49th International Conference on Environmental Systems
7-11 July 2019, Boston, Massachusetts

ICES-2019-126

Astronaut Mass Balance for Long Duration Missions

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Human spaceflight logistics requirements are strongly driven by the daily living needs of the astronauts, including their biological functions. Oxygen, water and food are absolute requirements to sustain life and must be supplied at adequate rates. However, these rates can vary from day to day and from person to person. Beyond the body's immediate physical needs, water is also required for important health and hygiene functions within the spacecraft. Undesirable weight loss or gain aside, human waste product mass outputs will equal the resource inputs over time, resulting in a mass balance that can be used for planning consumable resources for astronauts. Best planning values, as well as range of variability for inputs and outputs are explored at both the individual physiological level and the spacecraft level. These values are important for design of life support and habitability systems as well as for long duration mission planning. Current spacecraft life support systems are not fully closed loop, but the International Space Station does recycle most of its air and water. The astronaut mass balances at the personal and vehicle level can have different impacts at different levels of system closure. Recommendations are made for a consistent set of values representing a realistic astronaut mass balance over reasonable durations for exploration missions.

Nomenclature

BVAD = Baseline Values and Assumptions Document
ECLSS = Environmental Control and Life Support System
EVA = Extravehicular Activity
HIDH = Human Integration Design Handbook
ISS = International Space Station
WPA = Water Processor Assembly

I. Introduction

THE principle of mass conservation can be applied to the crew of a spacecraft in order to determine their life support and daily living needs. Over time, given steady body mass, each individual's mass inputs and outputs will balance. Inputs of oxygen, water and food will be greater for larger and more active astronauts, but reasonable ranges, averages, and realistic mission planning values can be determined based on mission and crew characteristics. Similarly, astronaut mass outputs can be estimated, calculated and/or measured, and over a timescale of weeks or months, input will equal output.

Metabolic input and output planning values for a representative astronaut will first be explored in section II along with data sources for these values. Design values for life support system hardware will often have to take into account transients, failure scenarios and other worst-case assumptions. These values will be different for open loop and regenerative life support architectures, which are discussed in section III. For long duration mission planning, metabolic values based on conservative crew characteristics should be good design values. However, even with many years of spaceflight experience, uncertainty still exists in these values, and the exact crew complement will not

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be known in time for vehicle design and early mission planning. Therefore specified design values are intentionally conservative to ensure that predicted consumable needs will meet actual mission requirements. Section IV discusses these issues.

II. Metabolic Mass Balance for a Reference Astronaut

Figure 1 shows a graphical representation of the most significant mass inputs and outputs of the human body. Daily values given here are based on an 82 kg reference astronaut who is eating and exercising well in order to maintain constant body mass and health during an extended mission. This includes 30 minutes of aerobic and 60 minutes of resistive exercise a day, which is greater than historical design requirements for shorter duration spacecraft such as Orion. These values are considered relatively conservative for the purpose of planning long duration mission consumables resupply. For life support system hardware design, low and high extreme values often have to be taken into account as well as transient behavior. Some of these situations are discussed below.

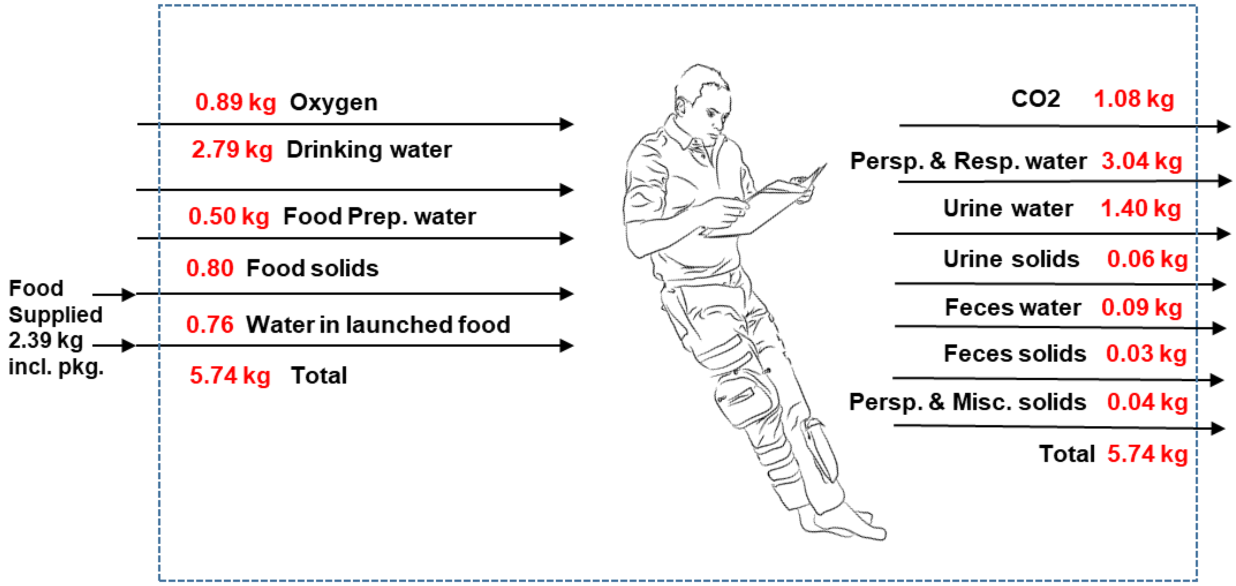

Figure 1. Daily mass balance of an 82 kg astronaut for consumables planning

Within the overall mass balance of solids, liquids and gases, it is often very useful to track just the water for the purpose of designing and operating the water recycling system. The water flows in and out should also balance as long as we take into account metabolic water generation within the body, which comes from oxidation of the food. The amount of metabolic water produced depends on the amount of food consumed as well as its composition. Figure 2 shows the water balance that corresponds to the astronaut in Figure 1.

A. Data Sources

A primary source of information for the mass balance in Figure 1 was NASA's Human Integration Design Handbook (HIDH).[1] The HIDH does not prescribe a "design to" astronaut size, but gives a reference dataset based on the projected mean male astronaut in the year 2015. The HIDH also stipulates provision of at least 0.5 kg of water for food rehydration and an additional 2.0 kg for drinking per person per day. The drinking water in our balance was increased to 2.79 kg due to increased perspiration as a result of the increased exercise profile discussed below in section II B.

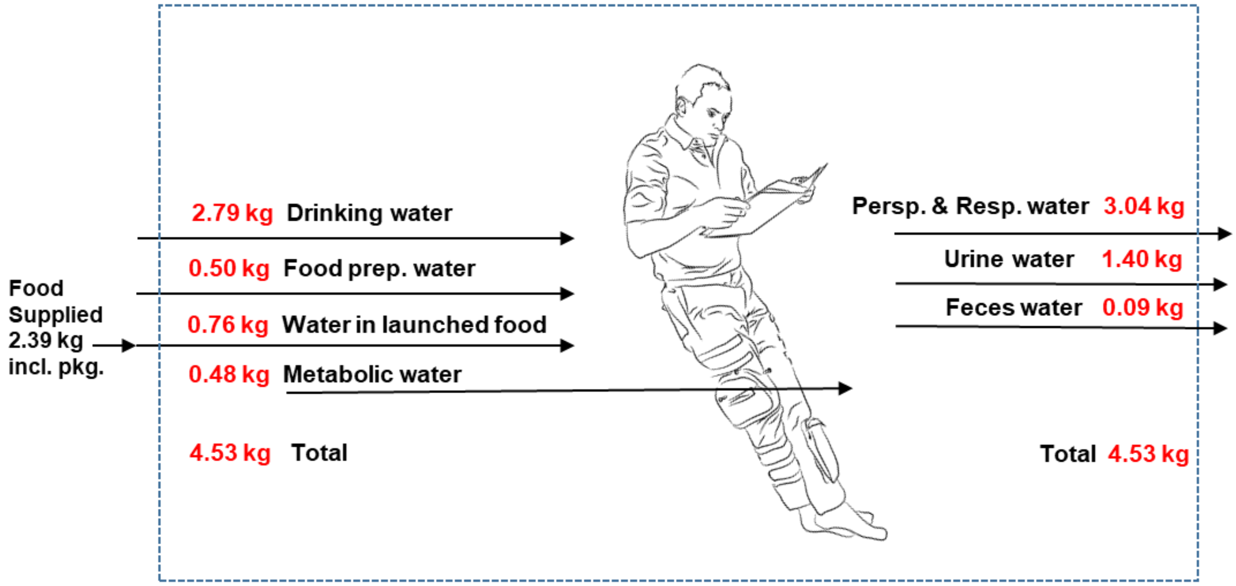

Figure 2. Daily water mass balance for the 82 kg astronaut

Another valuable source of information for life support system analysis is the "Life Support Baseline Values and Assumptions Document" (BVAD)[2]. Table 4-53 in this document gives an average food supply planning value of 2.39 kg of individually packaged food delivered per person per day on the International Space Station (ISS). From this number, 0.43 kg was subtracted for the packaging mass and then 0.20 kg (10%) was subtracted to account for food packages that are not opened and consumed. This conservatism assures that a decent variety of foods will still be available near the end of the mission, as opposed to eating the last packet on the last day. It was also assumed that an additional 0.2 kg of prepared food (60% hydrated) is wasted due to food that is left behind in the packages.

On the output side of the balance, the HIDH gives some metabolic output values; however, they are based on older assumptions about food intake and amount of exercise. The same method for determining these outputs was used here with our updated inputs. This is discussed further in section II B below. Urine output of course varies quite a bit with fluid intake and amount of perspiration. Values such as 1.63 kg/day for urine water in HIDH Table 7.4-1 and 1.4 to over 2 kg/day in BVAD Table 4-38 have been reported. In order to ensure mass closure with the large amount of perspiration in our balance, a relatively low value of 1.40 kg/day was used here. Several minor output values from BVAD Table 3-33 were used[2], including 0.06 kg of urine solids, 0.02 kg of perspiration solids, 0.02 kg of miscellaneous losses, 0.09 of feces water, and 0.03 kg of feces solids, all per person per day.

B. Human Metabolic Profile

Rather than use the daily metabolic profile (with exercise) from the 2014 HIDH, we have included an update based on recent work at the Johnson Space Center. Table 6.2-10 in the HIDH was developed about 12 years ago, primarily for the short duration Orion missions, and includes only 30 minutes of exercise per person per day. The current recommendation for missions over 30 days is 90 minutes of exercise (30 minutes aerobic plus 60 minutes resistive) per person per day. The human thermal modeling code MetMan, which was used to generate the metabolic profiles in the HIDH, was also updated[3] in 2018 to improve correlation with recent data from a human "sweat test".[4] Additionally, some of the modeling assumptions were also updated.[3] The results of the MetMan run with new daily exercise profile, model correlation, and assumptions are shown in Table 1. Since metabolic outputs are presented in 15-minute intervals, Table 1 can be used in transient analyses to predict dynamic performance of the spacecraft environmental control and life support system (ECLSS), as explained in section III. Here we focus on the daily total outputs of 1.08 kg of CO_2, 2.53 kg of combined perspiration and respiration water vapor, and 0.51 kg of liquid sweat. It should be noted that perspiration and respiration values this high have not been documented on ISS. A daily O_2 requirement of 0.89 kg is also predicted by the model.

Table 1. Updated metabolic profile for an 82kg astronaut exercising 90 minutes a day

Start time (hrs)	End time (hrs)	Duration (hrs)	Activity	Metabolic rate (kJ/hr)	Sensible heat (kJ/hr)	Total Latent Heat (kJ/hr)	Water Vapor Output (g/min)	Sweat Output (g/min)	O_2 Consumption (g/min)	CO_2 Output (g/min)
0.00	0.25	0.25	Nominal	500	310.8	216.8	1.49	0.00	0.59	0.69
0.25	0.50	0.25	Exercise - Aerobic	3487	475.5	1033.8	7.09	1.55	3.99	5.22
0.50	0.75	0.25	Exercise - Aerobic	3487	453.0	1958.6	13.44	13.63	3.99	5.22
0.75	1.00	0.25	Exercise - Resistance	1251	407.2	1704.6	11.70	14.44	1.43	1.89
1.00	1.25	0.25	Exercise - Resistance	1251	334.4	1274.5	8.73	2.77	1.43	1.89
1.25	1.50	0.25	Exercise - Resistance	1251	323.3	991.5	6.79	0.89	1.43	1.89
1.50	1.75	0.25	Exercise - Resistance	1251	327.3	875.1	5.99	0.49	1.43	1.89
1.75	2.00	0.25	Recovery 0-15	500	275.4	343.9	2.36	0.00	0.59	0.69
2.00	2.25	0.25	Recovery 15-30	500	296.1	291.3	2.00	0.00	0.59	0.69
2.25	2.50	0.25	Recovery 30-45	500	300.4	253.5	1.74	0.00	0.59	0.69
2.50	2.75	0.25	Recovery 45-60	500	302.4	232.2	1.59	0.00	0.59	0.69
2.75	3.00	0.25	Nominal	500	303.7	218.7	1.50	0.00	0.59	0.69
3.00	3.25	0.25	Nominal	500	304.5	210.0	1.44	0.00	0.59	0.69
3.25	3.50	0.25	Nominal	500	305.1	204.3	1.40	0.00	0.59	0.69
3.50	3.75	0.25	Nominal	500	305.5	200.5	1.38	0.00	0.59	0.69
3.75	4.00	0.25	Nominal	500	305.8	198.1	1.36	0.00	0.59	0.69
4.00	4.25	0.25	Nominal	500	306.0	196.5	1.35	0.00	0.59	0.69
4.25	4.50	0.25	Nominal	500	306.1	195.5	1.34	0.00	0.59	0.69
4.50	4.75	0.25	Nominal	500	306.2	194.8	1.34	0.00	0.59	0.69
4.75	5.00	0.25	Nominal	500	306.2	194.4	1.34	0.00	0.59	0.69
5.00	5.25	0.25	Nominal	500	306.3	194.2	1.33	0.00	0.59	0.69
5.25	5.50	0.25	Nominal	500	306.3	194.0	1.33	0.00	0.59	0.69
5.50	5.75	0.25	Nominal	500	306.3	193.9	1.33	0.00	0.59	0.69
5.75	6.00	0.25	Nominal	500	306.4	193.9	1.33	0.00	0.59	0.69
6.00	6.25	0.25	Nominal	500	306.4	193.9	1.33	0.00	0.59	0.69
6.25	6.50	0.25	Nominal	500	306.4	193.9	1.33	0.00	0.59	0.69
6.50	6.75	0.25	Nominal	500	306.4	193.9	1.33	0.00	0.59	0.69
6.75	7.00	0.25	Nominal	500	306.4	193.9	1.33	0.00	0.59	0.69
7.00	7.25	0.25	Nominal	500	306.4	193.9	1.33	0.00	0.59	0.69
7.25	7.50	0.25	Nominal	500	306.4	193.9	1.33	0.00	0.59	0.69
7.50	7.75	0.25	Nominal	500	306.4	193.9	1.33	0.00	0.59	0.69
7.75	8.00	0.25	Nominal	500	306.4	193.9	1.33	0.00	0.59	0.69
8.00	16.00	8.00	Nominal	500	306.4	193.9	1.33	0.00	0.59	0.69
16.00	24.00	8.00	Sleep	317	159.9	156.7	1.08	0.00	0.37	0.44
				kJ	**kJ**	**kJ**	**kg**	**kg**	**kg**	**kg**
Daily results		**24.00**		**12778**	**6288**	**6134**	**2.53**	**0.51**	**0.89**	**1.08**

III. Life Support System Options

A. Open Loop Life Support

An "open loop" life support system is one in which all required human inputs are supplied as consumables, in other words, no recycling of outputs to inputs. In this case, the assumed astronaut mass balance is most critical, especially for long exploration missions without intermittent resupply. Small deviations from the planned daily rates will add up over time, potentially leading to unacceptable shortages or costly oversupply. Once the crew has been selected for a given mission, adjustments based on personal characteristics may be possible, but during earlier vehicle design and mission planning phases conservative values will need to be used. In addition to the required oxygen, water and food supplies, systems to remove carbon dioxide and other contaminants from the spacecraft atmosphere will need to be on-board. Likewise, some form of storage and/or disposal of liquid and solid human wastes, as well as trash, will be required to maintain habitability and good health.

Thus, both input and output values from section II, with appropriate margin, are useful for design and planning of open loop life support systems. Oxygen at the rate shown in Figure 1 plus contingency margin for uncertainty in rate, mission length and leakage may be supplied as compressed gas, liquefied gas or water to be electrolyzed as needed. Likewise, food and potable water can be supplied at the rates shown in appropriate storage containers. The water values in Figure 2 may provide enough margin, depending on mission contingencies and risk posture. If water is the selected means of oxygen provision, then water margin is shared with oxygen margin, which could be an advantage. However, the water electrolyzer then becomes life critical.

B. Regenerative Life Support

The other extreme from “open loop” would be a fully “closed loop” life support system. Spaceship Earth operates this way, with many biological and chemical processes and cycles acting to recycle wastes into resources for another part of the system. Some argue that our ecosystem is out of balance and thus not sustainable for the long haul. Nonetheless, this example has inspired many studies and research efforts into closed ecological life support systems for space travel.[5]

Current technology, as demonstrated on the ISS, uses physical/chemical regenerative life support systems to almost completely close the air and water loops.[6] Food production in space, on the other hand, is nascent technology. But, efforts such as the European Union’s EDEN project[7] and NASA’s NextStep Green Wall development[8] seek to change this. For now, mostly-closed or “regenerative” life support systems can be designed using ISS-like technologies and the astronaut mass balance values from Figure 1. Figure 3 shows an example ISS-like regenerative life support system mass balance, focusing on water. Here the control volume for analysis is drawn around the crew’s habitation module rather than the individual crewmember. For easy scaling to various crew sizes, values are still given as per person per day.

In the case in Figure 3, oxygen is supplied to the crew by water electrolysis, and a portion of the carbon dioxide exhaled by the astronaut is recycled via the Sabatier process, as described in Eq. (1). The hydrogen required for this reaction is supplied from the byproduct of splitting water to produce oxygen, and this becomes the limiting factor. Extra CO_2 is vented overboard along with the methane (CH_4) and small amounts of other gases. Thus only 0.47 kg/person/day of water can be recovered by this process, assuming 90% recovery efficiency.

$$4\ H_2 + CO_2 \rightarrow 2\ H_2O + CH_4 \quad (1)$$

The value for hygiene water that a crewmember uses to clean themselves is a maximum based on the HIDH[1]. Since current habitats do not have hand wash or shower, actual usage has been less. Values for flush water, water to supply oxygen to the water processor assembly (WPA) and water in wet wipes are from the BVAD[2].

Other things that will affect the closure of the life support system, which are neglected here, include other requirements for oxygen and water such as module leakage, science experiments, and extravehicular activity (EVA). EVA can be a source of consumables loss in several ways, such as the airlock, cooling systems that vent water, and non-regenerative CO_2 removal systems in the space suit. On the other hand, water loop closure is aided in the ISS-like case by the fact that some water is supplied to the habitat in the form of hydrated food and pre-wetted hygiene supplies (most notably wet wipes). The body also produced some water, known as metabolic water, from the food it consumes. Thus, these water sources appear on the input, or supply side, of the balance in Figure 3. Red values in Figure 3 represent water flows within the habitat, whereas black values are bound in supplied commodities (input) or waste products (output). Future technologies can potentially recover more of this water from waste products.

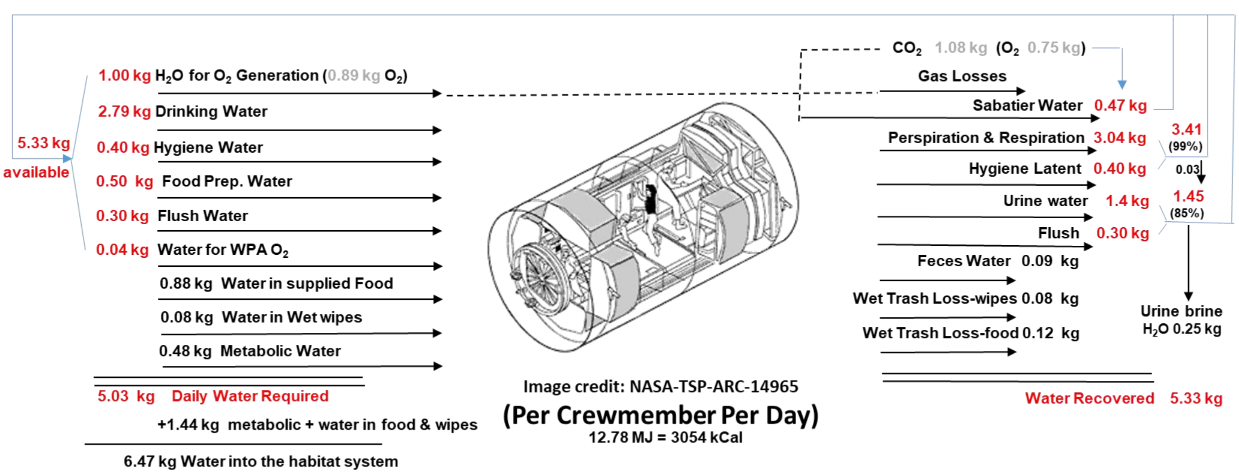

Figure 3. Water mass balance per crewmember/day for a habitat with regenerative life support system

Besides recovery of water from oxygen (via exhaled carbon dioxide) and hydrogen through the Sabatier process, other physical/chemical processors can recover potable water from atmospheric condensate and urine. On the ISS, as in Figure 3, about 99% of the water vapor that gets into the air from crew perspiration & respiration and evaporation of hygiene & other minor water sources can be recycled by the habitat's condensing heat exchanger and water processor. Here we assume that 100% of the hygiene water dispensed onto towels evaporates into the air since crews are trained to dry their towels before throwing them away. On the other hand, we assume that 100% of the water in pre-wetted wipes and disposed food packages goes into the trash and is lost from the system. It is likely that neither of these cases are 100%, but it is hard to determine just how much might evaporate before reaching the trash. Urine undergoes a distillation process before going to the same water processor and losses about 15% of its available water in the process.

In the theoretical balance in Figure 3, 5.33 kg of recycled water per person per day would be available for reuse, compared to the 5.03 kg of required water per person per day. In reality, with the other neglected losses mentioned above, this narrow margin of output versus input has not been enough to eliminate the requirement for water delivery to ISS. In addition, anytime one or more of the regenerative processors is down for maintenance, some water is lost, contributing to the deficit. Exact requirements or assumptions for EVA and science experiments need to be determined in order to critically analyze life support system closure. French and Lange[9] recently explored how different life support technologies can contribute to closing the spacecraft water loop (using slightly different values than presented here). Depending on the exact regenerative life support system architecture, degree of closure and contingency margins, the astronaut mass balance values may not be as critical as for open loop. However, one can easily see from the example above how they affect the habitat water balance as well as the crewmember's personal mass balance.

C. Other Hardware Design Considerations

Besides the daily mass balance values discussed above, transient information can be quite important for life support hardware design. One example of this is human metabolic waste output, which can be highly variable, particularly during an illness. For this reason, the HIDH and associated NASA requirements documents also contain information on extremes, such as maximum urine void or a diarrheal event. Thus, even with a regenerative life support system, sizing of buffer tanks becomes part of the design and optimization process.

Other examples where the transient data provided in section II B above is key to life support system design include the water vapor and CO_2 outputs from the astronaut during exercise. Since these can be significant spikes in the average rate and the space habitat volume is limited, transient analyses are generally required to size the CO_2 and moisture removal systems.

IV. Variations from the Planning Mass Balances

As was mentioned previously, larger and more active astronauts generally have larger mass inputs and outputs. The values listed in this paper are intentionally conservative in nature and represent rates for an 82 kg astronaut in conjunction with a heavy exercise regimen. Actual crew members selected for a mission will vary in sex, mass, and metabolic profile, and may complete differing amount of exercise on average. Therefore, it is helpful to also evaluate the impacts that variation in rates could have on consumables requirements for a given mission. Changes in crew size and consumption can reduce consumable needs but also reduces the amount of outputs available for recycling.

Some prior programs have used 5^{th} – 95^{th} percentile sized individuals as the range for vehicle design. The BVAD[2], mentioned in section II-A, gives realistic high and low values for many mass balance parameters and some information on different size crewmembers. Figures 4 and 5 show mass balances for 5^{th} and 95^{th} percentile individuals using similar assumptions to the daily balance in Figure 1. CO_2, O_2, perspiration and respiration values are from MetMan runs with metabolic rates adjusted for body size. The consumed food solids and water intake were scaled with metabolic rate as well. Urine water was kept constant at 1.4 kg/day, and feces and miscellaneous values were not scaled. These simplifications deserve more study.

Based on the 5^{th} – 95^{th} percentile mass balance data, ranges for a habitat ECLSS water balance are shown in Figure 6. These ranges illustrate how much effect crew body size can have on consumables planning and life support system sizing. For an open loop ECLSS, the water resupply requirement would need to be almost twice as much for a crew of all 95^{th} percentile individuals versus a crew of all 5^{th} percentile individuals. All real crew complements will be somewhere in between. Figure 6 also illustrates that for a mostly-closed-loop ECLSS, more water will be recovered from larger crewmembers that drink, eat and sweat more; therefore, the variation in amount of resupply consumables will not be as drastic as for the open loop case. Nevertheless, there is a significant effect. The implications of various realistic crew compositions on consumables and ECLSS sizing will be studied in future analyses.

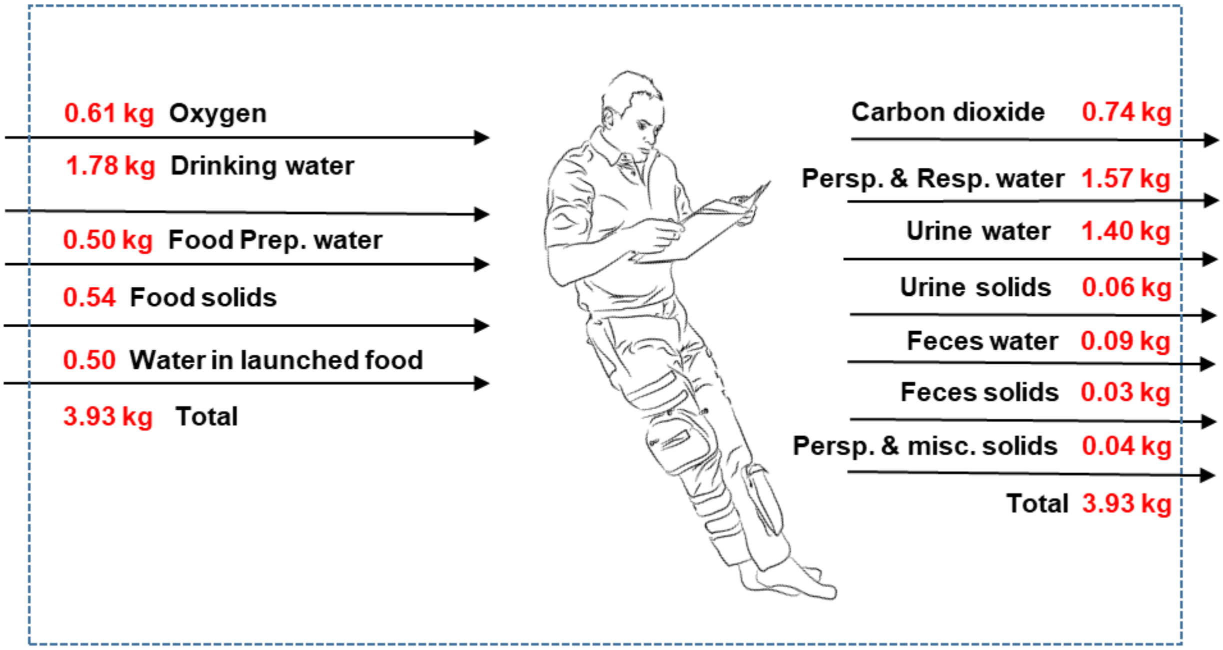

Figure 4. Daily mass balance of a 5th percentile astronaut

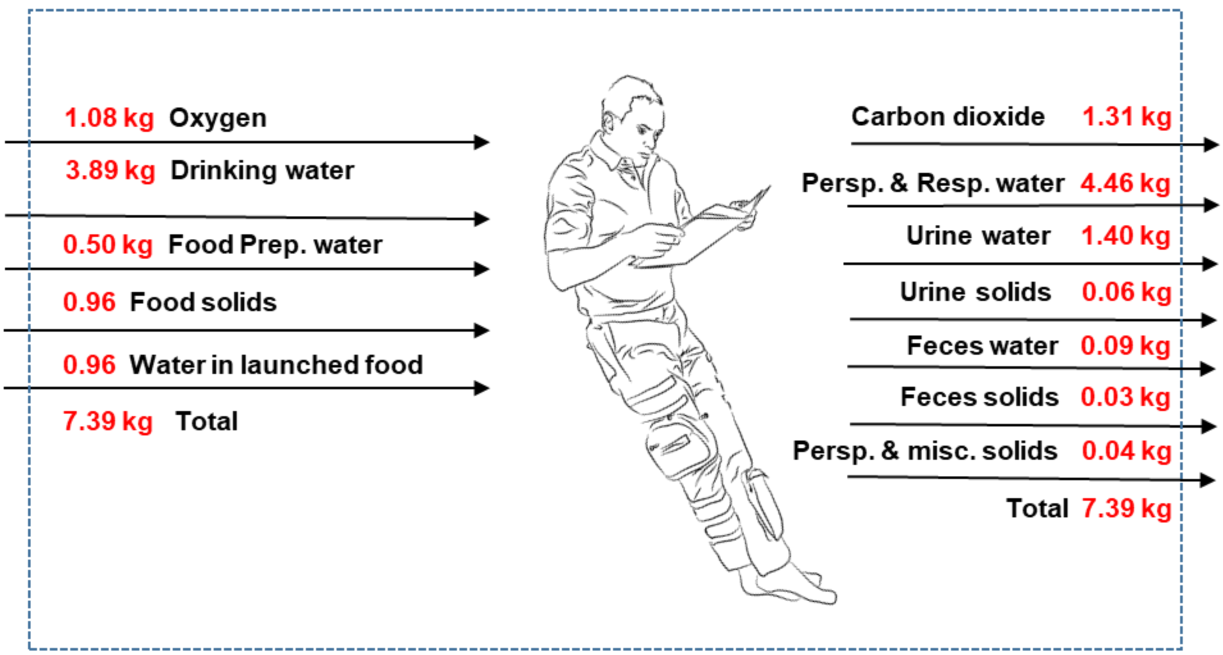

Figure 5. Daily mass balance of a 95th percentile astronaut

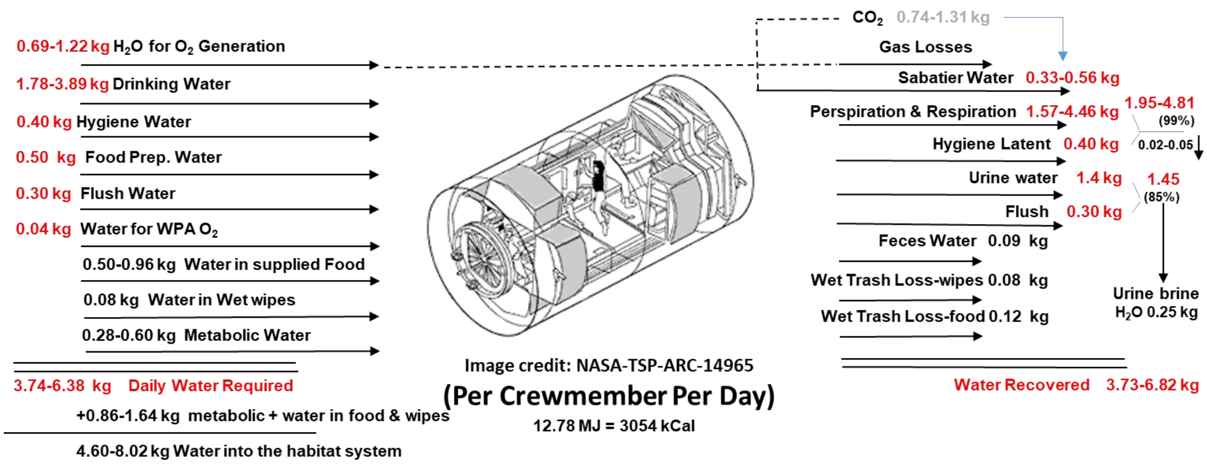

Figure 6. Water mass balance range per crewmember/day for a habitat with regenerative life support system

V. Conclusion

A theoretical astronaut mass balance for long duration exploration missions with an increased exercise profile has been presented based on spaceflight experience and analysis. These values are considered appropriate for early stage mission planning and life support system research and development. As is pointed out, additional details and specific mission requirements, as well as transient analyses, are required for final life support system hardware design. It has been shown that these values are important for crew health and spacecraft hardware development in both open and closed loop life support system architectures.

Having a consistent set of astronaut mass balance values can also be very valuable when trying to compare studies by various groups working together on a large program. Thus, the information presented here, along with other crew consumables data, will be published in a NASA Technical Memorandum.[10]

Acknowledgments

The authors would like to thank Dr. Kevin Lange and John Keener from the JETS contract at the Johnson Space Center. Kevin provided insightful comments and data sources during the preparation of this paper, and John conducted all of the MetMan human thermal model upgrades resulting in the updated metabolic profile. Additionally, thanks goes to Jeannie Corte for assistance with graphics.

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