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Would Current International Space Station (ISS) Recycling Life Support Systems Save Mass on a Mars Transit?

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The oxygen and water are recycled on the International Space Station (ISS) to save the cost of launching their mass into orbit. Usually recycling systems are justified by showing that their launch mass would be much lower than the mass of the oxygen or water they produce. Short missions such as Apollo or space shuttle directly provide stored oxygen and water, since the needed total mass of oxygen and water is much less than that of the recycling equipment. Ten year or longer missions such as the ISS or a future moon base easily save mass by recycling while short missions of days or weeks do not. Mars transit and long Mars surface missions have an intermediate duration, typically one to one and a half years. Some of the current ISS recycling systems would save mass if used on a Mars transit but others would not.

Nomenclature

CDRA = Carbon Dioxide Removal Assembly
CRS = Carbon Dioxide Reduction System
ECLSS = Environmental Control and Life Support System
ISS = International Space Station
LiOH = Lithium Hydroxide
MTBF = Mean Time Before Failure
OGS = Oxygen Generation System
ORU = Orbital Replacement Unit
UPA = Urine Processor Assembly
WPA = Water Processor Assembly
WRS = Water Recovery System

I. Introduction

THIS report considers the question, "Would Current International Space Station (ISS) Recycling Life Support Systems Save Mass on a Mars Transit?" The choice between stored or recycled oxygen and water depends largely on the duration of a human mission. Short missions of days and weeks, such as Apollo and Space Shuttle, use stored materials. Long missions of many years, such as the ISS, recycle oxygen and water and so greatly reduce the total launch mass.

A closed habitat such as the ISS produces many human metabolic products that are both wastes and potential resources for recycling. These wastes include exhaled carbon dioxide, atmospheric water condensate derived from respiration and perspiration, urine and flush water, and used wash water. The first concern is to remove these waste products from the habitat for the health and comfort of the crew, and the second is to recover them in a cost-effective way. If recycling is used to recover oxygen and water, the recycling itself produces products that are also wastes and potential resources for recycling. The notable recycling products are methane or hydrogen from oxygen recovery and concentrated brine from water recovery.

Increasing the mass closure of the human habitat requires recovering less abundant and more difficult resources, creating the problem of diminishing returns. Humidity condensate is plentiful and relatively easily to process to potable water, so it would be the first waste resource to recover. Some waste recovery systems were installed later on ISS or still remain to be designed and flown, which suggests that they might be less likely to save mass on a Mars transit.

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As is usual in preliminary feasibility analysis, only the mass of the required material is compared to the mass of the recycling systems. Selecting storage rather than recycling would require considering the mass of the tanks and packaging required and many other factors.

The current ISS recycling systems have been designed for ISS requirements and could probably be redesigned to better meet the different Mars transit requirements, but this reports investigates only the current ISS recycling system designs. All of the ISS life support recycling systems have sufficient capacity to support a crew of four. The three major factors in answering the title question are the mass of the oxygen and water required on a Mars transit, the mass of the current ISS recycling systems, and the mass of the spares required. The mass of oxygen and water required depends on the number of crew and the mission duration. The mass of the current systems is known.

The total mass of spares depends on the number of spares required to achieve the desired reliability. The ISS maintenance approach uses Orbital Replacement Units, (ORUs). The ISS typically has on board one or two spares of each ORU. Even if the current operating ORU has say a 95% chance of working throughout the expected ISS mission duration, a spare is needed to ensure higher than 95% reliability. This means that there is a 95% chance that the spare will never be needed, and most ISS spares are for insurance, not anticipated use.

If one or two spares are needed for ISS operating close to Earth, probably three or four will be needed for Mars transit. The exact number of spares needed for each ORU can be calculated for a particular probability of running out of spares, if the spares failure probabilities are known. Preliminary estimates and some actual failure data are available to help estimate the number of spares.

The objective is to compare the mass of ISS life support systems to the mass of the material they would produce on a Mars transit. Significant mass saving is a preliminary indication of feasibility. The mass of the ISS life support systems includes the required spares. The spares are estimated three different ways, first a guess that three spares are needed for all ORUs, second, the computed number of spares for a 0.001 system failure rate based on estimated failure rates, and third, the computed number of spares for a 0.001 system failure rate based on flight failure rates. The results are similar in all three cases.

II. Mars transit oxygen and water requirements and waste products

The amount of oxygen and water required and the waste produced on a Mars round trip depend on the crew size and the trip duration. Four crew are assumed. Typical conjunction class Mars missions have outbound and return transit times of 200 to 250 days each and Mars surface stays of 400 to 550 days. (Boden and Hoffman, 2000) The total transit time that recycling life support would operate is 400 to 500 days, interrupted by a quiescent period of 400 to 550 days if all the crew is on the surface.

The Mars DRA 5.0 provides useful mission definition. Conjunction class missions have "relatively short transits to and from Mars (less than 180 to 210 days)." Opposition class missions spend only 30 to 90 days at Mars and have total round trip transit times from 190 days to more than 400 days. The baseline planning transit time to and from Mars is 200 days. (Drake, 2009) If the mission plan includes an "abort to orbit," the crew time spent in the Mars transit vehicle could extend to nearly the entire mission duration, which would be 500 to 650 days for an opposition class mission and approximately 900 days for a conjunction class mission. (Drake, 2009) A nominal 450 day transit duration is used in the mass payback ratio calculations below. Using the 900 day full mission duration for a Mars transit vehicle safe haven would double the mass payback ratio. The recycling mass payback would be larger for longer missions and for several missions to the same location.

A. Oxygen and carbon dioxide processing requirements for Mars transit

The amount of oxygen required is about 0.84 kg per crewmember per day. The oxygen is consumed in the metabolism of food to produce carbon dioxide and water. About 1.00 kg of carbon dioxide and 0.35 kg of water are produced per crewmember per day. (Weiland, 1994) Table 1 gives the oxygen and product or material flows per crewmember-day and the total product mass and oxygen mass for a Mars transit. "These values are based on an average metabolic rate of 136.7 W/person (11,200 Btu/person/day) and a respiration quotient of 0.87." (Weiland, 1994)

Table 1. Mars transit oxygen, carbon dioxide, and lithium hydroxide mass. (Weiland, 1994)

	Mass, kg/crewmember-day	Total mass for 4 crew, 450 days, kg	Oxygen content mass for 4 crew, 450 days, kg
Oxygen consumption	0.84	1,512	1,512
Carbon dioxide produced	1.00	1,800	1,309
Metabolic water	0.35	630	560
Lithium hydroxide	1.75	3,150	

Not all the required oxygen can be derived from carbon dioxide. Water electrolysis must be used to supply the remainder.

The major resupply item needed for waste removal is lithium hydroxide (LiOH) for carbon dioxide removal, packed in canisters and disposed of after use. About 2 kg of LiOH is required to remove the 1 kg of carbon dioxide per crewmember per day. (Eckart, 1996) The shuttle LiOH canister weighs 7 kg and is rated at 4 crewmember-days, 1.75 kg/crewmember-day.

B. Water processing requirements for Mars transit

The Mars transit water use is shown in Table 2.

Table 2. Mars transit water flows.

	Mass flow rate, kg/crewmember-day	Total water for 4 crew, 450 days, kg
Water consumption		
Drinking and food preparation water	2.38	4,284
Urine flush water	0.50	900
Wash water	1.29	2,322
Total water	4.17	7,506
Waste water		
Respiration and perspiration condensate	2.28	4,104
Urine and flush water	2.00	3,600
Used wash water	1.29	2,322
Total waste water	5.57	10,026
UPA		
UPA input	2.00	3,600
UPA output (80%)	1.60	2,880
UPA final output (80% * 99%)	1.58	2,851
WPA without UPA		
WPA input without UPA	3.57	6,426
WPA output without UPA (99%)	3.53	6,362
WRS		
WRS input	5.57	10,026
WRS output	5.12	9,213

The individual crewmember water requirements are given in kg per crewmember per day (kg/CM-d). They are based on space station analysis, except that showers, dish washing, and most of the crew hygiene water have been eliminated. (Weiland, 1994) The total waste water output exceeds the total crew input because there is 1.15 kg/CM-day of water in the supplied food and because the crew's metabolism of the food produces 0.35 kg/CM-day of additional water. If fully dehydrated food was provided, an additional 1.15 kg/CM-day of drinking and food preparation water would be needed.

The UPA input water is equal to the urine and flush water. The condensate and used wash water enters the WPA without passing through the UPA. The total WRS input would be 10,026 kg. The UPA is assumed to have water recovery efficiency of 80% and the WRS of 99%. The WRS output results from first processing the urine and flush as 80% efficiency and adding the product to the condensate and used wash water, all processed at 99% efficiency. The crewmember water flow is used to compute the total water use for 4 crew over 450 days.

III. The mass breakeven date and mass payback ratio of ISS ECLSS systems with three sets of spares

Table 3 gives the masses of the ISS ECLSS systems, a single set of spares, and of the full system plus three sets of spares. It also gives the daily mass use, mass breakeven date, total mass used, and mass payback ratio for a Mars transit of 450 days.

Table 3. Mass, mass produced, mass breakeven date, mass payback ratio for ISS ECLSS systems with three sets of spares.

System	Full name	System mass, kg	One set of spares mass, kg	Mass of the system and three spares, kg	Mass use for 4 crew, kg/day	Mass breakeven date, days	Mass produced on 450 day Mars transit, kg	Mass payback ratio
OGS	Oxygen Generation System	676	399	1,873	3.36	557	1,512	0.81
CDRA	Carbon Dioxide Removal Assembly	195	156	663	7.00	95	3,150	4.75
CRS	Carbon Dioxide Reduction System	329	219	986	3.28	301	1,476	1.50
WRS = UPA + WPA	Water Recovery System	1,383	719	3,540	18.60	190	8,370	2.36
UPA + 31% WPA	Urine processing	742	366	1,840	5.76	319	2,592	1.41
69% WPA	Condensate and hygiene processing	641	353	1,700	12.84	132	5,778	3.40
ECLSS	Environmental Control and Life Support System	2,583	1,493	7,062	32.23	219	14,508	2.05

The system and spares masses in Table 3 are from Appendix A. Most ISS ECLSS ORUs have one or two spares, and three would be a reasonable allocation for Mars transit. The correct number of spares for each ORU depends on its failure probability. These are calculated later.

The current ISS Oxygen Generation System (OGS) would pay back the mass of the initial system and three spares in 557 days, longer than the typical 450 day Mars transit. The oxygen mass produced by the OGS and consumed by the crew would amount to only 81 percent of the mass of the system and three spares.

The current ISS Carbon Dioxide Removal Assembly (CDRA) would save lithium hydroxide mass equal to the mass of the initial system and three spares in only 95 days, much shorter than the typical 450 day Mars transit. Replacing the beds three times would not be called for in normal operations. Most ISS spares are for insurance and will never be used. Even with three spares, the CDRA saves considerable mass compared to lithium hydroxide.

The Carbon Dioxide Reduction System (CRS) converts carbon dioxide to water. The water equivalent of 1.00 kg per crewmember per day of carbon dioxide is 0.82 kg per crewmember per day. If all carbon dioxide is converted to water, 3.28 kg per day will be produced for four crew, paying back the mass of the system and three spares in 301 days. The mass payback ratio is 1.50 for a 450 day mission. (There is an additional mass penalty for the CRS that is ignored here. The Sabatier-based CRS uses hydrogen to produce water and methane from carbon dioxide. The hydrogen in the water is recovered when electrolysis is used to produce oxygen. The hydrogen in the methane must either be recovered using an additional processor or resupplied from the ground.)

The Water Recovery System (WRS) accepts condensate, used hygiene water, and urine and flush water and processes the inputs to potable. The current ISS WRS would pay back the mass of the initial system and three spares in 190 days, less than half of the typical 450 day Mars transit. The water mass produced by the WRS and consumed by the crew would amount to 236 percent of the mass of the system and three spares.

Calculating the mass pay back for the two components of the WRS is more complicated. The WRS consists of the Urine Processor Assembly (UPA) and the Water Processor Assembly (WPA). The UPA does not directly produce potable water. Its output must be fed through the WPA. Thus urine processing requires the mass of the UPA and its spares plus a proportionately allocated mass of the WPA and its spares. The allocation is based on the proportion of the WRS output product due to urine and flush or condensate and hygiene water, and is computed in Appendix A.

The current ISS urine processing arrangement would pay back its mass in 319 days on a Mars transit mission. The water produced would amount to 1.41 times the mass of the required equipment. A downsized remnant of the WPA would pay back its mass in 132 days and produce 3.40 times its mass in water. Considering system and spares mass, condensate and hygiene processing is much more advantageous than urine and flush processing.

The overall regenerative Environmental Control and Life Support System (ECLSS) consists of the OGS, CDRA, CRS, and WRS. The current ISS ECLSS would pay back its mass in 219 days on a Mars transit mission. The oxygen and water produced and the lithium hydroxide saved would amount to 2.05 times the mass of the ECLSS with three spares of each ORU. Using the current ISS regenerative ECLSS for Mars transit would reduce the launch mass by half.

An adjustment should be made to the mass payback ratios. Mars transit recycling systems must make the full round trip. They will be accelerated out to Mars, orbited, and then sent back to Earth. The propulsion mass, the rockets and fuel, required to move the system can be ten or twenty times as massive as the system itself. But since the propulsion mass is proportional to the hardware mass, recycling systems can be compared using their masses in low Earth orbit. However, the resupply mass is consumed during the mission. Only the second half the resupply mass for a Mars transit needs to be sent back toward Earth. The first half would be consumed outbound and would not wait at Mars or be sent back to Earth. This means that resupply mass for Mars transit costs only a little more than half as much as recycling mass. The ISS ECLSS mass payback ratios, based on launch mass, are really smaller by nearly a factor of two when the round trip propulsion mass is considered.

If the recycling mass payback ratios are adjusted to account for the fact that half the resupply mass but all the recycling mass is sent back to Earth, the payback ratios are cut in half. This means that using the current ISS regenerative ECLSS for Mars transit would reduce the launch mass by the mass payback ratio of $2.05/2 = 1.025$, an insignificant 2.5% mass savings.

The current ISS regenerative ECLSS systems were designed for a decades long or longer mission in low earth orbit and the order of magnitude shorter duration of a Mars transit makes mass payback ten times more difficult. If a system just breaks even on the year and a quarter Mars transit, it will pay back 12.5 times its mass on a ten year mission. Less closure is more cost-effective on a shorter mission. In the limiting case of a few days or weeks, open loop life support is clearly better than recycling.

The ISS regenerative ECLSS systems with shorter pay back time and higher mass payback ratio are those more suited for a Mars transit mission. The CDRA Carbon Dioxide Removal System would have first priority, followed by condensate and hygiene water recycling. The oxygen generation system is least mass cost effective on a shorter mission. Carbon dioxide reduction and urine and flush recycling have less than average payoffs and should have intermediate priority.

IV. The mass breakeven date and mass payback ratio of ISS ECLSS systems with spares for 0.001 failure rate

Table 4 gives the masses of the ISS ECLSS systems, a single set of spares, the total ORUs mass for 0.001 failure rate, and of the system and spare ORUs. It also gives the daily mass use, mass breakeven date, total mass used, and mass payback ratio for a Mars transit of 450 days. The calculations are in Appendix B and C.

Table 4. Mass, mass produced, mass breakeven date, and mass payback.

System	Full name	System mass, kg	One set of spares mass, kg	ORUs mass, kg	Mass of the system and spares, kg	Mass use for 4 crew, kg/day	Mass breakeven date, days	Mass used on 450 day Mars transit, kg	Mass payback ratio
OGS	Oxygen Generation System	676	399	1,128	1,405	3.36	418	1,512	1.08
CDRA	Carbon Dioxide Removal System	195	156	389	428	7.00	61	3,150	7.36
CRS	Carbon Dioxide Reduction System	329	219	657	986	3.27	301	1,476	1.50
OGS + CRS	Carbon dioxide to oxygen	1,005	618	1,785	2,391	3.36	712	1,512	0.63
WRS = UPA + WPA	Water Recovery System	1,383	719	2,985	3,649	18.60	196	8,370	2.29
UPA + 31% WPA	Urine processing	742	366	1,660	2,036	5.76	353	2,592	1.27
69% WPA	Condensate and hygiene processing	641	353	1,325	1,613	12.84	126	5,778	3.58
ECLSS	Environmental Control and Life Support System	2,583	1,493	5,159	6,249	32.23	194	14,508	2.32

The masses of the system and one set of spares are from Appendix A. The ORUs mass is from Appendix C. The mass of the required ORUs is the minimum mass of a set of ORUs that can achieve the required overall system reliability. The ORU Mean Time Before Failure (MTBF) is listed in Appendix B and is used to compute the probability that the ORU will fail during a 450 day Mars transit mission. It is assumed that all failures can be repaired using spares, so that the system fails only if the spares run out. The ORU failure probabilities are used to compute the needed redundancy for each system ORU so that the overall failure rate is less than 0.001. The total ORU mass is minimized. The Poisson distribution is used to compute the failure probabilities, rather than the usual formula for systems operating in parallel. Since only one ORU is operating at a time, the Poisson distribution is more accurate and gives a lower number of spares. Previous calculations using the standard formula gave a too high number and mass of spares and a too low a mass payback ratio. Since the mass of the ORUs includes the operating ORU and the spares, the total mass of the system and its spares is equal to the system mass minus the mass of one set of spares plus the mass of all the redundant ORUs.

Despite the extensive computations required to produce Table 4, the mass breakeven dates and mass payback ratios are very similar to those in Table 3, which simply assumed one operating system and three spares for each ORU. The number of spares found for the ORUs in Appendix C varied from 2 to 6, with most 3 or 4.

The implications of Table 3 are not changed much by Table 4. The CDRA Carbon Dioxide Removal System has even more clearly the highest mass payback, again followed by condensate and hygiene water recycling, and with the other systems offering little mass advantage.

Since no ORU MTBF data was found for the CRS (Carbon Dioxide Reduction System), mass breakeven date and mass payback ratio are unchanged from those assuming three spares. There is an important loop relation between the OGS (Oxygen Generation System) and the CRS (Carbon Dioxide Reduction System). The crew breathes in oxygen and breathes out carbon dioxide, which is removed by the CDRA. In the ISS, the Sabatier reaction of the CRS converts this carbon dioxide to water and the OGS converts a roughly equivalent amount of water to oxygen, closing the loop. If the OGS is not used and the oxygen directly supplied instead, there would be no need for the water produced by the CRS and no need to have the CRS. The OGS mass plus the CRS mass is 1,405 + 986 = 2,391 kg, which far exceeds the 1,512 kg mass of oxygen the crew uses.

In general, the decision to recycle materials or to use supplies from Earth would depend on the overall system design and mission environment. A human space habitat essentially operates with a water based economy. If water is readily available, as it once was for ISS when the space shuttle fuel cells supplied it with water, it is more attractive to use an OGS to produce oxygen from water. If water is in short supply, as when the shuttle was not flying, it is better to supply oxygen rather than water. Similarly, the Sabatier process in the CRS requires hydrogen to produce water from carbon dioxide. Some of the hydrogen becomes methane and is not recovered, which limits the amount of water that can be produced.

V. The mass breakeven date and mass payback ratio of ISS ECLSS systems with spares for 0.001 failure rate based on flight data

Table 5 considers only the ISS OGS, UPA, and WPA, which are the systems where Bagdigian et al. provide operating times. It gives the masses of a single set of spares, the total ORUs mass for 0.001 failure rate, and then of the system and ORUs. It also gives the daily mass use, mass breakeven date, total mass used, and mass payback ratio for a Mars transit of 450 days. The calculations are in Appendix D.

Table 5. Mass, mass produced, mass breakeven date, and mass payback.

System	Full name	System mass, kg	One set of spares mass, kg	ORUs mass, kg	Mass of the system and spares, kg	Mass use for 4 crew, kg/day	Mass breakeven date, days	Mass used on 450 day Mars transit, kg	Mass payback ratio
OGS	Oxygen Generation System	676	399	1,320	1,597	3.36	475	1,512	0.95
WRS = UPA + WPA	Water Recovery System	1,383	719	4,878	5,542	18.60	298	3,150	1.51
UPA + 31% WPA	Urine processing	742	366	3,464	3,840	5.76	667	1,476	0.67
69% WPA	Condensate and hygiene processing	641	353	1,414	1,702	12.84	133	1,512	3.40

The mass breakeven dates are longer and the mass payback ratios are lower than in Table 4 because some ORUs have experienced failure rates higher than were expected using the original overestimated MTBFs. The flight based and MADS MTBFs are in Appendix D. The UPA has four ORUs with estimated MTBFs 10 or 20 times longer than those observed in flight. These are being redesigned to improve reliability. If flown to Mars as they are, 10 to 20 spares would be required to achieve an estimated 0.0001 individual ORU failure rate. The number of spares calculated for the overestimated MTBFs was only 4 or 5. The probability of not having a needed spare would have been greater than 99%, which means a less than 1% chance of having a functioning UPA.

The spares approach to achieving reliability assumes that the number of spares can be correctly estimated. ISS ECLSS failures can be repaired using spare ORUs but some ORUs with higher than expected failure rates have required redesign. If the failure rate is under-estimated, providing the estimated required number of spares does not guarantee success, as seen above for the UPA.

VI. Conclusion

This paper computed the mass breakeven dates and mass payback ratios for a Mars transit for the ISS regenerative ECLSS systems. The total mass required by each system is equal to the mass of the system plus the mass of the system spares. The number and mass of the spares was calculated three ways, by assuming three spares of each ORU, by computing the number of spares to have less than a 0.001 probability of having all units fail using tabulated failure data, and by doing the same computation using flight failure data. The mass breakeven dates and mass payback ratios were similar in all three cases.

The current ISS Oxygen Generation System (OGS) would produce oxygen with roughly its own mass, making it the least attractive system. The current ISS Carbon Dioxide Removal Assembly (CDRA) would save five or seven times its own mass in lithium hydroxide, making it the most mass saving system. The Carbon Dioxide Reduction System (CRS), the Sabatier, would provide water with about 1.5 times its mass, which is not a strong justification for using it, but there is a complication. If the OGS is not flown but rather the crew oxygen is supplied, the need for water to convert to oxygen goes away. We can not close the oxygen – carbon dioxide – water – oxygen loop. We then do not need the CRS water. There is a significant mass savings if the crew oxygen is supplied and the OGS and CRS are not flown.

The Urine Processor Assembly (UPA) does not produce potable water and its output must be routed through the Water Processor Assembly (WPA). Processing urine to potable requires the UPA and a large part of the WPA's processing capacity. Urine processing does not have a high mass payback, and would have none with its current unreliable ORUs. The current ISS UPA does not seem suitable for Mars. The WPA would save five or seven times its own mass in water and is the second strongest regenerative candidate for Mars after the CDRA.

The overall regenerative Environmental Control and Life Support System (ECLSS) saves a little more than twice its own mass in water, oxygen, and lithium hydroxide. But it would save twenty times its own mass over the originally planned ten year ISS mission. Recycling systems payback their mass much more easily for longer missions. Approaching full mass closure is feasible for long missions, but fully open systems are indicated for brief missions. The appropriate approach for intermediate duration missions, such as Mars transit, is to implement only the recycling systems that are cost effective. As mission length increases from 10 days to 100 and from 100 to 1,000, additional recycling systems should be used. That is why the mass breakeven date is a common life support parameter. At 100 days, the CDRA begins to save mass, at 130 to 200 days, the WPA becomes mass effective, at 300 to 350 days, the UPA and CRS save mass, and at 400 to 550 days, the OGS saves mass. Clearly, the usual justification for recycling, that it produces very many times the material mass that would otherwise be launched, does not apply to using the current ISS ECLSS for Mars transit.

Obtaining some mass savings is only a preliminary feasibility check, it is not sufficient to make a design decision. The cost, design heritage, and reliability of both recycling and storage systems should be considered. A full systems engineering analysis and design tradeoffs should be made, and should consider the specific mission requirements. The mission duration and required reliability are very different for ISS and Mars transit.

The life support community is now intensely focused on operating, maintaining, and upgrading the ISS ECLSS. The Mars mission is in the future, but we need to add some analysis and hardware development work now for Mars life support. We need to take advantage of the time available for long duration reliability testing and of the availability of ISS for microgravity testing and human maintenance.

Appendix A: ECLSS system and ORU masses

This appendix tabulates the system and ORU masses of the OGS, CDRA, CRA, UPA, and WPA. These are used first in calculating the beak even dates and payback ratios assuming each ORU has three spares. In Appendix B the ORU MTBFs are tabulated. In Appendix C the mass of the computed number of spares is tabulated.

A. Oxygen Generation System (OGS)

Table A.1 gives the masses of the Oxygen Generation System (OGS) and its ORUs.

Table A.1. OGS ORU masses.

Acronym	Full name	Bagdigian et al. mass, lb	Bagdigian et al. mass, kg	BVAD mass, kg	MADS mass, lb	MADS mass, kg
OGS	Oxygen Generation System	1,487	676			
Hydrogen ORU	Hydrogen Pressure dome			161.6176	275.4	125.2
Controller	Process Controller			47.0836	81.7	37.1
O ORU	Oxygen Outlet			48.1723	71.9	32.7
H2 Sensor ORU	Hydrogen Sensor			4.3545	10.2	4.6
Pump ORU	Pump			17.9625	23.2	10.5
Inlet DI Bed ORU	Inlet Deionizing Bed			28.66775	44.0	20.0
Nitrogen Purge ORU	Nitrogen Purge			34.2468	51.0	23.2
PSM	Power Supply Module			42.6384	102.5	46.6
ACTEX	ACTEX - Recirculation				3.3	1.5
ACTEX	ACTEX –By-Pass					
Water ORU	Water			61.0545	76.2	34.6
	Sum of ORU masses	877	399	445.7980		336.1

The OGS initial system mass is from Bagdigian et al., figure 10. The sum of the ORU masses is 59% of the initial mass, also from Bagdigian et al. figure 10. (Bagdigian et al., 2015) The BVAD is (Hanford, 2004). MADS is the ISS Maintenance and Analysis Data Set. (MADS, 2015)

B. Carbon Dioxide Removal System (CDRA)

Table A.2 gives the masses of the Carbon Dioxide Removal System (CDRA) and its ORUs.

Table A.2 Masses of the Carbon Dioxide Removal System (CDRA) and its ORUs.

Acronym	Full name	BVAD mass, kg	Carrasquillo et al. mass, kg
CDRA	Carbon Dioxide Removal System	195.3793	201.0
	Air Pump Two-Stage ORU	10.8861	10.9
	Blower	5.5792	5.6
	Check Valves	39.9159	
	Desiccant Beds	42.6384	40.0
	Heat Controller	3.3112	3.3
	Precooler	5.5792	
	Pump Fan Motor Controller	2.7215	2.7
	Selector Valves	3.0390	3.0
	Sorbent Beds (Zeolite)	42.6384	40.0
	Sum of ORU masses	156.3089	105.5

The masses in Table A.2 are from the BVAD (Hanford, 2004) and (Carrasquillo et al., 1997).

C. Carbon Dioxide Reduction System (CRS)

Table A3 gives the masses of the Carbon Dioxide Reduction System (CRS) and its ORUs.

Table A3. Masses of the Carbon Dioxide Reduction System (CRS) and its ORUs.

Acronym	Full name	Jeng and Lin mass, kg	Do et al. mass, kg
CRS	Carbon Dioxide Reduction System		329
	Sabatier Reactor	120	120
	Condensing Heat Exchanger		49.71
	Phase Separator		11.93
	Valves		3.04
	Sensors		4.81
	Controller	3	3
	Compressor	27	27
	Sum of ORU masses	150	219

Do et al. took the available CRS ORU masses from Jeng and Lin and estimated the others by analogy to other ISS ECLSS. (Do et al., 2014) (Jeng and Lin, 2001) The total CRS system mass including rack and plumbing is estimated here at 150% of the total ORU mass.

D. Urine Processor Assembly (UPA)

Table A.4 gives the masses of the Urine Processor Assembly (UPA) and its ORUs.

Table A.4 Masses of the Urine Processor Assembly (UPA) and its ORUs.

Acronym	Full name	Carter et al., 2012, mass, lb	Carter et al., 2015, mass, kg	BVAD Mass, kg	MADS mass, lb	MADS mass, kg
UPA	Urine Processor Assembly	1,000	455			
FCA	Firmware Controller Assembly			23.0882	53.0	24.1
SPA	Separator Plumbing Assembly			16.7832	35.9	16.3
PCPA	Pressure Control and Pump Assembly			49.0795	98.7	44.9
DA	Distillation Assembly			92.7612	166.6	75.7
FCPA	Fluids Control and Pump Assembly			47.5826	100.5	45.7
	Sum of ORU masses			229.3		206.7

The WSTA and the now replaced RFTA are not included in the ORU spares mass. The masses are from (Carter et al., 2012) (Carter et al., 2015), the BVAD (Hanford, 2004), and (MADS, 2015).

E. Water Processor Assembly (WPA)

Table A.5 gives the masses of the Water Processor Assembly (WPA) and its ORUs.

Table A.5. Masses of the Water Processor Assembly (WPA) and its ORUs.

Acronym	Full name	Bagdigian et al., Carter et al., 2012, mass, kg	BVAD mass, kg	MADS mass, lb	MADS mass, kg
WPA	Water Processor Assembly	928			
	Catalytic Reactor		67.042	126.6	57.5
	Gas Separator		39.1456	86.6	39.4
	Ion Exchange Bed		13.0183	26.5	12.0
	Microbial Check Valve		5.7607	8.2	3.7
	Multifiltration Bed #1		149.2344	111	50.5
	Multifiltration Bed #2		149.2344	111	50.5
	Particulate Filter		32.2509	59	26.8
	pH Adjuster		2.5401		0.0
	Process Controller		44.9971	81.2	36.9
	Pump Separator		31.3437	60.8	27.6
	Reactor Health Sensor		16.8285	19	8.6
	Sensor		4.8081	8	3.6
	Separator Filter		7.6658	16	7.3
	Start-up Filter		9.4348	20.8	9.5
	Water Delivery		47.5372	86.3	39.2
	Waste Water		103.2847	192.6	87.5
	Water Storage		56.7453	108.4	49.3
	Oxygen Filter			2.5	1.1
	External Filter			2.2	1.0
	Sum of ORU masses		780.9		512.1

Carter et al., 2012, give the mass of the UPA as 1,000 lb. Bagdigian et al. give the mass of the WRS as 3,042 lb. Since the WRS is the combination of the UPA and the WPA, the system mass of the WPA is the difference, 2,042 lb or 928 kg. The masses are from (Carter et al., 2012), the BVAD (Hanford, 2004), and (MADS, 2015).

F. WRS mass allocation to urine and other processing

The UPA by itself does not produce potable water. All of the processed water product of the UPA is fed to the WPA. Thus some portion of the WPA mass must be charged to urine processing and not to condensate and hygiene water processing. The WPA mass allocation for urine processing should be proportional to the fraction of output due to urine. Table A.6 allocates the masses of the WPA system and spares.

Table A.6. WRS mass allocation to urine and other processing.

	WPA output, kg	Fraction	WPA system mass, kg	WPA spares mass, kg	UPA system mass, kg	UPA spares mass, kg	WRS system mass, kg	WRS spares mass, kg
Total			928	512	455	207		
Due to UPA input	2,592	0.31	287	159	455	207	742	366
Due to other input	5,778	0.69	641	353	0	0	641	353
Total	8,370						1,383	719

Appendix B: ISS ECLSS ORU MTBFs, failure rates, and failure probabilities

The reliability of ECLSS ORUs is usually measured by the Mean Time Before Failure (MTBF). MTBFs are first estimated before system operation and later updated based on experience. MTBFs for most of the ECLSS ORUs are tabulated in the BVAD and MADS.

The MTBF has a clear meaning. Half the ORUs are expected to fail by the MTBF. If a system has a certain MTBF, its failure rate over time is f = 1/MTBF. The MTBF must be much greater than the mission length, L, for a single system to provide a low probability of failure. Suppose the requirement is for less than a 1% probability of not having a needed spare. For F = f * L = L/MTBF = 0.01, the MTBF = 100 L. The MTBF must be 100 times the mission length for a single unit without spares to have a 1% probability of failure.

A. Oxygen Generation System (OGS) MTBFs and failure probabilities

Table B.1 gives the Oxygen Generation System (OGS) ISS spares, MTBFs, life limits, and failure probabilities.

Table B.1. OGS MTBFs and failure probabilities.

Acronym	Full name	ISS MDC spares	BVAD MTBF, hours	MADS MTBF, hours	Life limit, years	ORU failure probability
Hydrogen ORU	Hydrogen Pressure dome	1	27,156	29,551		0.365
Controller	Process Controller	2	103,208	75,677		0.143
O ORU	Oxygen Outlet	1	98,112	99,252		0.109
Pump ORU	Pump	2	144,540	189,433	2	0.057
Inlet DI Bed ORU	Inlet Deionizing Bed	1	296,710	442,487		0.024
Nitrogen Purge ORU	Nitrogen Purge	1	138,408	140,195		0.077
PSM	Power Supply Module	2	47,479	49,202		0.220
Water ORU	Water	1	33,288	37,885		0.285
	Totals					

The ISS spares are from the ISS MDC. All the ORUs have ISS spares listed in the MDC. (ISS MDC, 2015) The BVAD reports MTBFs as of 2004. (Hanford, 2004). MADS is the ISS Maintenance and Analysis Data Set. MADS provides current MTBFs and the life limits for scheduled replacement ORUs. Where both BVAD and MADS MTBF data are available, the MADS data is used. (MADS, 2015)

The ORU failure probability is the probability that the ORU will fail over the mission length L, which is F = L/MTBF. For the Mars transit, out and back, the mission length L = 450 days, 10,800 hours. The mission failure probability for an ORU is 10,800/MTBF. The failure probability for each ORU is listed. The H2 Sensor is not included, as it is an identified scheduled replacement ORU and may be replaced in a future design. The ACTEX is also a scheduled replacement unit and is not included in the later reliability calculations.

B. Carbon Dioxide Removal System (CDRA) MTBFs and failure probabilities

Table B.2 gives the Carbon Dioxide Removal System (CDRA) ISS spares, MTBFs, life limits, and failure probabilities.

Table B.2 CDRA MTBFs and failure probabilities.

Full name	ISS MDC spares	BVAD MTBF, hours	MADS MTBF, hours	Life limit, years	ORU failure probability
Air Pump Two-Stage ORU		156,200			0.069
Blower		129,700			0.083
Check Valves					
Desiccant Beds		77,100			0.140
Heat Controller		242,700			0.044
Precooler		129,700	129,700		0.083
Pump Fan Motor Controller		2,272,000			0.005
Selector Valves		117,000			0.092
Sorbent Beds (Zeolite)		77,100			0.140

No ISS spares or life limits were identified, but the table format is retained. The references are the same as for Table B.1.

C. Carbon Dioxide Reduction System (CRS) MTBFs and failure probabilities

No data was found for the Carbon Dioxide Reduction System (CRS) ISS spares, MTBFs, and life limits. Three spares are assumed for later computations of the ISS ECLSS mass.

D. Urine Processor Assembly (UPA) MTBFs and failure probabilities

Table B.4 gives the Urine Processor Assembly (UPA) ISS spares, MTBFs, life limits, and failure probabilities..

Table B.4 UPA MTBFs and failure probabilities.

Acronym	Full name	ISS MDC spares	BVAD MTBF, hours	MADS MTBF, hours	Life limit, years	ORU failure probability
WSTA	Wastewater Storage Tank Assembly	1	184,223	82,200		0.131
FCA	Firmware Controller Assembly		27,331	13,453		0.803
SPA	Separator Plumbing Assembly	2	384,652	88,993	2	0.121
PCPA	Pressure Control and Pump Assembly	1	181,507	59,221	2	0.182
DA	Distillation Assembly	1	142,252	41,376	2	0.261
FCPA	Fluids Control and Pump Assembly	1	90,140	22,759	4	0.475

The MADS MTBFs for the UPA are significantly lower than the earlier BVAD MTBFs. The references are the same as for Table B.1.

E. Water Processor Assembly (WPA) MTBFs and failure probabilities

Table B.5 gives the Water Processor Assembly (WPA) ISS spares, MTBFs, life limits, and failure probabilities.

Table B.5. WPA MTBFs and failure probabilities.

Acronym	Full name	ISS MDC spares	BVAD MTBF, hours	MADS MTBF, hours	Life limit, years	ORU failure probability
CR	Catalytic Reactor	1	25,579	27,077	1	0.399
GS	Gas Separator	3	84,008	61,182		0.177
IX	Ion Exchange Bed	1	296,701	442,478		0.024
MCV	Microbial Check Valve	1	13,489	178,447		0.061
MFB	Multifiltration Bed #1		296,701	349,650	1.15	0.031
MFB	Multifiltration Bed #2		296,701	349,650	1.15	0.031
PF	Particulate Filter	2	717,356	560,695	0.89	0.019
	pH Adjuster		137,182			0.079
PC	Process Controller	2	87,950	70,745		0.153
PS	Pump Separator	1	42,398	39,429	2	0.274
RHS	Reactor Health Sensor	1	56,677	134,077		0.081
S	Sensor	2	143,664	184,618		0.058
SF	Separator Filter	3	359,074	642,342		0.017
	Start-up Filter	1	226,884	226,850		0.048
WD	Water Delivery	2	64,561	81,797		0.132
WW	Waste Water	1	53,611	43,669		0.247
WS	Water Storage	1	44,676	40,463		0.267
	Oxygen Filter	2		342,548		0.032

The references are the same as for Table B.1.

Appendix C: ISS ECLSS ORU required redundancy and spares mass

This appendix calculates the number of spares needed to have a less than 0.001 probability of not having a needed spare. If all failures can be repaired using spares, the probability of an unrepaired system failure would be less than one tenth of one percent. The required mass of spares is also calculated.

A. Calculating the number of spares needed using the Poisson distribution

Suppose that a particular ORU has an MTBF equal to 10 times the mission length L. Then the single system probability of failure during the mission is F = L/MTBF = L/10 L = 0.10. Further suppose that all failures can be fixed by using spare parts and that the system must have less than a 0.001 probability of not having a needed spare. This can be achieved by having one operating ORU and two spares, since the probability that all three will fail is $F^3 = 0.1^3 = 0.001$. In general, suppose an ORU has failure probability F and N redundant units. All the N units, the original system and the N - 1 spare ORUs, must fail for the system to fail. The overall failure probability for N redundant units is F^N.

This approach is usually adequate, especially for small N, but here it overestimates the failure probability by roughly a factor of N. This formula is correct for hot spares, where all the units are operating all the time and all failing at the same rate. Some systems use on-line spares, but not ISS ECLSS, where the spare ORUs are simply stored. Only one unit is operating and the N - 1 off-line spares have a negligible failure rate. The formula that failure probability equals F^N is correct for hot spares but not for non-operating spares. Using the F^N formula for stored spares gives too high failure probability and too many required spares.

The probability of a given number of failures using cold spares is given by the Poisson distribution. It is used here to compute the number of spares needed to have a less than 0.001 probability of not having a needed spare.

The system is required to operate over the mission length L = 450 days. The system has a failure rate, rate f = 1/MTBF, the number of times it is expected to fail per year. The number of failures from time 0 to time t is n(t) and has a Poisson distribution.

The Poisson pdf gives the probability, for failure rate f = 1/MTBF, that there will be exactly n(t) = x failures in time t.

Poisson pdf $[n(t) = x] = (f\,t)^{x}\, e^{-f\,t}/x!$

The Poisson distribution's mean value, which is the expected number of failures during the mission of length L, is f * L = L/MTBF. The probability of n(t) or fewer failures is the summation of the Poisson pdf from x equals 0 to n(t). The probability of n(t) or more failures is the summation of the pdf from n(t) to infinity.

The Poisson distribution is available in Microsoft Excel®. It is possible to compute how many spares are required to have less than any particular probability of having all units fail.

The Poisson distribution is more appropriate than the formula F^{N} for non-operating spares. The formula F^{N} gives far too high a number of spares when the correct N is 5 or 6. It is impossible to use F^{N} when $F > 1$, which occurs for short lived components with $L < MTBF$. The Poisson distribution is necessary for $F > 1$.

The need to use the Poisson distribution is unusual in reliability analysis. By considering the use of ISS systems for Mars, we are taking systems designed for a lower reliability environment and putting them in a higher reliability environment. Naturally, the required redundancy is higher than typical and approximations that work for small N are not satisfactory.

B. Oxygen Generation System (OGS) MTBFs, failure probabilities, redundancy, and spares

Table C.1 gives the OGS MTBFs, failure probabilities, required redundancy, and total spares mass.

Table C.1. OGS ORU MTBFs, failure probabilities, redundancy, and spares mass.

Acronym	Full name	MADS MTBF, hours	Life limit, years	ORU failure probability	MADS mass, kg	Needed redundancy	ORUs mass, kg	Failure probability
Hydrogen ORU	Hydrogen Pressure dome	29,551		0.365	125.2	4	500.7	0.00056
Controller	Process Controller	75,677		0.143	37.1	4	148.5	0.00002
O ORU	Oxygen Outlet	99,252		0.109	32.7	4	130.7	0.00001
Pump ORU	Pump	189,433	2	0.057	10.5	3	31.6	0.00003
Inlet DI Bed ORU	Inlet Deionizing Bed	442,487		0.024	20.0	3	60.0	0.00000
Nitrogen Purge ORU	Nitrogen Purge	140,195		0.077	23.2	3	69.5	0.00007
PSM	Power Supply Module	49,202		0.220	46.6	4	186.4	0.00008
Water ORU	Water	37,885		0.285	34.6	4	138.5	0.00022
	Totals				301.5		1,127.5	0.00098

As before, the Hydrogen Sensor and ACTEX are not included. The ORUs mass is that of all the required ORUs, including those in the operating unit. (MADS, 2015)

C. Carbon Dioxide Removal System (CDRA) MTBFs, failure probabilities, redundancy, and spares

Table C.2 gives the CDRA MTBFs, failure probabilities, required redundancy, and total spares mass.

Table C.2. CDRA MTBFs, failure probabilities, redundancy, and spares mass.

Full name	BVAD MTBF, hours	Life limit, years	ORU failure probability	BVAD mass, kg	Needed redundancy	ORUs mass, kg	Failure probability
Air Pump Two-Stage ORU	156,200		0.069	10.9	3	32.7	0.00005
Blower	129,700		0.083	5.6	3	16.7	0.00009
Check Valves				39.9		0.0	
Desiccant Beds	77,100		0.140	42.6	3	127.9	0.00041
Heat Controller	242,700		0.044	3.3	3	9.9	0.00001
Precooler	129,700		0.083	5.6	3	16.7	0.00009
Pump Fan Motor Controller	2,272,000		0.005	2.7	2	5.4	0.00001
Selector Valves	117,000		0.092	3.0	3	9.1	0.00012
Sorbent Beds (Zeolite)	77,100		0.140	42.6	4	170.6	0.00001
Totals				156.3		389.1	0.00081

These MTBFs are from the BVAD. (Hanford, 2004).

D. Carbon Dioxide Reduction System (CRS) MTBFs, failure probabilities, redundancy, and spares

No data was found for the CRS MTBFs. Three spares and the original unit are assumed for the ISS ECLSS mass.

E. Urine Processor Assembly (UPA) MTBFs, failure probabilities, redundancy, and spares

Table C.4 gives the UPA MTBFs, failure probabilities, required redundancy, and total spares mass.

Table C.4. UPA MTBFs, failure probabilities, redundancy, and spares mass.

Acronym	Full name	MADS MTBF, hours	Life limit, years	ORU failure probability	MADS mass, kg	Needed redundancy	ORUs mass, kg	Failure probability
WSTA	Wastewater Storage Tank Assembly	82,200		0.131	47.9	3	143.6	0.00034
FCA	Firmware Controller Assembly	13,453		0.803	24.1	6	144.5	0.00019
SPA	Separator Plumbing Assembly	88,993	2	0.121	16.3	4	65.3	0.00001
PCPA	Pressure Control and Pump Assembly	59,221	2	0.182	44.9	4	179.5	0.00004
DA	Distillation Assembly	41,376	2	0.261	75.7	4	302.9	0.00016
FCPA	Fluids Control and Pump Assembly	22,759	4	0.475	45.7	5	228.4	0.00014
	Totals				254.5		1,064.2	0.00087

The Recycle Filter Tank Assembly is not included in the ORUs mass. The MTBFs are from (MADS, 2015).

F. Water Processor Assembly (WPA) MTBFs, failure probabilities, redundancy, and spares

Table C.5 gives the WPA MTBFs, failure probabilities, required redundancy, and total spares mass.

Table C.5. WPA MTBFs, failure probabilities, redundancy, and spares mass.

Acronym	Full name	MADS MTBF, hours	Life limit, years	ORU failure probability	MADS mass, kg	Needed redundancy	ORUs mass, kg	Failure probability
CR	Catalytic Reactor	27,077	1	0.399	57.5	5	287.7	0.00006
GS	Gas Separator	61,182		0.177	39.4	4	157.5	0.00004
IX	Ion Exchange Bed	442,478		0.024	12.0	3	36.1	0.00000
MCV	Microbial Check Valve	178,447		0.061	3.7	3	11.2	0.00004
MFB	Multifiltration Bed #1	349,650	1.15	0.031	50.5	3	151.4	0.00000
MFB	Multifiltration Bed #2	349,650	1.15	0.031	50.5	3	151.4	0.00000
PF	Particulate Filter	560,695	0.89	0.019	26.8	3	80.5	0.00000
	pH Adjuster							
PC	Process Controller	70,745		0.153	36.9	4	147.6	0.00002
PS	Pump Separator	39,429	2	0.274	27.6	4	110.5	0.00019
RHS	Reactor Health Sensor	134,077		0.081	8.6	3	25.9	0.00008
S	Sensor	184,618		0.058	3.6	3	10.9	0.00003
SF	Separator Filter	642,342		0.017	7.3	2	14.5	0.00014
	Start-up Filter	226,850		0.048	9.5	3	28.4	0.00002
WD	Water Delivery	81,797		0.132	39.2	4	156.9	0.00001
WW	Waste Water	43,669		0.247	87.5	4	350.2	0.00013
WS	Water Storage	40,463		0.267	49.3	4	197.1	0.00017
	Oxygen Filter	342,548		0.032	1.1	3	3.4	0.00001
	Totals				511.1		1,921.2	0.00094

The External Filter is not included in the ORUs mass. The MTBFs are from (MADS, 2015).

Appendix D: ISS ECLSS ORU required redundancy and spares mass using flight MTBFs

This appendix, like the previous one, calculates the number of spares needed to have a less than 0.001 probability of not having a needed spare, but it uses MTBFs based on flight experience rather than the BVAD or MADS MTBFs.

Bagdigian et al. show the observed lifetimes for the OGS, UPA, and WRS. These systems have operated on ISS for about eight years. Some ORUs have had no failures and some have had several. (Bagdigian et al., 2015) In cases where all the ISS OGA ORUs have reached the end of life, the estimated MTBF is the average observed lifetime. In cases where one unit has operated without failure for eight years, the MTBF is estimated as eight years, 70,000 hours. If equipment has operated for a time T with no failures, this suggests that the probability of failure was less than one-half. So the MTBF can be estimated as roughly T. If the MTBF was much less, we would have seen many failures. The MTBF could be much longer, but longer run time will be needed to show that. We do not assume any MTBF is longer than the successful test time, even where the previously estimated MTBF makes this seem reasonable. In cases where one unit has failed but its replacement continues to operate, the MTBF is estimated as the average of the two observed lifetimes. This produces a strictly flight data based estimate of the required spares mass.

A. Oxygen Generation System (OGS) redundancy and spares mass using observed flight MTBFs

Table D.1 gives the OGS ORU MTBFs based on their observed operating lives. The failure probabilities, required redundancy, and total spares mass are computed.

Table D.1. OGS ORU observed MTBFs, failure probabilities, redundancy, and spares mass.

Acronym	Full name	Flight MTBF, hours	MADS MTBF, hours	ORU failure probability	MADS mass, kg	Needed redundancy	ORUs mass, kg	Failure probability
Hydrogen ORU	Hydrogen Pressure dome	35,000	29,551	0.309	125.2	4	500.7	0.00030
Controller	Process Controller	70,000	75,677	0.154	37.1	4	148.5	0.00002
O ORU	Oxygen Outlet	70,000	99,252	0.154	32.7	4	130.7	0.00002
Pump ORU	Pump	35,000	189,433	0.309	10.5	4	42.2	0.00030
Inlet DI Bed ORU	Inlet Deionizing Bed	70,000	442,487	0.154	20.0	4	80.0	0.00002
Nitrogen Purge ORU	Nitrogen Purge	70,000	140,195	0.154	23.2	4	92.7	0.00002
PSM	Power Supply Module		49,202		46.6	4	186.4	0.00008
Water ORU	Water	38,000	37,885	0.284	34.6	4	138.5	0.00022
	Totals				336.1		1,319.8	0.00097

The MADS MTBF is used for the PSM since no flight data was found. (MADS, 2015) The flight MTBFs are based on (Bagdigian et al., 2015).

B. Urine Processor Assembly (UPA) redundancy and spares mass using observed MTBFs

Table D.2 gives the UPA ORU MTBFs based on their observed operating lives. The failure probabilities, required redundancy, and total spares mass are computed.

Table D.2. UPA ORU observed MTBFs, failure probabilities, redundancy, and spares mass.

Acronym	Full name	Flight MTBF, hours	MADS MTBF	ORU failure probability	MADS mass, kg	Needed redundancy	ORUs mass, kg	Failure probability
WSTA	Wastewater Storage Tank Assembly	70,000	82,200	0.154	47.9	4	191.5	0.00002
FCA	Firmware Controller Assembly	70,000	13,453	0.154	24.1	4	96.4	0.00002
SPA	Separator Plumbing Assembly	4,000	88,993	2.700	16.3	11	179.5	0.00012
PCPA	Pressure Control and Pump Assembly	3,000	59,221	3.600	44.9	13	583.2	0.00010
DA	Distillation Assembly	5,500	41,376	1.964	75.7	9	681.5	0.00021
FCPA	Fluids Control and Pump Assembly	1,000	22,759	10.800	45.7	24	1096.4	0.00036
	Totals				254.5		2,828.5	0.00083

Only flight MTBFs were used in the calculations. The flight MTBFs are based on (Bagdigian et al., 2015).

C. Water Processor Assembly (WPA) redundancy and spares mass using observed MTBFs

Table D.3 gives the WPA ORU MTBFs based on their observed operating lives. The failure probabilities, required redundancy, and total spares mass are computed.

Table D.3. WPA ORU observed MTBFs, failure probabilities, redundancy, and spares mass. (Part 1)

Acronym	Full name	Flight MTBF, hours	MADS MTBF	ORU failure probability	MADS mass, kg	Needed redundancy	ORUs mass, kg	Failure probability
CR	Catalytic Reactor	14,000	27,077	0.771	57.5	6	345.3	0.00015
GS	Gas Separator	70,000	61,182	0.154	39.4	4	157.5	0.00002
IX	Ion Exchange Bed		442,478	0.024	12.0	3	36.1	0.00000
MCV	Microbial Check Valve	70,000	178,447	0.154	3.7	4	14.9	0.00002
MFB	Multifiltration Bed #1		349,650	0.031	50.5	3	151.4	0.00000
MFB	Multifiltration Bed #2		349,650	0.031	50.5	3	151.4	0.00000
PF	Particulate Filter		560,695	0.019	26.8	3	80.5	0.00000
	pH Adjuster							
PC	Process Controller		70,745	0.153	36.9	4	147.6	0.00002
PS	Pump Separator	18,000	39,429	0.600	27.6	6	165.8	0.00004
RHS	Reactor Health Sensor	70,000	134,077	0.154	8.6	3	25.9	0.00055

Table D.3. WPA ORU observed MTBFs, failure probabilities, redundancy, and spares mass. (Continued)

Acronym	Full name	Flight MTBF, hours	MADS MTBF	ORU failure probability	MADS mass, kg	Needed redundancy	ORUs mass, kg	Failure probability
S	Sensor	70,000	184,618	0.154	3.6	4	14.5	0.00002
SF	Separator Filter		642,342	0.017	7.3	3	21.8	0.00000
	Start-up Filter		226,850	0.048	9.5	3	28.4	0.00002
WD	Water Delivery	70,000	81,797	0.154	39.2	4	156.9	0.00002
WW	Waste Water	70,000	43,669	0.154	87.5	4	350.2	0.00002
WS	Water Storage	70,000	40,463	0.154	49.3	4	197.1	0.00002
	Oxygen Filter		342,548	0.032	1.1	3	3.4	0.00001
	Totals				511.1		2,048.6	0.00092

Flight MTBFs were used where available, otherwise MADS MTBFs were used. (MADS, 2015) The flight MTBFs are based on (Bagdigian et al., 2015).

References

Bagdigian, R. M., Dake, J., Gentry, G., and Gault, M., “International Space Station Environmental Control and Life Support System Mass and Crewtime Utilization In Comparison to a Long Duration Human Space Exploration Mission,” ICES-2015-094, 45th International Conference on Environmental Systems 12-16 July 2015, Bellevue, Washington.

Boden, D. G., and Hoffman, S. J., “Orbit Selection and Astrodynamics,” in Larson, W. K., and Pranke, L. K, eds., *Human Spaceflight: Mission Analysis and Design*, McGraw-Hill, New York, 2000.

Carrasquillo, R. L., Reuter, J. L., and Philistine, C. L., “Summary of Resources for the International Space Station Environmental Control and Life Support System,” Proceedings of the 27th International Conference on Environmental Systems, SAE 972332, 1997.

Carter, L., Pruitt, J., Brown, C. A., Schaezler, R., and Lyndsey Bankers, L., “Status of ISS Water Management and Recovery,” ICES-2015-073, 45th International Conference on Environmental Systems 12-16 July 2015, Bellevue, Washington.

Carter, L., Tobias, B., and Orozco, N., “Status of ISS Water Management and Recovery,” AIAA 2012-3594, 42nd International Conference on Environmental Systems, 15 - 19 July 2012, San Diego, California.

Do, S., Ho, K., Schreiner, S., Owens, A., de Weck, O., “An Independent Assessment of the Technical Feasibility of the Mars One Mission Plan,” IAC-14-A5.2.7, 65th International Astronautical Congress, Toronto, Canada, October 2014. Downloaded October 10, 2014 from web.mit.edu/sydneydo/Public/Mars%20One%20Feasibility%20Analysis%20IAC14.pdf

Drake, B. G., ed., Human Exploration of Mars Design Reference Architecture (DRA) 5.0, NASA/SP–2009–566, Mars Architecture Steering Group, NASA Headquarters, July 2009.

Eckart, P., Spaceflight Life Support and Biospherics, Kluwer Academic, Dordrecht, 1996.

Hanford, A. J., Advanced Life Support Baseline Values and Assumptions Document (CTSD-ADV-484A), Houston, TX: 2004.

ISS MDC, ISS Vehicle Office’s Maintenance Data Collection,

https://iss-www.jsc.nasa.gov/nwo/vh1/lmmer/web/mr_mdc.shtml, orbit_spares.xls, Spares List as of 05/12/2105, accessed 9/23/15.

Jeng, F. F., and Lin, C. H., “A Trade Study on Sabatier CO2 Reduction Subsystem for Advanced Missions,” 31st International Conference on Environmental Systems, Orlando: SAE International, 2001.

MADS, ISS Maintenance & Analysis Data Set (MADS), https://iss-www.jsc.nasa.gov/nwo/apps/mads/web/, accessed Nov 3, 2015.

Wieland, P. O., Designing for Human Presence in Space: An Introduction to Environmental Control and Life Support Systems, NASA Reference Publication RP-1324, 1994.