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Developing the Water Supply System for Travel to Mars

Harry W. Jones[1] John W. Fisher[2] Lance D. Delzeit[3] Michael T. Flynn[4] and Mark H. Kliss[5]
NASA Ames Research Center, Moffett Field, CA, 94035-0001

What water supply method should be used on a trip to Mars? Two alternate approaches are using fuel cell and stored water, as was done for short missions such as Apollo and the Space Shuttle, or recycling most of the water, as on long missions including the International Space Station (ISS). Stored water is inexpensive for brief missions but its launch mass and cost become very large for long missions. Recycling systems have much lower total mass and cost for long missions, but they have high development cost and are more expensive to operate than storage. A Mars transit mission would have an intermediate duration of about 450 days out and back. Since Mars transit is about ten times longer than a brief mission but probably less than one-tenth as long as ISS, it is not clear if stored or recycled water would be best. Recycling system design is complicated because water is used for different purposes, drinking, food preparation, washing, and flushing the urinal, and because wastewater has different forms, humidity condensate, dirty wash water, and urine and flush water. The uses have different requirements and the wastewater resources have different contaminants and processing requirements. The most cost-effective water supply system may recycle some wastewater sources and also provide safety reserve water from storage. Different water supply technologies are compared using mass, cost, reliability, and other factors.

Nomenclature

AES = Air Evaporation System
BWP = Biological Water Processor
CDS = Cascade Distillation System
CM = Crew Member
d = day
ECLSS = Environmental Control and Life Support System
EDC = Electrochemical Depolarized Concentrator
EDI = Electrodialysis
ESM = Equivalent System Mass
ISS = International Space Station
LCC = Life Cycle Cost
LEO = Low Earth Orbit
LOC = Loss of Crew
LOM = Loss of Mission
MF = Multifiltration
MTBF = Mean Time Before Failure
ORU = Orbital Replacement Unit
Pr = Probability
Pr(LOC) = Probability of Loss of Crew
Pr(LOM) = Probability of Loss of Mission
RO = Reverse Osmosis
SCWO = Super Critical Water Oxidation

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[1] Systems Engineer, Bioengineering Branch, Mail Stop N239-8.
[2] Lead Engineer, Bioengineering Branch, N239-15.
[3] Chemist, Bioengineering Branch, Mail Stop N239-15.
[4] Lead Engineer, Life Support, Bioengineering Branch, N239-15.
[5] Chief, Bioengineering Branch, Mail Stop N239-15.

TIMES = Thermoelectric integrated membrane evaporation
UPA = Urine Processor Assembly (ISS)
VAPCAR = Vapor Phase Catalytic Ammonia Removal
VCD = Vapor Compression Distillation
VDC = Vapor Diffusion Compression
VPCAR = Vapor Phase Catalytic Ammonia Removal
WPA = Water Processor Assembly (ISS)
WRS = Water Recovery System (ISS)
WT = Water Tank

I. Introduction

THIS investigation considers water supply systems for a human trip to Mars and back. The water supply can use stored water from Earth or recycled wastewater or both. The factors influencing the water system design include the quantity of water needed, the mission duration, the expected system mass and cost, and the required reliability. The cost of reliability strongly influences the optimum water system design. The water system developed for the International Space Station (ISS) could be used for Mars transit, but it was not designed to meet Mars requirements. Mars transit systems should have lower mass and higher reliability.

The most important difference between ISS and Mars transit is that if the water supply fails, the ISS crew can return in a few days, but the Mars crew cannot. Much greater water supply reliability is required to meet the expected Probability of Loss of Crew [Pr(LOC)] requirement for Mars. The belief that significantly higher reliability is required for Mars suggests that the Mars transit water system could implement a combination of greater hardware reliability, more system redundancy, and a fail-safe mission plan.

II. International Space Station (ISS) life support and Mars

ISS life support and the path to develop Mars life support are discussed. The ISS and its life support systems are highly relevant for Mars transit. Many have suggested that the ISS life support system could be used for Mars transit. (Bagdigian et al., 2015-094) Others have proposed that a modified or improved ISS system should be used for Mars transit. (Jones et al., 2015-049) However, with the fundamental difference in the philosophy of operations between LEO and deep space missions, will a completely new system need to be developed?

A. International Space Station (ISS) and the technology used for Mars transit life support

The International Space Station (ISS) has been in development and operation for more than thirty years, weighs about 925,000 pounds, and has cost about $100 billion to develop. (Wikipedia, International Space Station) (ESA)

Recycling life support systems have been in development since the mid 1960's and the ISS's Environmental Control and Life Support System (ECLSS) has been in operation since the mid-2000's.The US ECLSS is heavy, weighing a total of about 19,000 pounds not including the onboard spares (Gentry, 2013), but this seems to include too much, since the major regenerative subsystems weigh only about 3,000 pounds without spares. (Jones, 2016-109) The ISS ECLSS is expensive, and estimates range as high as $1 billion. (Jones, 2016-111). Thus the ISS ECLSS accounts for about one or two percent of the mass and cost of the entire ISS.

A manned Mars mission is decades in the future. It could cost as little as did ISS, $100 billion, or as much as $500 billion. (Price et al., 2009-6685) (Jones, 2016-111) The Mars transit vehicle could be a little larger than a single ISS habitat module such as the Russian Zvezda, with mass of about 45,000 pounds. (Price et al., 2009-6685) The ISS ECLSS mass is very large compared to the expected total Mars transit mass, but the ISS total ECLSS mass of about 19,000 pounds is distributed over several modules. If the critical required regenerative ECLSS mass for Mars transit is 3,000 pounds, which would be 6.66 percent of a total 45,000 pounds. The life support for Mars transit will probably cost as much or more than ISS life support. Based on the ISS experience, the Mars transit life support system could take many years to develop and cost billions of dollars. (Jones, 2016-111)

B. Can the ISS life support be modified into a Mars transit life support system?

An obvious initial approach for Mars transit would be to use or modify ISS life support systems, but this does not seem practical. The ISS goals, assumptions, approaches, and detailed requirements have produced hardware that is designed for and suitable for Low Earth Orbit (LEO), but not for Mars transit. The ISS ECLSS is large, heavy, and power hungry. This is probably optimal for ISS, since life support was launched in the high capacity Space Shuttle, is powered by large solar arrays, and can pay for its mass and cost by providing water and oxygen over fifteen or more years. A Mars transit system will be much more expensive to launch per kilogram than a system remaining in LEO, and will only have about eighteen months to pay back the additional cost of the mass of the recycling system.

The ISS ECLSS was designed for crew maintenance and repair on orbit. Pre-flight integrated system testing was limited. This approach resulted in the discovery of design problems after launch and high maintenance. (Jones, 2016-113) This is acceptable for ISS, where materials and spares can easily be supplied from Earth, where the Russian life support system provides full diverse redundancy, and where the crew can return to Earth if life support fails. A Mars transit system should probably have much higher reliability than ISS ECLSS. This could be achieved by some combination of design for reliability, long duration testing, and planned on-board maintenance and repair.

The multi-decade research and development effort that produced the ISS ECLSS has been guided by ecosystem concepts of recycling. It seeks the ultimate ecological goal of full mass closure, "closing the loop." Much effort has been spent planning to capture the last difficult, yet unrecovered resource, the waste brine produced by water recycling. (Jones et al., 2014) Increasing system closure faces steeply higher relative costs per kilogram of water recovered. Approaching the ultimate long-term objective of a permanent space habitat independent of Earth is an ultimate research goal. Mars transit has much shorter mission duration than the ISS. It is well known that the longer the mission is, the better recycling pays. And some recycling systems become cost effective much sooner that others as mission duration increases. A Mars transit system with a much shorter mission duration than ISS probably would have a somewhat lower level of closure than ISS.

C. Further work needed for Mars

The many decades long effort to develop recycling life support led to the successfully operating ISS ECLSS, but further work is needed for Mars. The requirements for ISS and Mars differ. Life support systems for Mars transit must be more available, reliable, and maintainable than ISS systems because the crew cannot return to Earth if a problem occurs.

Very brief missions, with only a few days or weeks on crew vehicle, do not require recycling, but very long missions or permanent bases do. As the mission duration increases, recycling will become more and more cost effective. The Journey to Mars may involve steps of increasingly longer and more distant missions. It would be reasonable to first simply supply water and oxygen and then to provide first condensate, then hygiene, then urine, and finally brine recycling systems as they become cost effective. The current ISS and alternate Space Station water technologies are the prime candidates. It is also extremely important to look for innovative solutions that might leapfrog the known current problems and could provide improved recycling capabilities at lower cost and with higher reliability. In addition to refining and augmenting the current water recycling capabilities of ISS, the research effort should perform long term development and testing of Mars specific solutions.

III. Mars transit water requirements and water balance

The Mars transit water requirements are given in Table 1. It is assumed that the Mars mission will have a crew of four. Typical conjunction class Mars missions have outbound and return transit times of 200 to 250 days each and long 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 further useful mission duration 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 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 will be used in the mass payback ratio calculations below. Using a nominal 900 day full mission duration would double the mass payback.

Table 1. Mars transit water system requirements.

Requirements	Value
General	
Number of crew	4
Mission duration	400-500 days
Quiescent interval	400-550 days
Pr(LOC)	≤ 0.001
Water consumption	
Drinking and food preparation water	2.38 kg/CM-d
Urine flush water	0.50 kg/CM-d
Wash water	1.29 kg/CM-d
Total water	**4.17 kg/CM-d**
Waste water	
Respiration and perspiration condensate	2.28 kg/CM-d
Urine and flush water	2.00 kg/CM-d
Used wash water	1.29 kg/CM-d
Total waste water	**5.57 kg/CM-d**

CM - crew member, d - day

The crew water requirements in Table 1 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. (Reed and Coulter, 2000) (Wieland, 1994) The total wastewater output exceeds the total crew input because it is assumed that 1.15 kg/CM-day of water is provided 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 is provided, an additional 1.15 kg/CM-day of food preparation water would need to be supplied. If the water system design requires this much stored water, providing the water in the food would be an option. The quality of the food would be improved, but its launch mass would be greater.

The Probability of Loss of Crew, Pr(LOC), on a space mission has been about one percent for launch and one percent for reentry. The Pr(LOC) due to a life support failure has been roughly similar. (Jones, 2013-3315) For Mars exploration, an initial assumption could be to not exceed the past one percent Pr(LOC) for life support failures. Allocating the Pr(LOC) < 0.01 between water, oxygen, carbon dioxide, pressure, food, fire, and other vital life support systems, we assume that the Mars transit water system must have Pr(LOC) < 0.001.

The Mars transit water balance is shown in Table 2. As in Table 1, the water system must supply the crew with drinking and food preparation water, wash water, and urine flush water. The numbers are repeated from Table 1. (Reed and Coulter, 2000) (Wieland, 1994) The crew metabolism and washing produces respiration and perspiration condensate, used wash water, and urine and flush water. The 2.28 kg/CM-d of humidity condensate, including crew respiration, perspiration, and evaporated water, if fully recycled, would provide nearly enough potable water for drinking and food preparation. There is a small deficit of 0.10 kg/CM-d that could be supplied from storage or produced from other recycled water. The wash water, after it is used, would be more difficult to purify than condensate but seems usually less difficult than urine and flush water. The used wash water may not directly recovered, but instead be evaporated from damp towels or wipes and collected as humidity condensate.

Table 2. The Mars transit water balance.

Water inputs		Waste water	
Drinking and food preparation water	2.38 kg/CM-d	Respiration and perspiration condensate	2.28 kg/CM-d
Wash water	1.29 kg/CM-d	Used wash water	1.29 kg/CM-d
Urine flush water	0.50 kg/CM-d	Urine and flush water	2.00 kg/CM-d
Subtotal	**4.17 kg/CM-d**	**Subtotal**	**5.57 kg/CM-d**
Other water inputs			
Water in food	1.15 kg/CM-d		
Metabolic water	0.35 kg/CM-d		
Total	**5.67 kg/CM-d**	**Total**	**5.57 kg/CM-d**

Because of the water in the food and produced by food metabolism, the water system has a net positive water balance of 1.40 kg/CM-d. Since the total wastewater is 5.67 kg/CM-d and the required water is only 4.17 kg/CM-d, the overall recycling efficiency need be only 75%. The use of dehydrated food would require much higher recycling efficiency.

The ISS life support systems architecture combines treated urine and flush water with other wastewater for final processing. Separately treating condensate, used wash water, and urine and flush water might allow redundant independent subsystems or flexible operation if a failure occurs.

IV. Candidate water system technologies for Mars transit

Table 3 lists many of the water technologies that have been investigated for human space missions. Most of the candidate technologies are mentioned in the standard references. (Weiland, 1994) (Eckert, 1996) Some are not, including BWP and CDS, which are advanced development systems, and UPA and WPA, which are operational ISS systems. The EDC, VDC, and WT are less familiar alternatives.

Table 3. Candidate water technologies for Mars transit.

Acronym	Name	Process	References
AES	Air Evaporation System	Evaporation	(Akse and Wilson, 2012) (Weiland, 1994) (Eckert, 1996)
BWP	Biological Water Processor	Biological/microbial	(Flynn et al. 981538) (Anderson, 2004)
CDS	Cascade Distillation System	Phase change/ distillation	(Patel et al., 2014-12) (Reifer et al., 2001)
EDC	Electrochemical Depolarized Concentrator	Electrolysis	(Jones and Kliss, 2005-01-2810)
EDI	Electrodialysis	Electrolysis	(Xu amd Huang, 2008) (Weiland, 1994) (Eckert, 1996)
MF	Multifiltration	Filtration	(Weiland, 1994) (Eckert, 1996) (Carrasquillo et al., 1992)
RO	Reverse Osmosis	Filtration	(Weiland, 1994) (Eckert, 1996) (Carrasquillo et al., 1992)
SCWO	Super Critical Water Oxidation	Phase change/ distillation	(Hicks et al., 2012) (Weiland,1994) (Eckert, 1996)
TIMES	Thermoelectric integrated membrane evaporation	Phase change/ distillation	(Weiland, 1994) (Eckert, 1996)
UPA	Urine Processor Assembly (ISS)	Phase change/ distillation (VCD)	(Bagdigian et al., 2015-094) (Carrasquillo et al., 1992)
VAPCAR, VPCAR	Vapor Phase Catalytic Ammonia Removal	Phase change/ distillation	(Weiland, 1994) (Eckert, 1996) (Flynn et al. 981538) (Anderson, 2004)
VCD	Vapor Compression Distillation	Phase change/ distillation	(Weiland, 1994) (Eckert, 1996) (Carrasquillo et al., 1992)
VDC	Vapor Diffusion Compression	Phase change/ distillation	(Jones and Kliss, 2005-01-2810)
WPA	Water Processor Assembly (ISS)	Filtration (MF)	(Bagdigian et al., 2015-094) (Carrasquillo et al., 1992)
WT	Water Tank	Storage	(Carasquillo et al., 1997) (Weiland, 1994)

All of the water technologies in Table 3 have been considered for use in a space water system, but they use different processes and are not all candidates for the same application. The different processes are, in very rough order of increasing complexity and capability, storage, evaporation, filtration, distillation, and biological processing. The waste sources of Tables 1 and 2 are condensate, used wash water, and urine plus flush water. Condensate can be made potable and can be processed by filtration alone or by filtration and adsorption. Urine and flush water typically require processing such as distillation or biological processing. The requirements of Tables 1 and 2 are for drinking, washing, and flush water. Stored potable water can be used as washing and flush water. Possibly wash and flush water need only be processed to less than potable standards. Separate loops may be used for condensate, wash, and flush recycling. (Jones et al., 2015-049)

V. System design and technology selection factors

The Mars transit water system must meet the requirements of Table 1, but the system design technology selection must also consider performance, readiness, cost, safety, and other factors. The major life support technology selection factors are listed in Table 4.

Table 4. Life support technology selection factors and their components and metrics

Selection factor	Selection factor components and metrics
Performance	Waste water accepted, recycling efficiency, product quantity and quality, microgravity sensitivity, noise
Readiness	Technology Readiness Level (TRL)
Cost	Equivalent System Mass (ESM), mass payback, Life Cycle Cost (LCC)
Safety	Pr(LOC), hazards, contamination potential
‘ilities	Maintainability, reliability, complexity, flexibility, commonality
Other	Integration difficulty, testing needs
Risk	Performance, cost, schedule
Political	Management and community consensus support

The selection factors are listed in rough working order of their obviousness or importance, except that the essentially distinct project management issues are kept to last. The factors are similar to those that have been used before in life support, but are not taken from any specific source. Table 4 also gives some of the components and metrics of the life support technology selection factors. All of the factors components, and metrics in Table 4 are common in life support analysis and most are intuitive. The TRL, ESM, LCC, and Pr(LOC) metrics will be explained when used.

The favored approach to technology selection is using an overall numerical metric produced by scoring and weighting all the selection factors. It can be shown in contrived cases that eliminating the worst candidates at each step of a sequential checklist, going factor by factor, can produce a poor solution. This occurs when a candidate that is barely eliminated early on is much better in later factors. However, a composite metric may obscure important decision factors.

Technology should be selected and the design optimized by consciously trading-off conflicting goals and problems. Unfortunately a single factor is sometimes used to select candidates. The initial Space Station technology selection was limited to a few technologies with high Technology Readiness Level (TRL), typically those with working prototypes. (Carrasquillo et al., 1992) (Jones and Kliss, 2005-01-2810) A suggested approach for Mars transit is to use only technologies operated on ISS, but the shorter duration and longer distance of a Mars transit mission may require lower mass and higher reliability than suitable for ISS. Research technology selection has been made using only Equivalent System Mass (ESM). It may be reasonable to eliminate a technology based on one significant unfavorable factor, such as TRL or ESM, but it seems best to select flight technology only after considering all relevant factors.

Table 4 is used to guide a step-by-step independent consideration of each factor. This seems to be the only feasible approach, since Table 4 has a mix of quantitative, qualitative, and even debatable concepts, and since some are unknown for some technologies. The current state of knowledge does not allow quantifying and scoring all the candidates for all the selection factors, as would be desirable.

VI. Water technology selection for Mars transit

The selection factors of Table 4 are considered for different water processing technologies. The selection factors are Performance, Readiness, Cost, Safety, ‘ilities, Other, Risk, and Political.

A. Performance

Table 5 considers the wastewater accepted, potential recycling efficiency, and the product water of the technologies in Table 3.

Table 5. Candidate water technologies for Mars transit.

Acronym	Name	Waste water accepted	Efficiency	Product	Reference
AES	Air Evaporation System	Urine, brine	100%	Requires further processing	(Eckert, 1996)
BWP	Biological Water Processor	Condensate and wash	90-95%	Requires further processing	(Anderson, 2004)
CDS	Cascade Distillation System	Urine	93%		(Patel et al., 2014-12)
EDI	Electrodialysis	Condensate and wash	98%	Potable	(Eckert, 1996)
MF	Multifiltration	Condensate and wash	99.9%	Potable	(Eckert, 1996)
RO	Reverse Osmosis	Condensate and wash	80%	Potable	(Eckert, 1996)
SCWO	Super Critical Water Oxidation	All, solids	100%	Potable	(Eckert, 1996)
TIMES	Thermoelectric integrated membrane evaporation	Urine	91%	Requires further processing	(Eckert, 1996)
UPA	Urine Processor Assembly (VCD)	Urine	70-75%	Requires further processing	(Carter et al., 2015-073)
VAPCAR, VPCAR	Vapor Phase Catalytic Ammonia Removal	All	95%	Potable	(Eckert, 1996)
VCD	Vapor Compression Distillation	Urine	70%	Requires further processing	(Eckert, 1996)
WPA	Water Processor Assembly (MF)	Condensate and wash	88%	Potable	(Bagdigian et al., 2015-094)
WT	Water Tank	None	83%	Potable	(Carasquillo et al., 1997)

Urine can be recycled by AES, CDS, SCWO, TIMES, UPA, VCD, and VPCAR. Efficiency varies from 70 to 100%, with UPA and VCD at the lower boundary However, UPA and VCD data is from actual operational use is space and most other data are early estimates or from short duration ground testing. All except SCWO produce water that requires further processing. Low efficiency technologies have to store the unrecoved water as part of the brine waste. The AES and other technologies not included here can recover water from urine processing brine.

Condensate and wash water can be recycled by BWP, EDI, MF, RO, and WPA. Efficiency varies from 80 to 99.9%, with MF at the highest. They produce high quality water that may require polishing prior to meeting potable requirements.

As on ISS, a Mars transit water recycling system could have separate processors for urine and for combined condensate and wash water. Possibly the condensate and wash water could be processed separately. The Russians have operated a separate condensate recovery system on MIR The ISS has a separate condensate collection/processing system. It is called humidity condensate and is processed through the MF bed. (Eckert, 1996) On the other hand, a powerful distillation processor such as SCWO could handle all wastewater.

B. Technology readiness

The level of a technology's development is usually measured by the Technology Readiness Level (TRL). (Mankins, 1995) TRL is defined as follows:

TRL 1 - Basic principles observed and reported
TRL 2 - Technology concept formulated
TRL 3 - Critical function proof-of-concept
TRL 4 - Component or breadboard validated in laboratory
TRL 5 - Components validated in a relevant environment
TRL 6 - Prototype demonstrated in a relevant environment
TRL 7 - Prototype demonstrated in a space environment
TRL 8 - Design flight qualified

TRL 9 - System flight proven in mission operations

Table 6 gives the TRL of the water technologies in Table 3.

Table 6. Candidate water technologies for Mars transit.

Acronym	Name	TRL	Reference
AES	Air Evaporation System	5	(Eckert, 1996)
BWP	Biological Water Processor	4	(Anderson, 2004)
CDS	Cascade Distillation System	4	(Patel et al., 2014-12)
EDI	Electrodialysis	4	(Eckert, 1996)
MF	Multifiltration	9	(Carasquillo et al., 1992)
RO	Reverse Osmosis	6	(Carrasquillo et al., 1992)
SCWO	Super Critical Water Oxidation	3	(Eckert, 1996)
TIMES	Thermoelectric integrated membrane evaporation	6	(Carrasquillo et al., 1992
UPA	Urine Processor Assembly (VCD)	9	(Bagdigian et al., 2015-094)
VAPCAR, VPCAR	Vapor Phase Catalytic Ammonia Removal	3	(Eckert, 1996)
VCD	Vapor Compression Distillation	9	(Bagdigian et al., 2015-094)
WPA	Water Processor Assembly (MF)	9	(Bagdigian et al., 2015-094)
WT	Water Tank	9	(Carasquillo et al., 1997)

The Space Station technology selection process developed RO, MF, TIMES, and VCD to working prototypes that were extensively tested, reaching TRL 6. (Carrasquillo et al., 1992) The WPA implemented MF and the UPA implemented VCD on the ISS, bringing those technologies to TRL 9. WTs are used on ISS. The ISS systems have the highest TRL of 9 and the Space Station alternate prototypes the next highest TRL of 6.

C. Cost

Hardware mass is a good indicator of development and launch cost. The cost metrics include Equivalent System Mass (ESM), mass payback, and Life Cycle Cost (LCC).

1. Equivalent System Mass (ESM)

The Equivalent System Mass (ESM) is the launch mass charged to a system. ESM is computed from the system mass, m, volume, v, power, p, cooling, c, logistics mass per year, l, and d, the mission duration. ESM

$$ESM (m, v, p, c, l, d) = m + v * me(v) + p * me(p) + c * me(c) + l * d$$

me(v) is the mass charged for a cubic meter of volume in kg/m^3, me(p) is the mass charged for a kilowatt of volume in kg/kW, and me(c) is the mass charged for a kilowatt of cooling in kg/kW. (Jones, 2003-01-2635) (Levri et al., 2003) Table 7 gives the ESM of some water processing technologies for a crew of 4 on a 450-day Mars transit.

Table 7. ESM of Water processing technologies for a crew of 4 on a 450-day Mars transit.

Acronym	Name	Mass, kg	Volume, m^3	Power, kW	Cooling, kW	90-day spares and consumables mass, kg	90-day spares and consumables volume, m^3	ESM, 4 crew 450 days
AES	Air Evaporation System	345	3.35	1.57	1.57	27.67	0.30	2,136
MF	Multifiltration	232	1.81	0.92	0.92	33.02	0.43	1,604
TIMES	Thermoelectric integrated membrane evaporation	352	3.36	0.50	0.50	182.35	1.06	3,322
VCD	Vapor Compression Distillation	378	3.21	0.44	0.44	172.69	1.09	3,280
VPCAR	Vapor Phase Catalytic Ammonia Removal	176	1.95	0.16	0.16	36.29	0.24	1,100
	Mass equivalents	1	215.5	327.0	60.0	1	215.5	

The ESM is computed using mass, volume, power, and cooling data from an early Space Station technology assessment. (Hall et al, 1984) The mass equivalents for a Mars transit mission are given in the BVAD. (BVAD, 2004) VPCAR has the lowest ESM, multifiltration's ESM is similar to that used in the ISS ECLSS and is second lowest, while VCD's ESM is also similar to that used in the ISS ECLSS however it is highest. AES is intermediate. Similar studies have found low ESM for EDI and Times (Jones, 2008-01-2193) Perhaps the most surprising result in Table 7 is that the hardware mass is only a small part of the total ESM. Table 8 shows the contributions of volume, power, cooling, spares and consumables mass, and spares and consumables volume to ESM.

Table 8. Contributions of mass, volume, power, cooling, spares, and consumables to ESM, kg.

Acronym	Name	Mass	Volume ESM	Power ESM	Cooling ESM	450-day spares and consumables mass	450-day spares and consumables volume ESM	ESM, 4 crew 450 days
AES	Air Evaporation System	345	723	513	94	138	322	2,136
MF	Multifiltration	232	391	301	55	165	461	1,604
TIMES	Thermoelectric integrated membrane evaporation	352	724	164	30	912	1,141	3,322
VCD	Vapor Compression Distillation	378	693	144	26	863	1,175	3,280
VPCAR	Vapor Phase Catalytic Ammonia Removal	176	421	52	10	181	259	1,100
	Average percentages	13	26	10	2	20	29	

The actual hardware mass averages only 13% of the total ESM. Volume dominates ESM (26%) and spares and consumables volume ESM (29%) account for more than half the ESM (55%). Spares are half the ESM. Spares mass

(20%) and spares volume ESM (29%) account for 49% of ESM. Power and cooling at 12% are as small as the hardware mass at 13%.

If the average ESM values are examines, some interesting observations can be made. One might believe that hardware mass should the largest percentage of the ESM, however, it is only 13% of the total ESM. Even the total mass of the hardware and resupply make up only 33% of the total ESM. Spares and consumables make up 49% of the total ESM with 20% from their mass and 29% from their volume. However, the largest component actually come from the total ESM for the volume used at 55%, i.e., 26% for the hardware and 29% for the spares and consumables. Therefore, to decrease the ESM of future systems, the largest savings in ESM could come from reducing the systems volume or the spares and consumables required.

2. Mass payback

Tables 1 and 2 show that the total water to be provided to the crew is 4.17 kg/CM-d. This consists of 2.38 kg/CM-d of drinking and food preparation water, 1.29 kg/CM-d of wash water, and 0.50 kg /CM-d of urine flush water. If a crew of 4 is assumed as in Tables 7 and 8, they would require 16.68 kg of water per day and would consume 7,506 kg on a 450 day Mars transit mission. The mass of the water equals roughly 20 to 40 times the hardware masses shown in Tables 7 and 8, but only 2 to 7 times the ESM.

The ISS Water Recovery System (WRS) consists of the Water Processor Assembly (WPA) and the Urine Processor Assembly (UPA). The WRS is required to fit within two standard payload racks. The maximum launch weight of each rack is to be less than 806 kg. The power consumption of the WRS is to be less than 1,355 Watts. The resupply weight for expendables and spares is required to be less than 932 kg per year. (MSFC-SPEC-2841F, 2004) (Jones, 2008-01-2193) Table 9 shows the ESM of the WRS for a 450-day Mars transit based on these numbers.

Table 9. WRS ESM for a 450-day Mars transit.

Acronym	Name	Mass, kg	Volume, m^3	Power, kW	Cooling, kW	Logistics mass, kg/d	ESM, 450 days, kg
WRS	Water Recycling System	1,612	3.00	1.36	1.36	2.55	3,932
	Mass equivalents	1	215.5	327	60	1	

The mass of the water provided would be less than twice the WRS ESM. Water recycling does not guarantee a large mass payback.

3. Life Cycle Cost (LCC).

Life Cycle Cost (LCC) includes all the costs incurred during the development, launch and emplacement, and operations phases of a space mission. Development cost can be estimated using the Advanced Missions Cost Model (AMCM). The AMCM cost in millions of 1999 dollars is:

$$\text{Development cost} = 5.65 * 10^{-4}\, Q^{0.59}\, M^{0.66}\, 80.6^{S}\, (3.81 * 10^{-55})^{(1/(IOC - 1900))}\, B^{-0.36}\, 1.57^{D}$$

The parameters can be estimated for Mars transit. Q =1 is the total quantity of development and production units, M is the system dry mass in kilograms, S = 2.13 is the mission type for human habitat, IOC = 2030 (Initial Operation Capability) is the first year of operations, B = 2 is the hardware generation, and D is the estimated difficulty (0 for average and -2 for very easy). (Guerra and Shishko, 2000) (Jones, 2003-01-2635)

An optimistic future cost for launch to LEO is $10,000 /kg. A rocket's total-to-payload mass ratio or gear ratio is the ratio of the total payload, rocket, and propulsion mass needed in LEO to the final payload mass at the destination. The gear ratio for a full transit, from Earth to Mars and back to Earth, is 6.77. The gear ratio for material that is taken to Mars but becomes waste and can be disposed of before Mars orbit capture is 3.16. (BVAD, 2004) Recycling systems make the round trip but unrecycled waste derived from used resupply materials can be dumped.

For manned spacecraft, the operations cost per year can be estimated as 10.9% of the total development cost. (MOCM) (Jones 2003-01-2635)

Table 10 shows the development, launch and emplacement, and operations costs and the total LCC for some of the water technologies. The assigned difficulties based on judgment are -1 for evaporation and filtration, and 0 for distillation. The differences in the estimated LCC's reflect the differences in the hardware mass and the estimated difficulty of the technology

Table 10. The development, launch and emplacement, operations and the total Life Cycle Cost (LCC).

Acronym	Name	Mass	Difficulty, D	Development cost, $M	Launch cost, $M	Operations cost, $M	LCC, $M
AES	Air Evaporation System	345	-1	63	23	9	95
MF	Multifiltration	232	-1	76	16	10	102
TIMES	Thermoelectric integrated membrane evaporation	352	0	157	24	21	202
VCD	Vapor Compression Distillation	378	0	164	26	22	212
VPCAR	Vapor Phase Catalytic Ammonia Removal	176	0	99	12	14	125

D. Safety

The safety issues include safety hazards and Pr(LOC).

1. Safety hazards

Most water processing systems are not especially hazardous but some have high temperature or high pressure. These are noted in Table 11. Temperature and pressure are indicated for some of the technologies by Eckert. The other candidate technologies do not seem to have serious intrinsic safety hazards. Some technologies have mechanical moving parts. Wastewater and brine handling, exchange and handling problems can occur with some technologies. The brine produced by urine processing can be acidic, toxic due to hexavalent chromium, Cr(VI), and oxidative due to oxone. Brine and waste water can be conductive, breathing, eye, and spill hazards.

Table 11. Water technology safety hazards. (Eckert, 1996)

Acronym	Name	High temperature	High pressure
EDI	Electrodialysis		X
MF	Multifiltration		
RO	Reverse Osmosis		X
SCWO	Super Critical Water Oxidation	X	X
VAPCAR, VPCAR	Vapor Phase Catalytic Ammonia Removal	X	

Pr(LOC)

Suppose as an illustration that the Probability of Loss of Crew, Pr(LOC), due to a life support failure on a space mission must be less one percent. Then it would be reasonable to require the Pr(LOC) due to the water system alone to be less than one in a thousand, Pr(LOC) < 0.001. The water system Pr(LOC) should probably be about one-tenth of the overall life support system allocation.

If it is assumed that a water system failure causes Loss of Crew, the Pr(LOC) depends on the failure rate. Suppose that the water system has a ten percent chance of failing during a 450 day Mars transit mission. If we have only one system without back up or spare parts, Pr(LOC) = 0.1. If the water system failures are random and independent, not due to a common design or parts flaws, we can provide three identical systems and the probability that all three fail is the Pr(LOC) = 0.13 = 0.001 as required. If we are concerned about a common cause failure disabling all of a set of redundant systems, we can use diverse technology systems. It is often assumed that triple system level redundancy is required. (Connolly, 2000) The hardware launch mass and volume would be tripled, and the LCC roughly doubled for similar redundancy but tripled for diverse redundancy, since the second and third diverse systems would not have the reduced development cost of identical systems.

The redundancy approach used for the ISS is to provide Orbital Replacement Units, (ORU's). The number of spares of each ORU can be calculated to provide the required reliability and Pr(LOC) at minimum spares mass.

Calculations using the WRS UPA and WPA ORU reliability estimates show that three or more spares are required for each ORU. For Pr(LOC) < 0.001, the number of spares for some ORUs could be many times greater.

spares hardware mass may be five or ten times greater than the original system mass (Jones, 2016-109) The mass needed for high reliability may greatly reduce or even completely eliminate the mass payback provided by recycling.

Preliminary reliability estimates can be generated from tabulated parts reliabilities and these can be used to estimate the required quantities and mass of spares. The reliability estimates are not good indicators of actual initial reliability performance. They are essentially optimistic upper bounds, assuming no design or integration errors occur. Reliability estimates can provide useful comparisons of technologies based on best case reliability.

Water tanks are simple and have much higher reliability than active processors. If the water supply is provided in stored tanks, redundant smaller tanks can be used to increase the reliability. Very high reliability can be achieved using only a few additional spare tanks with water in excess of requirements, so the proportional increase in mass for higher reliability is much smaller for tanks than for active processors.

E. 'ilities

The 'ilities' include maintainability, reliability, complexity, flexibility, commonality. Probably any of the water technologies would have sufficient flexibility and commonality to be a reasonable candidate on any human space mission. Complexity is probably correlated with maintainability and reliability. The maintainability and reliability of the candidate technologies are ranked in Table 11.

Table 11. Water technology maintainability and reliability.

Acronym	Name	Maintainability, (Hall, 1984)	Estimated reliability/maintainability
AES	Air Evaporation System	-	
BWP	Biological Water Processor		-
CDS	Cascade Distillation System		- -
EDC	Electrochemical Depolarized Concentrator		- -
EDI	Electrodialysis		- -
MF	Multifiltration	++	
RO	Reverse Osmosis		-
SCWO	Super Critical Water Oxidation		- -
TIMES	Thermoelectric integrated membrane evaporation	- -	
UPA	Urine Processor Assembly (VCD)		- -
VAPCAR, VPCAR	Vapor Phase Catalytic Ammonia Removal	- -	
VCD	Vapor Compression Distillation	- -	
VDC	Vapor Diffusion Compression		- -
WPA	Water Processor Assembly (MF)		- -
WT	Water Tank	++	

++ is best, -- is worst.

Maintainability requirements are indicated by the needed crew time cited for some technologies in the survey by Hall. MF and WT require significantly less maintenance than the other technologies considered. (Hall, 1984) The maintainability and reliability are roughly estimated by the authors for the candidate technologies not considered by Hall.

As mentioned, deep space life support must have much higher reliability than ISS life support in LEO, because a deep space mission cannot be resupplied or aborted quickly. The direct relation between reliability and estimated Pr(LOC) was discussed.

Complexity can be assessed by considering the number of subsystems, the number and complexity of the interfaces including fluid flows and electrical connections, and the degree of internal and external control needed. In general, higher complexity can decrease reliability and increase cost and risk.

The assessment of flexibility depends on the anticipated changes that the system might face. Can the technology be used on other later planned missions? Can the technology adjust to different product flow requirements? Does it have the robustness to deal with external input degradation?

Commonality conflicts with technical diversity. Commonality is used to reduce the number and mass of spares by sharing spares between different systems. But if all the common spares weaken due to a common cause failure, the several systems using them will be lost. Commonality is ideal for small, well-tested, components with known but limited reliability, such as filters, fans, and valves. If they rarely required replacement, common spares would not save much mass. Technical diversity is best for large, specially built subsystems that may have hidden design errors and failure modes. The ‘ilities are usually secondary considerations in technology selection, unless some major problem is identified.

F. Other

The other considerations include integration and testing needs. Integration and test are usually considered together. Some more routine space systems such as communications satellites are assembled on standard busses using standard subsystems. Since the cost of such standard components decreases with the number made, typically half the total system cost of routine space systems is for integration and test. For unique systems such as space life support, the development cost can be very high and so the funding available for integration and test has been limited.

Experience has shown that long testing is needed to identify design and component problems and to work through the often-observed infant mortality. The extent, type, and level of testing required to improve, measure, and ensure reliability should be considered in technology selection.

G. Risk

There are important risks in the ability to achieve the required system performance including especially the ’ilities, and in meeting the expected cost and schedule. Risk is clearly less for higher TRL systems, and TRL is a major, often controlling selection factor.

Cost and schedule risk are almost inevitable, since low cost estimates and tight schedules are usually necessary to gain project approval. Some technologies may be more suitable to risk reducing design approaches, such as concurrent engineering. If technical unknowns require a classic step-by-step waterfall project, the schedule is more fragile. Minimizing a serious risk may be the controlling factor in technology selection, even if risk itself is not explicitly considered.

H. Political

Political factors such as competing goals, budget limits, organizational conflicts, and rival projects can strongly influence technology selection. A successful system development project requires support by management and the technical community. In the short term, political considerations can almost overwhelm technical issues, but in the long run reality rules. Frequent tests and demonstrations, supported by open, impartial, critical systems analysis, can help keep system development more responsive to technical factors.

Organizations are developed to achieve specific social purposes. Scientific organizations discover new knowledge, technical organizations develop new systems, and business and political organizations keep society’s wheels turning. But any organization tends to take on a life of its own. Organizations have a strong instinct for survival and a great ability to perpetuate themselves. Any potential change may seem a threat. Organizations may become too conservative and bureaucratic. Organizations can age, decline, become obsolete, and resist the change they need to do their job.

The life support system architecture and technologies of fifty years ago remain the unchallenged state of the art. The ISS ECLSS developed in the 1990’s has been proposed as the baseline system for Mars decades hence. The journey to Mars is a new and far greater challenge for space life support. Our wealth of engineering knowledge and skill must be applied with the utmost effort. New systems thinking is needed and this may require an improved political environment that prioritizes NASA systems engineering.

VII. Water system development

How should the water supply system for travel to Mars be developed? The goal, approach, and detailed implementation of a Mars transit water system are considered.

A. Goal

Mars transit requires a robust, reliable, and reparable water system. It should be cost-effective for the Mars transit mission, and should also be implementable in particular functional subsystems that are cost-effective for shorter initial missions. The system should be as small, simple, inexpensive, and easy to operate as possible while safely providing the crew water.

B. Approach

Brief early missions could simply use stored water, with recycling subsystems added as mission length increases missions. A better approach might be to instead implement recycling while the missions are still close to earth and can easily provide resupply or return the crew in an emergency. The initial mission cost would be greater but the overall journey to Mars would benefit. Since condensate is relatively plentiful and easy to process to potable, condensate processing is the first recycling process to become cost-effective as the mission duration increases. After that, as soon as hygiene water is provided, used wash water could be separately processed, perhaps to less than potable standards. Lastly, when cost-effective, urine and flush water would be recycled. As now on ISS, the purified urine and flush product could be combined with condensate for polishing, but a completely separate water loop would help increase reliability by providing redundant diverse crew water sources. The urine and flush recycling products could be a mix of potable, wash, and flush water as needed.

This gradual slow evolution of the water recycling system is suggested to minimize initial cost and to provide capability and gain operational experience as soon as possible. A more forceful direct approach with less multiple project overhead and coordination would be to develop the full Mars transit system without taking smaller steps, but to use it closer to Earth and with storage back up while demonstrating how it performs. Certainly lower level ground based research, as opposed to developing flight systems, should be continuously carried out for all required subsystems.

The ultimate objective is to have multiple parallel water storage and recycling system for Mars transit. It would consist of smaller, simpler, independent, parallel loops, with diverse redundant processors off-line to replace failed systems. Methods and plans are needed to maintain the working systems and repair failed systems. The water sources include tanked water, humidity condensate, wash water, and urine. Recovering and storing water in excess of current requirements would provide an additional stored water buffer for increased robustness.

Achieving reliable operation in space will require repeated cycles of testing, operations, and redesign. An incremental independent loop approach seems easier and safer but perhaps not more cost-effective to implement than a single all-inclusive integrated system as on ISS.

The only way to ensure high reliability without testing many systems for much longer than the Mars transit mission duration is to provide technically diverse redundant systems for each function in each water processing loop. Independent competing project teams should each develop their own diverse version of the required functional technology. Many more small projects should be started than the final number of diverse systems that will be needed. Funding of each effort should be incremental and competitive, reflecting actual demonstrated performance. As less successful candidates are eliminated, others should be started to ensure sufficient diversity.

C. Storage systems and hydrated food

Brief missions need only stored water. Until highly reliable recycling is demonstrated, the drinking and food preparation water, or at least enough water for crew survival, must be provided in reliable and secure storage tanks. Additional drinking water, and the wash and flush water, could be provided by less reliable recycling systems. Much of the water required for crew survival would be supplied in the food.

Hydrated food provides a guaranteed supply of water for the crew and make-up for recycling inefficiencies and losses. The use of dehydrated food can save launch mass if there is a reliable and efficient water recycling system, but dehydrated food is less palatable and no mass is saved unless the water to rehydrate the food is actually recycled.

Even when most water is reliably recycled and dehydrated food could be used, the normal amount of water in the food would greatly reduce the need for recycling efficiency and increase operational flexibility and the ability to deal with interruptions, failures, and losses.

D. Condensate recycling

A deep space water system will probably always use some stored water and have some water in the food, but recycling has the potential to reduce mass and cost for longer missions. The first step in recycling would be a cabin humidity condensate recovery system. Humidity and condensate are unavoidable, since the crew will exhale and perspire water that must be removed from the habitat atmosphere. A condensing heat exchanger is usually used to remove the humidity. The condensate water that could be used directly for some applications such as cleaning or flush, but as on ISS and Mir, condensate can be purified for crew consumption. Table 12 compares some condensate recycling technologies.

Table 12. Condensate recycling technologies.

Acronym	Name	TRL	ESM, 450 days, kg	Safety hazard	Maintainability, reliability
BWP	Biological Water Processor	4			
EDI	Electrodialysis	4		X	- -
MF	Multifiltration	9	1,604		
RO	Reverse Osmosis	6		X	-
WPA	Water Processor Assembly (MF)	9			- -

Multifiltration, which is the condensate water recycling technology used in the ISS WPA, is a promising technology to continue to develop for Mars transit. "Reliability, integration, and complexity all favor the MF." (Eckart, 1996) As implemented for the special circumstances of ISS, the WPA has higher mass and lower reliability than acceptable for Mars transit. The ISS WPA has significant excess capacity and is greatly oversized for ISS requirements, and it fills one and a half Space Station racks, so it is reasonable to expect that the mass of an improved multfiltration system for Mars transit can be much less. (Jones, 2008-01-2193) The ISS WPA has had a higher than expected number of failures due to limited preflight testing, so it is reasonable to expect that the reliability of a multfiltration system for Mars transit can be improved. (Bagdigian et al., 2015-094)

Another condensate recycling technology is reverse osmosis. Rreverse osmosis was the alternate to multifiltration in the Space Station technology selection. (Carrasquillo et al., 1992) Both of these technologies, multifiltration and reverse osmosis, along with several variants of each, could be considered to provide diverse alternate condensate processors for Mars transit. A possible third technology to develop is electrodialysis. (Eckart, 1996) Wash water can be processed using the same technologies. (Eckart, 1996)

E. Urine and flush recycling

Recycling urine and flush water to potable requires a phase change technology, and either evaporation or distillation could be used. Table 13 compares some of these technologies.

Table 13. Phase change/distillation recycling technologies.

Acronym	Name	TRL	ESM, 450 days, kg	LCC, $M	Safety hazard	Maintainability, reliability
AES	Air Evaporation System	5	2,136	95		-
CDS	Cascade Distillation System	4				- -
SCWO	Super Critical Water Oxidation	3			X	- -
TIMES	Thermoelectric integrated membrane evaporation	6	3,322	202		- -
UPA (VCD)	Vapor Compression Distillation	9	3,280	212		- -
VAPCAR, VPCAR	Vapor Phase Catalytic Ammonia Removal	3	1,100	125	X	- -

VCD is the technology selected for the ISS UPA, and TIMES was the alternate ISS prototype technology. (Carrasquillo et al., 1992) Because of current difficulties with VCD on ISS, the CDS is being developed to possibly replace it. (Patel et al., 2014-12) VPCAR with its lower mass was an earlier alternate candidate as a fully capable water system. (Eckart, 1996) AES is significantly different from the distillation technologies, with lower cost and greater safety and maintainability. Other evaporative technologies have been investigated for processing the brine produced by VCD on ISS. These include the Brine Evaporation Bag, Brine Residual In-Containment system, Closed-Loop Waste Water Processing Dryer, Enhanced Brine Dewatering System, Ionomer Water Processor, Ultrasonic Brine Dewatering System, and Forward Osmosis Brine Dryer. These technologies use either conduction drying or spray drying.

A NASA technology review that considered urine distillation technologies chose VCD and CDS for further development. Possibly both of these technologies, and perhaps also a new concept, could be developed to flight in order to provide diverse urine processing technologies for travel to Mars.

VIII. Conclusion

The water supply system for travel to Mars remains to be defined. The Space Station life support hardware, the Space Station flight experience, and the previous research and development process provide essential knowledge. The Mars water system will have separate but integrated functional subsystems. If Mars becomes the next NASA mission, the complete Mars water system with all subsystems should be developed in a consolidated program. If there are several shorter, closer, preparatory missions, the water system could be implemented one functional system at a time, as dictated by mission requirements. The water system could start with stored water and then proceed to recycling condensate, wash water, and finally urine and flush as each becomes cost-effective for longer missions. Several different recycling technologies from the history of past research should be developed to recycle condensate, wash water, and urine and flush. The development history of the Space Station provides alternatives and flight demonstrated technologies. Advanced research and development should be conducted to explore all possible technical approaches for the path to Mars. It is fundamental that effective research and development should include both incremental improvements of existing systems and high risk, potentially high return exploration of unproven innovations. To achieve the highest practically reliability, the final system should have independent recycling paths for condensate, used wash, and urine and flush, and each path should have technically diverse redundant processors.

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