192 (2)	0.1587 (1)	0.1587 (1)	0.0762 (1)						1
Intermodule Ventilation Fan [213]	4.1657 (1)	0.009283 (2)	0.2413 (1)	0.226 (1)	0.1701 (1)		55 (1)				1
Intermodule Ventilation Valve [213]	5.2162 (1)	0.008284 (2)	0.3256 (1)	0.1579 (1)	0.161 (1)	20 (1)	7.68 (1)				1
Node 1 Cabin Fan [211]	24.9474 (1)	0.13935 (1)	0.5905 (1)	0.4826 (1)	0.4889 (1)	1,000 (1)	180 (1)				1
Cabin Fan Delta Pressure Sensor	0.4535 (1)	0.000163 (1)					0.24 (1)				1

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[207] Function: heat removal

[208] Function: particulate and microbial growth control

[209] Function: intramodule atmosphere circulation

[210] Function: temperature and humidity control

[211] Function: intermodule atmosphere circulation

References: (1) de Vera (1999); (2) Calculation; (3) MADS (2001); (4) de Vera (1998b); (5) NASA (2001b); (6) Niehuss (2001); (7) NASA (2001c); (8) de Vera (1998a).
Note: Hardware entries in *italics* are components of assembly entries in **bold** type.

Table 7.3.4 International Space Station Fire Detection and Suppression

Assembly or Component	Mass [kg]	Volume [m³]	Length [m]	Width or Diameter [m]	Height [m]	Peak Power [W]	Operational Average Power [W]	MTBF [h]	CMMTTR [h]	Life Limit [y]	No.
Portable Fire Extinguisher [212]	7.7563 (1)	0.038409 (5)	0.4851 (1)	0.2606 (1)	0.2606 (1)						1
Smoke Detector [213]	1.5422 (1)	0.001968 (2)	0.1143 (1)	0.1301 (1)	0.1323 (1)		1.48 (1)				1

Table 7.3.5 International Space Station Vacuum Services

Assembly or Component	Mass [kg]	Volume [m³]	Length [m]	Width or Diameter [m]	Height [m]	Peak Power [W]	Operational Average Power [W]	MTBF [h]	CMMTTR [h]	Life Limit [y]	No.
Load Control Assembly [214]	10.8861 (8)	0.01246 (3)	0.2794 (3)	0.2209 (3)	0.2032 (3)						1
On-orbit Support Equipment [216]	3.5										1
VES/VRS jumper	2.13 (5)	0.002556 (5)	0.991 (5)	0.051 (5)	0.051 (5)						1
VS Equalization tool	1.37 (5)	0.000932 (5)	0.206 (5)	0.069 (5)	0.066 (5)						1
Vacuum Exhaust System (VES) [216]	35.02 (8)					150 (8)	80 (8)				1
Cold Cathode Transducer	2.5401 (8)	0.002832 (3)	0.3429 (3)	0.1041 (3)	0.0787 (3)	10 (8)	5 (8)	400,384 (3)	1.22 (3)	0.5 (3)	1 (3)
Flexible Metal Bellows	0.8436 (8)			0.0635 (8)							1
Non-Propulsive Vent (NPV)	1.7917 (3)	0.005947 (3)	0.1524 (3)	0.3048 (3)	0.127 (3)			2.0×10^{8} (3)	0.19 (3)		1 (3)
Pirani Gauge Transducer	1.1339 (8)	0.001132 (3)	0.2184 (3)	0.1041 (3)	0.0482 (3)	3 (8)	1.5 (8)	307,800 (3)	1.11 (3)		1 (3)
Positive Pressure Transducer	0.4535 (8)	0.000283 (3)	0.1016 (3)	0.0254 (3)	0.0254 (3)			682,611 (3)	1.11 (3)		1 (3)
Rack Isolation Valve (1 inch)	1.8143 (8)	0.002548 (3)	0.1371 (3)	0.0939 (3)	0.2032 (3)		30 (8)	428,700 (3)	4.54 (3)		13 (3)
Vent Valve (2.5 inch)	4.672 (3)	0.00538 (3)	0.2794 (3)	0.1727 (3)	0.1143 (3)		30 (8)	347,425 (3)	0.43 (3)		1 (3)
Vacuum Resource System (VRS) [216]	8.8 (8)					150 (8)	80 (8)				1
Cold Cathode Transducer	2.5401 (8)	0.002832 (3)	0.3429 (3)	0.1041 (3)	0.0787 (3)	10 (8)	5 (8)	400,384 (3)	1.22 (3)	0.5 (3)	1 (3)
Pirani Gauge Transducer	1.1339 (8)	0.001132 (3)	0.2184 (3)	0.1041 (3)	0.0482 (3)	3 (8)	1.5 (8)	307,800 (3)	1.11 (3)		1 (3)
Positive Pressure Transducer	0.4535 (8)	0.000283 (3)	0.1016 (3)	0.0254 (3)	0.0254 (3)			682,611 (3)	1.11 (3)		1 (3)
Vent Valve (2.5 inch)	4.672 (3)	0.00538 (3)	0.2794 (3)	0.1727 (3)	0.1143 (3)		30 (8)	347,425 (3)	0.43 (3)		1 (3)

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[212] Function: fire suppression

[213] Function: fire detection

[214] Function: supply vacuum services

References: (1) de Vera (1999); (2) Calculation; (3) MADS (2001); (4) de Vera (1998b); (5) NASA (2001b); (6) Niehuss (2001); (7) NASA (2001c); (8) de Vera (1998a).
Note: Hardware entries in *italics* are components of assembly entries in **bold** type.

Table 7.3.6 International Space Station Water Recovery and Management

Assembly or Component	Mass [kg]	Volume [m³]	Length [m]	Width or Diameter [m]	Height [m]	Peak Power [W]	Operational Average Power [W]	MTBF [h]	CMMTTR [h]	Life Limit [y]	No.
Condensate Water Storage Assembly [215]	21.3373 (3)	0.145848 (3)	0.9296 (3)	0.3962 (3)	0.3962 (3)						1
Contingency Water Container [217]	1.18 (5)	0.017663 (5)	0.61 (5)	0.381 (5)	0.076 (5)						1
Fuel Cell Water Tank [217]	72.1224 (3)	0.381187 (3)									1
Overboard Water Vent [216]	1.4605 (3)	0.007363 (3)	0.1955 (3)	0.193 (3)	0.193 (3)						2
Urine Processor Assembly [217]	291										1
Distillation Assembly	92.7612 (6)	0.142166 (6)	0.762 (6)	0.4318 (6)	0.4318 (6)			142,525.2 (6)	0.95 (6)	2 (6)	1 (6)
Firmware Controller Assembly	23.0882 (6)	0.028603 (6)	0.2921 (6)	0.3835 (6)	0.2565 (6)			27,331.2 (6)	1.15 (6)	2.4 (6)	1 (6)
Fluids Control and Pump Assembly	47.5826 (6)	0.073065 (6)	0.6883 (6)	0.4216 (6)	0.2514 (6)			90,140.4 (6)	2.066 (6)	4 (6)	1 (6)
Pressure Control and Pump Assembly	49.0795 (6)	0.115828 (6)	0.7416 (6)	0.4622 (6)	0.3378 (6)			181,507.2 (6)	0.916 (6)	2 (6)	1 (6)
Recycle Filter Tank Assembly	15.377 (6)	0.101102 (6)	0.8382 (6)	0.4318 (6)	0.2794 (6)			199,640.4 (6)	0.916 (6)	0.08 (6)	1 (6)
Separator Plumbing Assembly	16.7832 (6)	0.022939 (6)	0.8178 (6)	0.1727 (6)	0.1625 (6)			384,651.6 (6)	0.816 (6)	1 (6)	1 (6)
Wastewater Storage Tank Assembly	45.9496 (6)	0.039364 (6)	0.8255 (6)	0.2184 (6)	0.2184 (6)			184,222.8 (6)	1.716 (6)	10 (6)	1 (6)
Water Processor Assembly [218]	781										1
Catalytic Reactor	67.042 (6)	0.115545 (6)	0.7874 (6)	0.4191 (6)	0.3505 (6)			25,579.2 (6)	1.183 (6)	2.25 (6)	1 (6)
Gas Separator	39.1456 (6)	0.065985 (6)	0.7112 (6)	0.4064 (6)	0.2286 (6)			84,008.4 (6)	0.716 (6)	1 (6)	1 (6)
Ion Exchange Bed	13.0183 (6)	0.017275 (6)	0.8128 (6)	0.1905 (6)	0.1117 (6)			296,701.2 (6)	0.266 (6)	0.16 (6)	1 (6)
Microbial Check Valve	5.7607 (6)	0.006513 (6)	0.3175 (6)	0.1473 (6)	0.1397 (6)			143,488.8 (6)	0.266 (6)	1 (6)	1 (6)
Multifiltration Bed #1	149.2344 (6)	0.065702 (6)	0.7442 (6)	0.4394 (6)	0.2006 (6)			296,701.2 (6)	0.383 (6)	0.36 (6)	1 (6)
Multifiltration Bed #2	149.2344 (6)	0.065702 (6)	0.7442 (6)	0.4394 (6)	0.2006 (6)			296,701.2 (6)	0.383 (6)	0.36 (6)	1 (6)
Particulate Filter	32.2509 (6)	0.071649 (6)	0.6172 (6)	0.508 (6)	0.2286 (6)			717,356.4 (6)	0.25 (6)	0.22 (6)	1 (6)
pH Adjuster	2.5401 (6)	0.002548 (6)	0.2032 (6)	0.127 (6)	0.1016 (6)			137,181.6 (6)	0 (6)	1 (6)	1 (6)
Process Controller	44.9971 (6)	0.083827 (6)	0.7213 (6)	0.4445 (6)	0.2616 (6)			87,950.4 (6)	0.683 (6)	7.72 (6)	1 (6)
Pump Separator	31.3437 (6)	0.086942 (6)	0.7543 (6)	0.4318 (6)	0.2667 (6)			42,398.4 (6)	0.7 (6)	2 (6)	1 (6)
Reactor Health Sensor	16.8285 (6)	0.04248 (6)	0.6604 (6)	0.254 (6)	0.254 (6)			56,677.2 (6)	0.666 (6)	1 (6)	1 (6)
Sensor	4.8081 (6)	0.003398 (6)	0.1778 (6)	0.1524 (6)	0.127 (6)			143,664 (6)	0.65 (6)	10 (6)	1 (6)
Separator Filter	7.6658 (6)	0.010195 (6)	0.3429 (6)	0.1778 (6)	0.1676 (6)			359,072.4 (6)	0.233 (6)	0.84 (6)	1 (6)
Start-up Filter	9.4348 (6)	0.018408 (6)	0.635 (6)	0.2286 (6)	0.127 (6)			226,884 (6)	0 (8)	19.92 (6)	1 (6)
Wastewater	103.2847 (6)	0.163123 (6)	0.7772 (6)	0.4775 (6)	0.4394 (6)			53,611.2 (6)	0.65 (6)	4.71 (6)	1 (6)
Water Delivery	47.5372 (6)	0.09742 (6)	0.7874 (6)	0.4394 (6)	0.2819 (6)			64,561.2 (6)	0.633 (6)	5 (6)	1 (6)
Water Storage	56.7453 (6)	0.175017 (6)	0.8077 (6)	0.4394 (6)	0.4927 (6)			44,676 (6)	0.65 (6)	3.92 (6)	1 (6)

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[215] Function: water storage

[216] Function: water venting

[217] Function: process urine

[218] Function: process wastewater

References: (1) de Vera (1999); (2) Calculation; (3) MADS (2001); (4) de Vera (1998b); (5) NASA (2001b); (6) Niehuss (2001); (7) NASA (2001c); (8) de Vera (1998a).
Note: Hardware entries in *italics* are components of assembly entries in **bold** type.

7.3.2 Spacelab

Table 7.3.7 Spacelab Atmosphere Revitalization Subsystem

Assembly or Component	Mass [kg]	Volume [m^3]	Length [m]	Width or Diameter [m]	Height [m]	Peak Power [W]	Operational Average Power [W]	MTBF [h]	CMMTTR [h]	Life Limit [y]	No.
Cabin Fan Assembly [219]	18.96	0.081622	0.4612	0.3027	0.5844	399					1
Cabin Fan	2.7	0.00562	0.1428	0.1868	0.2105		395				2
Check Valve	0.205	0.004299	0.0421	0.1802							2
Debris Trap Filter	0.85	0.001482	0.381	0.2286	0.017						1
Power Factor Corrector	0.93	0.001032	0.1524	0.0889	0.0762		2				1
Carbon Dioxide Control Assembly [220]	24.1 (1)	0.191135 (2)	0.7 (1)	0.635 (1)	0.43 (1)		0.2 (1)				1
Carbon Dioxide Control Assembly [222]	3.06										1
Carbon Dioxide Absorber Element	3.06	0.025968	0.2872	0.1696							1
Humidity and Temperature Control Assembly [221]	19.43	0.078403	0.2529	0.5751	0.5389		0.85				1
Condensing Heat Exchanger	17.77	0.078401	0.2529	0.5751	0.5389		0.85				1
Temperature Control Valve	2.3	0.0272	0.4351	0.2159	0.2895						1
Water Separator Assembly [222]	97.6	0.040714	0.5003	0.3048	0.2669		48				1
Liquid Check Valve	0.055	0.000102	0.0508	0.0254							2
Power Factor Corrector	0.759	0.001032	0.1524	0.0889	0.0762		1				1
Rotary Separator	2.55	0.015127	0.1524	0.1778			43				2

Table 7.3.8 Spacelab Active Thermal Control Subsystem

Assembly or Component	Mass [kg]	Volume [m^3]	Length [m]	Width or Diameter [m]	Height [m]	Peak Power [W]	Operational Average Power [W]	MTBF [h]	CMMTTR [h]	Life Limit [y]	No.
Freon Pump Package [223]	22.4	0.044586	0.48	0.2997	0.0988		315				1
Water Pump Package [225]	21.09	0.036565	0.3937	0.2997	0.3098		66				1

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[219] Function: intramodule atmosphere circulation

[220] Function: carbon dioxide control

[221] Function: temperature and humidity control

[222] Function: humidity control

[223] Function: heat removal

References: (1) Doinier; (2) Calculation.

Note: Hardware entries in *italics* are components of assembly entries in **bold** type.

Table 7.3.9 Spacelab Temperature and Humidity Control

Assembly or Component	Mass [kg]	Volume [m³]	Length [m]	Width or Diameter [m]	Height [m]	Peak Power [W]	Operational Average Power [W]	MTBF [h]	CMMTTR [h]	Life Limit [y]	No.
Avionics Fan [224]	20 (1)	0.0516 (2)	0.5 (1)	0.43 (1)	0.24 (1)	670 130 (1) [225]					1
Avionics Heat Exchanger Assembly [226]	15.6 (1)	0.039525 (2)	0.383 (1)	0.43 (1)	0.24 (1)		4,510 (1)				1
Cabin Fan [226]	18.7 (1)	0.126449 (2)	0.85 (1)	0.483 (1)	0.308 (1)		403 (1)				1
Humidity and Temperature Control Assembly [226]	19.4 (1)	0.104147 (2)	0.539 (1)	0.582 (1)	0.332 (1)		51 (1)				1

Table 7.3.10 Spacelab Water Recovery and Management

Assembly or Component	Mass [kg]	Volume [m³]	Length [m]	Width or Diameter [m]	Height [m]	Peak Power [W]	Operational Average Power [W]	MTBF [h]	CMMTTR [h]	Life Limit [y]	No.
Condensate Overboard Dumping Assembly [227]	4.5 (1)	0.00896 (2)	0.4 (1)	0.14 (1)	0.16 (1)		150 (1)				1
Condensate Storage Assembly [228]	9.9 (1)			0.52 (1)							1
Water Separator Assembly [229]	9.8 (1)	0.04272 (2)	0.5 (1)	0.32 (1)	0.267 (1)		48 (1)				1

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[224] Function: temperature and humidity control

[225] The values here are for high-speed and low-speed settings, respectively.

[226] Function: intramodule atmosphere circulation

[227] Function: water venting

[228] Function: water storage

[229] Function: process wastewater

References: (1) Doinier; (2) Calculation.
Note: Hardware entries in *italics* are components of assembly entries in **bold** type.

7.3.3 Space Shuttle Program

Table 7.3.11 Space Shuttle Atmosphere Revitalization Subsystem

Assembly or Component	Mass [kg]	Volume [m^3]	Length [m]	Width or Diameter [m]	Height [m]	Peak Power [W]	Operational Average Power [W]	MTBF [h]	CMMTTR [h]	Life Limit [y]	No.
Ambient Temperature Catalytic Oxidizer [230]	1.5422	0.011163	0.3444	0.1016							1
ARS Instrumentation [231]	1.421										1
Cabin Temperature Controller	4.4452	0.010222	0.2603	0.1849	0.2123		16				1
Carbon Dioxide Partial Pressure Sensor	0.3855	0.000145	0.0635	0.0635	0.1524		0.2				1
Humidity Sensor	0.36 (1)						0.5 (1)				1
IR Carbon Dioxide Sensor	0.6 (1)					2.4 (1)					1
Pressure Sensor	0.25 (1)	0.000291	0.092	0.0317			0.5 (1)				1
Quantity Sensor	0.2268	0.000238	0.064	0.0576	0.0645		0.01				1
Speed Sensor	0.0453	0.000032	0.0254	0.0254	0.0508						1
Temperature Sensor	0.0771	0.000015	0.0731	0.0082							1
Temperature Sensor, Thermistor	0.0407 (1)	0.000054	0.0546	0.0177							1
Water Quantity Sensor	0.17 (1)										1
Avionics Cooling Assembly [232]	12.787	0.056609	0.3556	0.5969	0.2667	185					3
Avionics Check Valve	0.3538	0.007953	0.1041	0.1559							2
Avionics Fan	1.8597	0.010127	0.1388	0.1524		180					2
Avionics Heat Exchanger	6.3957	0.023644	0.353	0.3337	0.2006						1
Signal Conditioner	0.8618	0.002457	0.1778	0.16	0.0863		5				1
Beam Assembly [233]	7.9969	0.063857	0.1747	0.6096	0.5994						1
Cabin Air Fan [234]	18.6 (1)	0.038198 (2)	0.4699 (1)	0.3556 (1)	0.2286 (1)	70 (1)	20.5 (1)				1
Cabin Air Fan and Debris Trap Assembly [236]	17.191	0.1914	0.9042	0.3078	0.6876	495					1
Cabin Air Fan	2.6989	0.00562	0.1428	0.1868	0.2105	495					2
Check Valve	0.2041	0.003742	0.0393	0.1734							2
Debris and Filter Trap	0.1134	0.000492	0.2148	0.2148	0.0106						1
Signal Conditioner-ARS	0.9979	0.002465	0.1607	0.1785	0.0858		4				1
Nitrogen Storage Tank [235]		0.137337 (1)									4
Oxygen Auxiliary Tank [237]		0.13677 (1)									

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[230] Function: carbon monoxide control

[231] Function: temperature and humidity control

[232] Function: heat removal

[233] Function: equipment mounting

[234] Function: intramodule atmosphere circulation

[235] Function: nitrogen and oxygen storage

References: (1) Doinier; (2) Calculation.
Note: Hardware entries in *italics* are components of assembly entries in **bold** type.

Table 7.3.11 Space Shuttle Atmosphere Revitalization Subsystem (continued)

Assembly or Component	Mass [kg]	Volume [m^3]	Length [m]	Width or Diameter [m]	Height [m]	Peak Power [W]	Operational Average Power [W]	MTBF [h]	CMMTTR [h]	Life Limit [y]	No.
Carbon Dioxide Absorber and Temperature Control Assembly [236]	17.355	0.258958	0.635	0.6634	0.6146						1
Cabin Temperature Selector	0.2494	0.000585	0.0838	0.0838	0.0833	0.01					1
Carbon Dioxide Absorber Element (with LiOH Canister)	2.903	0.025968	0.2872	0.1696							2
Electric Actuator	0.4989	0.000561	0.1173	0.0627	0.0762	57.5	34.5				1
Temperature Control Valve	2.2952	0.035743	0.4351	0.2402	0.3418						1
Emergency Breathing Provisions [237]	5.6										1
Breathing Regulator	0.1 (1)										1
Oxygen System	5.5 (1)	0.00131 (1)	0.4318 (1)	0.0698 (1)							1
Humidity Control Heat Exchanger Assembly [238]	20.0718	0.092732	0.5384	0.5199	0.3312		0.003				1
Humidity Control Heat Exchanger	19.913	0.092583	0.5384	0.5207	0.3302						1
Signal Conditioner	1.8597	0.004358	0.207	0.207	0.1016		8				1
IMU Fan Assembly [239]	10.9317	0.068252	0.889	0.3556	0.2159		50				1
Check Valve	0.0408	0.000761	0.0447	0.0736							3
Filter	0.0095	0.476538	0.3479	0.6604							1
IMU Fan	2.1273	0.004817	0.2032	0.0889	0.2667						3
IMU Fan Motor	1.1793	0.001389	0.0762	0.0762			50				3
IMU Heat Exchanger	3.2886	0.008117	0.1892	0.2095	0.2047						1
Self Sealing Coupling	0.2268	0.000272	0.0685	0.0355							1
Signal Conditioner	0.9298	0.002464	0.1785	0.1607	0.0858		4				3
Multi-Purpose Heat Exchanger [240]	2.1772	0.005473	0.3131	0.1965	0.0889						1
Primary Water Pump Package [241]	14.4879	0.035708	0.4599	0.319	0.2433	239.5					1
Accumulator	2.0412	0.027972	0.2794	0.1785							1
Filter	0.0589	0.00042	0.0599	0.0472							1
Self-Sealing Couplings	0.17	0.000154	0.0762	0.0254							3
Water Bypass Controller	1.7917	0.00598	0.2329	0.2329	0.1102		8				1
Water Bypass Valve	1.2746	0.001839	0.1778	0.1163	0.0889	57.5	34.5				1
Water Pump	1.8824	0.001045	0.1651	0.0683	0.0927		197				2
Water Pump Check Valve	0.9072	0.000488	0.1407	0.0899	0.0386						1

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[236] Function: carbon dioxide control

[237] Function: emergency equipment

[238] Function: humidity control

[239] Function: intermodule atmosphere circulation

[240] Function: heat removal

[241] Function: temperature control

References: (1) Doinier; (2) Calculation.

Note: Hardware entries in *italics* are components of assembly entries in **bold** type.

Table 7.3.11 Space Shuttle Atmosphere Revitalization Subsystem (concluded)

Assembly or Component	Mass [kg]	Volume [m³]	Length [m]	Width or Diameter [m]	Height [m]	Peak Power [W]	Operational Average Power [W]	MTBF [h]	CMMTTR [h]	Life Limit [y]	No.
Regenerative Carbon Dioxide Removal System [242]	147 (1)	0.309998 (2)	0.4635 (1)	0.6794 (1)	0.9842 (1)	311 (1)	110 (1)				1
Canister Assembly	42.5 (1)	0.096816 (2)	0.8699 (1)	0.254 (1)	0.4381 (1)						1
Controller	8.8 (1)	0.014984 (2)	0.164 (1)	0.3238 (1)	0.2819 (1)						2 (1)
Crew Setting Valve	0.5 (1)	0.000514 (2)	0.0787 (1)	0.1186 (1)	0.0551 (1)						1 (1)
Fan	2.13 (1)	0.004817 (2)	0.2032 (1)	0.0889 (1)	0.2667 (1)		56 (1)				1 (1)
Inlet Muffler and Filter											1 (1)
Odor Filter: Charcoal, Shell Cartridge, Cloth Liner	2.5 (1)	0.011328 (1)		0.1696 (1)	0.287 (1)					0.0246575 (1)	1
Outlet Muffler	0.35 (1)			0.0762 (1)	0.3556 (1)						1 (1)
Pressure Equalization Valve	0.73 (1)			0.0508 (1)	0.1422 (1)						6 (1)
System Sensors											1 (1)
Ullage Save Compressor	6.21 (1)	0.005649 (2)	0.1143 (1)	0.1955 (1)	0.2527 (1)	250 (1)	180 (1)				1 (1)
Vacuum Cycle Valve (VCV)	1.23 (1)	0.001364 (2)	0.1056 (1)	0.1104 (1)	0.1168 (1)						2 (1)
Vacuum Cycle Valve Actuator	0.89 (1)	0.000469 (2)	0.0736 (1)	0.0533 (1)	0.1193 (1)						2 (1)
Secondary Pump and Accumulator Assembly [243]	12.6735	0.035708	0.4599	0.319	0.2433	239.5					1
Water Separator Assembly [244]	7.8472	0.024189	0.2656	0.448	0.2032						1
Fan / Separator	2.5401	0.015127	0.1524	0.1778		43					2
Fan / Separator Motor	1.0659	0.001389	0.0762	0.0762		40					1
Gas Check Valve	0.009	0.000145	0.0276	0.0408							2
Liquid Check Valve	0.0498	0.000102	0.0508	0.0254							2
Signal Conditioner	0.9208	0.002464	0.1785	0.1607	0.0858	4					1

Table 7.3.12 Space Shuttle Airlock Support Subsystem

Assembly or Component	Mass [kg]	Volume [m³]	Length [m]	Width or Diameter [m]	Height [m]	Peak Power [W]	Operational Average Power [W]	MTBF [h]	CMMTTR [h]	Life Limit [y]	No.
LCVG Heat Exchanger [245]		0.001966 (2)	0.0762 (1)	0.2032 (1)	0.127 (1)						

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[242] Function: carbon dioxide control

[243] Function: temperature control

[244] Function: humidity control

[245] Function: temperature and humidity control

References: (1) Doinier; (2) Calculation.

Note: Hardware entries in *italics* are components of assembly entries in **bold** type.

Table 7.3.13 Space Shuttle Active Thermal Control Subsystem

Assembly or Component	Mass [kg]	Volume [m³]	Length [m]	Width or Diameter [m]	Height [m]	Peak Power [W]	Operational Average Power [W]	MTBF [h]	CMMTTR [h]	Life Limit [y]	No.
Ammonia Boiler Subsystem [246]		0.346881 (2)	1.0668 (1)	0.6096 (1)	0.5334 (1)						1
Cold Plates											1
Evaporator / Control		0.224028 (2)	0.5334 (1)	0.5334 (1)	0.7874 (1)						1 (1)
Flash Evaporator Subsystem Water Accumulator			0.1676 (1)	0.0914 (1)							1 (1)
Flash Evaporation Assembly [248]	26.2543	0.130535	0.5461	0.4953	0.4826	200					1
Evaporator	7.4844	0.149054	0.4191	0.3365							2
Flash Evaporator Controller	1.7463	0.001769	0.1524	0.1524	0.0762		8				1
Flash Evaporator, Controller No.3	1.7463	0.001769	0.1524	0.1524	0.0762		9				1
High Load Duct Assembly	10.9										1
High Load Valve / Nozzle Assembly	0.4989	0.00043	0.0889	0.0762	0.0635		35				1
Nozzle Heater	0.254		0.3048				25				1
Sonic Nozzle Assembly	1.2247	0.015217	0.1778	0.1651			25				1
Topping Duct Assembly	25.7191										1
Topping Valve / Nozzle Assembly	0.5443	0.000399	0.0825	0.0762	0.0635		35				1
Flow Proportioning Module [248]	1.7236	0.004244 (2)	0.1778 (1)	0.1016 (1)	0.2495 (1)	57.5	34.5				1
Flow Proportioning Valve		0.004244	0.1778	0.1016	0.2495						2
Flow Sensor	0.7484	0.001721	0.1778	0.0645	0.1501		0.84				2
Signal Conditioner	2.0865	0.004034	0.1656	0.1498	0.1625		10				1
Freon Pump Package, Single Pumps [248]	19.0466	0.0854 (2)	0.7226 (1)	0.3276 (1)	0.3606 (1)	360					2
Check Valve	1.8144			0.019							1
Filter	0.136	0.000106	0.1016	0.0182							1
Freon Accumulator	10.8864	0.238894	0.6913	0.3317							1
Freon Pump	1.769	0.001585	0.2006	0.0889	0.0889	360					1
Freon Pump Package, Two Pumps [248]	20.294	0.0854 (1)	0.7223	0.3276	0.3606	360					2
Freon To Water Interchanger [248]	14.3791	0.023819 (2)	0.7467 (1)	0.2616 (1)	0.1219 (1)						1
Fuel Cell Heat Exchanger [248]	7.6114	0.010406 (2)	0.4114 (1)	0.2032 (1)	0.1244 (1)		0.002				1
Ground Support Equipment Heat Exchanger [248]		0.007039 (2)	0.3429 (1)	0.1879 (1)	0.1092 (1)						1
Hydraulics Heat Exchanger [248]	11.1132	0.020808 (2)	0.4699 (1)	0.2614 (1)	0.1676 (1)						
Payload Heat Exchanger [248]	19.6408	0.013225 (2)	0.5359 (1)	0.2159 (1)	0.1143 (1)						1
Radiator System [248]											

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[246] Function: heat removal

References: (1) Doinier; (2) Calculation.
Note: Hardware entries in *italics* are components of assembly entries in **bold** type.

Table 7.3.13 Space Shuttle Active Thermal Control Subsystem (continued)

Assembly or Component	Mass [kg]	Volume [m^3]	Length [m]	Width or Diameter [m]	Height [m]	Peak Power [W]	Operational Average Power [W]	MTBF [h]	CMMTTR [h]	Life Limit [y]	No.
Water Boiler, Thermal Control, Hydraulic [247]	71.6824	0.345493	0.8636	0.7874	0.508	150	100				3
Heater	0.1134	0.000032	0.2984	0.085	0.0012		14.7-31.7				1
Hydraulic Pressure Relief Valve	1.134	0.000201	0.1041	0.0762	0.0254						1
Water Boiler	33.0493	0.096167	0.4445	0.3111	0.6953						1
Water Shutoff Valve	0.6441	0.000225	0.1082	0.0482	0.0431		50				1
Water Spray Boiler Controller	4.3092	0.009107	0.1134	0.2413	0.3302		42				1
Water Tank	5.4432	0.258479	0.6906	0.3589							1
Water Spray Boiler Subsystem [249]	82.4644	0.388839	0.4826	1.0226	0.7879						3
Electrical Heater-1	0.2177						51				1
Electrical Heater-2	0.0453						33.5				1
Electrical Heater-3	0.0453						11.5				1
Hydraulic Bypass Relief Valve	4.8399	0.004144	0.3357	0.1468	0.084	57.5	34.5				1
Liquid Level Sensor	0.1134	0.00005	0.0508	0.0177		0.3					1
Liquid Level Sensor Electronics	0.068	0.000506	0.0571	0.0698	0.127						1
Nitrogen Regulator	0.6804	0.000644	0.0967	0.0873	0.0762						1
Nitrogen Shutoff Valve	0.6804	0.000558	0.1135	0.0787	0.0624		50				1
Nitrogen Storage Tank	0.9072	0.016351		0.1574							1
Spray Boiler	21.5097	0.0482	0.6985	0.3959	0.2032						1
Steam Dump Nozzle	2.1772	0.01681	0.1905	0.1676			51				1
Water Supply Valve	0.5307	0.000617	0.1097	0.0805	0.0698		50				1
Water Tank for Water Spray Boiler	21.4099	0.111143	0.7409	0.4051	0.3708						1

Table 7.3.14 Space Shuttle Water Recovery and Management

Assembly or Component	Mass [kg]	Volume [m^3]	Length [m]	Width or Diameter [m]	Height [m]	Peak Power [W]	Operational Average Power [W]	MTBF [h]	CMMTTR [h]	Life Limit [y]	No.
Potable Water Tank [248]	3.3 (1)										1
Wastewater Tank [250]	3.3 (1)										1

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[247] Function: heat removal

[248] Function: water storage

References: (1) Doinier; (2) Calculation.

Note: Hardware entries in *italics* are components of assembly entries in **bold** type.

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13. ABSTRACT *(Maximum 200 words)*

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 called a baseline. This baseline provides a common point of origin from which all systems integration, modeling, and analysis element studies will depart. The BVAD identifies quantities that define life support systems from an analysis and modeling perspective; provides a nominal or baseline value plus a range of possible or observed values for each physical quantity identified; and documents each entry with a description of the use, value selection rationale, and appropriate references of that quantity. Specifically, the BVAD allows the life support analysis community to carefully review and evaluate input study assumptions. Each study can benefit from the "best" available input values and assumptions by drawing on information collected by a group of researchers rather than an individual researcher. The BVAD process identifies quantities that are not well-defined by current information, allows researchers from multiple disciplines to effectively and quickly compare results from multiple studies, and allows these researchers to conduct a follow-on study to any previous work because assumptions from each study are clearly available and carefully recorded.

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