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MARS LIFE SUPPORT SYSTEMS

Donald Rapp[1]

[1] *Independent contractor, 1445 Indiana Avenue, South Pasadena, CA 91030, USA, drdrapp@earthlink.net*

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Abstract

Background: A critical element of planning human missions to Mars involves life support systems. The amount of air, food, water and waste disposal materials actually consumed in human missions to Mars will total well over 100 metric tons and possibly as much as 200 metric tons. If recycling is not employed, this will translate back into an equivalent mass required in low Earth orbit whereby this figure would increase by at least a factor of seven, depending on mission architecture, requiring at least half a dozen heavy-lift launches solely for life support, and thus driving the cost and complexity of human missions to Mars beyond any reasonable limit. Recycling and possibly in situ utilization of indigenous Mars water resources are therefore critical enabling capabilities for human missions to Mars. Previous "design reference missions" assumed that high-performance life support systems would function flawlessly for the ~ 2.7 year round trip to Mars. However, life support systems developed for the International Space Station do not appear to have the longevity and reliability needed for Mars. As NASA moves forward with the current human exploration initiative, we need some means of estimating the required mass of life support system that goes beyond wild optimistic guesses. NASA's Advanced Life Support (ALS) project has been advancing the technology of recycling of water and air resources ("environmental control and life support systems) in human space missions for some time. Emphasis has been placed on recovery percentage and trace contaminant removal.

Method: Mass estimates for physical plant and back-up caches are provided by NASA. A critical review was carried out based on NASA reports dealing with life support systems and these were judged in the context of "design reference missions" for humans making the round trip to Mars.

Conclusion: ALS estimates of masses of life support systems are based on research and analysis, but the sources of reported performance data are not traceable to experimental data, and the reliability and lifetime of these systems is very uncertain. These estimates are optimistic, and when translated into engineering systems requiring margins, spares and fail-safe performance, are likely to increase significantly. Nevertheless, even these optimistic estimates require a significant initial mass in low Earth orbit for life support, estimated as 240 metric tons. Life support remains at best, a significant mass, cost and risk factor for human missions to Mars, and at worst a major show stopper.

Introduction

The NASA Exploration Systems Architecture Study (ESAS) Final Report (Anonymous 2005) briefly outlines a design reference mission (DRM) for human exploration of Mars. This DRM concept is based to some extent on the DRM previously developed by NASA-JSC known as "DRM-3" (Drake 1998) that was a modification of a previous NASA-JSC DRM known as "DRM-1" (Hoffman and Kaplan 1997). This was followed by the so-called "Dual-Landers" DRM, but the ESAS has indicated that it is relying on DRM-3. In addition, independent Mars DRMs were developed by Robert Zubrin ("Mars Direct") and the Mars Society led by James Burke.

Life support during the three major legs of the mission (transit to Mars, surface stay, and return to Earth) poses major challenges for human missions to Mars. The estimated amount of consumables used by a crew of six for a round trip to the surface of Mars exceeds 100 metric tons (mT) and may be as much as ~200 mT. This would require roughly 7 to 14 launches with a heavy-lift launch vehicle (125 mT to low Earth orbit (LEO)) just to provide life support if neither recycling nor use of indigenous water from Mars were used. Clearly, life support is critical for human missions to Mars, and recycling and possibly use of indigenous Mars water resources are necessary elements of any rational plan to make such missions feasible and affordable. Unfortunately, none of the DRMs dealt with life support in any detail and it is impossible to derive reliable estimates of life support masses from these studies. Therefore it is appropriate to review the available data on life support technology with the goal of providing more reliable estimates of required life support masses for human missions to Mars to support future DRM development.

Life support, as defined by the NASA Advanced Life Support Project (ALS), includes the following elements:

- Air
- Biomass
- Food
- Thermal
- Waste
- Water

Each of these elements interacts in a comprehensive overall system that maximizes recycling of waste products. These systems are complex and highly interactive.

Not only must the life support system (LSS) provide the gross requirements for these elements, but it must also monitor trace contaminants and remove them to an acceptable level. It is also worth noting that reduction/ elimination of pollutants from air and water, even trace amounts of some pollutants, occupies a great deal of attention in various ALS reports, whereas the simple macroscopic mass balances do not get as much attention. Obviously, pollutant control is a vital part of an ECLSS system, but ultimately, resources must be supplied, a physical plant is required, a back-up cache is needed, and these masses must be estimated in order to plan a mission. Extracting such data from ALS reports is not always straightforward. However, from the ALS point of view, the simple macroscopic mass balances (and to some extent the energy balances as well) are well understood by the System Integration, Modeling and Analysis (SIMA) element within NASA and they are implemented in software tools such as the MS Excel-based Advanced Life Support Sizing Analysis Tool (ALSSAT). In other words, mass balances are regarded as a solved problem by the ALS. Nevertheless, it is argued here that the overall consumption of life support consumables defines the scope of the problem and ought to be repeated in each progress report.

Most of the available reports provide system estimates of masses for the various elements of the LSS. The basic element masses are listed, as well as "equivalent system masses" (ESM) that include additional mass to account for the required power system, thermal system and human oversight requirements associated with operation of the LSS. There are a number of reports, but these tend to be overlapping, and in some cases they are yearly updates of previous versions. As is typical at JSC, the actual work on LSS is contracted out. Most of the LSS reports were edited by Dr. Anthony J. Hanford. Dr. Hanford does a good job of reporting the ALS estimates of LSS masses although the actual experimental basis for the reported numbers remains unclear. ALS is working on this problem.

The ALS data are reported in two segments. One segment is claimed to be "state of art" based on "the International Space Station (ISS) Upgrade Mission" and the other segment is for an "Advanced Life Support" system (ALS) that is based on advanced technologies currently under development within NASA. It is claimed that only technologies at NASA TRL 5 or greater are included in the assessments. The ALS reports provide the reader with sets of numbers. However, the connection between the baseline data in the reports and actual experience with the ISS is very difficult to discern. It is not clear how much experimental data underlie the tables, and how much data are estimated from modeling. Nor is it clear whether these systems are reliable for the long transits and surface stays of Mars missions. Lifetimes and mean time between failures does not get much mention in this work.

A recent report (Sanders and Duke 2005) indicates that: "Experience with Mir, International Space Station (ISS), and Shuttle, have shown that even with extensive ground checkout, hardware failures occur. For long duration missions, such as Mir and ISS, orbital replacement units (ORUs) must be stored on-orbit or delivered from Earth to maintain operations, even with systems that were initially two-fault tolerant. Long surface stays on the Moon and Mars will require a different method of failure recovery than ORU's." This might add to the required back-up cache and/or require some spares or redundant units that would double (or more) the mass of the system. Obviously, long-term testing is needed here. Sanders and Duke (2005) emphasize the need for ISRU as a back-up for a Environmental Control and Life Support System (ECLSS), pointing out the unreliability of ECLSS. It is also interesting that the ALS appears to be rather cautious regarding the potential for widespread indigenous Mars water resources to impact life support on Mars, despite the fact that this impact could potentially be a major benefit in mass reduction and safety. Admittedly, acquisition of such water resources will require sophisticated machinery and there are concerns regarding planetary protection. Nevertheless, this aspect would seem to deserve more attention in ALS activities.

ALS has provided tables of data on estimated masses for LSS, but without a strong connection to experimental data and validation, these data are of uncertain validity. There is an Advanced Life Support Project with participating NASA field centers, Ames Research Center (ARC), Kennedy Space Center (KSC), Marshal Space Flight Center (MSFC) and the Johnson Space Center (JSC) serving as the lead center. This project is supposed to carry out simulation tests of closed LSS with humans in chambers. However, documentation of this project is lacking. In fact, no experimental data are available, although the usual extensive set of goals and objectives are well documented (Anonymous 2002).

It is difficult to judge the veracity of the data presented by ALS. In the present paper, primary emphasis is placed on "state of the art" technologies, but even these lack a direct connection to experimental performance data, and data on reliability and lifetime are unavailable.

A set of tenets for engineering of life support systems is provided by Graf, Finger and Daues (2002). However, these tenets apply more directly to flight hardware systems than they do to advanced technology. It is noteworthy that all of the mass estimates provided by the ALS are from the research arm of NASA, and they do not include allowances for margins, redundancy or spares. Furthermore, as stated previously, there is essentially no discussion of lifetimes and longevity of systems in these reports.

Fundamental Consumption Requirements

Fundamental design values are presented by Hanford (2004B). These values represent the current best estimates for various parameters based on an assemblage of data, analysis and experience. All subsequent reports are based on the values provided by Hanford (2004B). This report is the Advanced Life Support (ALS) Baseline Values and Assumptions Document (BVAD) that is aimed at providing analysts and modelers with a common set of initial values and assumptions, i.e., a baseline. The BVAD identifies specific physical quantities that define life support systems from an analysis and modeling perspective. For each physical quantity so identified, the BVAD provides a nominal or baseline value plus a range of possible or observed values. Finally, the BVAD claims to "document each entry with a description of the quantity's use, value selection rationale, and appropriate references." Unfortunately, it is difficult to determine the underlying basis of specific numbers presented in this report, as to what is based on experiment, what is estimated by analysis, and how well these figures apply to a system that is reliable for a lengthy Mars excursion. Nevertheless, the following requirements are based, at least partly on this report.

Oxygen Consumption Requirements

Hanford (2004B) provides data for oxygen consumed (kg/CM-d) as ranging from 0.385 (minimum) to 0.835 (nominal) 1.852 (maximum). The origin of these numbers is not completely clear. No data seem to be given on requirements for buffer gas. Lange et al. (2003) provide the data in Table 1A. The round figure of 1 kg/CM-d for oxygen seems to be widely accepted for planning purposes.

Water Consumption Requirements

For short-duration lunar missions of 30 days or less, they indicate a *water usage rate* in kg/CM-d ranging from 2.9 (minimum), to 4.5 (nominal), to 7.7 (maximum). The basis for these figures is cited as a "personal communication from Ewert and Drake in 2000."

Water usage on planetary bases are provided in Table 1B. The figures in Table 1B for a long-term base are in a range that seem to be widely used. Note however, that a shower is allocated 5.4 kg and this equals 5.4 liters, which is a rather quick sparse shower. There may be ways to reduce the need for water compared to Table 1B. For example, one might use throw-away clothing and paper plates. However, these would add significantly to the volume requirements, and when recycling of water is taken into account, the net benefit of such changes will decreases substantially or possibly even go negative.

Table 1A. Oxygen consumption requirements. (Lange et al. 2003).

Category	Oxygen Requirements: [kg/(person-day)]
Low Activity Metabolic Load	0.78
Nominal Activity Metabolic Load	0.84
High Activity Metabolic Load	0.96
5th Percentile Nominal Female	0.52
95th Percentile Nominal Male	1.11

Table 1B. Water consumption requirements (kg-CM-day). (Hanford 2004B).

Water Need	Short Term Landed Base	Long Term Landed Base
Crew Drinks	2.00	2.00
Shower (one per two days)	2.72	2.72
Urinal Flush	0.50	0.50
Oral Hygiene	0.37	0.37
Hand Wash	4.08	4.08
Laundry	n/a	12.47
Dish Wash	n/a	5.44
Food Processing and Preparation	TBD	TBD
Total Hygiene Consumption	7.67	25.58
Metabolic and related consumption	2.0	2.0
Total Water Consumption	9.67	27.58

Waste Disposal Materials Requirements

Wastes include crew metabolic wastes, food packaging, wasted food, paper, tape, soiled clothing, brines, inedible biomass, expended hygiene supplies, and equipment replacement parts from the other subsystems. Current NASA spacecraft waste-handling approaches essentially rely on dumping or storage of wastes.

Hanford (2004B) refers to historical waste data from Skylab and the Shuttle. For longer-term Mars missions, this report says:

"Waste treatment and removal for missions to Mars and other likely near-term destinations will be more challenging due to the longer mission duration regardless of complications from the environment. Waste management for such missions may employ more efficient versions of technologies developed for Shuttle and ISS, or completely different approaches may be more cost effective. Future missions may also generate significant amounts of inedible biomass. In later or far-term missions, inedible biomass may dominate all other trash sources.... Though unavailable here, waste volumes can be significant.... Because many spacecraft [ECLSS] systems routinely replace parts [e.g. filters] during scheduled maintenance on long-duration missions, a comprehensive list of wastes is contingent upon the hardware and configurations used throughout the vehicle.... The degree of confidence in data values is highly variable and often unknown. In some cases, data have not been diligently collected, and mass estimates are included. In other cases, the values are contingent upon environmental variables...."

Solid waste management for future long-duration missions requires consideration of:

- Feces
- Urine
- Menstruation
- Paper
- Miscellaneous Body Wastes
- Consumable Hygiene Products
- Food Packaging, Inedible Biomass, and Wasted Food
- Paper, Tape, Hygiene Products, and Clothing
- Grey water and Brine
- Other Waste Streams

While Hanford (2004B) provides estimates of these waste streams, it is not clear how much materiel must be brought on board specifically for collection and storage of waste materials. The discussion of waste treatment is difficult to comprehend. According to ALS, waste disposal on long-duration missions is still under study. Table 1C provides a very crude estimate.

Table 1C. Fundamental Consumption Requirements for Mars Surface Habitat (kg/CM-day).

	Hanford (2004A)	Hanford (2005)	Hanford (2004B)	This paper
Oral Hygiene Water	0.363	0.363	0.37	
Hand / Face Wash Water	4.082	4.082	4.1	
Urinal Flush Water	0.494	0.494	0.5	
Laundry Water	12.474	12.474	12.5	
Shower Water	2.722	2.722	2.7	
Dishwashing Water	0	0	5.4	
Drinking Water	2.000	2.000	2.0	
TOTAL WATER	**22.1**	**22.1**	**27.6**	**30.0(a)**
OXYGEN			**0.84(b)**	**1.0**
BUFFER GAS (N2?)			**2.1(c)**	**3.0**
FOOD			**(d)**	**1.5**
WASTE DISPOSAL MTLS				**0.5**

(a) Potable = 4 and wash = 26, (b) Range depends on metabolic rate, varies from 0.39 to 1.85, (c) Buffer gas requirement was not specified. However, cabin pressure and oxygen partial pressure were specified and based on that, I estimated the buffer gas requirement. Buffer gas requirements depend on the vehicle leakage rate, both through seams and from airlock operations. (d) The discussion of food in Ref. 3 was extensive, tedious and confusing and it was difficult to extract a specific requirement.

Summary of Consumption Requirements

Consumption requirements are summarized in Table 1C. These consumption requirements are independent of any recycling that might be employed to reduce the mass brought on the mission. As Table 1C shows, subsequent reports utilized the same values as given in Hanford (2004B), although it is not clear why Hanford (2004A) and Hanford (2005) left out dishwashing water. In addition, Lange et al. (2003) provide additional details on oxygen requirements (Table 1A). The far right column of Table 1B was derived by averaging several unpublished reports, compendia and textbook recommendations.

Characterizing LSS for a Human Mission to Mars

In order to characterize LSS for a human mission to Mars, a first step would be to catalog the inventory of consumables that must be consumed on each leg of the trip to support a crew of six, assuming no ECLSS. One should tabulate how much food, water (various qualities), oxygen, nitrogen and waste disposal materials are consumed, first on a per-crew-member-per-day basis, and then for the whole stay for a crew of 6. This basic information is not presented in any of the ALS reports.

The mass of the physical plant needed to supply the consumables must be estimated for each ECLSS system under consideration, as well as the recovery percentages for the air and water systems. From the recovery percentage, one can calculate the size of the back-up cache needed for replenishment of lost resources during recycling. Then, for each of the air and water systems, five quantities would be reported:

1) The total mass of the resource consumed for crew of six over 600 days (MT).

2) The mass of the physical plant (MPP)

3) The recovery percentage (RP)

4) The mass of the back-up cache for replenishment:

MB = (100 - RP) MT/100

5) Total mass of the LSS that supplies MT of resource:

MLS = MPP + MB

A useful figure of merit is the ratio *MLS/MT* that specifies the total mass of the system per unit mass of resource consumed.

In addition to these performance estimates, the reliability and longevity of such systems should be discussed, and additional mass provided for margins, spares, and redundancy, as needed.

Finally, the potential impact of utilizing indigenous water on Mars for surface systems should be considered and incorporated into plans as appropriate.

ALS Estimates of LSS Mass for Mars Missions

Introduction

Hanford (2005) presents a considerable amount of relevant data but the source of the data is not indicated. Hanford's data are separated into two groups, one for "state of art" based on "the ISS Upgrade Mission" and the other for an "Advanced Life Support" system (ALS). In the present paper, only "state of art" data are utilized.

Hanford (2004A) appears to be an earlier version of Hanford (2005) but it is interesting that Hanford (2004A) provides recovery percentages whereas Hanford (2005) merely indicates that recovery is high. For each of the three Mars vehicles, Hanford (2004A) says:

"Urine is processed by vapor compression distillation. Eighty-eight percent water recovery is claimed. The brine is dumped or placed in waste storage. All grey water, including hygiene water, effluent from the vapor compression distillation, and condensate from dehumidification, is processed through a water processor. The water processor employs two multi-filtration units, a volatile removal assembly, phase separators, and an ion exchange bed. A process control water quality monitor provides water quality assurance. Efficiency of recovery is high, but many expendables, mostly filter cartridges, are needed."

Hanford (2005) also provides the following caveats:

"This type of analysis includes several inescapable sources of variation from actual flight systems. (1) These estimations fail to consider contingency or redundancy in any detail. (2) All calculations above use only single-string life support system architecture. (3) The preliminary nature of the data employed for the advanced equipment."

LSS Data for Mars Missions

The results of Hanford (2005) for a (two-way) Mars Transit Vehicle, a Mars Ascent/ Descent Lander, and a Mars Surface Habitat Lander for a crew of six are summarized in Tables 2, 3 and 4, respectively.

Table 2. Total Mass of ECLSS System for *Mars Transit Vehicle* using Baseline ECLSS Technologies. ESM is equivalent system mass including estimates of mass for power system, cooling and crew time. (360-day duration - crew of six) (Hanford 2005)

Subsystem / Interface	M kg	V m^3	P kWe	C kWth	CT CM-h	ESM kg
Air	2190	3.3	4.2	2.7	12.8	3334
Biomass	761	17.0	6.1	6.1	0.0	2607
Food	2840	13.1	1.9	1.9	0.0	3475
Thermal	329	1.0	0.9	0.9	2.0	586
Waste	382	9.7	0.0	0.0	0.0	475
Water	3353	5.5	1.1	1.1	0.0	3715
Extravehicular Activity Support	0	0.0	0.0	0.0	0.0	0
Human Accommodations	1763	6.9	0.0	0.0	0.0	1826
Totals	11617	56.6	14.2	12.7	14.8	16018

M = mass, V = volume, P = power, C = cooling, CT = crew time and ESM = equivalent system mass.

The masses provided in Tables 2, 3 and 4 are total, including both the ECLSS and a back-up cache to account for the fact that recovery is not 100%. To distinguish between the physical plant and storage, additional detailed data are required, and this is shown for the Mars Transit Vehicle in Tables 5 and 6. Similar data were available for the other vehicles. Note in Tables 5 and 6, that Hanford (2005) did not distinguish between the mass of the storage tank and the mass of the resource stored within the tank. Therefore it is difficult to infer the mass of the back-up cache in these systems.

Table 3. Total Mass of ECLSS System for *Mars Ascent/Descent Lander* using Baseline ECLSS Technologies. ESM is equivalent system mass including estimates of mass for power system, cooling and crew time. (30-day duration - crew of six) (Hanford 2005)

Subsystem / Interface	M kg	V m^3	P kWe	C kWth	CT CM-h	ESM kg
Air	1071	2.16	4.251	2.742	1.07	2586
Biomass	0	0.00	0.000	0.000	0.00	0
Food	620	3.37	2.128	2.128	0.00	1638
Thermal	296	0.92	0.822	0.822	0.17	665
Waste	69	1.02	0.014	0.014	0.00	142
Water	737	2.88	0.896	0.896	0.00	1263
Extravehicular Activity Support	22	0.25	0.000	0.000	0.00	38
Human Accommodations	188	0.65	0.000	0.000	0.00	231
Totals	3001	11.25	8.111	6.602	1.24	6560

M = mass, V = volume, P = power, C = cooling, CT = crew time and ESM = equivalent system mass.

Table 4. Total Mass of ECLSS System for *Mars Surface Habitat Lander* using Baseline ECLSS Technologies. ESM is equivalent system mass including estimates of mass for power system, cooling and crew time. (600-day duration - crew of six) (Hanford 2005)

Subsystem / Interface	M kg	V m^3	P kWe	C kWth	CT CM-h	ESM kg
Air	4195	5.52	5.847	3.732	21.30	5315
Biomass	898	17.03	6.099	6.099	0.00	2469
Food	7580	38.39	4.272	4.272	0.00	8923
Thermal	382	1.17	1.032	1.032	3.33	636
Waste	668	17.66	0.014	0.014	0.00	833
Water	10380	9.82	1.285	1.285	0.00	10768
Extravehicular Activity Support	1292	2.91	2.500	2.500	0.00	1899
Human Accommodations	2938	11.45	0.000	0.000	0.00	3043
Totals	28333	103.95	21.048	18.934	24.63	33900

M = mass, V = volume, P = power, C = cooling, CT = crew time and ESM = equivalent system mass.

An overall comparison of data from Hanford (2005) and Hanford (2004C), including a breakdown of masses for storage vs. physical plant is provided in Table 7. The ALS does not calculate the total amount of resource that would be required if there were no recycling. Therefore the data in the requirements column were estimated herein. Table 7 shows that ALS has continued to refine their models, with the trend being downward. Table 7 also indicates that the estimated mass of the air and water systems are far lower than the total amounts of these resources consumed, implying a high recovery rate.

Table 5. Mass breakdown for *air* system in Mars Transit Vehicle. (Hanford 2005)

Air Subsystem	**2190.10**
Atmospheric Control System	
Atmospheric Pressure Control	119.40
Atmosphere Revitalization System	
Carbon Dioxide Removal	179.12
Carbon Dioxide Reduction	0.00
Oxygen Generation	379.16
Gaseous Trace Contaminant Control	85.81
Atmosphere Composition Monitoring Assembly	54.30
Sample Delivery System	35.11
Airlock Carbon Dioxide Removal	0.00
Gas Storage	
Nitrogen Storage	1,028.73
Oxygen Storage	300.17
Fire Detection and Suppression	
Fire Detection System	1.50
Fire Suppression System	6.80

Table 6. Mass breakdown for **water** system in Mars Transit Vehicle. (Hanford 2005)

Water Subsystem	**3353.03**
Urine / Waste water Collection System	**4.55**
Water Recovery System	
Water Treatment Process	2,463.74
Urine, Hygiene & Potable Water, & Brine Storage Tankage	181.57
Microbial Check Valve	5.72
Process Controller	36.11
Water Quality Monitoring	14.07
Product Water Delivery System	51.73
Water Storage	
Hygiene Water Storage	0.00
Potable Water Storage	595.54
Urine Storage	0.00
Waste water Storage	0.00

Implied Recovery Efficiencies

Because Hanford (2005) does not provide the overall consumption levels that need to be supplied, it is not clear from his tables what recovery percentages are implied. Therefore, Table 8, 9 and 10 were prepared herein as companions to Tables 2, 3, and 4, respectively, using estimated values for the total requirement. The 2nd columns of Tables 8, 9 and 10 present the mass data for the physical plant from Hanford (2005). The 3rd columns present the masses allocated by Hanford (2005) to water or air storage. It is not clear what fraction of these values represents water and air, and what fraction represents tankage mass. If we assume that these quantities are all air and water (defined as *MB*) and neglect tankage mass, we can calculate a lower limit to the recovery percentage:

$$RP = 100\,(MT - MB)/MT$$

where *MT* the total amount of resource required and is provided in columns 4 of Tables 8, 9 and 10 from estimates made herein (the lower values in the ranges were used). The recovery percentages *(RP)* are given in column 5 of these tables.

For air and water, the results for recycle percentages and ratios of ECLSS system mass to required resource mass are summarized in Table 11. For the Mars Ascent/Descent Lander, the required ECLSS air system seems to be much heavier than the required air mass. This may be due to the heavy mass of tankage and limited recycling on this vehicle but it is still difficult to understand. In general. the mass of the air supply system is a much higher percentage of the required resource mass than the comparable ratio for the water system.

Trade Analysis

Anderson (2004) carried out system trade comparisons of alternative water recovery systems. It is claimed that the baseline ISS water recovery system "achieves approximately 95% total recovery." This reference compared the "Integrated Water Recovery System" (IWRS) and the "Vapor Phase Catalytic Ammonia Removal System" (VPCAR) with the baseline. The IWRS and VPCAR system are claimed to achieve 98% water recovery.

After a mass estimate for a system was prepared, it was multiplied by a factor to account for the mass due to components such as lines, packaging or acoustic enclosures, brackets, bolts, and other miscellaneous hardware used to install the ECLSS system into a vehicle. Based on limited data, they used a factor 1.6 for the IWRS and 1.4 for the VPCAR.

For the 360-day Mars transit mission it was estimated that wastewater production from a crew of six is 29 kg/day. Wastewater was included from urine, flush water, condensate, and water recovered from CO_2 reduction in a Sabatier reaction. For a 500-day surface habitat with crew of six, it was estimated that the total wastewater load was 77 kg/day. This included wastewaters from urine, flush-water, oral hygiene, hand-wash and face-wash, shower, as well as condensate water and water recovered from a Sabatier reaction. Apparently, it was assumed that for the two 180-day transfers to and from Mars, there would be no oral hygiene, hand-wash, face-wash, or showers, which may not be realistic. Our estimate for a crew of six for either vehicle is 6 x 30 = 180 kg/day. Hanford (2005) would have estimated about 132 kg/day and Hanford (2004B) would have estimated about 166 kg/day. The figures given by Anderson (2004) appear to be unusually low.

The equivalent system masses estimated by Anderson (2004) for water processing units are in the range around 1800 kg for Mars transit and 4500 kg for the surface habitat, using IWRS or the baseline ISS system. With the VPCAR, these masses drop roughly in half. These estimates are considerably more optimistic than those of Hanford (2005).

Requirements Document

Lange et al. (2003) specifies that hygienic water amounts to 2.84 kg/person per day. This reference provides more details in regard to air, and their data are reproduced here as Table 1C.

Advanced Life Support Project

ALS has embarked on a program to acquire relevant data via the Advanced Life Support Project.

The Lunar-Mars Life Support Test Project (LMLSTP) consisted of a series of closed-chamber, human tests that demonstrated operation of closed-loop life support systems for increasingly longer durations. The final test in the series, the Phase III test, incorporated the use of biological systems as well as physicochemical (P/C) life support system technologies to continuously recycle air, water, and part of the solid waste stream generated by a four-person crew for 91 days (Anonymous 2002).

According to this report, the Phase III test was conducted using two environmental test chambers at the National Aeronautics and Space Administration's (NASA) Johnson Space Center (JSC). The Integrated Life Support Systems Test Facility (ILSSTF) housed the crew as well as most of the life support systems. This chamber was integrated with the Variable Pressure Growth Chamber (VPGC) in which wheat was grown to provide supplemental food and air revitalization for the crew during the test. The human portion of the test began on September 19, 1997, and ended on December 19, 1997, with a duration of 91 days. The wheat crop was initially planted on July 23, 1997, and the final harvest was on January 9, 1998.

The Phase III test was the first test conducted by NASA integrating human test subjects with biological and P/C life support systems. This integration was accomplished in four distinct ways. First, the CO_2 generated by the crew in the ILSSTF was separated from the atmosphere, concentrated, and used by wheat in the VPGC as the major source of CO_2 for photosynthesis. In tandem with this process, 95% of the O_2 produced by the wheat plants was separated, concentrated, and used by the crew during respiration. On average, the plants consumed CO_2 and generated O_2 equal to that required by one crew person over the course of the test. The remaining three person-equivalent's worth of CO_2 removal and reduction and O_2 production was accomplished with P/C systems.

The second biological and P/C integration involved the Water Recovery System (WRS). The WRS processed 111 kg of waste water each day, equivalent to the daily requirement for a crew of four. Bioreactors were used as the primary treatment step for the combined waste water stream generated by the crew's showering, hand washing, clothes washing, and urination as well as humidity condensate from the chamber. These bioreactors depended on microbial species to oxidize organic carbonaceous and nitrogenous materials in the waste water. These bioreactors were integrated with P/C subsystems, which removed inorganic salts and performed final polishing of the water before being reused by the crew. The initial 8-day supply of water cycled though the chamber and the crew 10 times. No additional water was required during the test.

The third biological and P/C integration method pertained to the Solid Waste Incineration System (SWIS) and the wheat plants. The crew's fecal material was incinerated in a fluidized bed incinerator. Oxygen required for the combustion of the fecal material was provided from the O_2 produced by the wheat plants. The CO_2 produced as a result of the incineration reaction was used as a second source of CO_2 for wheat photosynthesis. The test utilized a hierarchical control system for handling the competition for resources. This competition is inevitable when biological systems, which operate continuously, are used to provide the life support function for a crew. Wheat was harvested periodically throughout the test and after drying, threshing, and milling, the wheat flour was provided to the crew to bake bread in the ILSSTF. The wheat provided less than 5% of the crew's caloric intake during the course of the test.

The final biological and P/C integration method was the incorporation of a small chamber to grow lettuce within the ILSSTF. This chamber was able to provide 4 heads of lettuce for the crew approximately every 11 days.

The test was claimed to be very successful in integrating biological and P/C life support system technologies for long-duration life support. The use of a biologically based WRS demonstrated the operation of a system that recovered essentially 100% of the influent waste water for reuse. In addition, the first step in recovering useful materials from the crew's fecal material was demonstrated in an integrated system. Future testing would be aimed at developing these capabilities to bring about closure of the food and waste loops using regenerative life support technologies.

These tests appear to have been a good start, but only a first step toward proving that an ECLSS for Mars is feasible. In 2002, this work seems to have evolved into another program called the Advanced Life Support Project. A Plan for this project is available on the ALS web site (Anonymous 2002). The plan seems very ambitious. However it is not clear how much progress was made since the plan was published 4 years ago.

Required Mass in Low Earth Orbit

In planning design reference missions, an important consideration is the required initial mass in low Earth orbit (IMLEO). The required IMLEO for any mass that must be used in transit to Mars, on the surface of Mars, or in return from Mars can be estimated from the mission architecture using the rocket equation for propulsion steps, and taking into account aero-entry where appropriate. A simple calculation based on use of H_2-O_2 propulsion for Earth departure and CH_4-O_2 propulsion thereafter, along with full aero-assist for Mars orbit insertion and Mars descent, leads to the following approximate results for the ratio of IMLEO to the transferred payload mass:

- Mass utilized on outward leg toward Mars: 2.8
- Mass utilized in Mars orbit: 3.9
- Mass utilized during descent or on the surface of Mars: 5.5
- Mass used during ascent: 21.5
- Mass utilized on return leg from Mars: 15.2

According to Table 12, the ALS estimates for the LSS masses (outbound, during descent, on the surface, during ascent and inbound) are 5 mT, 1 mT, 22 mT, 1 mT and 5 mT, respectively. The equivalent IMLEO values are 14 mT, 6 mT, 120 mT, 22 mT, and 75 mT, respectively, for a total IMLEO of ~240 mT.

Indigenous Water on Mars

As Table 12 shows, the largest single LSS mass is that required to supply water to a crew of six for up to 600 days on the surface of Mars. The ALS does not seem to have addressed the possibility of utilizing indigenous water from Mars that in principle could eliminate the need to recycle water and oxygen while on the surface. Feldman, et al. (2004) have demonstrated the widespread occurrence of near-surface water on Mars by remote sensing with a neutron spectrometer, and this observation is supported by numerous theoretical studies such as that of Schorghofer and Aharonson (2005).

Summary and Conclusions

The requirements for life support for the lengthy excursions involved in Mars missions require further study. It is likely that requirements will be more demanding than those for the limited periods involved in ISS or lunar sorties. Table 1C provides some rough guesses estimates of consumption requirements for life support that can be used for purposes of early planning.

When combined with the durations involved, these levels of individual consumption requirements lead to predictions of macro consumption requirements for a crew of six over Mars mission segments shown in column 3 of Table 12. Table 12 also provides ALS estimates of the masses of systems to provide these consumption requirements. However, the underlying experimental basis for the ALS estimates in Table 12 in terms of experimental data are unclear. Of particular concern is the need for fail-safe systems on missions to Mars that are not amenable to repair using orbital replacement units. As Hanford (2005) said:

"This type of analysis includes several inescapable sources of variation from actual flight systems. (1) These estimations fail to consider contingency or redundancy in any detail. (2) All calculations above use only single-string life support system architecture. (3) The preliminary nature of the data employed for the advanced equipment."

According to Table 12 the required LSS for a round trip Mars mission is about 32 mT, and as mentioned previously, this requires an initial mass in LEO of ~240 mT. But this is an optimistic estimate based on the lower requirements in column 3 of Table 12. Furthermore when contingency and redundancy requirements are taken into account, this is likely to increase considerably.

Use of indigenous water on Mars may provide significant mass savings as well as great risk reduction.

It is hoped that in the future, the ALS will:

(1) Concentrate on systems with very high reliability for long durations rather than systems with very high recovery percentages. For Mars, a LSS with 90% recovery and 99.8% reliability would be far more valuable than one with 99.8% recovery and 90% reliability.

(2) Provide clearer delineation of data sources with particular emphasis on which data are based on experiment, and what the duration of the experiments were.

(3) Give more attention to use of the widespread near-surface water resources on Mars.

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Table 7. ALS estimates of system and storage masses for Mars human missions.

	Resource	Requirement (kg)	Hanford (2005)		Hanford (2004C)	
			System	Storage	System	Storage
Mars Transit Vehicle	air	6500-8700	864.5	1328.9	876.1	1339.9
	water	47,500-65,000	2762.5	596.0	1980.6	606.7
Mars Ascent/ Descent Lander	air	540-720	809.5	263.3	859.9	270.1
	water	4000-5400	648.8	90.8	645.8	96.2
Mars Surface Habitat	air	10,800-14,400	1270.9	2929.2	980.8	2942.4
	water	79,200-108,000	4142.3	6248	2906.9	6247.1

Table 8. Comparison of ALS estimated masses with Rapp estimates (this paper) of required resource masses for *Mars Transit Vehicle* using Baseline ECLSS Technologies.

Subsystem / Interface	Phys. Plant MPP [kg]	Maximum MB [kg]	Resource Need MT (kg)	Implied recycle efficiency	(MPP+MB)/MT
Air	2,190	1329 (b)	6,500-8,700	>80%(a)	0.5
Biomass	761				
Food	2,840		3,200		
Thermal	329				
Waste	382				
Water	3,353	596 (b)	47,500-65,000	>99%(a)	0.08
Extravehicular Activity Support	0				
Human Accommodations	1,763				
Totals	11,617				

(a) Cannot be exact here because data for storage includes both tankage and air or water. Calculation is based on lower value for feedstock need. (b) Assumes tankage mass is zero and all storage is air or water.

Table 9. Comparison of ALS estimated masses with Rapp estimates (this paper) of required resource masses for *Mars Ascent/Descent Lander* using Baseline ECLSS Technologies.

Subsystem / Interface	Phys. Plant MPP [kg]	Maximum MB [kg]	Resource Need MT (kg)	Implied recycle efficiency	(MPP+MB)/MT
Air	1,071	263 (b)	540-720	>51% (a)	2.4
Biomass	0				
Food	620		270		
Thermal	296				
Waste	69				
Water	737	91 (b)	4000-5400	>98%(a)	0.20
Extravehicular Activity Support	22				
Human Accommodations	188				
Totals	3,001				

(a) Cannot be exact here because data for storage includes both tankage and air or water. Calculation is based on lower value for feedstock need. (b) Assumes tankage mass is zero and all storage is air or water.

Table 10. Comparison of ALS estimated masses with Rapp estimates (this paper) of feedstock masses for *Mars Surface Habitat Lander* using Baseline ECLSS Technologies.

Subsystem / Interface	System Mass [kg]	Maximum MB [kg]	Rapp estimate of feedstock need (kg)	Implied recycle efficiency	(MPP+MB)/MT
Air	4,195	2956 (b)	10,800-14,400	>73% (a)	0.67
Biomass	898				
Food	7,580		5400		
Thermal	382				
Waste	668				
Water	10,380	6243 (b)	79,200-108,000	>92%(a)	0.20
Extravehicular Activity Support	1,292				
Human Accommodations	2,938				
Totals	28,333				

(a) Cannot be exact here because data for storage includes both tankage and air or water. Calculation is based on lower value for feedstock need. (b) Assumes tankage mass is zero and all storage is air or water.

Table 11. Summary of implied recycle efficiencies and (MPP+MB)/MT mass ratios.

	Duration (days)	Resource	Requirement (kg)	Maximum Cache (kg)(c)	Implied recycle efficiency	(MPP+MB)/MT
Mars Transit Vehicle	360 (a)	air	6500-8700	1329	>80%	0.5
		water	47,500-65,000	596	>99%	0.08
Mars Ascent/ Descent Lander	30 (b)	air	540-720	263	>51%	2.4
		water	4000-5400	91	>98%	0.2
Mars Surface Habitat	600	air	10,800-14,400	2956	>73%	0.67
		water	79,200-108,000	6243	>92%	0.2

(a) No account seems to have been taken of the need to store the system for a significant period between two 180-day transits. (b) 30 seems like "over-kill" here. (c) Neglects tankage mass. Assumes Hanford (2005) stated storage mass is 100% resource.

Table 12. Crude Estimates for Preliminary Planning Purposes. Cells marked * have masses included in the habitat, not the LSS.

	Resource	Requirement (kg)	Physical Plant (kg)	Back-up Cache (kg)	Total ECLSS Mass (kg)
Mars Transit Vehicle (360 days)	Air	6500-8700	870	1350	2220
	Water	47,500-65,000	2770	600	3370
	Food	3240	*	3240	3240
	Waste Disposal Mtls	1100	*	1100	1100
	Total				**9930**
Mars Ascent/ Descent Lander (30 days)	Air	540-720	800	270	1070
	Water	4000-5400	650	90	740
	Food	270	*	270	270
	Waste Disposal Mtls	90	*	90	90
	Total				**2170**
Mars Surface Habitat (600 days)	Air	10,800-14,400	1270	2930	4220
	Water	79,200-108,000	4140	6250	10390
	Food	5400	*	5400	5400
	Waste Disposal Mtls	1800	*	1800	1800
	Total				**21810**

Acronyms List

ALS	Advanced life support system
BVAD	Baseline Values and Assumptions Document
CM	Crew member
DRM	Design reference mission
ECLSS	Environmental Control and Life Support System
ESM	Equivalent system mass
ILSSTF	Integrated Life Support Systems Test Facility
ISRU	In situ resource utilization
ISS	International Space Station
IWRS	Integrated Water Recovery System
JSC	NASA Johnson Space Center
LMLSTP	Lunar-Mars Life Support Test Project
LSS	Life support system
MB	Mass of back-up cache
MLS	Mass of LSS
MPP	Mass of physical plant
ORU	Orbital Replacement Unit
P/C	Physico-chemical
RP	Recovery percentage
SIMA	System Integration, Modeling and Analysis
SWIS	Solid Waste Incineration System
TRL	Technology readiness level
VPCAR	Vapor Phase Catalytic Ammonia Removal System
VPGC	Variable Pressure Growth Chamber

Supporting Data

Most of the documents referenced in this article were not published in the open literature. For the convenience of the reader, these documents are included in pdf form as supporting data to this paper.

References

Anderson, Molly S. (2004) "Summary of Water Processing Trade Studies and Analysis of JSC Integrated Water Recovery System (IWRS)" CTSD-ADV-543, JSC 62185, August 30, 2004.

Anonymous (2002) "Advanced Life Support Project Plan" CTSD-ADV-348 Rev C, JSC 39168, February, 2002.

Anonymous (2005) The NASA Exploration Systems Architecture Study (ESAS) Final Report

Drake, B. G. (1998) DRM-3: "NASA/SP—6107–ADD, Reference Mission Version 3.0, Addendum to the Human Exploration of, Mars: The Reference Mission of the NASA, Mars Exploration Study Team," Lyndon B. Johnson Space Center, Houston, Texas, 1998.

Feldman, W. C., T. H. Prettyman, S. Maurice, J. J. Plaut, D. L. Bish, D. T. Vaniman, M. T. Mellon, A. E. Metzger, S. W. Squyres, S. Karunatillake, W. V. Boynton, R. C. Elphic, H. O. Funsten, D. J. Lawrence, and R. L. Tokar, (2004) "Global distribution of near-surface hydrogen on Mars," J. Geophys. Res., VOL. 109, E09006, doi:10.1029/2003JE002160, 2004.

Graf, J., Finger, B. and Daues, K. (2002) "Life Support Systems for the Space Environment: Basic Tenets for Designers, Rev. A" Informal NASA JSC Report, June 27, 2002.

Hanford, Anthony J. (2004A) "Advanced Life Support Research and Technology Development Metric – Fiscal Year 2004" NASA/CR–2004–208944 Lockheed Martin Space Operations, Houston, Texas 77058, October 2004.

Hanford, Anthony J. (2004B) "Advanced Life Support Baseline Values and Assumptions Document, Doc. Number CTSD-ADV-484 A, NASA CR-2004-208941, JSC 47804 Lockheed Martin Space Operations, 16 August 2004. (This was an update to a previous version CTSD-ADV-484, 08 May 2002).

Hanford, Anthony J. (2004C) "Subsystem Details for the Fiscal Year 2004 Advanced Life Support Research and Technology Development Metric" MSAD-04-0306, September 2004.

Hanford, Anthony J. (2005) "Advanced Life Support Research and Technology Development Metric – Fiscal Year 2005" ESCG-4470-05-TEAN-DOC-0157, Lockheed Martin Space Operations, Houston, Texas 77058, October 2005.

Hoffman, S. J. and Kaplan, D. I. (1997) DRM-1: "Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team," Lyndon B. Johnson Space Center, Houston, Texas, July 1997, NASA Special Publication 6107.

Lange, K. E., Lin, C. H., Duffield, B. E., and Hanford, A. J. (2003) "Advanced Life Support Requirements Document," JSC-38571C, CTSD-ADV-245C, February 2003.

Sanders, J. and Duke, M. (2005) "ISRU Capability Roadmap Team Final Report" Informal report edited by J. Sanders (JSC) and M. Duke (Colorado School of Mines) March 2005.

Schorghofer, N. and Aharonson, O. (2005) "Stability and exchange of subsurface ice on Mars," Journal of Geophysical Research, Vol. 110, E05003, doi:10.1029/2004JE002350, 2005.

Stafford, K. W., Drysdale, A. E., Levri, J. A., Hanford, Anthony J. and Ewert, M. K. (2001) "Advanced Life Support Systems Integration, Modeling, and Analysis Reference Missions Document," JSC-39502, CTSD-ADV-383, 5 November 2001.