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Advanced Life Support Systems Integration, Modeling, and Analysis Reference Missions Document

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Advanced Life Support
Systems Integration, Modeling, and Analysis
Reference Missions Document

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1 Introduction

1.1 Goal

The Advanced Life Support Systems Integration, Modeling, and Analysis Reference Missions Document (RMD) provides the Advanced Life Support (ALS) Project with several reference missions that are likely scenarios for early human exploration and development of near-Earth space. It expounds mission details to allow meaningful system-level analyses of proposed life support system (LSS) concepts. As such, this document is a supplement for other analysis reference documents.

Another specific goal of this document is to define realistic technology options for each mission. Two approaches to providing life support for these missions are documented. The first approach applies currently existing, flight-qualified hardware, including equipment in use and planned for the International Space Station (ISS). The second approach, referred to as the "Advanced Life Support Straw Man concept," applies technologies under development within the ALS Project. The technology selections presented for the missions described in this document are not meant to serve as absolute, approved approaches. Further, these architecture scenarios are not intended to be a definitive selection of technologies, but rather, possible guides or feasible starting points for analytical studies.

1.2 Approach

The technologies recommended for the ALS Straw Man architecture associated with each mission are those that, based on engineering judgment, may be more economical, in terms of overall system mass, after considering a variety of current and near-term technologies. For this compilation, technologies were drawn from the state-of-the-art, based on ISS technology (Carrasquillo, *et al.*, 1997, and Wieland, 1998), ALS systems using mostly physicochemical technologies (Lin, 1997a and 1997b), and ALS bioregenerative concepts based on the Bioregenerative Planetary Life Support Systems Test Complex (BIO-Plex) biomass production system.

The current state-of-the-art for long-duration life support is embodied in the ISS environmental control and life support system (ECLSS) (Carrasquillo, *et al.*, 1997, and Wieland, 1998). Much of the hardware for the ISS ECLSS has been ground-tested and is fairly mature, and some is already on orbit. This approach is documented for comparison with ALS approaches.

The ALS Project explores technologies that may provide significant improvements over current technologies, reducing overall mass, power, cooling, and crew time requirements, for specified levels of performance. The Systems Integration, Modeling, and Analysis (SIMA) Project Element has the task of recommending the optimal set of technologies for each advanced mission. The technologies selected will depend critically on the mission parameters, the range of technologies deemed ready for flight, and on the infrastructure costs. This document defines realistic initial ALS system concepts for the missions considered. Future analyses will improve and refine these ideas.

An approach often used for comparing system options is to compute a metric, such as the equivalent system mass (ESM) for each proposed configuration. For each configuration, technology scenarios are developed, resizing components for the number of crew and mission operating environments. The ESM computation is based upon the mass, volume, power, cooling and crewtime requirements of the life support system. Infrastructure equivalencies are used to convert volume, power, cooling and crewtime needs to units of mass. For each proposed configuration, a reduction in the required ESM of the LSS for a specific mission reflects an improvement in mission architecture or a beneficial use of ALS technology.

In this document, contingency provisions are separated from nominal provisions. This makes the contingency assumptions more visible and, hopefully, more completely defined.

1.3 Scope

The LSS is defined broadly to include the traditional ECLSS functions of providing a habitable environment, including clean air and water, plus solid waste processing, food processing, biomass production and thermal control, and supporting interfaces with other subsystems. Table 1.1 provides a complete list of advanced life support subsystems according to function, their descriptions, and corresponding interfaces selected by the ALS Project. Table 1.1 defines subsystems based on similar functionality or interaction with a specific life support commodity. Table 1.2 provides a list of external LSS interfaces, their descriptions, and their respective LSS subsystem interfaces. [1]

Table 1.1 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, 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 Control, Waste, Water, In-Situ Resource Utilization, Integrated Control, Power
Food	The Food Subsystem receives harvested agricultural products from the Biomass Subsystem, stabilizes them as necessary, and stores raw and stabilized agricultural products, food ingredients, and prepackaged food and beverage items, and 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, 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 environment. Note: Equipment to remove thermal loads from the cabin atmosphere normally provides sufficient air circulation.	Air, Biomass, Food, Waste, Water, Human Accommodations, Integrated Control, Power
Waste	The Solid Waste Subsystem collects and conditions solid waste material from anywhere in the habitat, including packaging, human wastes, inedible biomass, and brines from other subsystems such as the Water Subsystem. The Solid 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, EVA Support, Integrated Control, Human Accommodations, Power, Radiation Production
Water	The Water Subsystem collects wastewater from all possible sources, recovers and transports potable water, and stores and provides that water at the appropriate purity for crew consumption and hygiene as well as external users.	Air, Biomass, Food, Thermal, Waste, EVA Support, Human Accommodations, In-Situ Resource Utilization, Integrated Control, Power, Radiation Protection

1 Table 1.1 and Table 1.2 are repeated here for convenience. Please see the most recent revision of the "Advanced Life Support Systems Integration, Modeling, and Analysis Project Baseline Values and Assumptions Document," JSC-39317 (currently Drysdale and Hanford, 1999a) for the current edition of these tables.

Table 1.2 Advanced Life Support External Interfaces Descriptions and Interfaces

External Life Support Interfaces	Description	Life Support System Interfaces
Extravehicular Activity Support	The Extravehicular Activity Support Interface provides life support consumables for extravehicular activities, including oxygen, water, and food, and carbon dioxide and waste removal.	Air, Food, Waste, Water, 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, 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, Integrated Control, Radiation Protection, Power
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, In-Situ Resource Utilization, Power

This document defines one ISS technology set and one ALS technology set for each of the following mission scenarios:

- International Space Station Evolution Mission: an orbiting research facility
- Mars Dual Lander Architecture: an exploration format independent of previous or future site selection
- Mars Split Mission Architecture: an exploration format providing surface infrastructure and a concentrated examination of a single site
- Evolved Mars Base

The Evolved Mars Base mission considers only the nominal or steady state base operation. The base construction phase is not defined, but evolution from infrastructure emplaced by precursor exploration missions is a possible scenario. The Mars Split Mission Architecture presented below is unchanged from the original references (Hoffman and Kaplan, 1997, and Drake, 1998) and so does not benefit from the recent ideas illustrated in the Mars Dual Lander Architecture.

Where known, each mission scenario also provides estimates for overall power consumption and expected thermal loads. This information is essential for sizing the thermal control subsystem when considering it directly rather than as a utility. Further, the listed values are accurate for the mission scenario as originally envisioned and including the implied ISS hardware choices, but rigid adherence to these values will unrealistically constrain life support system studies aimed at determining the optimal overall system regardless of absolute mass, power, and volume usage. In this latter case, such overall power values are suggestions for the anticipated magnitude of power available and not rigid restraints.

Thus, analysts should assume sufficient power to adequately support their architecture, regardless of the given values. Promising and innovative life support system designs offset increased power consumption with significant reductions elsewhere.

Some other options for mission architecture are also of interest, notably using the same transit vehicle for both the outbound and return trip, like the Mars Dual Lander, but visiting the same site several times, as in the Mars Split Mission format.

The architecture compiled for either the ISS baseline technologies or the ALS Straw Man technologies presented in this document is organized according to subsystems and external interfaces (for example, see Figure 2.4). Descriptions of each of the subsystems and external interfaces are listed in Table 1.1 and Table 1.2. The ALS subsystems for the LSS figures, including Air, Biomass, Food, Thermal, Waste, and Water, are shown within solid boundaries. The external interfaces to ALS, including Extravehicular Activity (EVA) Support and the Human Accommodations Subsystem, are shown within dashed boundaries.

The RMD is part of a coordinated effort by SIMA to document assumptions used in ALS analyses. In most cases, to perform any more than a top-level assessment, the analyst must have some idea of the mission for which a particular piece of hardware or system will be used. Of course there may be many possibilities, but here are some ideas of what humanity may attempt in the future as the National Aeronautics and Space Administration (NASA) seeks to "boldly expand frontiers in air and space." Thus, several reference missions are documented here as a starting point. As priorities change, new reference missions can be added to compliment these.

The diagram below, Figure 1.1, illustrates how SIMA considers inputs from the Johnson Space Center Exploration Office and the ALS project management as these reference missions are defined. The diagram also shows how this document and other ALS documents form a basis for the ALS Research and Technology Development Metric and other engineering parametric studies.

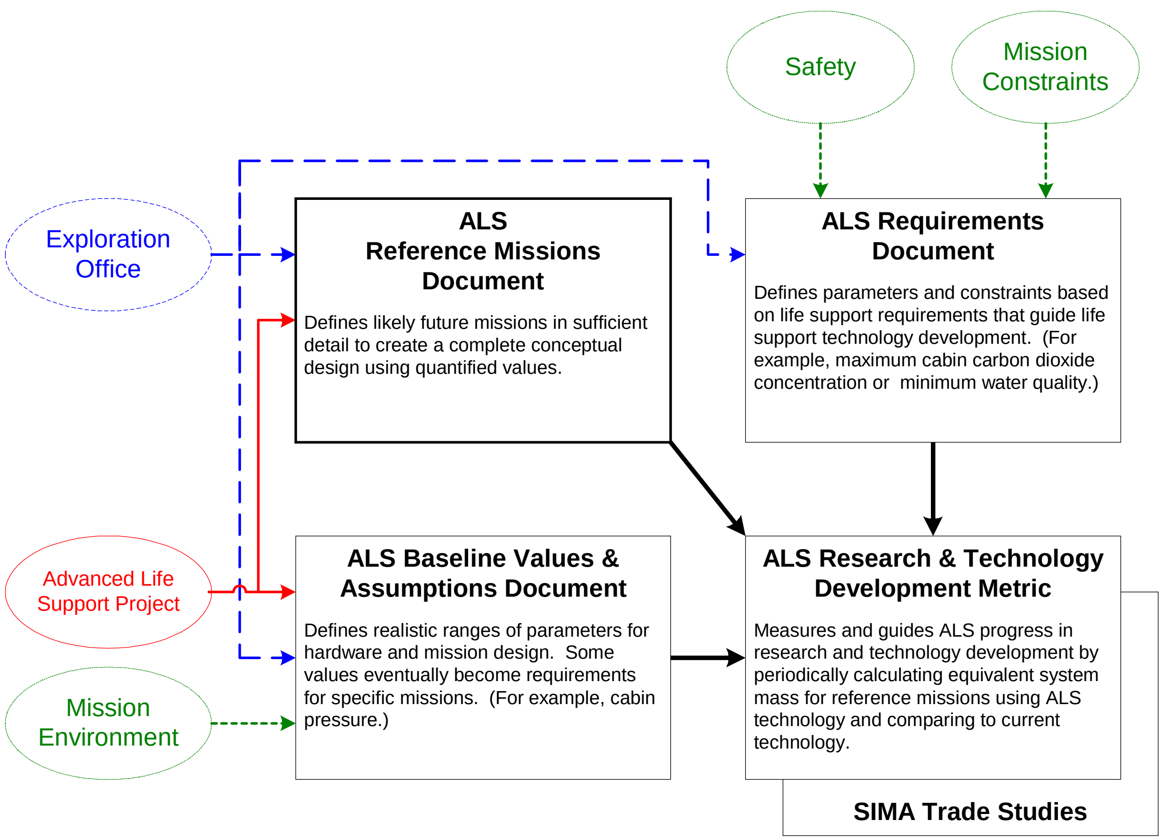

Figure 1.1 Relationships between SIMA Reference Documentation

1.4 Applicable Documents

The following documents are considered to be of some importance, and if there are conflicts between these documents and the RMD, more recent versions of these other documents will have precedence. The most recent releases of these documents are:

- Behrend, A. F., Jr., *et al.* (1999) "Advanced Life Support Project Plan," JSC-39168 (CTSD-ADV-348), Revision B, National Aeronautics And Space Administration, Johnson Space Center, Houston, Texas
- Drysdale, A. E., and Hanford, A. J. (2001) "Advanced Life Support Systems Integration, Modeling, and Analysis Project Baseline Values and Assumptions Document," JSC-39317 (CTSD-ADV-371), Revision A, National Aeronautics and Space Administration, Johnson Space Center, Houston, Texas. In preparation.

Another document related to the RMD is:

- Drysdale, A. E. and Hanford, A. J. (1999) "Advanced Life Support Research and Technology Development Metric Document," JSC-39503 (CTSD-ADV-384), National Aeronautics and Space Administration, Johnson Space Center, Houston, Texas.

- Duffied, B.E., (2001) "Advanced Life Support (ALS) Technologies List Version 4," MSAD-01-0221, Lockheed Martin Space Operations, Houston Texas.

1.5 Authority and Revision Control

This document will be revised as needed. Change control authority will reside with the ALS Project Manager. As currently envisioned, other documentation may update the ALS Straw Man architecture concepts presented below as current and emerging life support technologies become more cost-effective and reliable through research and development or through more efficient architecture concepts. Further, additional reference missions may be added to future revisions of this document to reflect changes in NASA's plans and goals. Suggested changes should be provided to:

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2 Orbital and Microgravity Missions in Near-Earth Space

Missions away from a planetary surface are most strongly characterized by a lack of gravity. Without a force like gravity, fluids, in particular, behave differently than on Earth or even under reduced gravity such as on the surface of Luna or Mars. Further, such behavior can be problematic for flows within life support equipment such as thermal control loops and water processing equipment.

In near-Earth space, the thermal environment is relatively benign. With proper positioning of radiant surfaces, heat loads generated within the vehicle crew cabin can be rejected to the environment without excessive cost or difficulty. This is true in low Earth orbit or in a Lunar orbit. Further, thermal control systems for human vehicles in this realm generally employ common thermal working fluids without difficulties. (See Ewert, *et al.*, 1999, for a more detailed discussion.)

The radiation environment of near-Earth space varies considerably. In low Earth orbit, the Van Allen Belts deflect a significant portion of the intense solar and galactic radiation away from an equatorially orbiting vehicle. For operations in Lunar space and most other near-Earth destinations, mission vehicles pass beyond the Van Allen Belts and, therefore, are subject to the full effects of solar and galactic radiation. (See Tribble, 1999, for a more detailed discussion.)

2.1 Orbiting Research Facility: International Space Station Mission

ISS provides a permanently habitable facility in low Earth orbit for conducting scientific research across various disciplines, including biomedical and microgravity research. It has a designed life of ten years and the United States On-orbit Segment (USOS) ECLSS is generally sized for a crew of seven. It is expected that "ISS upgrades," sometime in the future, may afford the opportunity to apply ALS technologies. But the current ISS technologies also provide a technology starting point for planning other advanced missions.

The ISS supports a crew of three at permanent human capability (Phase 2) and will support seven following assembly complete (Phase 3). The life support system is described in Reuter and Reysa (1997) and Wieland (1998a). ECLSS components are distributed among the various modules. Design responsibility is similarly spread among the various partners. Compatibility among the components must be assured since design philosophies differ according to the design responsibility. As international partner elements are added, international responsibilities are added, though primarily for temperature and humidity control, fire detection and suppression, and for experimental support such as vacuum systems.

Phases 2 and 3 of the International Space Station Mission are defined here as a starting point for ALS analysis and as a basis for "current technology." Phase 2 is the current configuration and Phase 3 assumes the current assembly complete baseline configuration as of the date of publication of this report. A duration of ten years with a crew of six is assumed for Phase 3 and a duration of ten years with a crew of three is assumed for the Phase 2 configuration. Progression from Phase 2 to Phase 3 depends on many factors.

2.1.1 International Space Station Life Support System Hardware

Several subsystems make up the life support system of the ISS including atmosphere control and supply, atmosphere revitalization, temperature and humidity control, water recovery and management, waste management, and fire detection and suppression. Life support aboard ISS is based on a 90-day resupply schedule, with an additional 45-day contingency cache. Few interfaces exist between the American and Russian life support systems. Both systems are described below.

2.1.1.1 Russian Segment Hardware - Phase 2

Initial components of the ISS are a Russian responsibility and additional ones are an American responsibility. The Russian Segment (RS) ECLSS is similar to the system used on *Mir*. Actual RS ECLSS equipment are improved models of the corresponding *Mir* components (Wieland 1998b). The Russian life support subsystems and technologies are described in this document using the ALS categories.

Air Subsystem

The RS Air Subsystem removes carbon dioxide (CO_2) from the habitat atmosphere and supplies oxygen (O_2) by water (H_2O) electrolysis. Pressure gauges and sensors monitor the pressure in the RS. Tanks supplied by Progress resupply vehicles sustain the total atmospheric pressure by supplying oxygen, nitrogen (N_2), and air. As shown in Figure 2.1, *Vozdukh* assemblies, using regenerable adsorbents, remove carbon dioxide from the atmosphere, and vent it overboard. An *Elektron* water electrolysis unit produces oxygen to resupply the cabin atmosphere. Water for electrolysis is acquired from condensate processing. Excess hydrogen (H_2), a by-product, is vented overboard. Gas analyzers (GA) monitor major constituents and gas contaminates, and the RS trace contaminant equipment, or BMP, removes trace contaminants. Samples of the air are routinely returned to Earth for further analysis. Fire detection and suppression (FDS) equipment isolates and extinguishes fires when detected.

Food Subsystem

The Russian menu provides four meals per day for each crewmember. Food in the RS is stored in containers at ambient storage (AS) temperature. Hot or cold water reconstitutes dehydrated foods to be consumed. Electric food warmers heat food in cans and plastic pouches to serving temperature. Russian food lockers store 18 meals, and have an empty mass of 0.9 kg.

Thermal Subsystem

The Thermal Subsystem removes heat from the atmosphere using air conditioners to provide thermal conditioning for the RS. Internal thermal control subsystem (ITCS) cooling loops transport excess heat to liquid-to-liquid heat exchangers (HX) where it is transferred to external thermal control subsystem (ETCS) coolant. The ITCS uses Triol, a water/glycerin mixture, as the heat transfer fluid. The ETCS utilizes polymethylsiloxane-silicon, an organic silicon fluid, to transfer heat to body mounted ammonia (NH_3) heat pipe radiators where it is rejected to space. Humidity condensate from the cabin atmosphere is removed for processing into potable water for food preparation, drinking, and hygiene use.

Waste Subsystem

The Waste Subsystem involves bagging solid metabolic waste, non-metabolic waste, and urine and placing it on Progress to burn up during re-entry to Earth.

Water Subsystem

The Water Subsystem includes the water recovery system from condensate (WRS-CM). The WRS-CM processes condensate collected in the RS. A mechanical gas/liquid mixture filter removes particles from the humidity condensate. A filter-reactor filled with a catalyst oxidizes organic impurities. Separation of the condensate from the atmosphere occurs in static separators. A multifiltration unit (MFU) purifies the water by removing dissolved organic and inorganic impurities. Following quality control by electrical conductivity, the water conditioning unit (WCU) disinfects the water and adds mineral salts for palatability and silver ions for microorganism control. The potable water is stored until it is distributed through the distribution and heating unit (DHU) for food preparation, drinking, and hygiene. *Rodnik* tanks, transported from Earth, also resupply potable water to the RS.

Extravehicular Activity Support Interface

EVA is not categorized as part of the LSS in this document, but rather interfaces with the LSS. The RS interfaces with the *Orlan* pressure suit to perform an EVA. The *Elektron* supplies compressed oxygen to recharge the Russian *Orlan* oxygen tanks. The RS provides energy through rechargeable batteries and cooling water to the *Orlan* suit. If necessary, tethers can supply power to the space suit for EVA operations.

Human Accommodations Interface

Clothing is packaged and shipped to the ISS clean from Earth (Rogers, 1999). Dirty clothes return for laundering on the ground. Thus, clothing is a consumable in the broadest sense on ISS because the clothing allotment is directly proportional to each crewmember's flight duration.

A washing chamber provides a location for hygiene activities such as hand washing. Towelettes and wash clothes used for hygiene purposes are supplied in the RS. Napkins are used for general station cleaning, and wet napkins are used for purposes such as bathing, face cleaning, and pre-meal hand wash. Dry towels are provided for drying the body after exercise or bathing. These towels return to Earth after use with the dirty clothing. (See Rogers, 1999)

2.1.1.2 Russian Segment Hardware - Phase 3

The RS provides living and working space for the crew at Phase 3 assembly complete. The RS ECLSS supports a crew of three nominally, with the capability to support six up to ten days if necessary. Specialized laboratory modules allow for long-term scientific research.

Thermal Subsystem

The Thermal Subsystem for the Phase 3 ETCS configuration includes radiator rotary joints. The rotary joints allow the radiators to be positioned optimally for heat rejection to space. The ITCS remains identical to the Phase 2 configuration.

Waste Subsystem

Urine and urine flush water in the RS Waste Subsystem is collected and processed into water for oxygen production by electrolysis. Sulfuric acid (H_2SO_4) and chromium oxide (CrO_3) treats urine to control odor and bacterial growth. The urine tank collects the treated urine prior to processing. Solid metabolic waste, non-metabolic waste, and brine from urine processing return to Earth during re-entry of Progress.

Water Subsystem

The assembly complete Water Subsystem consists of two separate systems: the WRS-CM and the water recovery system from urine (WRS-UM). The WRS-CM configuration is identical to the Phase 2 system described above.

The WRS-UM will reclaim water from urine for oxygen generation through distillation and purification, as shown in Figure 2.2. The urine-processing unit consists of a heater, evaporator, and condenser. Brine from the urine processor is disposed of in Progress. A MFU similar to the one used in the WRS-CM treats the distillate by multifiltration. The product water is stored until used for electrolysis. The WRS-UM equipment is planned to launch on flight 3R with the Russian Universal Docking Module. Waste hygiene water is treated and disposed of in Progress.

Extravehicular Activity Support Interface

EVA depressing and repressing occurs in the airlock (A/L) of the Docking Compartment of the RS. Russian EVA equipment previously stored in the Service Module is relocated to the A/L where all Russian station EVAs are conducted.

Other Subsystems and Interfaces

The Air Subsystem, the Food Subsystem, the Waste Subsystem, and the Human Accommodations Interface remain functionally identical to the corresponding subsystems and interfaces for the RS Phase 2 configuration in Figure 2.1.

2.1.1.3 United States On-Orbit Segment Hardware - Phase 2

The initial ISS construction phase establishes permanent crew presence and operations. The USOS has few ECLSS responsibilities during this stage. The modules launched during this phase include the US Laboratory, Node 1, and the Airlock. Power generation on ISS is by solar photovoltaic cells, and batteries provide energy storage. Table 2.1 describes the power and thermal loads of the USOS upon completion of Phase 2 following flight 7A.1.

Table 2.1 Power and Thermal Loads for International Space Station Mission - Phase 2

U. S. On-Orbit Segment International Space Station at Phase 2	Power [kW_e]	Cooling Load [kW]
Total Electrical Power to Users (average at end-of-life)	12.5	12.5
Additional Thermal Load from Power Generation		2
Total	**12.5**	**14.5**

Air Subsystem

Within the USOS Air Subsystem, oxygen is provided by high-pressure (HP) gas storage, as shown in Figure 2.3. The total pressure of the module is controlled to 14.7 ± 0.2 psia and monitored by the pressure control assembly. Major components of the pressure control assembly include a pressure control panel, a vent and relief valve assembly, and overboard venting to control the oxygen and nitrogen partial pressures and cabin over- or under-pressurization. Oxygen and nitrogen are supplied by the oxygen and nitrogen storage hardware and distribution system. Manual pressure equalization valves equalize pressure between two adjacent modules. The high efficiency particulate air (HEPA) filter removes particulates and microorganisms. A four-bed molecular sieve (4BMS) carbon dioxide removal assembly (CDRA) removes carbon dioxide from the cabin atmosphere, venting it to space. Humidity is removed from the cabin atmosphere using the condensing heat exchanger/water separator in the common cabin air assembly (CCAA). Higher molecular weight airborne compounds are removed by the trace contaminant control subsystem (TCCS) using activated carbon. The TCCS includes a high temperature catalytic oxidizer that converts low molecular weight compounds to water vapor and carbon dioxide. The catalytic oxidizer requires replacement once a year. Major gaseous contaminants are continuously monitored in the major constituent analyzer (MCA). Samples drawn for MCA are delivered through the sample distribution subsystem throughout the ISS. The FDS subsystem detects, isolates, and extinguishes fires. FDS is located in each powered equipment rack.

Food Subsystem

The Food Subsystem during initial construction utilizes a joint Russian and US system. Russian Progress vehicles deliver most of the US food including fresh fruits and vegetables to the station. Most of the food for ISS will be thermo-stabilized and require no hydration before serving. However, many beverages are supplied dehydrated. US food shipped to ISS will be packaged in Russian food lockers. One locker contains provisions for 18 meals, and has an empty mass of 0.9 kg. Since US foods are not compatible with the Russian food heater, a US food warmer provides heating capability.

Thermal Subsystem

Within the Thermal Subsystem, intermodular ventilation circulates the cabin atmosphere between modules, ensuring good distribution of oxygen, maintaining atmospheric temperature and relative humidity within comfort bounds, and dissipating localized concentration of carbon dioxide and airborne contaminants. Thermal loads collected via CCAA, avionic air assembly (AAA), and individual coldplates transfer the excess thermal load to the ITCS fluid loops. Two types of loops comprise the ITCS, a low temperature loop (LTL) and a moderate temperature loop (MTL). ISS circulates water in all ITCS loops within the crew cabin. In Phase 2, the ITCS loop transfers its heat to an early external active thermal control subsystem (EEATCS) loop, via a common heat exchanger. The EEATCS working fluid is single-phase anhydrous ammonia. The EEATCS enables early research during the initial station assembly by providing thermal conditioning to the US Laboratory. ISS dissipates heat via stationary deployable radiators.

Waste Subsystem

The Waste Subsystem involves bagging non-human solid and wet waste in the USOS and placing it on Progress to burn up during re-entry of Progress to Earth. Shuttle also provides a means of disposing waste to Earth.

Water Subsystem

The Phase 2 Water Subsystem consists of manually transferring humidity condensate, which is collected in a condensate storage tank, to the WRS-CM in the RS for purification. The water vent system removes excess condensate that is not transferred to the RS by overboard venting.

Extravehicular Activity Support Interface

The EVA Support Interface includes the A/L air save pump, shown schematically in Figure 2.3, that reduces the pressure in the entire A/L from 101.3 kPa (14.7 psia) to 70.3 kPa (10.2 psia) for EVA campout. During EVA check out, the air save pump reduces the A/L pressure to 3.4 kPa (0.5 psia). The U.S. extravehicular mobility unit (EMU) receives oxygen for metabolic respiration, water for cooling and drink, and food, directly from the LSS. Current EMU designs reject thermal loads to the environment using sublimation of water, which is denoted by a loss of water from the EMU as spent water. All solid and liquid human wastes that return with the crewmember following EVA are designated as EMU solid waste. Additionally, EVA Support removes carbon dioxide from the A/L atmosphere during the campout that precedes an EVA using the metal oxide (Metox) system. The EMU uses either lithium hydroxide (LiOH) or Metox canisters for carbon dioxide removal. The Metox canisters from both the EMU and the A/L are regenerated by baking the carbon dioxide out of the canisters to the cabin atmosphere where it is removed permanently by the CDRA.

Human Accommodations Interface

Clothing on ISS is only supplied clean from the ground. Before leaving Earth, each crewmember selects a set of clothes from an approved list, and those clothes are packaged and shipped to the ISS (Rogers, 1999). Dirty clothes are returned and laundered or otherwise processed on the ground.

ISS crewmembers bathe using procedures similar to sponge bathing. Ivory soap and no rinse body bath solution provide the cleansing agents while moistened towelettes allow application of water. The towelettes, or wipes, are not recycled. Wash clothes are also provided, but these return to Earth after use with the dirty clothes. (See Rogers, 1999)

2.1.1.4 United States On-Orbit Segment Hardware - Phase 3

The overall power consumption and thermal loads of the assembly complete configuration of the USOS are described in Table 2.2 [2]. The Habitation Module, Node 2, Node 3, Japanese Experiment Module, European Space Agency Laboratory, and Centrifuge Accommodations Module are added to complete Phase 3.

Table 2.2 Power and Thermal Loads for International Space Station Mission - Phase 3

U. S. On-Orbit Segment International Space Station Assembly Complete	Power [kW_e]	Cooling Load [kW]
Total Electrical Power to Users (average at end-of-life)	75	75
Additional Thermal Load from Power Generation		7
Total	**75**	**82**

Air Subsystem

The Air Subsystem revitalizes the crew cabin atmosphere. The oxygen generation assembly (OGA) produces oxygen by electrolysis from high purity water, as shown in Figure 2.4. The OGA, which is an addition to the Phase 2 configuration, uses solid polymer electrolysis, venting the hydrogen by-product to space.

Food Subsystem

ISS food, using the ISS assembly complete menu, is supplied every 90 days via a multipurpose pressurized logistics module brought by Shuttle. Because solar photovoltaic panels provide electrical power, the power system will not provide any water [3]. Food planned for the USOS will be refrigerated in a refrigerator freezer rack (RFR) or thermo-stabilized. Food will be heated to serving temperature in a conduction oven, and moistened towelettes, or wipes, are provided for galley cleaning operations.

Thermal Subsystem

The Thermal Subsystem collects heat from system and user payloads within the USOS modules via the ITCS and transfers the heat to the external active thermal control subsystem (EATCS). The activation of the EATCS on Flight 12A.1 deactivates the EEATCS. Heat exchangers transfer heat from the ITCS to the single-phase ammonia loops of the EATCS. Flex hose rotary couplers (FLHC) position radiators to optimize heat rejection to space.

Waste Subsystem

Human solid waste collection is provided by a removable and reusable canister in the commode that collects the waste for return or disposal to Earth. Here this storage also collects brine from urine processing and EVA solid waste. Other solid wastes are compacted, stored, and returned or disposed of to Earth. Urine is stabilized with oxone and sulfuric acid before passing to the urine processor.

Water Subsystem

The urine processor utilizes vapor compression distillation (VCD) as its main separation process, recovering nominally 95% of the water from pretreated urine. Any undissolved gases and vapors in the VCD product water are removed in the gas/liquid (G/L) separator. Grey water, including water from urine processing and cabin humidity condensate, is collected in the wastewater (WW) tank. From this feed, the

2 These values assume the U. S. On-Orbit Segment of the International Space Station at assembly complete and are accurate for that configuration with all anticipated equipment. However, these values may be inappropriate for some alternate life support system designs.

3 On board the Shuttle Orbiter, power is generated by hydrogen/oxygen fuel cells, producing potable water as a reaction product.

water processor produces water of potable quality for crew drinks, hygiene use, OGA feed water, EVA water use, and food preparation.

Grey water drawn from the WW tank is first processed through the mostly liquid separator (MLS) and a particulate filter to remove undissolved gases, vapors, and small particles. The product stream then passes to a two-stage multifiltration (MF) unit to further remove particles and solutes. The stream is heated before entering the volatile removal assembly (VRA). The VRA catalytically oxidizes low molecular weight organic compounds in the wastewater stream. The final water-processing stage includes an ion exchange (IX) bed and a microbial check valve (MCV) to ensure high water quality. Following the IX bed, the MCV adds iodine as a biocide. Conductivity sensors, represented by the diamond in Figure 2.4, determine acceptability of the outlet water stream from the water processor. If processed water does not meet quality requirements, it is rerouted for reprocessing.

Extravehicular Activity Support Interface

EVA following assembly complete of ISS is assumed to average two 2-crew-member excursions per month. While EVA will be necessary for maintenance, the majority of ISS tasks will be conducted inside the vehicle. Phase 3 operations are functionally identical to Phase 2 operations.

2.1.1.5 Russian Segment and United States On-Orbit Segment Integrated Operations

Interfaces between the RS and USOS include water and atmosphere transfer. Portable water tanks transfer water manually among ISS segments. Humidity condensate in the atmosphere moves through open hatches in the ISS causing an exchange in water. The integrated FDS signals alarms in both the RS and USOS modules if a fire is detected.

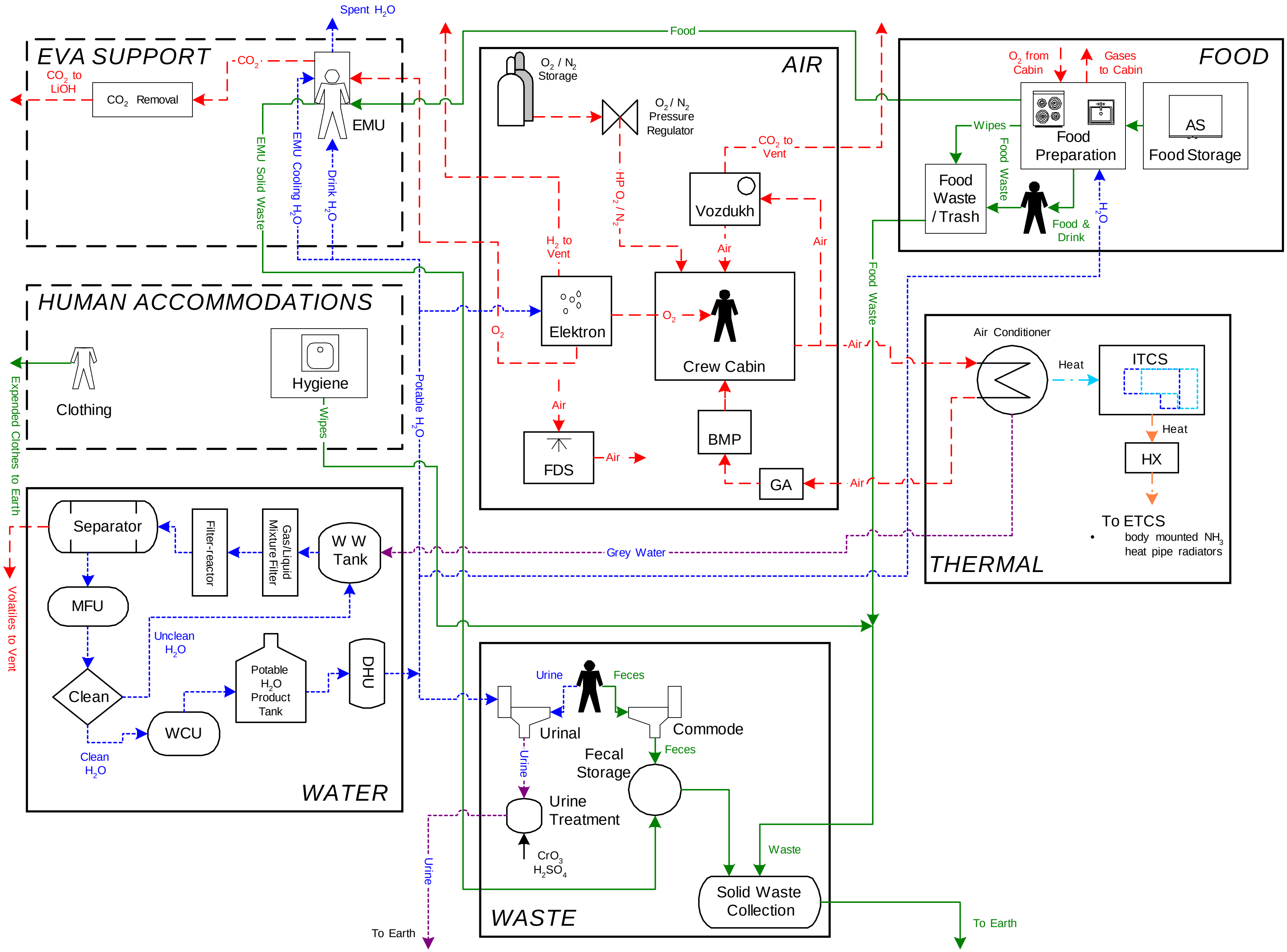

Figure 2.1 Life Support Design for **Phase 2** of the **Russian Segment** of the **International Space Station Mission** Using **ISS Baseline Technologies**.

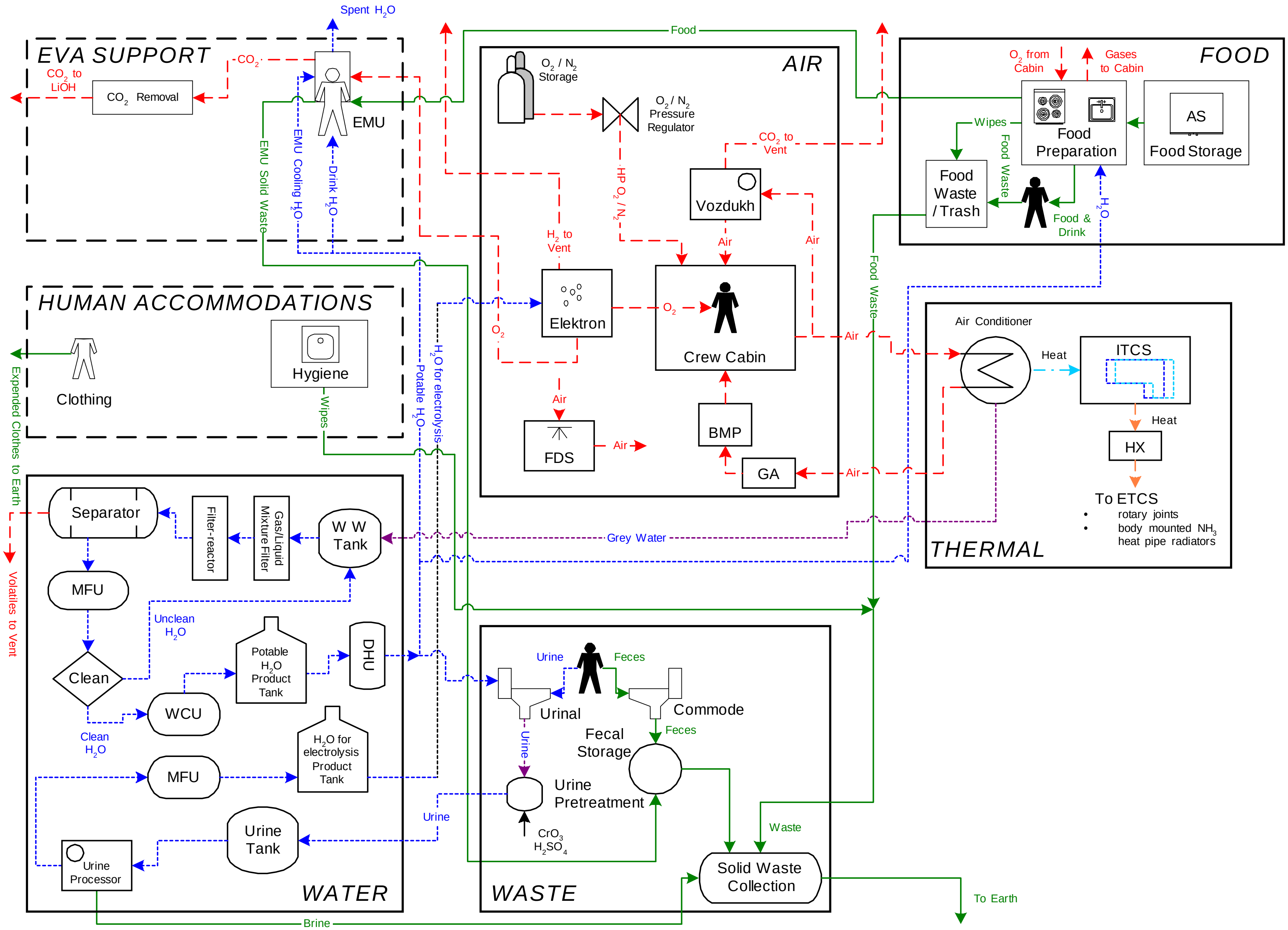

Figure 2.2 Life Support Design for **Phase 3** of the **Russian Segment** of the **International Space Station Mission** Using **ISS Baseline Technologies**.

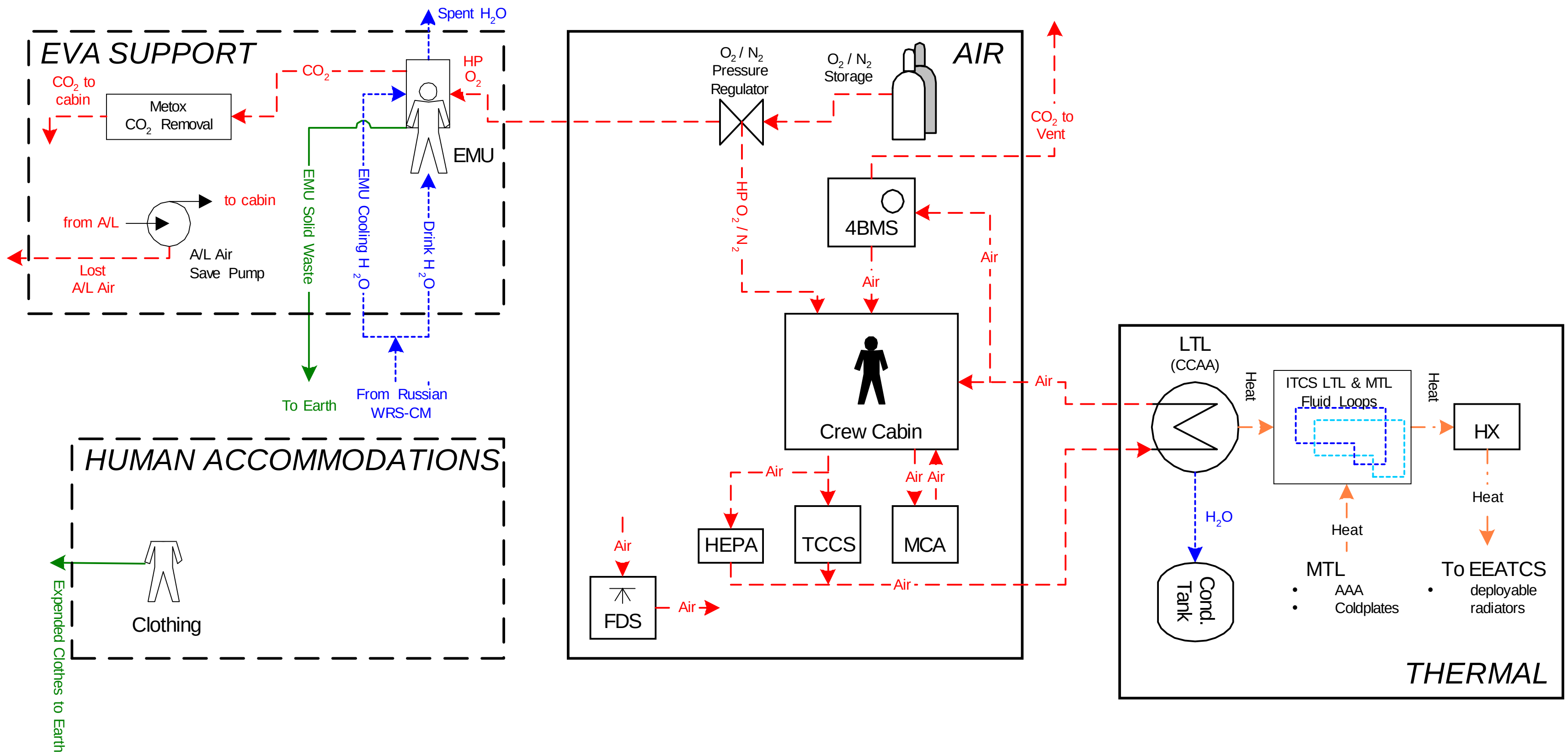

Figure 2.3 Life Support Design for **Phase 2** of the **US Segment** of the **International Space Station Mission** Using **ISS Baseline Technologies.**

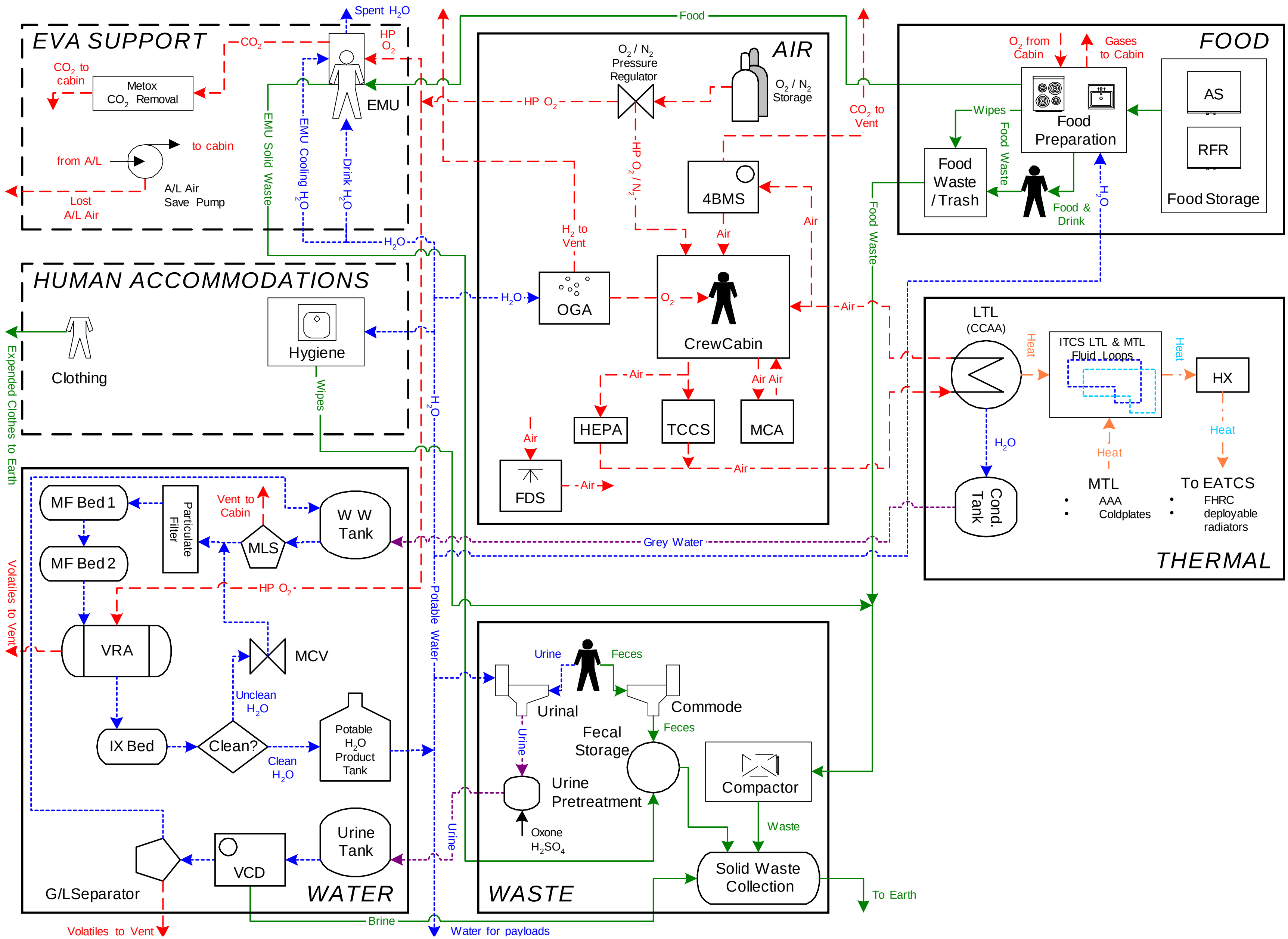

Figure 2.4 Life Support Design for **Phase 3** of the **US Segment** of the **International Space Station Mission** Using **ISS Baseline Technologies**.

2.1.2 Advanced Life Support Straw Man Architectures for International Space Station

Though ISS technology is mature and provides a set of baseline technologies for all missions presented here, some technology options to reduce ISS life support operating costs are potentially available. Additionally, if certain ALS technologies are ready in time, they might be applied to ISS post Phase 2 and post Phase 3 in order to reduce cost or provide another program benefit. It is desirable to pursue technology advances beyond the baseline ECLSS for the ISS upgrade, not only for the benefit of the ISS, but also as an on-orbit ALS test bed for future long-duration human space missions. Without completely revising the ISS ECLSS architecture, possible regenerative LSS upgrades for ISS include a carbon dioxide reduction system (CRS), an advanced water processor, and an improved TCCS. These options could benefit ISS by decreasing annual resupply and power requirements compared with the baseline ECLSS technologies.

It is possible that ISS might replace the currently planned ECLSS suite housed in Node 3 with an ALS suite. The new equipment should fit into existing configurations. Either Phase 2 or Phase 3 might be used as the starting point for life support upgrades depending on the future of the program.

2.1.2.1 ALS Straw Man Architecture - Post Phase 2

To allow the greatest flexibility for ALS analysis, Phase 2 is identified as the starting point to develop an ALS Straw Man Architecture for ISS upgrade. ALS technologies might be applied to ISS in a 2010 planning date. The non-life support additions to ISS assumed here are the same as those in the baseline, including 75 kW of power, Habitation Module, Node 2, Node 3, Japanese Experiment Module, European Space Agency Laboratory, Centrifuge Accommodation Module, and a six person crew.

Air Subsystem

Potential Air Subsystem upgrades of the TCCS include regenerable beds, improved catalytic oxidizers, and better adsorption materials to decrease power consumption and catalyst poisoning. A technology that easily integrates into the existing TCCS location is required. A potential upgrade includes the development of a catalyst capable of converting trace contaminants to carbon dioxide, water vapor, or other controlled species without requiring expendable charcoal beds.

The baseline USOS does not include carbon dioxide reduction. The current Air Subsystem vents the excess carbon dioxide overboard. The addition of a Sabatier reactor, as shown in Figure 2.5, would recover water from carbon dioxide generated from human metabolic output for production of oxygen from electrolysis or for other water requirements. This would enhance the current Air Subsystem and reduce the amount of water resupply. The subassembly would integrate with the baseline CDRA and the OGA. Added mass, volume, and power consumption to the ISS are penalties of the Sabatier, however this is less expensive than resupply.

Food Subsystem

The ALS Straw Man architecture proposes the continued use of ambient stored food and the development of additional thermo-stabilized food items to improve variety and nutrition.

Water Subsystem

The addition of a vapor phase catalytic ammonia removal (VPCAR) process could enhance the Water Subsystem on the ISS. The VPCAR would replace the current planned VCD urine processor and the water processor assembly. A WW tank collects grey water from urine, hygiene use, and humidity condensate. The VPCAR oxidizes impurities from the wastewater into gaseous products, which vaporize with the process water. The VPCAR produces a clean condensate and concentrated brine. An air evaporation subsystem (AES) would process the recovered brine producing a condensate and leaving the nonvolatile impurities in a replaceable wick. The reclaimed water from the AES returns to the WW tank for further processing. An IX bed, a PCWQM and a MCV provide final polishing and water quality monitoring to the water reclaimed from the VPCAR.

Other Subsystems and Interfaces

No upgrades are proposed in this Straw Man architecture for the Thermal Subsystem, the Waste Subsystem, or the Human Accommodations Interfaces. They remain functionally identical to the current assembly complete USOS configuration in Figure 2.4. However, ALS researchers are encouraged to consider other LSS configurations that improve upon the ISS baseline.

2.1.2.2 ALS Straw Man Architecture - Post Phase 3

Phase 3 also provides a reasonable starting point to develop an ALS straw man architecture for ISS upgrade. This configuration assumes a 2025 planning date. It also assumes that the baseline ISS technologies as defined in Section 2.1.1.4 are installed and the crew size increased to six. An additional Laboratory module and 50 kW of power beyond Phase 3 are assumed.

Air Subsystem

The ALS Air Subsystem concentrates carbon dioxide using a liquid amine carbon dioxide removal technology. The removed carbon dioxide passes to a Sabatier, which produces water for electrolysis using the OGA technology. Other Air Subsystem functions are identical to the ISS assembly complete configuration shown in Figure 2.4.

Food Subsystem

An ALS upgrade to the Food Subsystem of the ISS includes bulk packaging to reduce the overall subsystem mass. However, multiple serving entrees may require more crew time for meal preparation than individual serving entrees. Food storage utilizes both ambient storage and a vapor compression refrigerator freezer rack (VCRFR).

Thermal Subsystem

Within the ALS Thermal Subsystem, lightweight heat pipe radiators replace ISS baseline deployable radiators. A solar heat pump, which is a vapor compression heat pump, allows an increase in the rejection of thermal loads.

Water Subsystem

The ALS Water Subsystem utilizes biological water processors as presented in Figure 2.6. An aerobic/anaerobic bioreactor degrades organic compounds while a second unit, a nitrifying bioreactor, oxidizes ammonia to nitrite (NO_2^-) and then to nitrate (NO_3^-). Following the G/L separator, a portion of the liquid stream recycles to the bioreactor feed to provide nitrate and nitrite to the first bioreactor. Reverse osmosis (RO), a membrane technology, removes inorganic compounds from the process stream. The RO brine passes to an AES. Final finishing steps include an IX bed and an ultraviolet photo-oxidation (PhOx) unit to degrade residual organic compounds. PCWQM and MCV provide water quality monitoring and control.

Waste Subsystem

The ALS Waste Subsystem carries urine and flush water directly to the Water Subsystem without pretreatment. Fecal waste and food waste from the Food Subsystem are dried in a waste dryer to recover bound water before passing to the trash compactor and solid waste storage. Drying reduces the overall volume of the waste and the moisture content, inhibiting biological activity in the fecal material during storage.

Human Accommodations Interface

To reduce the mass of clothing, the ALS Human Accommodations Interface recycles clothing using a laundering system. Grey water loads for the Water Subsystem increase with the activation of a laundry. However, a laundry is more economical if longer missions are desired (Jeng and Ewert, 2001).

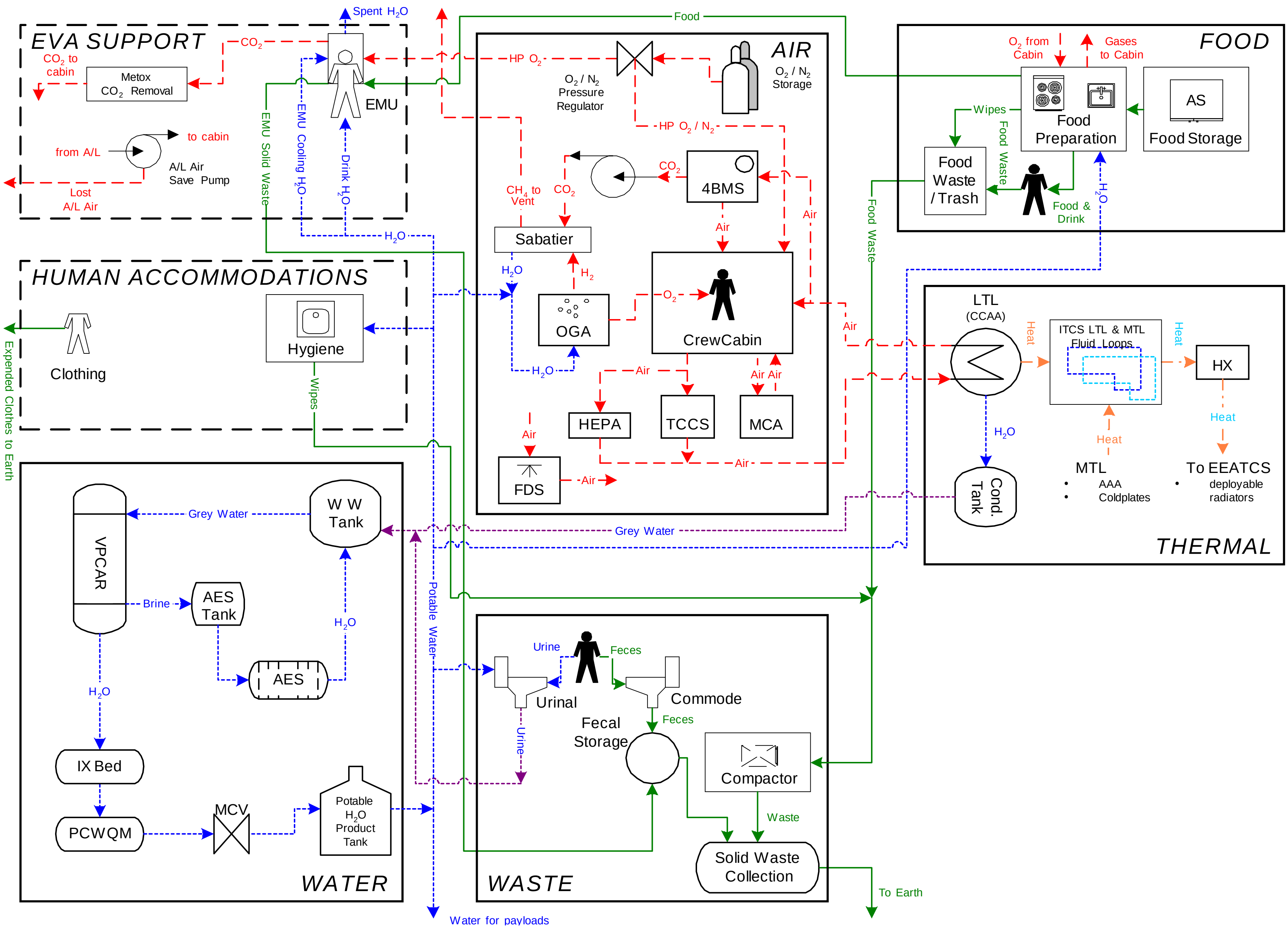

Figure 2.5 Life Support Concept for **Post Phase 2** of the **United States On-orbit Segment** of the **International Space Station** Using **ALS Technologies**.

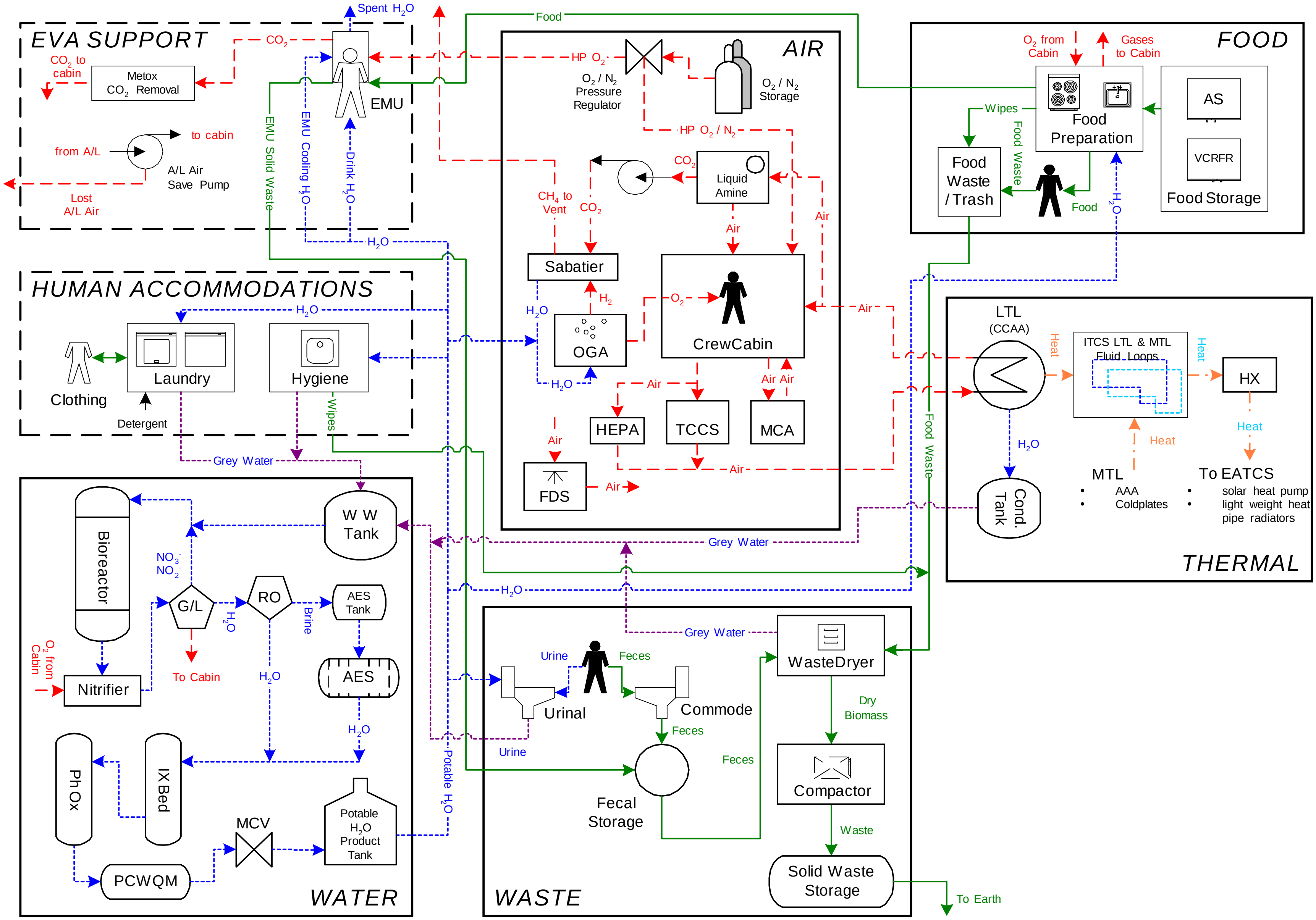

Figure 2.6 Life Support Concept for **Post Phase 3** of the **United States On-orbit Segment** of the **International Space Station** Using **ALS Technologies**.

3 Mars Surface Missions

Human missions to the surface of Mars may vary widely in their protocols and constraints depending on the primary mission objectives. In some situations, careful preservation of the Martian surface may be vital to mission success, while in other cases the rules of exploration may be more lenient. Such protocols affect how the life support system provides commodities to the crew. Such protocols are unique to each mission and will likely not be specified until an actual flight program is formulated.

Generally, however, from the perspective of life support, the Martian surface environment differs significantly from other locales. Thermally, the Martian surface is again fairly benign and rejection of heat loads from the crew cabin should not be problematic (Ewert, *et al.*, 1999). Dust storms may provide a unique challenge, but at present they are not expected to invalidate traditional radiant heat rejection approaches. The radiation environment is currently unknown. It is likely more severe than on Earth, but the crew may not be as vulnerable on the Martian surface as in interplanetary space (Mendell, *et al.*, 1999). Mars also provides a gravitational field that is roughly three eighths as strong as that of Earth. While some physical and chemical processes exhibit significant differences under such low gravity, other processes are relatively unaffected. Finally, the Martian surface may offer resources in its atmosphere and regolith that are completely unavailable in interplanetary space depending on the landing site and mission protocols.

3.1 Independent Exploration Mission: Mars Dual Lander Architecture

The Mars Dual Lander mission architecture employs three vehicles: a Mars Transit Vehicle, a Surface Habitat Lander, and a Mars Descent/Ascent Lander (Drake, 1999). This approach proposes employing a common descent stage for both the Surface Habitat Lander and the Mars Descent/Ascent Lander. Therefore, the Surface Habitat Lander and the Mars Descent/Ascent Lander are referred to as the Dual Landers. A single Mars Transit Vehicle is used for the outbound and return trips. The Surface Habitat Lander, which contains an inflatable structure to provide an expanded habitable volume once on the Martian surface, provides the crew's habitat quarters. The Surface Habitat Lander is piloted robotically during the trip from Earth to the Martian surface. A second lander, the Mars Descent/Ascent vehicle, transports the six crewmembers from Martian orbit to the surface at the beginning of the surface mission phase, and returns the crew to the orbiting Mars Transit Vehicle at the conclusion of the surface phase. Since surface site selection is independent of any previous or following missions, multiple trips to Mars will allow explorers to visit any site, targeting exploration opportunities to satisfy demands for scientific information. This overall mission design also permits multiple visits to the same site where redundancy or common use of previous vehicles in whole or in part can reduce the overall cost of multiple missions.

The Mars Transit Vehicle launches initially into low Earth orbit. After outfitting, the Mars Transit Vehicle boosts to high Earth orbit to await transfer of the crew. Similarly, the Surface Habitat and Mars Descent/Ascent Landers initially launch into low Earth orbit before boosting to a high Earth orbit. In both cases, the Mars Transit Vehicle and the Dual Landers use energy efficient electrical propulsion and lengthy transfer orbits to reach high Earth orbit. All three vehicles are serviced for the voyage to Mars and the crew is delivered to the Mars Transit Vehicle by a taxi flight just before departure. The voyage to Mars will nominally take 180 days for the crew. The Dual Landers, because they transfer to Mars under robotic control, follow a somewhat slower yet more energy efficient transfer orbit than the Mars Transfer Vehicle, so they depart from Earth ahead of the crew so as to arrive at Mars just before the crew. The Mars Transit Vehicle and the Dual Landers all enter into a low Mars orbit through aerocapture and then rendezvous.

Once they arrive in low Martian orbit, the crew transfers to the Mars Descent/Ascent Vehicle and descends to the Martian surface. At this time, the Surface Habitat Lander is already in place on the Martian surface. The Surface Habitat Lander deploys automatically, checks and verifies its functionality, and adopts a protected mode prior to crew arrival. Upon arrival, the crew has 30 days for acclimation and an in-depth habitat checkout. The crew need not commit to landing until the Surface Habitat Lander is operational. During the surface mission, nominally 600 days, the Mars Transit Vehicle awaits in stand-by mode untended in low Mars orbit, while the Mars Descent/Ascent Lander waits in stand-by mode on the Martian surface. After a second rendezvous in Mars orbit following the surface mission, the crew transfers to the Mars Transit Vehicle and returns to Earth. The return interplanetary voyage nominally requires 180 days.

The average overall power generation requirements are presented in Table 3.1. [4] Either solar or nuclear power generation might supply these loads. Additional thermal loads for power generation are currently unknown, so the corresponding cooling loads are assumed to equal the listed power generation.

Table 3.1 Power Generation for the Mars Dual Lander Mission

Mars Transit Vehicle	**Power [kW_e]**
While the Crew is Awake ("Day")	15
While the Crew is Asleep ("Night")	12
Mars Descent/Ascent Lander	**Power [kW_e]**
Available Power during Landing	4.0
During Daylight	8.5
During Night	5.5
Surface Habitat Lander	**Power [kW_e]**
During Daylight with Clear Weather	18
During Daylight with a Dust Storm (contingency)	7.4
During Night	9

3.1.1 Applying International Space Station Life Support Hardware

Excluding differences in overall mission duration and EVA frequency, the Mars Dual Lander LSS hardware using ISS ECLSS baseline technologies is similar to that presented in Section 2.1.1. However, each vehicle requires a complete life support equipment suite in addition to appropriate supplies.

3.1.1.1 Mars Transit Vehicle

The Mars Transit Vehicle transports the crew to and from Mars so it carries a full set of life support hardware. Each voyage between Earth and Mars nominally requires 180 days. EVA is not anticipated, except as a contingency, so no EVA allowance is provided for nominal operations on the Mars Transit Vehicle. This vehicle uses an aluminum exterior shell derived from ISS technology augmented with full radiation protection for interplanetary travel.

Figure 3.1 shows the architecture for the Mars Transit Vehicle using ISS baseline technologies. Except for the absence of EVA Support, the life support system for the Mars Transport Vehicle is functionally similar to the International Space Station Mission life support system illustrated in Figure 2.4. However, human vehicles operating beyond low Earth orbit require radiation protection. Here, conformal water tanks with internal bladders wrapped around a portion of the crew cabin fulfill this role.

3.1.1.2 Surface Habitat Lander

The Surface Habitat Lander will journey to Mars without a crew. After arriving in Martian orbit, the Surface Habitat Lander will perform de-orbit, entry, descent, and land on Mars at a pre-determined location autonomously. Once on Mars, the Surface Habitat Lander will deploy the deflated habitat, set up the power system, perform initial habitat outfitting, system checkout, and place the vehicle in stand-by mode. Thus, the Surface Habitat Lander will be operational when the crew arrives in the Mars Descent/Ascent Lander. The fully inflated and operational Surface Habitat Lander boasts a full LSS hardware suite and provides a crew habitat for the 600-day surface mission. During surface operations, the crew is expected to perform extensive EVA operations, totaling 700 half-day employing two crewmembers for each sortie.

4 These values are based on Drake (1999) and Drake (2001a) and are accurate for those vehicle configurations with all anticipated equipment. However, these values may be inappropriate for some alternate life support system designs.

Figure 3.2 shows the architecture for the Mars Dual Lander Surface Habitat Lander using ISS baseline technologies. The LSS for the Surface Habitat Lander using ISS baseline technologies is similar to the corresponding configuration for the Mars Transit Vehicle presented in Figure 3.1.

However, unlike the transit phase, operations on the Martian surface, driven by scientific objectives, require a robust EVA capability. Thus, assuming ISS baseline technologies, the life support architecture for the Surface Habitat Lander provides EVA Support facilities with functionality similar to those associated with the International Space Station Mission, Figure 2.4. The crew performs 700 half-day EVA sorties from the Surface Habitat Lander using two crewmembers each during the surface mission. Drysdale and Hanford (2001) provides details for this EVA format, including usage rates for consumables and physical parameters for the A/L. Supporting operations on the Martian surface will place a greater load on the life support system than corresponding systems sized to support space walks for ISS.

Conformal water tanks with internal bladders provide augmentation for a portion of the crew cabin against radiation. However, it is likely Mars itself will provide some yet to be determined protection versus radiation, thus reducing the mass of radiation protection on the vehicle itself.

3.1.1.3 Mars Descent/Ascent Lander

The Mars Descent/Ascent Lander is a smaller vehicle designed to support a crew for a short time. It also journeys to Martian orbit without a crew. It launches from the Earth's surface into low Earth orbit. After outfitting, it boosts to high Earth orbit and transfers to Mars on near-minimum energy trajectory. At Mars, it aerocaptures into orbit. After the Mars Transit Vehicle reaches Martian orbit, the Mars Descent/Ascent Lander and the Mars Transit Vehicle rendezvous. The crew transfers from the Mars Transit Vehicle to the Mars Descent/Ascent Vehicle, de-orbits, and lands near the Surface Habitat Lander. To ensure crew safety while in orbit and initially on the Martian surface, the Mars Descent/Ascent Lander is designed to support the crew in all aspects for up to 30 days to permit sufficient time for surface acclimation and during any Surface Habitat Lander checkout activities. As such, technologies from the envisioned Shuttle Extended Duration Orbiter LSS technology suite [5] are recommended to outfit the Mars Descent/Ascent Lander.

For the Mars Descent/Ascent Lander LSS, water for potable and hygiene use is produced as the byproduct of on-board fuel-cell operation. Since no water recovery is planned, and current demand for power generation is unlikely to produce adequate water to support the Mars Descent/Ascent Lander for 30 days, additional water is supplied from stored water stocks. Assuming wastewater dumping is not allowed, all wastewater will be stored within the descent stage tankage. Stored gases, either bottled or cryogenic, provide atmospheric gases. A solid amine vacuum desorbed (SAVD) carbon dioxide removal system and a TCCS remove atmospheric contaminants. Under nominal operations, the mission architecture requires one A/L cycle on the surface of Mars for the Mars Descent/Ascent Lander. More specifically, assuming the crew depresses the entire cabin before transferring to the Surface Habitat Lander, the entire crew may leave at once. When the crew returns to the Mars Descent/Ascent Lander just prior to departure, sufficient stored gases allow pressurization of the crew cabin. [6] Human accommodations employ moistened towelettes for bathing. The Food Subsystem also employs moistened wipes for cleaning operations. Due to its mass, a compactor does not appear justified for this short mission. Conformal water tanks with internal bladders protect a portion of the crew cabin against radiation, effectively providing a "storm shelter." Other life support systems are similar to configurations on other vehicles using ISS baseline technologies. Figure 3.3 shows the LSS of the Mars Descent/Ascent Lander using current technologies. Due to a relatively short duration for crew occupancy, no ALS Straw Man concept is proposed for this vehicle at this time.

5 The Extended Duration Orbiter, as currently envisioned, would allow Shuttle to operate in low Earth orbit for up to 30 days. For this to become reality, the current Orbiter ECLSS will require some upgrading to allow such extended missions.

6 This assumes the crew cabin is not pressurized during the crew's entire surface stay.

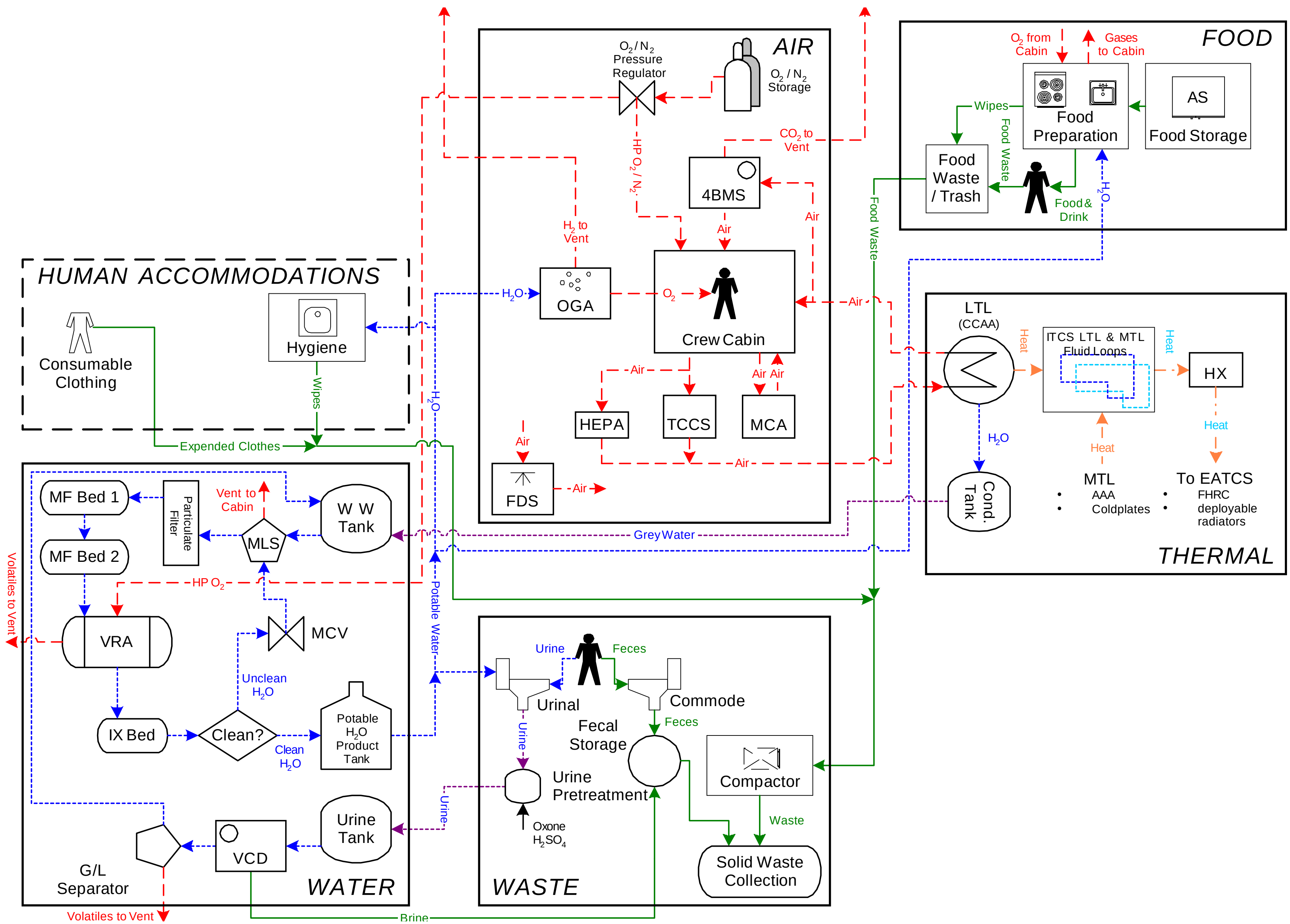

Figure 3.1 Life Support Design for the **Mars Transit Vehicle** in the Mars Dual Lander Architecture Using **ISS Baseline Technologies**.

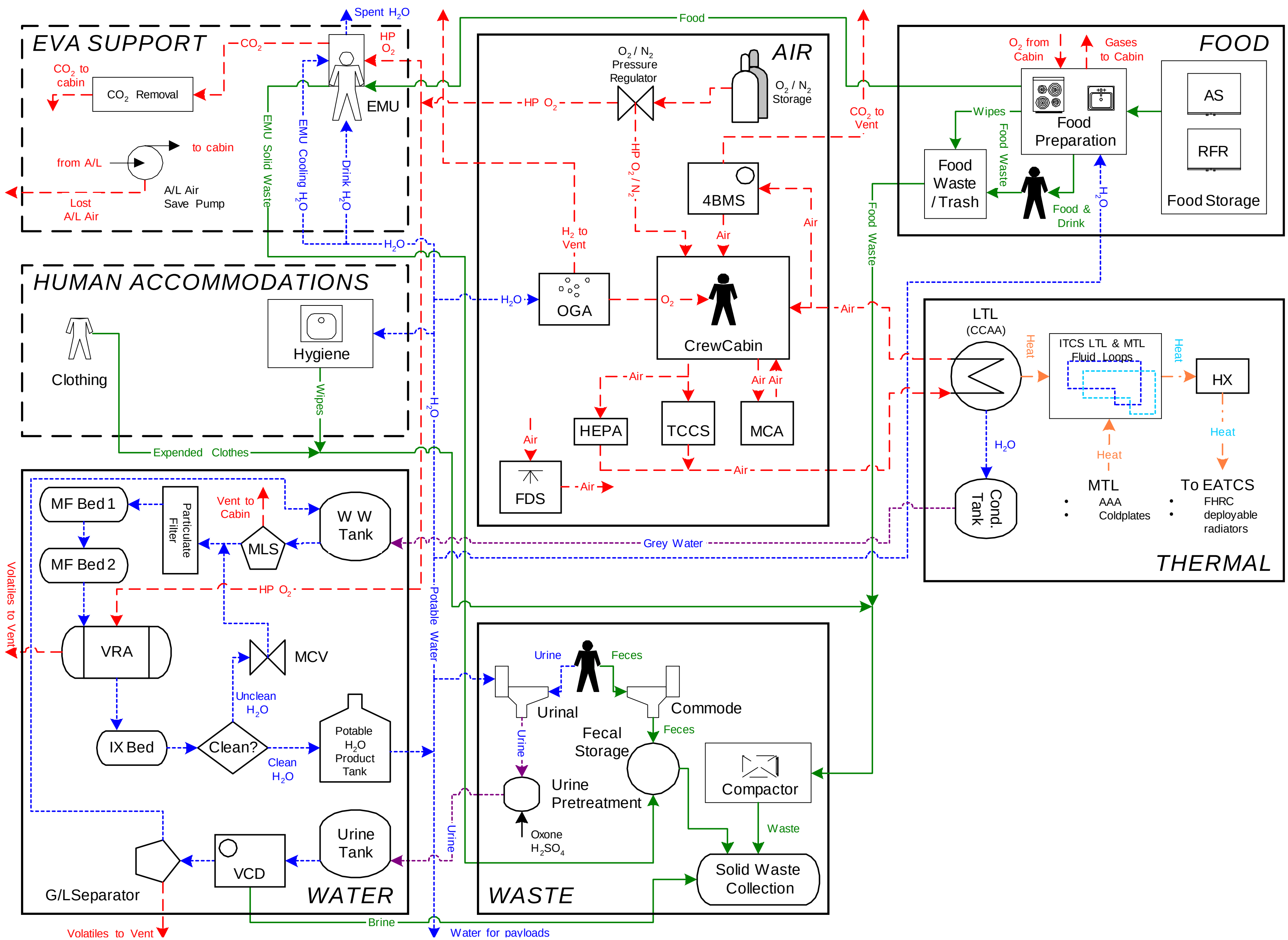

Figure 3.2 Life Support Design for the **Surface Habitat Lander** in the Mars Dual Lander Architecture Using **ISS Baseline Technologies**.

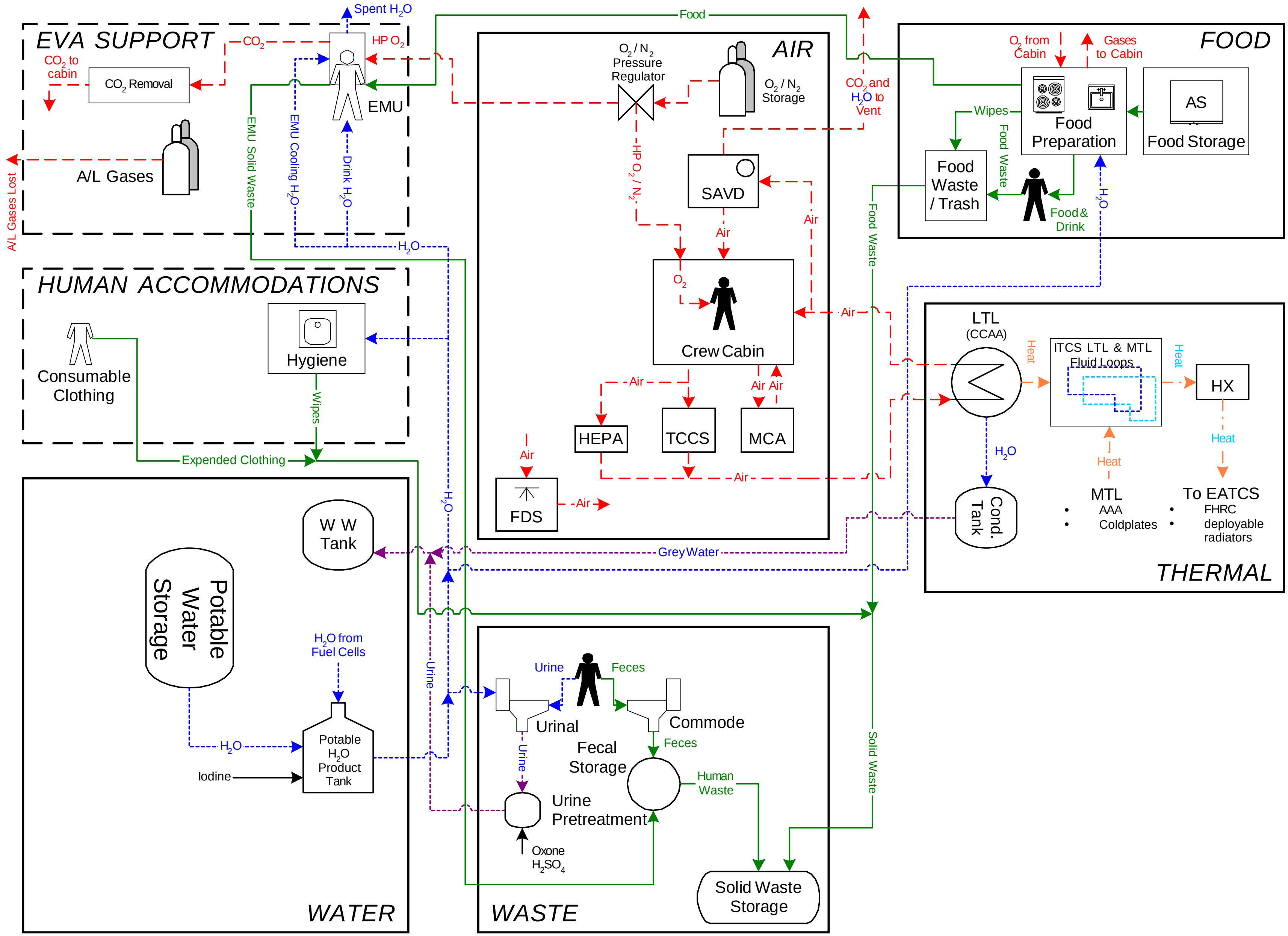

Figure 3.3 Life Support Design for the **Mars Descent/Ascent Lander** in the Mars Dual Lander Architecture Using **ISS Technologies** (without ISRU)

3.1.2 Advanced Life Support Straw Man Architecture

The proposed ALS Straw Man architecture concept for this independent exploration mission is a mix of Space Transportation System, or Shuttle, ISS, and ALS technologies. The ALS Straw Man architecture concept presented here provides an example of one approach to provide life support aboard the vehicles for this mission. This allows each subsystem to identify realistic interfaces and provides mission planners with essential details. However, this straw man concept is not definitive and will likely change and evolve as research, development, and analysis continues.

3.1.2.1 Mars Transit Vehicle

The Mars Transit Vehicle is a pure spacecraft. As such, the technologies employed must be insensitive to changes in local acceleration, including an absence of gravity. In general, the technologies presented here as part of the Exploration Mission ALS Straw Man concept do not have any known theoretical limitations that prohibit their use in microgravity. However, different development may be required for this case compared to the surface case. Also, radiation protection for the Mars Transit Vehicle must rely solely on commodities brought from Earth, such as water, or those generated from supplied commodities, such as waste products. Figure 3.4 illustrates the corresponding architecture for the Mars Transit Vehicle using ALS technologies.

Air Subsystem

The ALS Air Subsystem is functionally similar to the configuration in Figure 3.1 using ISS technologies. Assuming fairly high water recovery within the Water Subsystem, the Mars Transit Vehicle is “water rich” due to the derivation of water, both bound and metabolically produced, from stored food. Thus, there is little need to recover oxygen from carbon dioxide so a carbon dioxide reduction system is unnecessary. To collect excess cabin carbon dioxide, it employs a SAVD with a moisture recuperator. The Biomass Subsystem also provides partial carbon dioxide removal from the crew cabin. Solid polymer water electrolysis, an OGA, provides oxygen from water and vents the hydrogen to space. The TCCS employs catalytic oxidation. The remaining equipment is similar to the configuration using ISS technology.

Biomass Subsystem

ALS technologies add a Biomass Subsystem that has no counterpart in the ISS technology suite. Primarily, the Biomass Subsystem here includes a small salad machine with a nutrient solution system, cooling, and lighting. This is sufficient to regularly supply the Food Subsystem with fresh produce requiring minimal post-harvest processing. Typical plants might include salad crops, white potatoes, and/or sweet potatoes. This salad machine provides some air revitalization, although alone it is insufficient to handle the crew’s entire atmospheric load due to metabolic activities. This system will not process any grey water. Because mineral nutrients and chemicals for controlling acidity are not recovered in this configuration, they are supplied.

Food Subsystem

The ALS Food Subsystem here provides a diet similar to the ISS assembly complete menu assumed above. However, to reduce the overall subsystem mass, bulk packaging is employed whenever possible. This approach may require additional crew time for meal preparation than with individual serving entrees. Additionally, the ALS Food Subsystem receives some fresh food from the Biomass Subsystem. Though the foodstuffs provided by the Biomass Subsystem provide only a fraction of the crew’s overall nutrition, they significantly enhance the crew’s psychological perception of the diet. Galley cleaning operations employ water, as needed, producing a grey water waste stream.

Thermal Subsystem

The ALS Thermal Subsystem employs several refinements over the ISS baseline technologies. An anti-microbial condensing heat exchanger (Cond. HX) replaces the CCAA to control atmospheric temperature and humidity. Where ISS employs separate structural components and coldplates, ALS technology employs a coldplate shelf fabricated from composite materials fulfilling both the structural and thermal functions using significantly less mass. Finally, ALS technology replaces the metallic flow-through radiators from the ISS baseline technology with lightweight, body-fitted radiators fabricated from composite materials.

Waste Subsystem

The Waste Subsystem within the ALS configuration for the Mars Transit Vehicle employs the ISS baseline technologies sized to account for differences in waste production between the two technology suites. Comparing Figure 3.4 with Figure 3.1, the Waste Subsystem is relieved of storing VCD brine but now accepts inedible biomass from the Biomass Subsystem. Storage tanks containing liquids are bladderless. An oxidation process, such as incineration or composting, is not employed here. The reclamation of products from waste is neither necessary nor economically viable because the plant biomass is insufficient to support the crew itself. Thus, any oxidation of waste products would require additional oxygen or additional air revitalization capacity within the Air Subsystem (See Wheeler, 1996, and Gertner, 1999a).

Water Subsystem

The ALS Water Subsystem relies on the single-pass, yet energy intensive VPCAR technology. VPCAR removes most contaminants from the water stream, producing a clean condensate and concentrated brine. The brine passes to the AES, which recovers almost all of the water, leaving the brine's impurities in a replaceable wick. Because downstream processors provide incomplete polishing, reclaimed water from the AES returns to the WW tank. An ion exchange bed, a PCWQM, and a MCV provide final polishing and water quality control. Storage tanks are bladderless. This configuration is expected to provide greater than 99% water recovery per pass.

Human Accommodations Interface

To reduce the mass of clothing and wet trash generation, the ALS Human Accommodations Interface assumes a laundry and a dishwasher for reusable food preparation utensils. Additionally, the ALS approach provides full showers for crew hygiene. While this approach recycles clothing and eliminates wet wipe usage, it increases the grey water loading to the Water Subsystem and adds a consumable, detergent. Overall, however, this approach is more economical for a longer mission.

Radiation Protection Interface

The ALS Radiation Protection Interface employs bladderless conformal tanks in place of the assumed ISS baseline technology. Water still provides the media to deflect radiation from the crew cabin.

3.1.2.2 Surface Habitat Lander

The Surface Habitat Lander may use gravity-dependent technologies because its LSS will not operate except on the Martian surface. Thus, the Water Subsystem or the Biomass Subsystem might use gravity-assisted technologies on the surface of Mars. In-situ resource utilization is minimized for the LSS described here, although the vehicle may employ bags filled with local regolith on the exterior of the vehicle for radiation protection. Figure 3.5 shows the architecture for Mars Dual Lander Surface Habitat Lander using ALS technologies.

Air Subsystem

The Air Subsystem using ALS technologies for the Surface Habitat Lander displays greater closure than the technologies within the ISS baseline or for the Mars Transit Vehicle. Unlike the Mars Transit Vehicle, intensive EVA with the associated water losses will consume any excess water derived from consumption of the stored food. Thus, carbon dioxide reduction significantly reduces mass losses associated with the Air Subsystem.

The ALS Air Subsystem concentrates cabin carbon dioxide using a 4BMS. Once compressed, the carbon dioxide stream and hydrogen pass to a Sabatier to produce water and methane. The water passes to the OGA and the methane vents to space. Solid polymer water electrolysis, the OGA technology, provides oxygen and hydrogen from water. The oxygen discharges into the crew cabin while the hydrogen passes to support the Sabatier. Other functions within the Air Subsystem use technologies common with the Mars Transit Vehicle Air Subsystem.

Waste Subsystem

The ALS Waste Subsystem (Figure 3.5) for the Surface Habitat Lander differs from the corresponding ISS baseline configuration (Figure 3.2). The ALS configuration carries urine and flush water directly to the Water Subsystem without pretreatment. Fecal waste is dehydrated using lyophilization to reduce its overall volume when placed in storage. Lyophilization also reduces the moisture content, inhibiting biological activity in the fecal material during storage. For simplicity, water removed from the fecal waste is vented to the external environment. [7] Inedible biomass from the Biomass Subsystem, plus food waste from the Food Subsystem, are dried in a waste dryer to recover bound water before passing to the trash compactor and solid waste storage.

Water Subsystem

The ALS Water Subsystem for the Surface Habitat Lander employs biological primary water processors. The configuration presented in Figure 3.5 presents two bioreactors operating in series to process a combined grey water stream. The first unit, an aerobic/anaerobic bioreactor, degrades organic compounds while the second unit, a nitrifying bioreactor, oxidizes ammonia to nitrate and nitrite. Following the G/L separator, a portion of the liquid stream recycles to the bioreactor feed to provide nitrate and nitrite to the first bioreactor. RO removes inorganic compounds from the process stream. The RO brine passes to an AES. Final finishing steps include an IX bed and an ultraviolet photo-oxidation unit to degrade residual organic compounds. PCWQM and MCV provide water quality monitoring and control.

Other Subsystems and Interfaces

The Biomass Subsystem, the Food Subsystem, the Thermal Subsystem, the Human Accommodations Interface, and the Radiation Protection Interface for the ALS configuration within the Surface Habitat Lander are functionally identical to the corresponding subsystems and interfaces for the ALS configuration of the Mars Transit Vehicle (Figure 3.4). However, actual hardware sizing differs between the Surface Habitat Lander and the Mars Transit Vehicle due to variations in the radiation and thermal environments on the surface of Mars compared with interplanetary space. Further, systems on Mars do not operate in the complete absence of gravity.

Because EVA equipment is not managed by the LSS, the ALS LSS will supply oxygen, water, and food to the EVA Support Interface and receive solid wastes back from the EVA Support Interface. Functionally, the EVA Support Interface is identical to the configuration using ISS baseline technology (Figure 3.2), although advanced EVA technologies may reduce the magnitude of LSS commodities consumed.

3.1.2.3 Mars Descent/Ascent Lander

No alternative ALS concept is presented for the Mars Descent/Ascent Lander. Rather, for the ALS configuration it uses the same technology suite detailed above in Section 3.1.1.3 and Figure 3.3. ALS technologies typically offer a savings in overall ESM for longer duration missions while open loop approaches, where the life support commodities are stored rather than recycled, are generally less massive for shorter duration missions. However, new LSS concepts utilizing some ALS technologies may arise in the future.

7 Alternatively, for the costs associated with a vacuum pump, the fecal water could be recovered.

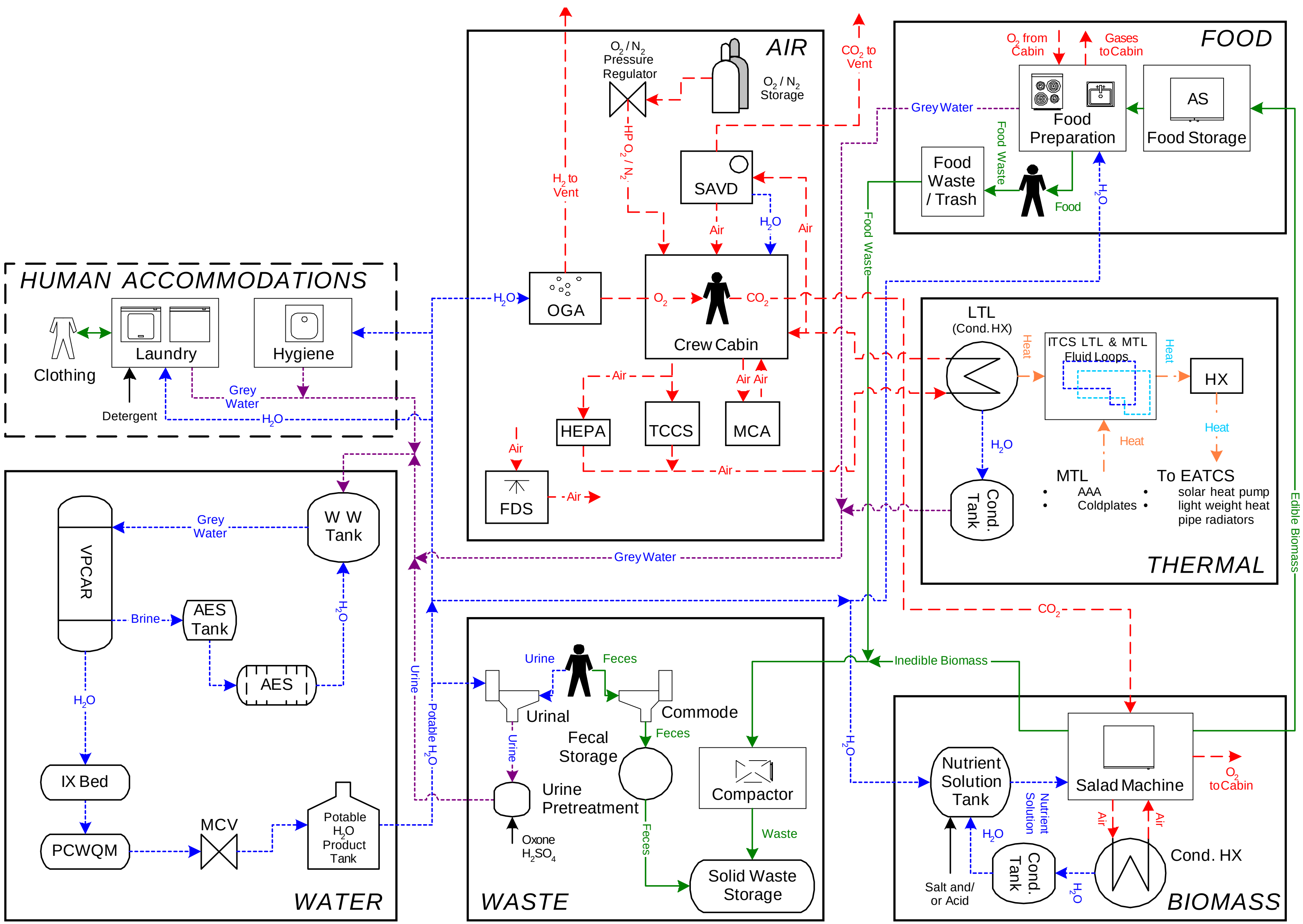

Figure 3.4 Life Support Concept for the **Mars Transit Vehicle** in the Mars Dual Lander Architecture Using **ALS Technologies** (without ISRU)

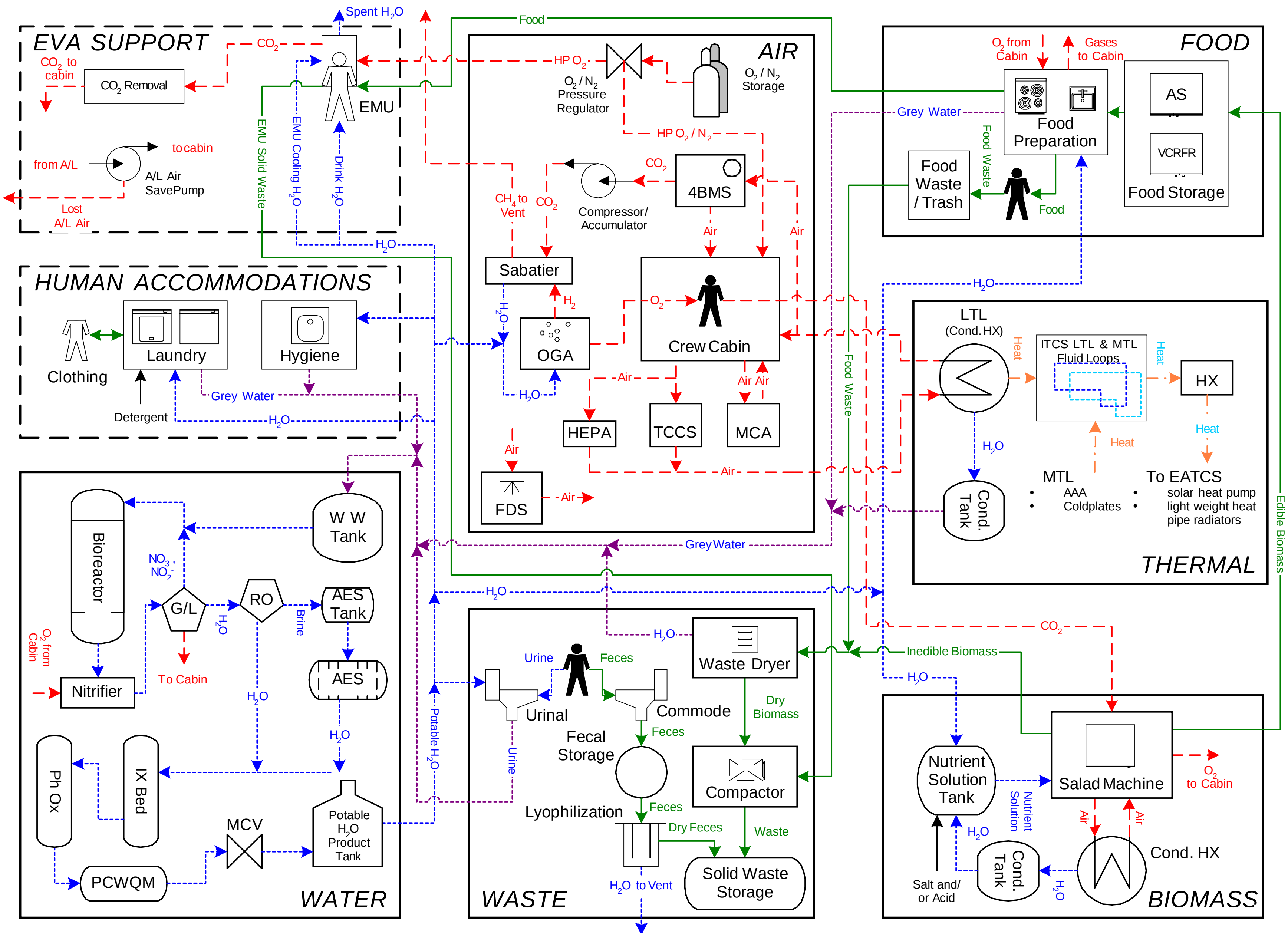

Figure 3.5 Life Support Concept for the **Surface Habitat Lander** in the Mars Dual Lander Architecture Using **ALS Technologies** (without ISRU)

3.2 Concentrated Exploration Mission: Mars Split Mission Architecture

The Mars Split Mission Architecture presented here is unchanged from the original references and does not benefit from more recent approaches such as those illustrated by the Mars Dual Lander Architecture, Section 3.1. Further, this section below retains its format and content from earlier drafts of this document and, therefore, may seem "incomplete" when compared to material for other missions.

The Split Mission architecture is a well-documented approach for landing people on Mars and returning them safely to Earth (Hoffman and Kaplan, 1997, and Drake, 1998). Three missions are assumed, all landing at the same location on Mars in order to build up an infrastructure that will provide a safer site than any other place in the Solar System except for Earth itself.

For each mission, two flights preposition equipment around and on Mars before the crew transit. A cargo flight lands on Mars carrying a Mars Ascent Vehicle, an ISRU plant, and an inflatable habitat. A second flight prepositions an Earth Return Vehicle in a stable Martian orbit. At the next Mars transfer opportunity, a Surface Habitat Lander transports the crew from Earth to the surface of Mars, rendezvousing on the surface with the prepositioned surface assets. During the same transfer opportunity, the two flights with the prepositioned assets for the next crew also transit to Mars and arrive while the first crew conducts surface operations. Thus, the first crew could, if necessary, use the assets originally intended for the second crew for contingencies. As with the previous Mars exploration scenario, transit to or from Mars nominally takes 180 days, while the surface mission is nominally 600 days. Following the surface mission, the crew ascends to Martian orbit in the Mars Ascent Vehicle and rendezvous with the Earth Return Vehicle. The Earth Return Vehicle transports the crew to Earth.

The second crew departs from Earth while the first crew is returning. The second crew voyages to Mars and lands their Surface Habitat Lander at the site prepared by the first crew, integrating their vehicle into the existing infrastructure. Thus, each successive mission will expand the habitable volume. The cargo flights for the second and third crews each bring a pressurized rover in place of the inflatable habitat manifested for the first crew's cargo flight.

3.2.1 Applying International Space Station Life Support Hardware

The Mars Split Mission LSS hardware using ISS ECLSS technologies is similar to the material presented in Section 2.1.1 once the differences in overall mission duration, environment, and EVA frequency are considered. As noted above, this mission architecture uses four vehicles. Three vehicles transit to Mars during the first Mars transportation opportunity. An inflatable Habitat Module and the Mars Ascent Vehicle land on Mars, while the Earth Return Vehicle is placed in a stable Martian orbit. At the second Mars transportation opportunity, the crew travels from Earth to the surface of Mars in the Surface Habitat Lander. This vehicle houses the crew for the descent to Mars and during their surface stay. The separate Mars Ascent Vehicle returns the crew to Martian orbit to rendezvous with the Earth Return Vehicle for the trip back to Earth.

3.2.1.1 Surface Habitat Lander

The Surface Habitat Lander transports the mission crew from Earth to the surface of Mars and provides the crew with a primary habitat during surface operations. As noted above, the Surface Habitat Lander volume, which is housed in an aluminum shell, is augmented on the surface by an inflatable habitat and/or additional vehicles from previous missions. As the Surface Habitat Lander is an independent vehicle, it carries a full suite of LSS hardware. Further, it carries food for the outbound voyage and for surface operations, which totals 780 days of supplies. As for the previous mission, EVA will be used only for contingency during interplanetary transit phases, while during surface operations the crew is expected to average one 2-crew-member EVA per weekday. Development of the LSS architecture using ISS technologies for the Surface Habitat Lander is a continuing research topic.

3.2.1.2 Predeployed Surface Assets

Several important mission assets are predeployed on the Martian surface using robotic cargo missions on the Mars transportation opportunity before each crew transit. These assets include a Mars Ascent Vehicle, which arrives on Mars with dry fuel tanks. The Mars Ascent Vehicle is fueled on the surface with fuels from an ISRU plant operating on the Martian atmosphere with hydrogen feedstock to produce methane and oxygen. The first cargo flight also brings an inflatable module to expand the first crew's living volume. The second and third cargo flights each provide a pressurized rover.

3.2.1.3 Mars Ascent Vehicle

As noted above, the Mars Ascent Vehicle is essential to mission success. However, under the Split Mission Architecture the crew only occupies it while they ride from the surface of Mars to the Earth Return Vehicle. The Mars Ascent Vehicle may also provide the crew with direct return to Earth's surface as a re-entry capsule. Due to the limited operational lifetime, it is likely that the LSS for the Mars Ascent Vehicle will use consumable life support technologies similar to those employed for the Space Transportation System, or Shuttle. Thus, the Mars Ascent Vehicle is not considered further here.

3.2.1.4 Inflatable Habitat

While the inflatable habitat manifested for the first crew's cargo flight will provide crew living volume, it will probably derive most or all it's life support functions from the initial Surface Habitat Lander. As such, the inflatable habitat is not considered here.

3.2.1.5 Pressurized Rovers

Like the Mars Ascent Vehicle discussed above, the pressurized rovers will probably use consumable life support technologies similar to those employed for the Space Transportation System, or Shuttle.

3.2.1.6 In-Situ Resource Utilization Facilities

Because ISRU is not one of the ISS technologies, ISRU is confined, under the present scenario, to providing only methane and oxygen for the Mars Ascent Vehicle using a stock of hydrogen from Earth.

3.2.1.7 Earth Return Vehicle

The Earth Return Vehicle is an independent vehicle with an aluminum habitat module that houses the crew on the 180-day return voyage. Thus, this vehicle carries a full suite of LSS hardware. Additionally, the Earth Return Vehicle provides a contingency habitat for the crew should they abort surface operations early and live in Martian orbit until the next transfer opportunity to Earth is available. As such, the Earth Return Vehicle must provide food and life support functions for a complete 600 day stay in the Martian system. However, EVA support is not provided because such operations are assumed only for contingencies while the crew is in space. The LSS architecture using ISS technologies for the Earth Return Vehicle is a continuing research topic.

3.2.2 Advanced Life Support Straw Man Architecture

The ALS Straw Man concept for the Mars Split Mission Architecture uses the systems and technologies outlined above for the Mars Dual Lander Architecture. As both exploration missions are similar in scope and duration, the expected technologies are similar. One exception, however, does arise with the Mars Split Mission Architecture. The life support systems on the first Surface Habitat Lander will operate for all three crews at the landing site for a nominal total duration of 1,800 days. This duration is sufficient that a large-scale plant growth chamber might seem like a prudent investment for the first landing vehicle. However, such early utilization of plant growth systems is not consistent with the current mission documentation (Hoffman and Kaplan, 1997, and Drake, 1998). As such, a highly physicochemical LSS is suggested here.

3.2.2.1 Surface Habitat Lander

The Surface Habitat Lander carries the crew from Earth orbit to the surface of Mars and then provides a habitat for the entire surface mission. Therefore, the life support systems employed must function efficiently for extended periods of time both in microgravity and on the surface of Mars. While the technologies outlined in Section 3.1.2.2 are not known to have inherent gravity dependencies, this multi-segment mission is extremely demanding. While it is possible that local regolith at the site may provide some radiation protection, the mission segment in interplanetary space is the limiting environment and so defines the radiation protection requirement for the Surface Habitat Lander. However, use of regolith for radiation protection on the surface of Mars could allow material provided for radiation protection in interplanetary space, such as water, to be used elsewhere. Development of the ALS Straw Man architecture for the Surface Habitat Lander is a topic for continuing research.

3.2.2.2 Earth Return Vehicle

The Earth Return Vehicle is a pure spacecraft. Thus, like the Mars Transit Vehicle discussed in Section 3.1.2.1, the LSS technologies employed must be insensitive to changes in local gravity, including microgravity. Further, radiation protection for the Earth Return Vehicle must rely solely on commodities initially included on the vehicle, such as water, or those generated from supplied commodities, such as waste products [8]. Finally, because the Earth Return Vehicle will loiter inactive in Martian orbit for an extended period before the crew boards for the trip to Earth, the systems selected must be highly reliable both while crew-tended and while operating autonomously. Currently, the technologies proposed here do not have any known limitations that prevent them from operating for the duration of the prescribed mission. Development of the ALS Straw Man architecture for the Earth Return Vehicle is a topic of continuing research.

3.3 Extended Presence: Evolved Mars Base

An extended human presence on Mars requires a base using either infrastructure established during an earlier exploration initiative or as an entirely new project. The Evolved Mars Base scenario developed here considers the nominal, or steady state, operation of such a facility. In short, the facility is assumed to be fully functional when the crew arrives on Mars. Because of this assumption, the construction events that lead up to completion of the base are not discussed in detail. While the build up of the Evolved Mars Base is not a trivial task and could drive the facility's design, including that of the life support system, those challenges are not addressed here. The scenario here provides a case for study and not a projection of future human missions. This scenario assumes present or near-term technologies both for life support and other applicable areas.

As with the Mars exploration scenarios in Section 3.1 and Section 3.2, crew transit to or from Mars nominally takes 180 days. Following the surface mission for each crew, the crew ascends to Martian orbit and returns to Earth. It is likely that one vehicle transports the crew from Earth to Mars and back to Earth. Further, it is likely that a second vehicle transports the crew from Martian orbit to the surface and back to orbit. It is assumed here that the second crew departs from Earth while the first crew returns.

In this reference mission, the completed Mars base habitation structure consists of two aluminum-shelled habitats, each with a pressurized volume of 90 m^3. Additionally, the ALS equipment suite includes a bioregenerative system with a plant growth module in a sufficiently voluminous inflatable structure that provides food production, water recovery, and air revitalization. Power for the Evolved Mars Base is assumed to come from nuclear reactors positioned on the surface about a kilometer from the facility.

Like the other reference missions, the Evolved Mars Base under the nominal scenario supports a crew of six. During each 600-day surface segment, the crew of the Evolved Mars Base will perform 700 half-day EVA sorties using two crewmembers each. Thus, EVA Support will have greater importance for this longer mission, especially if EVA continues to consume life support commodities like the current EMU developed for the Shuttle/ISS programs.

Nominally, a transfer opportunity between Earth and Mars occurs once every 26 terrestrial months. Assuming the first permanent crew members stay at least 600 days on Mars and the last

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8 Waste products could replace other forms of consumable radiation protection, such as food. The driving issue that defines radiation protection is the occurrence of solar particle events, rather than the distance from the sun.

crewmembers leave when the seventh transfer opportunity to Earth opens, the facility lifetime is 600 days plus 13 years, or 14.6 years. While transit between Earth and a Mars Base will not be trivial, the mission description here does not consider the transit except for its impact on crew assignments and resupply schedules. Further, some life support equipment, other than just consumables, may require replacement during the facility's lifetime. Thus, maintenance takes on greater importance for longer duration facilities.

The Evolved Mars Base will support one or more pressurized surface rovers that may employ LSS technologies that depend on consumables. However, these systems have not been investigated yet.

The average overall power generation for all users, assuming nuclear power generation (Landis, *et al.*, 1999, and Drake, 2001b), is estimated in Table 3.2. [9] Because the additional thermal loads for power generation are currently unknown, the corresponding cooling loads are assumed to equal the listed power generation.

Table 3.2 Power Generation for the Evolved Mars Base

Evolved Mars Base	Power [kW_e]
Total Base Power Generation (average at end-of-life)	250

3.3.1 Applying International Space Station Life Support Hardware

The Evolved Mars Base hardware using ISS ECLSS technologies is similar to the material presented in Section 2.1.1 once the differences in overall mission duration, environment, and EVA frequency are considered. Figure 2.4 provides a life support system diagram from a functional perspective for a large, long-duration facility and is applicable without modification here for the Evolved Mars Base.

For this study scenario, when the crew arrives at the base location, all of the necessary infrastructure for the Evolved Mars Base will be in place. The completed Evolved Mars Base habitation structure consists of two aluminum-shelled habitats, with a pressurized volume of 90 m^3 each. This combined living volume provides a complete suite of life support equipment, although the exact placement of systems within the overall habitat is not currently defined.

3.3.2 Advanced Life Support Straw Man Architecture

Figure 3.6 shows the architecture for an Evolved Mars Base using ALS technologies. The significant difference between the ALS approach for the Evolved Mars Base and the corresponding concepts for the Mars exploration missions in Section 3.1 and Section 3.2 is the addition of inflatable structures to house plant growth. More specifically, the plant growth modules here support the majority of the crew's diet with the remainder provided as prepackaged food from Earth. In such a scenario, the majority of the dietary carbohydrates and fiber originates in crops grown in the plant growth chamber while spices, protein, fat, and oil are provided from Earth. Plant growth for this ALS Straw Man concept is supported by artificial lighting drawing energy from nuclear power generation.

Employing large plant growth modules allows bioregenerative air revitalization and water recovery. As an increasing percentage of the crew's diet is supplied by locally grown crops, the plant growth chambers provide enough fresh water in the form of transpired moisture to provide the daily allowances of potable and hygiene water. Reverse osmosis limits accumulation of phytotoxic ions, such as sodium, in the nutrient solution. As the percentage of the crew's diet provided by locally grown crops increases, plant photosynthesis consumes carbon dioxide and produces oxygen in sufficient quantities to completely revitalize the crew's atmosphere. As the percentage of food provided by local production increases yet further, it becomes necessary to provide additional carbon dioxide to support the additional plant growth. The necessary carbon dioxide is obtained here from oxidizing solid waste.

Typically more efficient plants provide the initial crops for on-site food production within a bioregenerative life support system. As greater closure is required, less efficient crops are selected based on their nutritional contribution to the overall diet rather than their efficiency in producing edible biomass.

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9 This value is based on a recent study (Levri, 2001) and assumes an intermediate amount of food production from crops on site and artificial lighting. However, life support systems that produce higher closure for food may require considerably more power.

Thus, while somewhat unrealistic using current technologies and a limited crop selection, as the production of crops grown on-site approaches providing all of the crew's dietary requirements and the food resupply approaches zero, specific productivity of the Biomass Subsystem decreases because all crops are not equally efficient in terms of providing edible biomass from the resources they consume.

Air Subsystem

The Air Subsystem maintains the nominal total pressure for all chambers at 70.3 kPa, allowing easy crew access to any part of the base. Separate atmospheres for the crop growth modules allow more optimal crop growth conditions within the biomass production modules. The atmospheric temperature within the biomass production modules is maintained to maximize biomass production as a function of time. A biomass production module atmospheric relative humidity of 70% will be sufficiently low to inhibit excessive microbial growth while promoting reasonable moisture transpiration from the plant canopy. The atmospheric temperature and humidity within the crew cabin is maintained to maximize crew comfort. Atmospheric gas leakage is assumed to occur at a rate of 0.18% by mass per day (Drysdale and Hanford, 1999a). To offset gas leakage, stored gases, either bottled or cryogenic, and water are supplied from Earth. Nitrogen or other inert gases are supplied as pressurized gases while oxygen is supplied as a cryogen.

To promote high crop productivity, the nominal atmospheric composition for the biomass production modules maintains the carbon dioxide partial pressure at 0.12 kPa and the partial pressure of oxygen at 17.27 kPa. This latter value for oxygen provides sufficient oxygen partial pressure within the biomass production modules to support crew accessibility (Lange and Lin, 1998). This minimum oxygen partial pressure allows for reasonably timed crew acclimation, except for the case of maximum oxygen uptake such as during hard work (Waligora, *et al.*, 1994). The remaining biomass production module atmospheric constituents are water vapor and an inert gas, such as nitrogen.

The nominal atmospheric composition for the crew habitat modules maintains the carbon dioxide partial pressure below 0.4 kPa and the oxygen partial pressure at 19.50 kPa [10]. As above, the remaining atmospheric constituents are water vapor and an inert gas.

To maintain two separate atmospheres at differing compositions, a suite of physicochemical life support equipment facilitates gas transfer between the biomass production modules and the crew habitat as needed. A 4BMS concentrates carbon dioxide from the crew's atmosphere for use in plant growth. An oxygen scrubber concentrates oxygen from the plant chamber atmosphere, which is part of the Biomass Subsystem, for use by the crew and the Waste Subsystem. A TCCS assures adequate air quality through catalytic oxidation and a particulate and microbe control unit consisting of reusable filters.

Biomass Subsystem

Early permanent research facilities on Mars, such as is represented by the Evolved Mars Base, will probably utilize higher plants to provide full water regeneration and atmospheric revitalization plus a significant portion of the crew's food. Thus, the Biomass Subsystem raises higher plants that provide the primary air revitalization and water recovery functions in the absence of duplicate primary processors. More specifically, the plants, through photosynthesis, consume atmospheric carbon dioxide to produce biomass and oxygen, thus fulfilling the primary air revitalization task. Further, plants filter organic compounds from slightly processed grey water and urine mixed with the hydroponic solution, returning transpirate to the Water Subsystem for final polishing. To fully revitalize the crew cabin atmosphere, the crops also provide at least half, by mass, of the crew's diet (Drysdale, *et al.*, 1999). When the Biomass Subsystem produces sufficient oxygen beyond the crew's metabolic requirements, the Waste Subsystem may oxidize solid wastes.

Staple crops that supply mainly carbohydrate, such as sweet potato, wheat, and white potato, more efficiently generate edible dietary mass on a per photon, per volume, and per time basis than other crops. Crops that supply protein and fat, such as peanut and soybean, are relatively inefficient at generating edible dietary mass. Further, while some salad crops are fairly efficient, the dietary intake from these crops is typically low. Based on Behrend and Henninger (1998), the assumed salad crops are cabbage, carrot,

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10 The "Advanced Life Support Systems Integration, Modeling, and Analysis Project Baseline Values and Assumptions Document," JSC-39317 (currently Drysdale and Hanford, 1999a) provides the most recent values for recommended crew cabin atmospheric composition and temperature.

chard, fresh herbs, lettuce, onion, spinach, and tomato. Thus, for flight systems that allow or require some resupply, it appears most expedient to grow the crew's dietary carbohydrate and some salad crops while providing protein and fat by resupply from Earth.

The Biomass Subsystem hardware includes a plant chamber and supporting equipment. Plants grown within the plant chamber consume carbon dioxide from human metabolic activities and other sources. As products, the plant chamber provides edible biomass to the Food Subsystem, oxygen to the Air Subsystem, and clean transpirate to the Water Subsystem. An oxygen scrubber concentrates oxygen from the plant chamber, passing it to the crew cabin. To control the atmospheric temperature and humidity, an anti-microbial condensing heat exchanger dehumidifies the cabin atmosphere. Condensate passes either to the Water Subsystem for final polishing or is recycled to the nutrient solution tank. Recycling excess condensate within the Biomass Subsystem both reduces the overall load on the Water Subsystem and helps to dilute incoming grey water sent from the Water Subsystem. In this arrangement, the Biomass Subsystem provides both the primary air revitalization and water purification functions. Inedible biomass passes to the Waste Subsystem.

Under the ALS Straw Man concept, the Biomass Subsystem utilizes completely artificial lighting for crop growth. Further, lighting photoperiod, photosynthetic photon flux levels, and biomass production module environmental conditions are set to maximize crop productivity as a function of time. Alternative formats for this scenario consider using natural lighting for biomass production (See Section 3.4.2)

Food Subsystem

The Food Subsystem processes harvested crops into bulk ingredients, prepares crop ingredients and resupply items into final products, cleans and sanitizes the equipment, utensils, and areas of use, and stores food and equipment (Peterson, 2000). Resupply items, such as foods rich in protein and fat, are shipped in bulk packages, with small quantities individually packaged when necessary.

Because crops are generally grown and harvested in batches, the Food Subsystem stores harvested crops until use. Though some salad crops, such as tomatoes, are "pick and eat" crops, the baseline here assumes all crops are grown and harvested in a batch mode. Refrigerators and freezers provide storage for any perishable crops, ingredients processed in bulk that are not shelf-stable, and meal leftovers. Wheat and other crops are harvested at maturity and, as necessary, dried in a crop dryer [11]. This approach is in contrast to the traditional agricultural practice of drying grain in place in the field before the farmer harvests the grain. Dry, cool bulk storage houses raw wheat, potatoes, and sweet potatoes.

In this ALS Straw Man concept, equipment for processing crops into bulk ingredients includes a grain mill, a gluten/starch separator, an extruder, a dryer, a dehydrator, a food processor, a juicer, and an oven. Equipment for preparing crop ingredients and resupply items into final products includes a pasta maker, a bread machine, a microwave oven, heating range, scales, and standard cooking equipment (pans, pots, utensils, etc.). Equipment for cleaning and sanitizing includes a sink with a faucet, a dishwasher, and cleanser. As a baseline value, sanitation of food processing equipment, excluding the dishwasher [12], uses 75 kg/d of potable water for a crew of six, or 12.5 kg/CM-d. [13] This becomes an additional grey water load for the Water Subsystem.

Thermal Subsystem

The ALS Thermal Subsystem collects heat loads with coldplates, coldplate shelves, and condensing heat exchangers, as appropriate. To facilitate cabin atmospheric temperature and humidity control, the Biomass Subsystem plant chamber and Waste Subsystem incinerator have dedicated condensing heat exchangers in addition to the crew cabin anti-microbial condensing heat exchanger and AAA. The Thermal Subsystem rejects heat to the environment using either body-mounted lightweight radiators or lightweight radiators deployed on the planetary surface near the spacecraft. A solar heat pump,

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11 With respect to the current Evolved Mars Base crop list, wheat alone requires drying. However, other crops proposed in later scenarios might require such treatment.

12 Drysdale and Hanford (2001) provides a grey water model including estimates for a dishwasher. However, the actual grey water stream depends on inputs from the crew activity and all other life support subsystems and thus is highly case dependent.

13 A "crewmember day" (CM-d) is defined as one day, or 24 hours, of an individual crewmember's time.

which is a vapor compression heat pump with a dedicated photovoltaic solar panel and no energy storage devices, raises thermal load temperatures during daylight hours, allowing rejection of greater thermal loads using the same radiator area.

Waste Subsystem

The typical waste stream for this scenario includes inedible biomass, food-processing waste, food waste, urine and feces solids, sweat solids, food packaging, and other wastes such as used filters and paper [14]. To maintain a healthy local environment, the assumed mission protocol requires that all wastes are dry before they are stored. Wastes containing potential human pathogens are sterilized before they are stored. Carbonizing or oxidative waste processing technologies supplement storage of solid waste to recover carbon dioxide and support biomass production. For purposes here, when appropriate, waste products are oxidized in the following order: (i) urine, feces, and sweat solids, (ii) wasted edible biomass, (iii) inedible biomass, (iv) food packaging and other solid wastes. For this ALS Straw Man concept, presented in Figure 3.6, waste oxidation provides carbon dioxide for biomass production and human waste sterilization, although additional oxidative treatment might be used in place of more extensive storage and/or sterilization for the remaining waste stream components. In such a case, excess carbon dioxide would be vented.

The representative ALS Waste Subsystem, in Figure 3.6, is built around an incinerator [15]. All human solid wastes and the RO brine are oxidized under the assumption that the Biomass Subsystem provides sufficient oxygen beyond the crew's metabolic requirements to support oxidation of such wastes. Regenerable catalytic beds remove the products of incomplete combustion from the incinerator exhaust gases, and a condensing heat exchanger transfers the moisture and heat load to the Water and Thermal Subsystems, respectively. After exiting the incinerator equipment, exhaust carbon dioxide passes directly to the plant chamber within the Biomass Subsystem. Other solid waste products, besides human solid waste, are dried in a waste dryer. Depending on the Biomass Subsystem's need for carbon dioxide, the dry biomass is either incinerated or compacted and stored. Thus, under nominal operating conditions, the Waste Subsystem controls atmospheric composition through selective oxidation of waste products.

Water Subsystem

The ALS Straw Man concept for the Water Subsystem utilizes the plant chamber as the primary water processor to remove organic impurities with supporting physicochemical systems to remove inorganic impurities and polish the final product stream before returning it for crew use. RO treats incoming grey water for inorganic impurities before it passes to the nutrient delivery system within the Biomass Subsystem. Water transpires from the plants as almost a pure product stream (Sager and Drysdale, 1996). Once the transpirate is collected and condensed, it passes to an aqueous phase catalytic oxidation system (APCOS) before being rendered potable for crew consumption. An advanced microbial control technology, which is not phytotoxic, controls bacteria before the water passes through quality monitoring and control hardware.

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14 Drysdale and Hanford (2001) provides a solid waste stream model. However, the actual solid waste stream depends on waste inputs from the crew activity and all other life support subsystems. Thus, actual solid waste streams are highly case dependent.

15 A composter might work equally well as the primary ALS Waste Subsystem oxidation process for an Evolved Mars Base. Further, for configurations with insufficient biomass production to support oxidation of human waste, other non-oxidative processes, such as carbonization or pyrolysis, could provide the requisite sterilization without consuming oxygen. However, such varying configurations are beyond the scope of the present version of the RMD manuscript.

Extravehicular Activity Support Interface

Assuming no major technological advances in EVA technology that reduce consumption of life support commodities, the EVA Support Interface will receive atmospheric gases, water, and food from the LSS and send human solid waste and carbon dioxide to the LSS. [16] During the 600-day surface mission, the crew of the Evolved Mars Base performs 700 half-day EVA sorties using two crewmembers each. Drysdale and Hanford (2001) provides details for this EVA format, including usage rates for consumables and physical parameters for the A/L.

Human Accommodations Interface

Human accommodations will employ a full shower and a regenerative clothing system for the Evolved Mars Base, including an aqueous clothes laundry with an ozone detergent. For sizing purposes, each crewmember receives two weeks of clothing [17] for the first six months of service and one additional week of clothing for each additional six months. Thus, each crewmember's allotment for a 600-day surface stay is five weeks of clothing. Further, all personal care products, such as toothpastes and soaps, will be compatible with the life support systems mentioned above. [18]

Radiation Protection Interface

Radiation protection, if needed beyond what the modules and Mars provide, employs bladderless conformal tanks in place of the ISS baseline technology. Water provides the media to deflect radiation from the crew cabin.

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16 Future EVA designs will likely incorporate more regenerative technologies than current ISS and historical designs. However, advanced EVA technologies are currently in the design phase and the exact commodity loads on the LSS are unknown. While it may be possible to make EVA air and thermal technologies completely regenerative, it is unlikely that crew metabolic loading will decrease significantly nor will regenerative technologies address human solid waste generated during EVA.

17 In other words, each crewmember has sufficient clothes to wear for two-weeks without laundering any.

18 Note: This approach may require some additional equipment within the LSS as well as some selection restrictions for the crew.

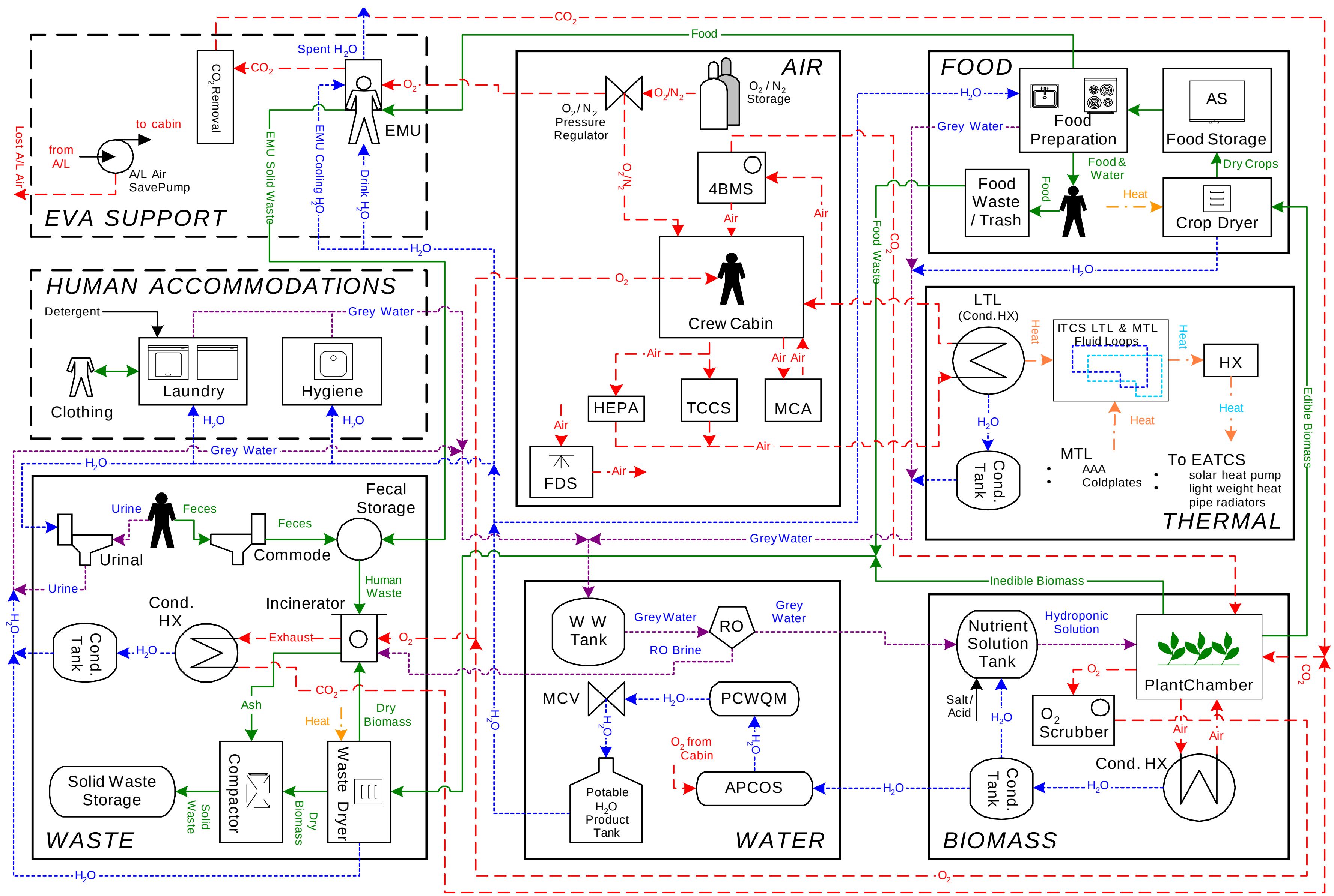

Figure 3.6 Life Support Concept for an **Evolved Mars Base** Using **ALS Technologies** (without ISRU)

3.4 Alternate Life Support Formats for the Surface of Mars

The reference missions detailed above for the surface of Mars present moderately conservative approaches for life support system configurations. Many other ALS configurations are possible, and it is expected that better systems will be found as development and analyses progress. The most significant masses associated with life support are related to supplying food, and to a lesser extent, fresh air and water. For plant chambers, nutrient solution to support plant growth, photosynthetic photon flux to permit photosynthesis, crew time for facility operation and maintenance, and, to a lesser extent, pressurized volume to house plant growth, can also be significant issues. All of these can be addressed to some extent by other technologies or approaches.

3.4.1 In-Situ Resource Utilization

Development of ISRU techniques for Mars surface habitats will ultimately play a vital role in carrying out human Mars missions that are both economical and safe. The most critical resources for human exploration of Mars that can likely be drawn from the environment include habitat atmospheric gases, water, fuel, minerals, plant growth substrate and radiation shielding. Any of the Mars mission approaches presented in this document could potentially use resources on the planetary surface if it were deemed economical and appropriate.

The Mars Split Mission Architecture assumes an ISRU plant to manufacture rocket propellant for Mars ascent using hydrogen brought from Earth and oxygen derived from the Martian atmosphere. In fact, because the ISRU plant is scheduled to arrive on Mars with the predeployed assets from the cargo flight, a full load of fuel for the Mars Ascent Vehicle will be manufactured and waiting before the mission crew leaves Earth. This concept of fuel generation from Martian resources could be incorporated for any Mars mission. This ISRU plant could also provide a cache of life support commodities, including the gases and maybe water. The contingency LSS ISRU sizing requirements given in Hoffman and Kaplan (1997) and Drake (1998) would make the life support commodities a significant driver for sizing an ISRU system.

Considering just gas production, ISRU could provide initial atmospheric gases for crew modules or to refill modules in a contingency. As a minimum, ISRU might provide gases to offset cabin leakage or gases lost during EVA and A/L operations. Further, ISRU could provide all atmospheric gases in place of regenerative approaches or as a contingency supporting regenerative approaches.

The composition of the Martian atmosphere is detailed in Table 3.3 (Smith and West, 1983), assuming a total pressure of 0.6 kPa. These commodities can be modified in various ways to produce an atmosphere for either plants or humans. For an atmosphere appropriate for humans, an ISRU plant could obtain oxygen, from decomposition of carbon dioxide without any reactants from Earth. Additionally, inert gases, such as nitrogen and argon, could be separated from the other atmospheric constituents.

The natural partial pressure of carbon dioxide on Earth is about 0.04 kPa, while the optimal partial pressure of carbon dioxide for plant growth chambers is about 0.12 kPa. Thus, the level of carbon dioxide in the Martian atmosphere is excessive for plants even before it is compressed. However, the optimum atmosphere for plant production, in terms of productivity per unit cost of the atmosphere, has yet to be determined. A plant growth atmosphere can be produced from ISRU by compressing the gas, removing the majority of the carbon dioxide and trace contaminants and adding oxygen as needed.

The Martian atmosphere also contains the best-documented source of water available at any Mars surface site, and utilization of such water might provide a contingency supply. However, the economics of water production are questionable, due to low concentrations in the Martian atmosphere. The Martian atmosphere is relatively humid, but is so cold that it carries little water in absolute terms. Some other source of water would be required to provide a significant mass of water economically in-situ.

On Mars, water could be made available from the atmosphere, despite its dryness, from permafrost located a meter or two below the surface, from surface snow, from polar ice, or from subsurface water or ice deposits. Unfortunately, the relative abundance and location of most of these water sources is currently unknown or inconvenient for other activities. The acquisition cost would depend on the cost of accessing it, extraction, and purification. Thus, use of such sources may or may not unreasonably restrict landing site selection, but more information is needed before this can be determined.

Table 3.3 Composition of the Martian Atmosphere

Component	Percentage (by Volume)	Partial Pressure [kPa]	Assumed Mass Leverage
Carbon Dioxide (CO_2)	95.32	0.572	47
Nitrogen (N_2)	2.7	0.016	106 [19]
Argon (Ar)	1.6	0.0096	
Oxygen (O_2)	0.13	0.00078	19
Carbon Monoxide (CO)	0.07	0.00042	
Water Vapor (H_2O)	0.03	0.0018	

Water could also be manufactured from atmospheric carbon dioxide, if a source of hydrogen is available. Hydrogen can be supplied from Earth in the form of liquid hydrogen. Using this approach, the mass of liquid hydrogen is five times lighter than the corresponding mass of water, even including tankage. One reaction to produce water from hydrogen and carbon dioxide is exactly the reaction already proposed to produce methane for the Mars Ascent Vehicle in the Mars Split Mission Architecture.

For highly-bioregenerative life support systems, the most significant costs associated with using crops for critical life support functions are life support commodities in the form of air and water to support plant growth, photosynthetic flux to permit photosynthesis, and crew time for facility operation and maintenance. Because highly-bioregenerative systems require large volumes for growing plants, the mass for pressurized volume, though a lesser concern when using lightweight structures, can still be significant. Utilization of Martian resources for the supply of air and water has been discussed above. All of the remaining entities, except for crew time, can be addressed, to some extent, by other approaches.

ISRU could provide minerals, plant-rooting substrates, and raw material for structures that could be used to house biomass production operations. Unfortunately, the location of minerals on Mars is not well understood. In place of hydroponic production, growth in substrates buffers the uptake of both water and minerals by the plants, reducing the potential for spread of pathogens and, in like manner, pathogens become more difficult to eradicate. However, there are indications that Martian surface materials are quite toxic due to the presence of peroxides and sulfur oxides. Furthermore, the physical properties of readily accessible materials are relatively unknown. A good plant substrate would be porous and have a particle size on the order of a millimeter. Much of the surface of Mars is covered by dust that is much finer than a millimeter.

Mars regolith might also be used as a method of radiation shielding for the habitat. Several studies investigated building structures on Mars using local materials. However, most of them do not provide sufficient engineering detail nor do they consider the economic impacts involved to the level that would allow for critical evaluation.

3.4.2 Bioregeneration

While the most obvious source of light for plant growth is natural sunlight, this source is diminished on the Martian surface due to Mars' increased distance from the Sun and the incidence of Martian dust storms. Thus, the Martian environment reduces naturally available photosynthetically active radiation so alternative sources of lighting may be required. However, because artificial lighting costs are high, low-cost, low-productivity greenhouses may be competitive from an overall perspective. A hybrid system combining natural solar radiation with some level of artificial lighting may be a viable alternative (Durbin, *et al.*, 2000).

Natural sunlight can be collected for plant growth in two ways. One way is to concentrate the light falling over a wide area of surface into a more intense beam for plant growth (See Schwartzkopf, 1991, for an example of such a system). Unfortunately, the ubiquitous Martian dust scatters a percentage of the incident sunlight, and though this irradiation often reaches the surface, it does so as diffuse irradiation that would rapidly render a system relying on specular reflections, such as a mirror concentrator, ineffective. As the atmospheric dust loading increases, the percentage of incident sunlight scattered also

19 The leverage given is for an Argon/Nitrogen mixture.

increases. Therefore, light concentration systems, which efficiently concentrate and transport only the direct beam component of sunlight, are less effective on Mars than they are in free space.

Another approach is to use the available energy "as is," whether direct beam irradiation or diffuse irradiation, by placing the crops within a greenhouse. Because plants use any impinging solar irradiation within the proper wavelengths, this approach avoids the issues associated with concentrating the sunlight. However, as light intensities of naturally available sunlight do not approach the intensities achieved with artificial lighting or light concentration systems, the crops grow more slowly so a greater volume is required to maintain the same production of daily edible biomass. There may also be seasons, just as on Earth, when it is difficult to grow plants using only natural sunlight. Preliminary work by Gertner (1999b) indicates that growing plants with natural lighting, or a combination of natural and artificial lighting, may be possible.

If a plant unit is at the same pressure as the crew spaces, a single air loop can be used. The temperature and humidity would normally differ for the crew, but the pressure and atmospheric compositions for both plants and crew are compatible. Another approach segregates the atmospheres for the biomass production chamber and the crew cabin.[20] Gas transfer is more problematic if different pressures are used for the crew and the plants. Further, gas separation might be needed. While the additional equipment would not be expensive, such an approach is more complex and, therefore, more susceptible to faults. Though a lesser concern here, this approach requires more power.

Growing crops in sufficient quantities to provide regenerative life support functions requires significant volume. An inflatable module provides the greatest pressurized volume at the lowest cost. To estimate the volume necessary for plant growth, an example is useful. In this example, the biomass production module will provide 25%, by dry mass, of the food for a crew of six. The average crop here is assumed to produce 30 g of dry edible biomass per square meter of growing area per day and grow to a height of 0.7 m. Assuming crew access to the growth bays adds an additional fifty percent to the volume required for plant growth, this rather modest chamber requires a volume of 36 m^3. Supporting equipment requires additional volume. The average crop growth rate here assumes full artificial lighting and, for some crops, extended photoperiods to achieve this relatively high productivity. Thus, if natural Martian lighting provides some or all of the photosynthetically active radiation for crop growth, the average productivity will decrease and the corresponding plant growth volume will increase.

Of the Mars missions presented in this document, the Evolved Mars Base is the only case in which a high degree of plant growth may prove economical, based on the state of current plant growth technology (Drysdale and Hanford, 1999b). While a large biomass production chamber might provide air and water revitalization in addition to food, such a system is probably not cost-effective for a mission of the duration proposed by the Mars Dual Lander or Mars Split Mission architectures without significant reductions in the infrastructure-associated costs. As plant growth and ISRU technologies advance, supplying the crew's food through crop production may become more economical for shorter-duration missions.

3.4.3 Solar Power

A major issue for any Mars mission is power generation. Nuclear propulsion and nuclear power generation on the surface may well be necessary for an affordable mission. Solar propulsion in the outer solar system requires very large arrays, perhaps too large to be practical. Solar power on Mars would also require very large arrays to provide adequate power during dust storms (Drake, 1998), and these would be costly and hard to keep clear of dust. Solar cases would be much worse for high latitudes compared with equatorial sites.

Politically, however, power generation systems using solar energy have greater viability. Thus, scenarios employing solar generation should receive serious attention even though nuclear power may carry fewer costs and risks from an overall engineering perspective. In fact, the true costs for nuclear power are likely unknown as the strict protocols and procedures for its use are likely to add significant mass above what is deemed necessary for less controversial systems.

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[20] The Evolved Mars Base, Section 3.3, assumes separate atmospheres with differing compositions for the crew cabin and the biomass production chamber. Both chambers, however, operate at the same overall pressure.

4 Other Considerations

The information above identifies proposed life support systems for each mission. However, each format presents just a single approach and even these concepts are not sufficiently robust to ensure a high level of mission success. Thus, this section discusses contingency approaches as well as mission concepts that provide variations for the previously presented ideas.

4.1 Contingencies

A wide variety of contingencies are important from a life support perspective. Adequate contingency planning must be performed and implemented for significant failure modes. Some significant concerns already identified, listed alphabetically, are:

- accidents
- environmental hazards
- equipment failure
- excessive consumption
- inadequate performance of life support and related systems
- leakage
- human error

Given sufficient time, accidents are inevitable. Accidents, which directly interfere with life support functions, include puncturing the pressure vessel, fires, and a release of toxins. LSS equipment must be designed to make accidents unlikely, and to limit the severity of accidents when they do occur. A technology that is inherently hazardous will require additional safety precautions, which will generally increase the technology's ESM compared to competing technologies.

Environmental hazards on Mars that could interfere with life support functions, aside from the surface being generally uninhabitable by human beings, would include dust, meteoroid strikes, radiation, and thermal cycling. Dust is almost ubiquitous on Mars. Pathfinder measured deposition rates of 0.3% coverage per day (Appelbaum, *et al.*, 1997) locally at its site in the northern hemisphere. Pathfinder landed during summer in the northern hemisphere, so the local weather at the landing site throughout the 30-day primary mission was characteristic of the clear weather on Mars. Further, the dust may be toxic or corrosive, possibly containing high levels of sulfur trioxide. Dust accumulation will probably occlude solar collectors, windows, and radiators. It blows high into the air, sometimes forming planet-wide dust storms during fall and winter in the northern hemisphere. The thin Martian air will provide some protection from meteoroid strikes, but Mars is closer to the asteroid belt and a greater frequency of strikes might be anticipated than would be seen on Earth with a similar atmosphere. The Martian atmosphere will also provide some protection from radiation, though, again, less than on Earth. Unlike Earth, Mars lacks a strong magnetic field to provide radiation protection. The temperature on Mars ranges from the freezing point of carbon dioxide up to slightly above the freezing point of water. This cycling will stress equipment, and make EVA demanding.

Equipment failure is highly probable on missions of extended duration. While designs should focus on preventing failures, total prevention is unlikely, so failures must be dealt with in planning. Appropriate strategies include redundancy, repair, and replacement. Redundancy, while costly, can be used where continuous functionality is critical or equipment access is problematic. Because the functions provided by many life support systems are not extremely time-critical, repair is likely to be appropriate. Repair will require spares, tools, consumables, and appropriate data and instructions. Replacement of larger units can be more costly than repair, but this approach should be less expensive than extensive redundancy.

Consumption of life support commodities will depend on the physical workload of the crew, as well as possible luxury consumption and wastage. Workload can be approximated from the planned tasks and anticipated difficulty of performing them. However, Mars is a new environment and predictions may be inaccurate due to unanticipated additional tasks or unanticipated effort to perform the listed tasks. While the crew's behavior and capabilities during training may be well known and documented, such information may not predict crew behavior in an unusual environment for a long duration mission. Isolation may, for example, result in overeating. Equipment failures may lead to commodity wastage.

Another issue is that plant production systems may not perform as well in the new environments such as on Mars. To offset any shortages in the production of food or other life support commodities during early missions, the initial plant growth chambers design should support a greater capacity than just the anticipated nominal load. Additionally, stocks of consumable life support commodities could be used to offset any shortages in production from the plant growth chambers. As systems are operated in new and hostile environments, performance cannot be guaranteed. To ensure life support, actual equipment must have the capability to increase its output and offset shortages.

Leakage cannot be addressed by regenerative life support alone, because the lost gas must be replaced either by resupply or local production. Shipment from Earth is costly. Permanent gases in pressure vessels require an additional 36% to 64% mass penalty. ISRU costs and availability depend on the commodity and the source. The composition of and the ability to process the Martian atmosphere are fairly certain. Other potential sources of LSS commodities are not as certain. While large holes in the vehicle hull may not be immediately life threatening, they need to be closed off to prevent unacceptable losses of consumables. Further, as seen on Mir, such holes may be difficult to locate. While a punctured inflatable structure will eventually sag as gas is lost, it will not do so rapidly even when supporting a considerable load so long as the gas bladder material retards rapid crack propagation.

Crew errors are possible and even likely on long-duration missions. The probability of human error increases just due to the inevitable onset of stress associated with isolation. The resulting procedural errors may lead to equipment failures, to commodity loss, and possibly to acute hazards for the crew.

Actual life support designs will most likely use a mixture of approaches to ensure a high availability of life support functions during long duration missions. Contingency approaches will maximize chances of success and minimize the cost of doing so. Different technologies might provide robust redundancy for critical functions. Thus, a mix of supplied commodities, physicochemical technologies, bioregeneration, and ISRU are likely to provide life support contingency capability as well as baseline capability.

4.1.1 International Space Station Contingency Approach

International Space Station plans a 45-day contingency supply of all life support systems commodities (Leonard). ISS carries three oxygen generators, two of which operate at all times. ISS contingency plans would not be economically feasible for long duration missions. This is particularly true, as the criterion for the 45-day contingency duration is a missed resupply. Such an event for a Mars mission would result in a delay of 26 terrestrial months. The specific life support contingency approach for ISS (Leonard) is presented below in Table 4.1. Table 4.2 provides mass estimates for ISS contingency approaches.

Table 4.1 International Space Station Contingency Approach

Function	Redundant Regenerative Approach	Resupply Approach
Carbon Dioxide Removal	Additional CDRA	45-day supply of LiOH canisters.
Oxygen Generation	Additional oxygen generator	45-day supply of bottled oxygen
Trace Contaminant Control		45-day supply of TCCS consumable beds
Food		Additional 45-day supply of food
Water		45-day supply of water
Electrical Energy / Power	Additional short-term energy storage in batteries	
Thermal Control	Thermal control loops are redundant. Both external thermal control loops are sized to transport 80% of the full ISS heat load. Heat acquisition devices for critical systems are served by two thermal control loops.	
General	Over-sized equipment	
Catastrophic Failure Safety	Abort to Earth at any time using crew return vehicles.	

Table 4.2 International Space Station Contingency Analysis

System	Mass [kg]	Rationale	Reference
Air	317.8	0.84 kg/CM-d for consumption for 45 days + 91 kg tankage	
Carbon Dioxide Removal	466	22 LiOH canisters	Lowen
Cabin Pressure	1,307	777 kg for a cabin repressurization + 530 kg tankage	
Clothes	432.9	1.6 kg/CM-d for 45 days	
EVA Support	6.1	3.06 kg per 8 hours of EVA per crewmember for one, 2-crewmember EVA excursion.	
Food	621	2.3 kg/CM-d for 45 days	
Radiation Protection	0	No additional radiation protection is necessary	
Waste Disposal	TBD	Waste disposal depends on availability of Progress spacecraft	
Water	1,890	7 kg/CM-d for drink, food preparation, hand/face washing, and urinal flushing for 45 days	
Total	**5,041**		

Masses are calculated for a crew of six. EVA support would be limited to emergency repair only. The mass given is for one 2-crewmember EVA with a duration of 8 hours.

4.1.2 Advanced Life Support Straw Man Contingency Approach

A key difference between missions to ISS orbit and missions to Mars is that the crew can always leave ISS on short notice using a crew return vehicle, loiter as necessary for orbit phasing, and return to Earth. Such an option is physically impossible from Mars, given the state of our transportation technology. Thus, ensuring high overall reliability and availability for the LSS is even more important.

The approach to contingencies for the Mars Dual Lander Architecture and Mars Split Mission Architecture is as follows:

- The basic life support system provides equipment and consumable commodities to provide complete life support for the crew. The equipment will be designed for repair. Spares are provided for critical pieces of equipment so that there is high confidence that no failures will occur that cannot be repaired on-site with the resources and time available. This approach is expected to include scheduled and unscheduled maintenance, and significant work will be required during design and qualification to estimate sparing, tool, and crew time requirements.
- A contingency energy store to maintain critical life support systems for seven days without additional power generation will be provided.
- To ensure thermal control contingency, a design of multiple cooling loops sized to accommodate greater than nominal heat loads functions to service mission-critical systems, should any single cooling loop fail.
- A seven-day supply of critical life support commodities, such as air and water, is provided as an on-board cache. Such supplies should provide “open-loop” life support capability while the primary systems are repaired. Additionally, all long-duration vehicles are supplied with sufficient gases to repressurize the vehicle once following the complete loss of cabin atmosphere.
- Provide the capability to produce all emergency water and air from ISRU. If the equipment is prepositioned, it should produce and verify a cache of life support commodities before the crew is committed to the mission.
- Clothing quantities are planned for the duration of the mission assuming use of a laundry. If the laundry fails, clothes could be laundered by hand if necessary.
- Prepackaged food, when supplied, is provided for the entire mission plus any feasible extension, perhaps 5%, and for any reasonable long-term consumption rate, such as the nominal rate plus 20%. Thus, food is provided for 125% of the nominal mission. Emergency rations for 100% of the nominal mission are provided in the form of completely shelf-stable, low-mass products and distributed as appropriate to each mission vehicle. In both mission

scenarios, 600-days of contingency rations are provided on board of either the Mars Transit Vehicle or the Earth Return Vehicle in case the crew must abort to Martian orbit or they fail to rendezvous with the landing vehicle. This excess can be jettisoned prior to leaving Mars orbit.

- Support for two, two-person, eight-hour contingency EVA excursions during transit.

This approach provides up to three strings of life support on Mars, depending on the system, but only a single string of life support in transit, though Lin (1997a) proposed a redundant CDRA and short term emergency supplies would be available.

For a mission design with multiple crews using the same facility, such as the Split Mission Architecture or Evolved Mars Base, only contingency and emergency supplies and equipment that are actually used really need to be replaced, assuming such commodities are shelf stable for the duration of the overall mission. However, in actual practice this issue is more complex because transit times between Earth and Mars are significant. For example, using the Split Mission Architecture the first crew does not leave Mars until after the second crew departs from Earth, making it impossible for the first crew to completely account for any contingency supplies it might use on the surface before the second crew leaves.

For a Mars base, the basic life support system provides equipment and consumable commodities providing complete life support for the current crew. In addition to the primary air revitalization and water recovery system, which is the plant growth chamber, secondary systems that provide sufficient air and water for the crew are present in each distinct surface structure.

The plant growth chamber is a special case in that it is too large to duplicate completely. Most likely the plant growth capability will be compartmentalized and oversized so as to maintain 100% of the rated capacity even with one compartment not functioning. While changing the production rate in a plant growth system to add capacity is at best a slow process, other critical LSS equipment will have the ability to provide more than just the nominal commodity production.

Maintaining adequate food production is the critical issue following a failure in a bioregenerative life support system because typical staple crops require two to three months to produce edible biomass. Further, other fairly economic options for air and water regeneration are available. Resupply and overproduction within the plant growth chamber could maintain and replace contingency stores of food, bearing in mind that transportation opportunities from Earth to Mars for resupply occur only once every 26 months. A certain amount of buffering is possible by modulating the rate of oxidation of inedible biomass and other waste products. A bioregenerative LSS is in balance when the oxidation rate for inedible biomass and the crew’s metabolic rate provide sufficient carbon dioxide to support any plant growth. However, the oxidation of waste can be reduced to conserve oxygen while the carbon dioxide required by the plants can be provided from other sources, such as ISRU.

4.1.3 Contingency Issues

Several unanswered contingency issues include:

- What are the radiation levels experienced by crews in Martian orbit should they abort from their surface site to a waiting transit vehicle? The solar intensity at Mars averages 43% of the value at Earth, although Mars does not have a magnetosphere. Contingency food and other masses can provide some protection as radiation shielding. The waste resulting from consuming the food would provide a similar level of protection as the original food, but the risk of biohazards due to inadequate stabilization is a concern. In any case, the level of additional protection would be less than ideal for such a long stay.
- What are the gravitational effects on the crew of aborting to orbit? The 180-day transit is sufficient to raise concerns about physiological deconditioning in weightlessness. An additional 600 days is certain to be of greater concern. However, the crew can spend several hours a day exercising, and the alternative of remaining on the surface with a major system failure would obviously be worse.
- How long can food technology extend the effective life of food systems including prepackaged foodstuffs before the food loses significant nutritional value?
- What additional capability arises from sending multiple missions to the same site? Which strategies for hazard management are most effective in such an environment?

4.2 Potential Additional Scenarios

The scenarios addressed in detail above represent scenarios that have attracted interest among mission planners. While many factors influenced these mission selections from the many possible alternatives, these missions currently have the most detailed supporting documentation and the missions themselves represent a wide range of demanding situations.

Other scenarios that might involve long duration missions include, in no particular order, a return to Luna or long-duration installations on Luna, visits to asteroids, particularly Earth-grazers such as the Apollo and Amor asteroids, a visit to the co-orbital asteroid Cruithne or other destinations at high Earth orbits, and trips to the Martian moons. Trips to comets are probably less likely due to the risk of debris strikes from the comet itself and the high propulsive requirements associated with rendezvous and return to Earth. Venus does not, to date, have any moons and its surface is too inhospitable to be a likely target with current or near-term technologies. Mercury and the outer planets are probably too far away, requiring high-energy propulsion and long transit times. Further, these celestial bodies either exist in or generate too much natural radiation to be likely destinations using current or near-term technologies.

The more probable destinations will be similar to the cases described above in terms of the life support systems, though mission parameters, such as crew size, mission duration, and infrastructure equivalencies, will differ. Such parametric variations could affect the technology selection by favoring different technologies from those selected for the missions above.

For visits to or bases on Luna, the main issues that differ from the Martian scenarios and will impact life support technology selection are:

- The long Lunar nights
- The availability of life support commodities, notably hydrogen, nitrogen, and carbon
- Rejection of life support thermal loads during the Lunar day
- Wide environmental temperature swings
- Dust

For missions in near-Earth space, such as visits to near-Earth asteroids, the co-orbital asteroid Cruithne, and high Earth orbit, or sites on the Martian moons, the main issues that differ from the Martian scenarios above and will impact life support technology selection are:

- Weightlessness
- Mission duration
- Radiation protection

Life support commodities may be available at some near-Earth destinations and on Luna, but the low gravity, high vacuum, and high solar radiation flux will likely boil off volatile compounds at most sites. The asteroids in the main belt, however, are expected to be rich in useful life support commodities like water, methane, carbon dioxide, and ammonia. The near-Earth missions are most similar to the Mars transit scenario described in Section 3.1.1.1. In near-Earth space solar power is available continually and heat rejection is relatively easy. Operations on Luna are a notable exception as identified above. While plant growth is attractive for missions with ready access to continuous sunlight, most of these missions may be too short to benefit significantly from plant growth modules. Longer missions will require more radiation shielding than is noted here and either a form of artificial gravity or more effective countermeasures than currently exist for the physiological changes induced by weightlessness.

Current (Shuttle) missions are restricted to low Earth orbit. While this is below Earth's radiation belts, and thus relatively benign for radiation, natural lighting is blocked by Earth's shadow for 40 minutes out of every 90 minutes. Some terrestrial plants do not react favorably under such light cycling, which limits the applicability of bioregeneration in low Earth orbit. Additional investigation, however, could be useful. Alternatively, one could employ continuous artificial lighting if energy storage is utilized to provide power while the vehicle is in the Earth's shadow, but this adds expense to the plant growth system.

Higher Earth orbits have higher radiation levels. The radiation is markedly higher within the radiation belts, and somewhat higher beyond them. Geosynchronous Earth orbits would be potentially useful for satellite servicing, particularly if satellites continue to grow in size. However, these are within the radiation belts and are unlikely to be used extensively for long-duration human missions any time soon. The Lagrange points, between the Earth and Luna and between the Earth and Sun, are all above the radiation belts. These points would have reduced propulsion requirements for station-keeping compared to other orbits in near-Earth space. They have been suggested as logical places for large-scale habitations for space manufacturing and human colonies. For such facilities, bioregenerative life support would be attractive as sunlight would be readily available, with only occasional interruptions for an eclipse of the Sun.

Luna has local resources for radiation shielding in the form of regolith. Luna also has some gravity, perhaps enough to allow extended missions without permanently disabling the crew. It also is readily accessible with current propulsion technology, with return to Earth in a few days being a viable option from most surface sites. However, it does have an unconventional diurnal cycle, compared to terrestrial standards, and limited quantities of certain critical resources.

Bioregenerative life support could be attractive on Luna for longer missions, but generally would require artificial lighting for most crops during the Lunar night. Notably, however, lettuce would not require significant artificial lighting because most of its vegetative growth takes place during a 14-day period that corresponds to the length of the Lunar day. Plants can withstand fourteen days of darkness or near-darkness (Dougher, *et al.*, 2000), but productivity may drop, increasing the average cost of biomass produced. Algae could also be grown during the Lunar day, but it is not attractive as a major part of a traditional American diet in its natural form.

There is strong evidence recently for the presence of water at the Lunar poles. Such resources could provide useful materials, but it might still be difficult to access and exploit. Conversely, investigating the Lunar water-ice deposits present at the poles and possibly elsewhere on Luna might provide sufficient incentive to return to Luna. Such missions might provide opportunities to test technologies and equipment for the longer and more technically demanding human missions beyond the Earth-Luna system.

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6 Appendices

6.1 Appendix A: Acronyms and Abbreviations

4BMS	four-bed molecular sieve
AAA	avionic air assembly
AES	air evaporation subsystem
A/L	airlock
ALS	advanced life support
APCOS	aqueous phase catalytic oxidation subsystem
Ar	argon
AS	ambient storage
BIO-Plex	Bioregenerative Planetary Life Support Systems Test Complex
CCAA	common cabin air assembly
CDRA	carbon dioxide removal assembly
CM-d	crewmember day
CO	carbon monoxide
CO_2	carbon dioxide
Cond. HX	anti-microbial condensing heat exchanger
CrO_3	chromium oxide
CRS	carbon dioxide removal subsystem
CTSD	Crew and Thermal Systems Division at Johnson Space Center
DHU	distribution and heating unit
EATCS	external active thermal control subsystem
ECLSS	environmental control and life support systems
EEATCS	early external active thermal control subsystem
EMU	extravehicular mobility unit
ESM	equivalent system mass
ETCS	external thermal control subsystem
EVA	extravehicular activity
FDS	fire detection and suppression
FHRC	flex hose rotary coupler
GA	gas analyzer
G/L	gas/liquid
H_2	hydrogen
H_2O	water
H_2SO_4	sulfuric acid
HCF	harmful contaminants filter
HEPA	high efficiency particulate air
HP	high-pressure (gas)
HX	heat exchanger
ISRU	in situ resource utilization
ITCS	internal thermal control subsystem
ISS	International Space Station
IX	ion exchange
JSC	NASA Johnson Space Center
kg	kilogram (mass)
kPa	kilopascal (pressure)
kW	kilowatt (power or thermal load)
kW_e	kilowatt-electric (electrical power)
LiOH	lithium hydroxide
LSS	life support system
LTL	low temperature loop
m^3	cubic meters (volume)
MCA	major constituent analyzer
MCV	microbial check valve
METOX	metal oxide
MF	multifiltration
MFU	multifiltration unit
MLS	mostly liquid separator
MTL	moderate temperature loop
N_2	nitrogen
NASA	National Aeronautics and Space Administration
NH_3	ammonia
NH_4^+	ammonium
NO_2^-	nitrite
NO_3^-	nitrate
O_2	oxygen
OGA	oxygen generation assembly
PCWQM	process control water quality monitor
PhOx	photo-oxidation (unit)
RFR	refrigerator freezer rack
RMD	Reference Missions Document
RO	reverse osmosis
RS	Russian Segment
SAVD	solid amine vacuum desorbed
SIMA	Systems Integration, Modeling, and Analysis
TBD	to be determined
TCCS	trace contaminant control subsystem
TCS	thermal control subsystem
USOS	United States On-orbit Segment
VCD	vapor compression distillation
VCRFR	vapor compression refrigerator freezer rack
VPCAR	vapor phase catalytic ammonia removal CWRS condensate water recovery subsystem
VRA	volatile removal assembly
WCU	water conditioning unit
WRS-CM	water recovery system from condensate
WRS-UM	water recovery system from urine
WW	wastewater

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