Lunar Life Support System Study: Metabolic Energy and Water Considerations

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This research is focused on requirements and methods for supporting human life in space. One of the primary issues investigated is the range of life support consumables (e.g., water, oxygen, and food) needed to support active humans on the surface of the moon on a per-crew per-day basis. A set of hypothetical daily lunar activity scenarios is developed to attempt realistic estimation of lunar energy expenditure levels for both mission planning and consumables provisioning purposes. Metabolic energy expenditures for lunar astronauts will probably be significantly higher on a regular basis than that of average earth-based North Americans. Estimates of life support system consumables (food, oxygen, drinking water, and wash water) clearly indicate that a concerted effort should be made to close the gray water cycle, and possibly the black water cycle as well.

Nomenclature

CO_2	=	carbon dioxide
EVA	=	extravehicular activity
FTCSC	=	Food Technology Commercial Space Center
ISS	=	International Space Station
IVA	=	intravehicular activity
O_2	=	diatomic (molecular) oxygen
kcalories	=	kilocalories
kcals	=	kilocalories
mps	=	meters per second
STS	=	Space Transportation System (i.e., Space Shuttle)

I. Introduction

With President George W. Bush's January 2004 announcement of his new vision for the country's space exploration program, America's dream of a human mission to Mars has become a federal priority. NASA is being directed to plan and execute a series of return missions to the moon and eventually a manned mission to Mars. In order to accomplish these future spaceflight objectives, we must gain a thorough understanding of what is needed to support the life and health of humans living in remote, low-gravity, synthetic environments over extended periods of time.

II. Background

There are many physiological issues associated with human spaceflight, such as cardiovascular deconditioning, bone loss, muscular atrophy, neurovestibular problems, and excessive radiation exposure. These issues - already disturbing during limited duration space missions - must be much more thoroughly addressed before undertaking the long, complex, and hazardous two year plus proposed roundtrip to Mars. A human base on the vacuous and dusty low-gravity lunar surface would provide a relatively close, safe, and fairly analogous test-bed. Such a test-bed would enable scientists and engineers to gain greater understanding of these spaceflight physiological issues outside Earth's life-friendly biosphere, as well as to develop preventative countermeasures and treatments. A lunar base also offers the possibility to investigate some of the unanswered questions remaining from the Apollo missions regarding

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the moon's formation, composition, and structure. In addition, there is great potential for conducting significant moon-based astronomical observations, as well as for developing practical methods of mining and utilizing lunar resources.

One of the most fundamental elements of a human settlement on the moon would be the life support system. Without it, humans would not survive. Some of the components of such a system would be similar to life support systems used in other contexts, such as aircraft, spacecraft, submarines, and earth-based biospheres. However, the remote location, reduced gravity level, unusual surface environment, and extended duration of use all contribute unique challenges to the design of a robust and reliable lunar life support system.

III. Objectives

Our research for this project is focused on the requirements and methods involved in supporting human life in extreme environments – in particular, outer space. The purpose of this on-going study is to identify the life support system requirements for a human mission to the moon (which can also be used to a large extent as the basis for design of a life support system for a Mars mission). One of the primary issues we are investigating is the range of life support consumables (e.g., water, oxygen, foods) needed to support active humans on the surface of the moon on a per-crew per-day basis. A related issue concerns realistically determining the level of metabolic and food energy the lunar astronauts will expend and consume during their lunar stay. Another vital issue is that of developing a methodology to determine the optimal level of life support system "closure", or regeneration of consumables, in the face of practical constraints (such as cost, weight, volume, and the state of technology development).

IV. Discussion

A. Mission Planning

The first step in developing requirements for a lunar life support system is to understand the mission. The overall function of mission planning is to provide a very detailed answer to the following question: "Where and why are we going, and what are we going to do once we get there?" The answer to this one sweeping question will dictate top-level requirements for the design of all the systems and hardware needed to support the entire mission.

In order to accurately account for all life support system requirements, a thorough understanding of the entire projected mission is necessary. The mission parameters would include such information as mission objectives, mission duration, crew size and composition, astronaut tasks, daily activity schedules, launch vehicle specifications, and overall mission schedules and timelines. Lacking this information, we must start with looking simply at life support requirements in terms of what is needed by each crewmember for each day.

To begin with, we can do a ballpark conceptual trade study of expensive regeneration technologies for a closed life support system versus weights of all required consumables masses for an open life support system. Early in the process we will realize that in general, open systems might be more advantageous for shorter missions, whereas at least partially closed systems might be required for longer term missions, especially if the habitat and support hardware are expected to be reused. Thus, mission duration and permanency significantly affect life support system design.

Concomitantly, the greatest constraints on any spacecraft system design are those of cost, launch weight, and volume. The lunar landing craft, including the habitat and all its support equipment, must be accommodated in terms of both mass and volume by the launch vehicle. If it is either too heavy or too large for the designated launch vehicle, then either a larger vehicle or multiple vehicles will have to be used, or possibly a new vehicle would have to be developed. As with any federally funded project, development, fabrication, test, verification, and launch costs for the entire mission (e.g., launch vehicle, descent vehicle, habitat, rover, return vehicle) must remain within realistic budget allocations.

B. Life Support System Requirements: Inputs and Outputs

Within any life supporting environment there are three critical consumable supply cycles: atmosphere, water, and food. Throughout the course of this project, we will investigate each of these three supply cycles to determine its impact on the overall life support system design.

Our research to date provides averaged estimates of the daily inputs and outputs of an active, healthy astronaut, based on past spaceflight experience and averaged physiological metabolic data. In general, the inputs include food, water, oxygen, and vitamins/minerals. The outputs include urine, feces, sweat, water, and carbon dioxide. Summaries of these quantities have been compiled into the two charts below, which display averages for each of the inputs and outputs per crewmember per day.

Table 1: Life Support System Inputs [3,5,6]

Input	*Average Amount (per person/day)*
Oxygen	0.8 kg
Nitrogen	1.5 kg
Water (total*)	29.35 kg
Carbohydrates	0.28 kg
Fiber	0.015 kg
Proteins	0.05 kg
Fats	0.06 kg
Food (dry total)	0.7 kg
Vitamin C	90 mg
Calcium	1000 mg

* drinking water, water in food, hygiene water, and wash water

Table 2: Life Support System Outputs [3,5,6]

Output	*Average Amount (per person/day)*
CO2	1 kg
Sweat	1.4 kg
Urine	1.4 kg
Feces	0.1 kg
Water (total*)	29.35 kg

* drinking water, water from food, hygiene water, and wash water

C. Estimating Lunar Energy Expenditure

Notwithstanding the general estimates given above, energy expenditure for projected moon-based activity levels must be evaluated in order to intelligently adjust the food, water, and oxygen intake requirements for the lunar astronauts, and we will devote a large part of this paper to that task. In order to calculate reasonable caloric and associated food, water, and oxygen input as well as waste product output values for this particular mission, approximate crew activity levels for each day must be estimated. Using average energy expenditure levels for generalized groups of activities, we have developed a set of hypothetical daily activity scenarios by estimating how many hours the lunar astronauts might spend engaging in similar activities over the course of each mission (considering past spaceflight work schedules, as well as, fitness, sleep, and leisure routines), and calculated energy expenditures for each. A limited summary of representative potential daily lunar activity scenarios is provided in the charts below. The energy expenditure rates are based on estimates given in the First Lunar Outpost Study, a Working Group Report coming out of NASA Ames Research Center in 1992 [3].

Scenario 1: 10-Hour Lunar EVA Work Day Energy Expenditure

Daily Activity	Daily Time Spent	Energy Expenditure	Daily Activity Energy for 71 kg astronaut
Off-Duty			
Sleeping	8 hours	0.015 kcal/kg/min.	511 kcalories
Meals: prep/eat/clean	2 hours	0.04 kcal/kg/min.	341 kcalories
Personal Hygiene	1 hour	0.03 kcal/kg/min	128 kcalories
Reading/Sitting	1 hour	0.022 kcal/kg/min	94 kcalories
Housekeeping Chores	1 hour	0.06 kcal/kg/min	256 kcalories
Conditioning Exercise	1 hour	0.115 kcal/kg/min.	490 kcalories
Total Off-Duty:	14 hours		1819 kcalories
Work-Duty			
Walking	3 hours	0.07 kcal/kg/min.	895 kcalories
Standing	2 hours	0.03 kcal/kg/min.	256 kcalories
Kneeling	2 hours	0.025 kcal/kg/min.	213 kcalories
Crouching	2 hours	0.04 kcal/kg/min.	341 kcalories
Digging	1 hour	0.12 kcal/kg/min	511 kcalories
Total Work-Duty:	10 hours		2215 kcalories
Grand Totals:	24 hours		4034 kcalories

Scenario 1 would involve a long and strenuous day of extravehicular field work. This could be considered the worst case energy expenditure scenario, as can be seen from the very high total expenditure of 4034 kcalories. The total kcalories for Scenario 1 could be reduced by substituting another hour of sitting (at 94 kcalories) for the hour of conditioning exercise (at 490 kcalories), for a net reduction of 396 kcalories, bringing the daily grand total down to 3638 kcalories.

Scenario 2: 8-Hour Lunar EVA Work Day Energy Expenditure

Daily Activity	Daily Time Spent	Energy Expenditure	Daily Activity Energy for 71 kg astronaut
Off-Duty			
Sleeping	8 hours	0.015 kcal/kg/min.	511 kcalories
Meals: prep/eat/clean	2 hours	0.04 kcal/kg/min.	341 kcalories
Personal Hygiene	1 hour	0.03 kcal/kg/min	128 kcalories
Reading/Sitting	3 hours	0.022 kcal/kg/min	281 kcalories
Housekeeping Chores	1 hour	0.06 kcal/kg/min	256 kcalories
Conditioning Exercise	1 hour	0.115 kcal/kg/min.	490 kcalories
Total Off-Duty:	16 hours		2006 kcalories
Work-Duty			
Walking	2 hours	0.07 kcal/kg/min.	596 kcalories
Standing	1 hours	0.03 kcal/kg/min.	128 kcalories
Kneeling	2 hours	0.025 kcal/kg/min.	213 kcalories
Crouching	2 hours	0.04 kcal/kg/min.	341 kcalories
Digging	1 hour	0.12 kcal/kg/min	511 kcalories
Total Work-Duty:	8 hours		1789 kcalories
Grand Totals:	24 hours		3796 kcalories

Scenario 2 involves a somewhat shorter (albeit still very energy intensive at 3796 total kcalories) day of extravehicular field work. The total kcalories required for Scenario 2 could be reduced by substituting another hour of sitting (at 94 kcalories) for the hour of conditioning exercise (at 490 kcalories), for a net reduction of 396 kcalories, bringing the daily grand total down to 3400 kcalories.

Scenario 3: 6 EVA + 2 IVA Hour Lunar Work Day Energy Expenditure

Daily Activity	Daily Time Spent	Energy Expenditure	Daily Activity Energy for 71 kg astronaut
Off-Duty			
Sleeping	8 hours	0.015 kcal/kg/min.	511 kcalories
Meals: prep/eat/clean	2 hours	0.04 kcal/kg/min.	341 kcalories
Personal Hygiene	1 hour	0.03 kcal/kg/min	128 kcalories
Reading/Sitting	3 hours	0.022 kcal/kg/min	469 kcalories
Housekeeping Chores	1 hour	0.06 kcal/kg/min	256 kcalories
Conditioning Exercise	1 hour	0.115 kcal/kg/min.	490 kcalories
Total Off-Duty:	16 hours		2006 kcalories
Work-Duty			
Lab/Desk Work	2 hours	0.035 kcal/kg/min	298 kcalories
Walking	1 hours	0.07 kcal/kg/min.	298 kcalories
Standing	1 hours	0.03 kcal/kg/min.	128 kcalories
Kneeling	2 hours	0.025 kcal/kg/min.	213 kcalories
Crouching	1 hours	0.04 kcal/kg/min.	170 kcalories
Digging	1 hour	0.12 kcal/kg/min	511 kcalories
Total Work-Duty:	8 hours		1619 kcalories
Grand Totals:	24 hours		3625 kcalories

Scenario 3 would involve a full 8-hour work day, but only 6 hours would involve heavy, extravehicular field work, with the remaining 2 hours involving work in the laboratory or at a desk. The total kcalories required for Scenario 3 could be reduced by substituting another hour of sitting (at 94 kcalories) for the hour of conditioning exercise (at 490 kcalories), for a net reduction of 396 kcalories, bringing the daily grand total down to 3229 kcalories.

Scenario 4: Light 6 EVA + 2 IVA Hour Lunar Work Day Energy Expenditure

Daily Activity	Daily Time Spent	Energy Expenditure	Daily Activity Energy for 71 kg astronaut
Off-Duty			
Sleeping	9 hours	0.015 kcal/kg/min.	575 kcalories
Meals: prep/eat/clean	1.5 hours	0.04 kcal/kg/min.	256 kcalories
Personal Hygiene	1 hour	0.03 kcal/kg/min	128 kcalories
Reading/Sitting	4 hours	0.022 kcal/kg/min	375 kcalories
Housekeeping Chores	0.5 hour	0.06 kcal/kg/min	128 kcalories
Conditioning Exercise	0	0.115 kcal/kg/min.	0 kcalories
Total Off-Duty:	16 hours		1461 kcalories
Work-Duty			
Lab/Desk Work	2 hours	0.035 kcal/kg/min	298 kcalories
Walking	0.5 hours	0.07 kcal/kg/min.	149 kcalories
Standing	2 hours	0.03 kcal/kg/min.	256 kcalories
Kneeling	2.5 hours	0.025 kcal/kg/min.	266 kcalories
Crouching	0.5 hour	0.04 kcal/kg/min.	85 kcalories
Digging	0.5 hour	0.12 kcal/kg/min	256 kcalories
Total Work-Duty:	8 hours		1309 kcalories
Grand Totals:	24 hours		2771 kcalories

Scenario 4 was created in an attempt to reduce energy expenditure to minimum levels for a lunar work day while still accomplishing substantial EVA work.

Scenario 5: Lunar IVA 10-Hour Work Day Energy Expenditure

Daily Activity	Daily Time Spent	Energy Expenditure	Daily Activity Energy for 71 kg astronaut
Off-Duty			
Sleeping	8 hours	0.015 kcal/kg/min.	511 kcalories
Meals: prep/eat/clean	2 hours	0.04 kcal/kg/min.	341 kcalories
Personal Hygiene	1 hour	0.03 kcal/kg/min	128 kcalories
Reading/Sitting	1 hours	0.022 kcal/kg/min	94 kcalories
Housekeeping Chores	1 hour	0.06 kcal/kg/min	256 kcalories
Conditioning Exercise	1	0.115 kcal/kg/min.	490 kcalories
Total Off-Duty:	14 hours		1819 kcalories
Work-Duty			
Lab/Desk Work	8 hours	0.035 kcal/kg/min	1193 kcalories
Walking	1 hours	0.07 kcal/kg/min.	298 kcalories
Standing	1 hours	0.03 kcal/kg/min.	128 kcalories
Total Work-Duty:	10 hours		1619 kcalories
Grand Totals:	24 hours		3438 kcalories

Scenario 5 would be a long work intravehicular work day, with no field work. The total kcalories required for Scenario 5 could be reduced by substituting another hour of sitting (at 94 kcalories) for the hour of conditioning exercise (at 490 kcalories), for a net reduction of 396 kcalories, bringing the daily grand total down to 3042 kcalories.

Scenario 6: Lunar IVA 8-Hour Work Day Energy Expenditure

Daily Activity	Daily Time Spent	Energy Expenditure	Daily Activity Energy for 71 kg astronaut
Off-Duty			
Sleeping	8 hours	0.015 kcal/kg/min.	511 kcalories
Meals: prep/eat/clean	2 hours	0.04 kcal/kg/min.	341 kcalories
Personal Hygiene	1 hour	0.03 kcal/kg/min	128 kcalories
Reading/Sitting	3 hours	0.022 kcal/kg/min	281 kcalories
Housekeeping Chores	1 hour	0.06 kcal/kg/min	256 kcalories
Conditioning Exercise	1	0.115 kcal/kg/min.	490 kcalories
Total Off-Duty:	16 hours		2006 kcalories
Work-Duty			
Lab/Desk Work	6 hours	0.035 kcal/kg/min	895 kcalories
Walking	1 hours	0.07 kcal/kg/min.	298 kcalories
Standing	1 hours	0.03 kcal/kg/min.	128 kcalories
Total Work-Duty:	8 hours		1321 kcalories
Grand Totals:	24 hours		3327 kcalories

Scenario 6 would be a normal 8-hour intravehicular work day with no field work. The total kcalories required for Scenario 6 could be reduced by substituting another hour of sitting (at 94 kcalories) for the hour of conditioning exercise (at 490 kcalories), for a net reduction of 396 kcalories, bringing the daily grand total down to 2941 kcalories.

Scenario7: Light IVA 8-Hour Lunar Work Day Energy Expenditure

Daily Activity	Daily Time Spent	Energy Expenditure	Daily Activity Energy for 71 kg astronaut
Off-Duty			
Sleeping	9 hours	0.015 kcal/kg/min.	575 kcalories
Meals: prep/eat/clean	1.5 hours	0.04 kcal/kg/min.	256 kcalories
Personal Hygiene	1 hour	0.03 kcal/kg/min	128 kcalories
Reading/Sitting	4 hours	0.022 kcal/kg/min	375 kcalories
Housekeeping Chores	0.5 hour	0.06 kcal/kg/min	128 kcalories
Conditioning Exercise	0	0.115 kcal/kg/min.	0 kcalories
Total Off-Duty:	16 hours		1461 kcalories
Work-Duty			
Lab/Desk Work	4 hours	0.035 kcal/kg/min	596 kcalories
Sitting	2 hours	0.07 kcal/kg/min.	187 kcalories
Standing	2 hours	0.03 kcal/kg/min.	256 kcalories
Total Work-Duty:	8 hours		1039 kcalories
Grand Totals:	24 hours		2501 kcalories

Scenario 7 was created in an effort to reduce energy expenditure to minimum levels for a lunar work day while still accomplishing substantial IVA laboratory work.

Scenario 8: Lunar Rest Day Energy Expenditure

Daily Activity	Daily Time Spent	Energy Expenditure	Daily Activity Energy for 71 kg astronaut
Off-Duty			
Sleeping	10 hours	0.015 kcal/kg/min.	639 kcalories
Meals: prep/eat/clean	1.5 hours	0.04 kcal/kg/min.	256 kcalories
Personal Hygiene	1.5 hours	0.03 kcal/kg/min	192 kcalories
Reading/Sitting	10 hours	0.022 kcal/kg/min	937 kcalories
Housekeeping Chores	0	0.06 kcal/kg/min	0 kcalories
Light Exercise	1 hour	0.07 kcal/kg/min.	298 kcalories
Total Off-Duty:	24 hours		2322 kcalories
Work-Duty			
Walking	0	0.07 kcal/kg/min.	0 kcalories
Standing	0	0.03 kcal/kg/min.	0 kcalories
Kneeling	0	0.025 kcal/kg/min.	0 kcalories
Crouching	0	0.04 kcal/kg/min.	0 kcalories
Digging	0	0.12 kcal/kg/min	0 kcalories
Total Work-Duty:	0 hours		0 kcalories
Grand Totals:	24 hours		2322 kcalories

Scenario 8 was developed to estimate energy expenditure for astronauts on off-duty days.

Let us assume for the sake of discussion that a normal lunar mission month (30 days) includes one 10-hour EVA work day (Scenario 1 @ 4034 kcals/day), one 8-hour EVA work day (Scenario 2 @ 3796 kcals/day), six 6-hour EVA/2-hour IVA work days (Scenario 3 @ 3625 kcals/day), four light 6-hour EVA/2-hour IVA work days (Scenario 4 @ 2771 kcals/day), two 10-hour IVA work days (Scenario 5 @ 3438 kcals/day), two 8-hour IVA work days (Scenario 6 @ 3327 kcals/day), eight light 8-hour IVA work days (Scenario 7 @ 2501 kcals/day), and six rest days (Scenario 8 @ 2322 kcals/day). In this monthly scheme, each astronaut would burn about 88,134 kcalories per month, or an average of 2938 kcalories per day.

By current spaceflight standards, this average work-day of 6.6 hours is quite low (STS and ISS work-days routinely run 10-12 hours with one rest day per week, bringing the daily average in at 9.4 hours [§]), hence our energy expenditure estimates are quite conservative. Nevertheless, our daily average kcalorie expenditure is very high when compared with most general dietary recommendations, which average about 2467 kcalories per day (2867 kcals/day for males, and 2067 for females [5,6]). If, in an effort to reduce energy expenditure, we remove all conditioning exercise sessions from this monthly schedule and replace that time with sitting (not a recommended course of action due to low-gravity physiological deterioration), we can bring the monthly total down to 83,379 kcalories, and the daily average down to 2779 kcalories, which is still quite high compared with most of our general dietary references.

However, if we compare these energy estimates with estimates for Olympic and professional athletes who expend and consume an average of about 5640 kcalories per day while training (ranging from 4600 to 7000 kcals/day depending on the particular sport), they seem quite modest [5].

More suitably, if we use the equations from the NASA Food Technology Commercial Space Center's nutrition for spaceflight recommendations [**], we come up with numbers that are much closer to our estimates:

- For men, 30-60 years: 1.7((11.6*mass) + 879) = kcals/day;
  for the average 81 kg male astronaut => 3092 kcals/day
- For women, 30-60 years: 1.6((8.7*mass) + 829) = kcals/day;
  for the average 61 kg female astronaut => 2176 kcals/day[††]

Averaging these values for males and females, we get an energy expenditure/consumption figure of 2634 kcals/day.

Furthermore, the NASA Food Technology Commercial Space Center (FTCSC) advocates the addition of another 500 kcalories to the daily total for days on which extravehicular work is performed. Our hypothetical month of scenarios includes 12 days in which EVA would be performed. Hence, the FTCSC recommendations would dictate an energy expenditure/consumption average of 2634 kcalories/day for18 days (47,412 kcals), plus an average of 3134 kcalories/day for the 12 EVA days (37,608 kcals), for a monthly total of 85,020 kcalories, or a daily average of 2834 kcalories/day. This figure is only slightly lower than the 2938 kcalories/day established by our hypothetical 30-day set of lunar scenarios, and it is slightly higher than the 2779 kcalories/day achieved by eliminating physical conditioning sessions.

Another impact of the substantially higher than average earth day energy expenditure levels is an associated requirement for additional drinking water, which the NASA FTCSC estimates at 1.5 milliliter of water per kcalorie. While this issue will require further analysis, taken at face value this impact is graphically represented in Figure 2 below.

Of course, the included set of eight hypothetical daily activity scenarios (as well as the grouping of 30 daily scenarios making up our hypothetical month) is far from exhaustive, let alone conclusive. However, the constituent pieces can be used, modified, and customized as part of an iterative process for refining lunar energy expenditure levels and associated caloric intake requirements.

For mission planning as well as consumables provisioning purposes, the following table may be useful in estimating times and distances that can be covered by a lunar astronaut for each 500 kcalorie increment of energy in either unloaded or maximum loaded (carrying 270 percent of his or her body mass). This data was developed during simulated lunar gravity water tank testing conducted at NASA Ames Research Center by the lead author [6].

[§] "An Astronaut's Work," NASA website, posted May 27, 2004. Accessed on August 28, 2004, at http://www.nasa.gov/audience/forstudents/9-12/features/F_Astronauts_Work.html.

[**] "Nutrition for Spaceflight Recommendations," NASA Food Technology Commercial Space Center website. Accessed on August 30, 2004, at http://www.ag.iastate.edu/centers/ftcsc/pages/insig.htm.

[††] Astronaut mass data obtained from "Gender issues related to spaceflight: A NASA perspective," Science Blog, 2004. Accessed on August 28, 2004, at http://www.scienceblog.com/community/older/2001/A/200110803.html.

Table 3: Distances & Times Traveled with and without a Maximum 270% Body Mass Load at 1.2 & 1.9 meters/second in Lunar Gravity per 500 Kcalorie Increment of Energy

Kcalorie Increment	DISTANCE (in km) for MOON		
(loading condition)	1.2 mps		1.9 mps
500 (no load)	8.0	>	10.1
500 (maximum load)	4.7	>	5.8
	TIME (in hours) for MOON		
500 (no load)	1.9	>	1.5
500 (maximum load)	1.1	>	0.9

All of the resources we discovered while developing these potential daily activity scenarios (various NASA, military, medical, and industrial standards of caloric intake recommendations, suggested daily servings, and various energy expenditure estimates for different activity levels) are still being evaluated to more accurately determine how much oxygen, water, and each type of food a lunar astronaut must consume every day in order to maintain optimum health.

D. Methods of Provisioning: Earth Supply, In-Situ Resources, Regeneration of Supplied Resources

Once we have settled the question of how much of each consumable (food, water, and oxygen) an astronaut needs each day, we will turn our attention to where these consumables will come from. These decisions depend on whether the various cycles of the life support system will be closed, partially closed, or completely open. In other words, will food, water, and oxygen be resupplied from earth? Or will some or all of these inputs be completely recycled, regenerated, and reused? In all likelihood, for the initial relatively short duration recurring stays on the moon, some of the oxygen, most of the food, and at least some (possibly all) of the drinking water will need to be replenished from the earth. Some fast-growing, hardy plants, such as lettuce, carrots, and radishes, might be a few food items that could be freshly grown while on the moon. Fresh, lunar-grown produce would serve multiple purposes for the astronauts: as appetite enhancers, as living reminders of the home planet, and as small contributors to the CO_2/O_2 regeneration process. More research will have to be done, however, to decide which plants will be best suited for this purpose.

The Excel spreadsheet models illustrated in Figures 1 and 2 were constructed to estimate human life support consumable mass provisions for a lunar mission, calculated in terms of kilograms of oxygen, food, drinking water, and wash water required for each crewmember every day. Initial literature search and informal questionnaire surveys indicate that regeneration of black water into potable water would not be palatable to most individuals[2]. As quickly becomes obvious from Figures 1 and 2, the mass cost for provisioning of fresh drinking water and other consumables (e.g., oxygen and food) is small compared to that for wash water. Therefore, effective techniques for recycling gray/wash water offer the greatest potential launch mass savings of any of the basic groups of life support consumables. For example, the wash water mass requirement for 360 crew days is about 9360 kg, whereas the drinking water mass is only about 990 kg (or 1440 kg, using the NASA FTCSC formula[‡‡]), the whole/wet food mass is only about 468 kg, and the oxygen mass is only about 288 kg. The significance of this issue is currently being recognized on the International Space Station, where the number of crewmembers is constrained to two (rather than the nominally planned three) due to limited provisioning of water.

Multiple technologies currently exist which are able to regenerate both gray and black water to standards exceeding those of most municipal water providers[§§]. If wash water (and eventually maybe drinking water) are purified and recycled in situ, less mass will have to be transported to the space habitat, and larger numbers of astronauts can be more efficiently supported. This, of course, will lead to cost savings and increased productivity in space.

[‡‡] "Nutrition for Spaceflight Recommendations," NASA Food Technology Commercial Space Center website. Accessed on August 30, 2004, at http://www.ag.iastate.edu/centers/ftcsc/pages/insig.htm.

[§§] Private communication with Mr. Thomas Berger, Senior Principal of The Berger Partnership Landscape Architects, regarding field test data presented to the Au Sable Institute of Environmental Studies. Coupeville, WA, June 22, 2004.

In addition, it will be worthwhile to investigate alternative uses for recycled black water, such as for toilet water and watering plants, as well as uses for other biomass waste products, such as for fertilizer, garden soil, fuel, and building materials. We should also explore the potential long-term use of the known and suspected in-situ resources on the moon, such as oxygen, hydrogen, silicon, iron, aluminum, titanium, and magnesium.

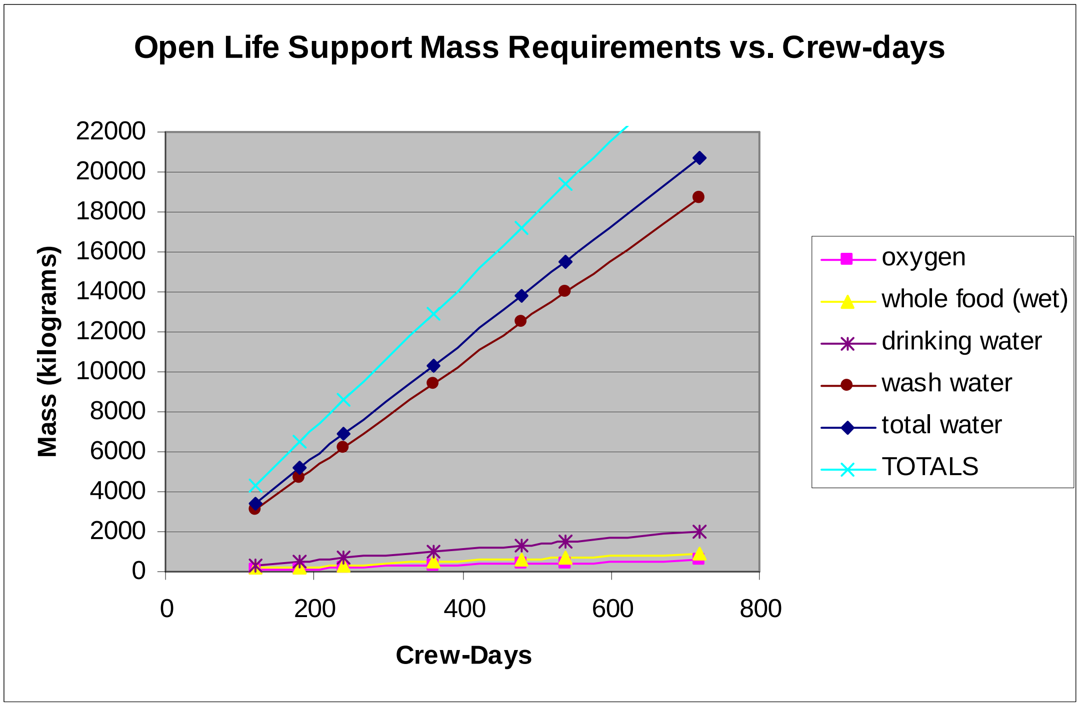

Figure 1: Open Life Support System Consumables Masses per Crewmember per Day

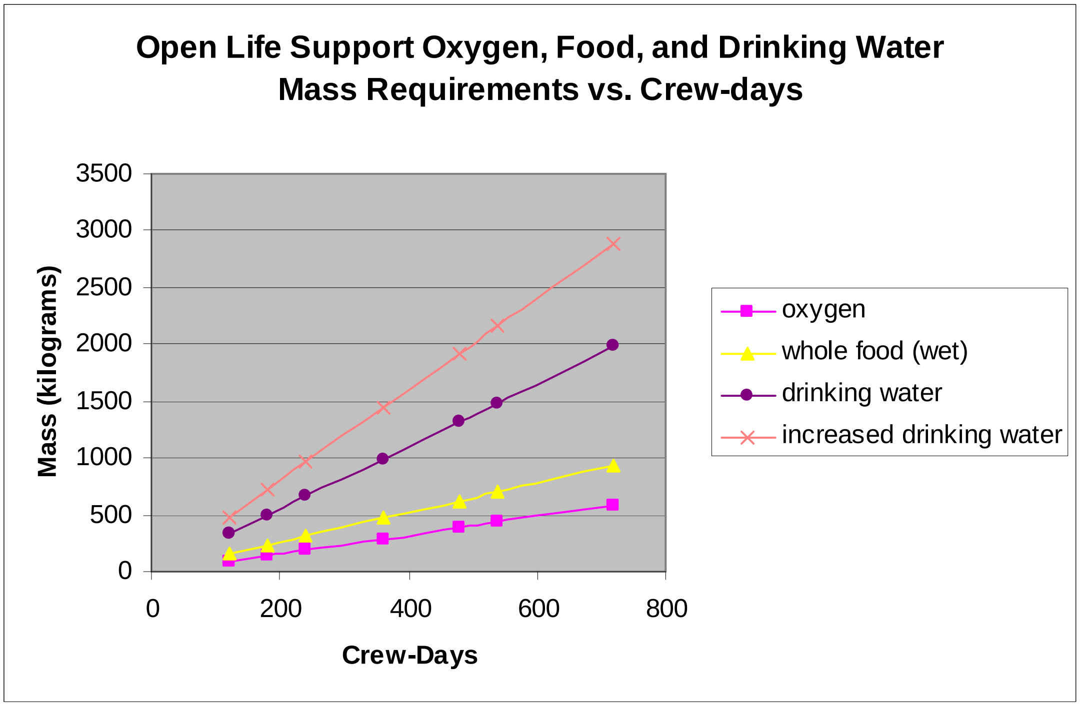

Figure 2: Open Life Support System Consumable Oxygen, Food, and Drinking Water Masses per Crewmember per Day

V. Future Work

We are currently in the process of surveying the various life support technologies used in spacecraft, underwater habitats, and arctic environments with regard to their performance, efficiency, reliability, weight, volume, and cost-effectiveness.

No single life support component or full system has been selected as optimal; rather we are simply compiling information on many system components in order to compare each component's strengths and weaknesses.

The still to be completed goals of this on-going research project are to answer the following essential technical questions, as well as others that arise during the course of our investigations:

- What are the critical decision points for choosing between the various physical, chemical, and biological technologies?
- How long does it take each water/atmospheric/solid waste treatment component to stabilize and become functional?
- What are the mass, volume, cost, and readiness level of each technology component for a nominal projected mission flow rate system?
- What is the maximum flow rate for each technology component?
- What is the effluent/exhaust contaminant level for each technology component?

VI. Conclusion

A set of hypothetical daily activity scenarios was developed to estimate lunar energy expenditure levels for both mission planning and consumables provisioning purposes. Energy expenditures for lunar astronauts, especially on days during which extravehicular field work is performed, will be significantly higher than that of average earth-based North Americans.

Reflecting on our estimates of life support system consumables (food, oxygen, drinking water, and wash water) on a per crew, per mission day basis, it is clear that a serious effort should be made to close the gray water cycle, and possibly the black water cycle as well.

Work in this area will serve not only to advance the efficiency and productivity of our space exploration efforts, but also to promote better stewardship of our limited natural resources here on planet Earth.

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