Water System Architectures for Moon and Mars Bases

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Water systems for human bases on the moon and Mars will recycle multiple sources of wastewater. Systems for both the moon and Mars will also store water to support and backup the recycling system. Most water system requirements, such as number of crew, quantity and quality of water supply, presence of gravity, and surface mission duration of 6 or 18 months, will be similar for the moon and Mars. If the water system fails, a crew on the moon can quickly receive spare parts and supplies or return to Earth, but a crew on Mars cannot. A recycling system on the moon can have a reasonable reliability goal, such as only one unrecoverable failure every five years, if there is enough stored water to allow time for attempted repairs and for the crew to return if repair fails. The water system that has been developed and successfully operated on the International Space Station (ISS) could be used on a moon base. To achieve the same high level of crew safety on Mars without an escape option, either the recycling system must have much higher reliability or enough water must be stored to allow the crew to survive the full duration of the Mars surface mission. A three loop water system architecture that separately recycles condensate, wash water, and urine and flush can improve reliability and reduce cost for a Mars base.

Nomenclature

CM	=	Crew Member
CR	=	Cost of reference moon base recycling system.
CS	=	Cost of reference Mars base storage system.
d	=	day
ISS	=	International Space Station
LCC	=	Life Cycle Cost
LOC	=	Loss of Crew
LOM	=	Loss of Mission
MTBF	=	Mean Time Before Failure
Pr	=	Probability
Pr(LOC)	=	Probability of Loss of Crew
Pr(LOM)	=	Probability of Loss of Mission
VCD	=	Vapor Compression Distillation

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I. Introduction

THIS paper considers requirements and alternate systems architectures for water supply systems for long term bases on the moon and Mars. The water supply systems can use recycling or storage or both. The factors influencing the water system design include the quantity and quality of water to be provided, the planned mission duration, the expected Life Cycle Cost (LCC), and the required water supply reliability. LCC includes all costs for design, development, and operation. Water supply reliability is an important factor in crew safety, as measured by the probability of Loss of Crew, Pr(LOC). Water supply reliability also affects mission success, as measured by the probability of Loss of Mission, Pr(LOM). The cost-reliability trade-off determines the optimum water system designs. The water systems developed for the International Space Station (ISS) could be used on the moon and Mars, but they are designed for microgravity. Since both the moon and Mars have partial Earth gravity, similar water supply system architectures and technologies could be used. However, different reliability and other requirements can produce different designs. (Jones, Hodgson, and Kliss, 2014-074)

The most important difference between the moon and Mars is that if the water supply fails, the moon crew can return in a few days, but not the Mars crew. Much greater water supply reliability is required to meet the Pr(LOC) requirement on Mars than on the moon. The fact that significantly higher reliability is required on Mars than on the moon suggests that the Mars water system requires either more intrinsic hardware reliability, a higher level of system redundancy, or a more reliable overall system design approach.

II. Water System Requirements

The requirements affecting water system design for the moon and Mars bases are given in Table 1.

Table 1. The water system requirements for moon and Mars bases.

Requirement	Moon	Mars
Number of crew	4	4
Mission duration	6 months, 10 years total	18 months
Return delay	10 days	Up to 18 months
Water consumption		
Drinking and food preparation water	2.38 kg/CM-d	2.38 kg/CM-d
Urine flush water	0.50 kg/CM-d	0.50 kg/CM-d
Wash water	1.29 kg/CM-d	1.29 kg/CM-d
Total water	4.17 kg/CM-d	4.17 kg/CM-d
Waste water		
Respiration and perspiration condensate	2.28 kg/CM-d	2.28 kg/CM-d
Urine and flush water	2.00 kg/CM-d	2.00 kg/CM-d
Used wash water	1.29 kg/CM-d	1.29 kg/CM-d
Total waste water	5.57 kg/CM-d	5.57 kg/CM-d
Pr(LOC)	≤ 0.001	≤ 0.001
Pr(LOM)	≤ 0.1	≤ 0.1

(Reed and Coulter, 2000) (Wieland, 1994)

It is assumed that both the moon and Mars bases will have a crew of four. NASA's Exploration Program planned to maintain a moon base for 10 years, with crews rotated every six months. The long stay Mars surface missions typically have a duration of up to18 months.

For the moon, it is assumed that an attempt to repair the water system that failed and necessitated that the crew return to Earth would require up to 10 days. If the crew cannot leave the Mars base ahead of schedule, the surface time after a water system failure could be as long as 18 months, corresponding to a failure very early in a long surface mission. Although the crew could not depart for Earth ahead of schedule, they could abort to orbit and rely on the transit life support system until time to leave. In that case, the Mars base water system reliability would be more similar to that of a moon base, but the Mars transit system has no abort options and must have significantly higher reliability than a moon base.

The crew 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. (Reed and Coulter, 2000) (Wieland, 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. If the water system design requires this much stored water, providing the water in the food would increase food palatability.

Experience indicates that the Probability of Loss of Crew, Pr(LOC), on a space mission is 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 early Mars exploration missions, it will be important not to exceed the past one percent Pr(LOC) for life support failures. Allocating portions of the Pr(LOC) < 0.01 between water, oxygen, carbon dioxide, pressure, food, fire, and other vital life support systems, we assume that the water system has an overall requirement for Pr(LOC) on the order of 0.001. If the crew can return to Earth or if there is minimum survival supply of stored water, the crew can stay alive but the mission will be lost. It seems reasonable to set the Probability of Loss of Mission, Pr(LOM), ≤ 0.1. With this Pr(LOM), 18 of the 20 six-month moon base missions occurring over 10 years would complete successfully and only 2 would be terminated early due to a water system failure. With Pr(LOM) ≤ 0.1 there would be a 10% chance of losing part of the Mars mission. The failure could occur any time, so there would be a 50% chance that the first half or more of the mission would be accomplished.

III. A Recycling and Storage Water System Architecture for a Moon Base

Suppose the moon base water system uses a primary water recycling system and an emergency backup water storage system. How can this design achieve the required reliability? If the recycling system fails, the crew can attempt to repair it and then return to Earth if repair fails. Suppose that the sequence of primary system failure diagnosis, parts supply, attempts to repair, failure to repair, and departure requires up to 10 days. The crew will survive if the backup water storage system does not fail during this 10 day period. The crew could be lost if both the primary recycling system fails during normal continuous operation and the backup storage system fails when called on after the primary failure. Pr(LOC) = Pr(primary fails) * Pr(backup fails). If the probability that the 10 day water storage fails is less than 0.001, the design will achieve the required Pr(LOC) ≤ 0.001, even if the recycling system has a very high probability of failure. But if the crew must return, the remainder of the current six-month mission is lost. To meet the requirement Pr(LOM) ≤ 0.1, the recycling system must have less than 10% probability of an unrecoverable failure during the six months mission. To consider relative cost, this system will be a recycling cost reference and is assigned a total Life Cycle Cost (LCC) of CR.

The simplest and least expensive way to provide a reliable backup system is to use stored water. 4 CM * 4.17 kg/CM-d * 10 days = 167 kg is sufficient. Using many small bottles that the crew can open directly and providing many additional spares beyond 10 days needs can provide very high reliability at very small cost. If Pr(backup fails) is very small, so is Pr(LOC), regardless of how high Pr(primary fails) can be. The reference cost, CR, would not be noticeably increased.

However, Loss of Mission remains a significant concern. If the primary water system fails and cannot be repaired, the remainder of the six-month mission is lost. Pr(LOM) = Pr(primary fails and is not repaired) is required to be ≤ 0.1. This corresponds to reasonably reliable recycling. If Pr(failure) ≤ 0.1 in six months, the failure rate is ≤ 0.2 or 20% per year, and the recycling system's Mean Time Before Failure (MTBF) is five years. But this failure rate and MTBF include only unrecoverable failures. Most failures should be repairable using the parts, skills, and time available.

A Pr(LOM) = 0.1 would give two failures during the 20 six-month missions over the ten year moon base lifetime. To the reduce the expected number of unrepairable failures and the Pr(LOM), two redundant recycling systems could be used. If the original recycling system specification was Pr(LOM) ≤ 0.1, using one recycling system and one spare will give Pr(LOM) ≤ 0.1 * 0.1 = 0.01. A well researched cost model indicates that cost increases to the 0.6 power of the number of units, so total cost for two identical systems would be about 1.5 CR. (Guerra and Shishko, 2000)

Suppose instead the reliability requirement was loosened to twice the original value, Pr(LOM) ≤ 0.2, corresponding to four failures during the 20 six-month missions. In a simple assumed cost of reliability model, the system development cost is inversely proportional to the achieved failure probability. Using this model, the system development cost would be cut in half, to ½ CR. (Jones, 2012-3618) This inverse cost model is considered below. Table 2 shows the relative costs of single and dual redundant systems meeting different reliability requirements.

Table 2. The water system reliability, design, and relative costs for a moon base.

Reliability	Design	Relative cost
Pr(LOM) ≤ 0.1	One reference system	CR
Pr(LOM) ≤ 0.01	Two redundant reference systems	1 1/2 CR
Pr(LOM) ≤ 0.2	One half as reliable, half cost system	1/2 CR
Pr(LOM) ≤ 0.04	Two redundant, half as reliable, half cost systems	3/4 CR

The reference system with Pr(LOM) < 0.1 has the reference cost CR, and two identical redundant reference systems have Pr(LOM) < 0.01 and cost 1 ½ CR. A system with half the original failure rate, Pr(LOM) < 0.2, would have half the original cost, ½ CR.

A. The inverse cost-failure rate model

The assumption that the cost to develop a system is inversely proportional to its failure probability is reasonable and conservative. The cost of higher reliability should always be greater than zero. The cost of achieving a fixed final reliability should be the same whether it is accomplished in one or several steps. The cost to increase reliability by a certain amount should be greater at a higher reliability. The cost of reliability equal to one should be infinite. The inverse cost-failure rate model used here is reasonable in that it meets these requirements. (Jones, 2012-3618) (Aggarwal, 1993)

The model used here, where cost varies inversely to reliability, like any linear model, obviously has a limited range. The costs of increasing reliability as a fraction of the total system cost considered over a wide range of reliability are highly non-linear. They would be relatively low for infant systems with low reliability where the costs are dominated by the fundamental task of creating something that can meet the other system requirements at all, and extremely high for a matured design where simply finding what to fix requires extended operation of multiple systems and every change demands extensive testing over and above the design, analysis and manufacturing effort involved in trying to improve on an already highly reliable design.

Reflecting these considerations, it is usually assumed that the cost for higher reliability increases exponentially rather than linearly. That is, rather than cost increasing proportionally to 1/failure probability, cost is usually assumed to increase as some number to the power of 1/failure probability. (Jones, 2012-3618) (Aggarwal, 1993) (Mettas, 2000) The linear and exponential cost increases are similar for small changes such as half or double in failure probability but differ greatly for large changes. The linear inverse cost-failure rate model is more conservative than the usual exponential model. The usual result that achieving a particular reliability target by design is more expensive than using redundancy is much stronger if the more correct exponential increase is used.

In the current state of life support design, the cost-reliability trade-off is uncertain. It seems likely that further efforts to improve reliability will produce cost-effective gains. But design and test to increase reliability ultimately faces diminishing returns and then using redundancy would be the more cost effective way to achieve even higher reliability. There is a point at which increasing unit reliability is more costly than adding unit redundancy and the trade-off needs to be carefully considered in designing for a Mars mission that demands very high reliability.

Applying this simple linear cost-reliability tradeoff model produces a surprising and potentially distracting result. Using two redundant systems that were half as reliable with half the cost would have higher reliability and lower cost than the original reference system. Two identical design systems with Pr(LOM) < 0.2 would cost ½ * 1 CR for the first unit and ½ * ½ CR = ¼ Cr for the second identical unit, for a total of ¾ CR and would have Pr(LOM) < 0.04, beating both the reliability and cost of one reference system. Clearly, deliberately designing or selecting systems with lower reliability to save cost is a doubtful strategy.

B. Recycling and Storage Water Systems for the Moon Base

Diverse, not identical, system designs should be used for redundancy levels greater than two, to reduce common cause failures. (Jones, 2015-047) This is not to suggest that the need for good reliability can be neglected because redundancy can compensate. It would be very difficult and expensive to develop, test, and fly multiple diverse water systems. However, the water system for a moon base would not require very high reliability and should not require redundancy.

The moon base water system can probably use the architecture and technologies of the current ISS water system to achieve the required Pr(LOM). The recycling water system does not affect the Pr(LOC). The safety of the crew's water supply can be guaranteed by providing a few weeks' supply of stored water in multiple containers. However, a moon mission can be terminated prematurely if the primary water recycling system fails and cannot be repaired. The cost of improving water recycling reliability by design, redundancy, or maintenance and repair must be traded off against the costs of losing a mission, of supplying spare parts, and of crew time for maintenance and repair.

IV. Recycling and Storage Water System Architectures for a Mars Base

The eighteen-month mission on a Mars surface base has the same requirements for Pr(LOC) and Pr(LOM) as the moon base and a similar design will be considered. However the reliability requirements are more difficult to meet on Mars for two reasons. The eighteen-month Mars stay is longer than the six-month incremental moon mission. A crew can return from the moon in a few days, but cannot leave the Mars base ahead of schedule. Pure storage water systems and largely recycling systems with limited storage will be considered in addition to combined recycling and storage systems.

This section considers integrated water system architectures using recycling, storage, recycling, or both. The next section will consider recycling water system architectures that use separate waste water loops.

A. A Pure Storage Water System for a Mars Base

A simple and reliable but very expensive way to provide water for a Mars base would be to use transported and stored water. The amount required is 4 CM * 4.17 kg/CM-d * 548 days = 9,130 kg. Probably the 1.15 kg/CM-d water in the food should be included, bringing the total to 4 CM * (4.17 + 1.15 = 5.32) kg/CM-d * 548 days = 11,660 kg. The launch and emplacement cost for this water could be 100's of millions to a billion or more dollars, which might be acceptable within a total mission cost of 100's of billions. Providing many water tanks and additional spares can provide very high reliability, far in excess of the requirements. To compare relative costs, this Mars storage system will be a cost reference and is assigned a total Life Cycle Cost (LCC) of CS.

B. A Recycling Water System for a Mars Base

If a Mars base uses recycling only, without storage, the recycling system must be much more reliable than the moon base recycling system. If the Mars base pure recycling system fails and cannot be repaired, the failure will cause both Loss of Crew and Loss of Mission, so the more difficult controlling requirement is Pr(LOC) $\leq$ 0.001.

The moon base water recycling system had Pr(LOM) = Pr(recycling fails) $\leq$ 0.1 in six months, so Pr(recycling fails) is $\leq$ 0.3 over the eighteen-month Mars mission. The Mars base Pr(recycling fails) $\leq$ 0.3 is 300 times the required Mars base Pr(recycling fails) = Pr(LOC) $\leq$ 0.001. Since development cost typically increases by the same ratio that failure probability is decreased, the cost of a recycling system meeting Pr(recycling fails) $\leq$ 0.001 would be 300 CR, seemingly prohibitive. Instead, multiple redundant recycling systems can be used, with each having Pr(recycling fails) $\leq$ 0.3. The Pr(recycling fails for N redundant systems) = 0.3^{N}. For N = 6, 0.3^{6} = 0.0007, so six redundant recycling systems are required. Since common cause failures would easily defeat such high levels of redundancy, six different recycling designs should be used. Their cost would be 6 CR.

Using three pairs of two identical recycling designs would produce similar reliability at reduced cost. For N = 2, 0.3^{2} = 0.09, and 0.09^{3} = 0.0007, as before, but only neglecting common cause failures. If common cause failures are the typical ten percent of all failures, each identical pair of recycling systems would have an additional failure rate of 0.03 and a total failure rate of 0.09 + 0.03 = 0.12. (Jones, 2012-3602) The overall failure rate is then 0.12^{3} = 0.0017, which slightly exceeds the requirement. However, the total cost for three sets of two identical systems would be significantly less, 3 * 1.5 CR = 4.5 CR, a twenty-five percent savings.

C. A Recycling with Survival Only Storage Water System for a Mars Base

The Moon base water system architecture uses recycling with sufficient emergency water storage to allow time for repair of the recycling system and a return to Earth if the repair fails. The water system for a Mars base can be similar, with a primary water recycling system and an emergency back up water storage system. If the crew cannot leave the Mars base ahead of schedule, in the worst case the emergency water storage must be sufficient to keep the crew alive throughout a full eighteen-month surface mission.

If the Mars base emergency water storage was sufficient to support all the crew activities over eighteen months, it would provide as much water as, and be identical to the pure storage system described before. To achieve a low Pr(LOC), the Mars emergency water storage needs only to provide for crew survival, but not the ability to complete the mission. The Mars base water recycling system must be sufficiently reliable to meet the required Pr(LOM).

How much water storage is required for crew survival? The absolute bare minimum water loss possible for a person resting at a cool temperature is about 1.3 kg per day. (Sawka, Cheuvront, and Carter, 2005) (Jones, 2012-5121) This is about one-fourth (24.4%) of the total requirement of 5.32 kg/CM-d, equal to the specified input of 4.17 kg/CM-d in Table 1 plus the 1.15 kg/CM-d water in the food. The Mars base emergency water storage system should be one-fourth the size of a pure water storage system. Dividing the supply into many tanks and providing spares should provide very high reliability, better than Pr(LOC) $\leq$ 0.001. The cost would be one-fourth the pure storage system cost, ¼ CS.

If fully hydrated food was provided, it would supply 1.15 kg/CM-d of water, nearly 90% (88.5%) of the required survival water, 1.3 kg/CM-d. In this case, the total stored emergency water could be quite small, less than 500 kg. The cost book-kept against the water system could be small.

The Mars base water recycling system must provide three-fourths of the total crew water requirement, whether the remaining one-fourth is in food or stored water. Since the emergency water storage system does not provide enough water to support the full mission, the mission will be lost if the water recycling system fails and cannot be repaired. The recycling reliability must be high enough to achieve Pr(LOM) = Pr(recycling fails) $\leq$ 0.1 over eighteen months.

The original moon base water recycling system has Pr(recycling fails) $\leq$ 0.1 in six months, so Pr(primary fails) $\leq$ 0.3 in eighteen months on Mars. The probability that recycling fails and the mission is lost is higher than the allowed Pr(LOM) $\leq$ 0.1. The two options are to improve the reliability of the recycling system by redesign or to use two redundant systems. Since development cost typically increases by the same ratio that failure probability is decreased, the cost of a recycling system meeting Pr(recycling fails) < 0.1 would be 3 CR, three times the cost of the moon base recycling system. If two redundant systems are used, their combined failure probability is 0.3 * 0.3 = 0.09, which is less than the allowed Pr(LOM) < 0.1. The cost for two identical recycling systems would be one and a half times the cost for one, 1 ½ CR. The total cost for redundant recycling with survival storage is ¼ CS + 1 ½ CR.

D. Which is the Least Expensive System that Meets Reliability Requirements?

The system designs, reliability, and relative costs for Mars base water systems are given in Table 3.

Table 3. The water system designs, reliability, and relative costs for a Mars base.

Design	Reliability requirement	Relative cost	Relative cost assuming CR = ½ CS
Full storage, no recycling	Pr(LOC) = Pr(LOM) << < 0.001	CS	CS
Ultra reliable recycling, no storage	Pr(LOC) = Pr(LOM) $\leq$ 0.001	300 CR	150 CS
6 diverse redundant recycling, no storage	Pr(LOC) = Pr(LOM) $\leq$ 0.001	6 CR	3 CS
2 redundant recycling, ¼ storage	Pr(LOC)) $\leq$ 0.001 Pr(LOM) $\leq$ 0.1	¼ CS + 1 ½ CR	CS

All four Mars base water system designs in Table 3 meet the reliability requirements, but three have a much better Pr(LOM) than required, with Pr(LOM) = Pr(LOC). Which design is least costly? Ultra reliable recycling with no storage is far more expensive, 50 times as expensive, than 6 diverse redundant recycling with no storage.

It has long been assumed that recycling would be used for all long space missions, such as a moon or Mars base, but reliability and cost were usually not considered. Detailed work that considered the reliability and LCC of storage and recycling life support for Mars found that the cost of recycling life support would be more that two times the cost of storage. (Jones, 2013-3407) The recycling systems used three or four redundant systems rather than the six suggested here. Taking this result as a rough indication of the relative costs of storage and recycling, 2 CS = 4 CR, or CR = ½ CS. Using this approximation in Table 3 allows costs to be directly compared. All storage with no recycling and 2 redundant recycling and ¼ storage have the same lowest estimated cost of CS.

E. Changed Requirements

If the requirement on probability of Loss of Mission was reduced to Pr(LOM) $\leq$ 0.3, only a single recycling system would be required. The water system cost would be lower than full storage, at ¼ CS + CR ~ 3/4 CS, as shown in Table 4.

Table 4. The water systems design, reliability, and relative costs for changed requirements.

Design	Reliability requirement	Relative cost	Relative cost assuming CR = ½ CS
Single recycling, ¼ storage	Pr(LOC) $\leq$ 0.001 Pr(LOM) $\leq$ 0.3	¼ CS + CR	3/4 CS
Single recycling, full storage	Pr(LOC) = Pr(LOM) $\leq$ 0.001	CS + CR	1 ½ CS

If it was desired to provide the crew with more water, full storage could be used with a single recycling system. This cost would be CS + CR ~ 1 ½ CS.

The water system architectures for Mars that use full or one-fourth storage have costs ranging from ¾ to 1 ½ times the cost of a full storage system without recycling. A recycling only system for Mars is expected to be at least twice as expensive as full storage, based on the previous results mentioned. The least expensive Mars base water systems would cost CS, about twice as much as the cost of a moon base recycling system, CR.

V. A Separate Loop Water Recycling System Architecture for Mars

The current state of the art space water recycling system is that implemented in the ISS life support system. A separate loop water recycling system architecture is suggested for a Mars base.

A. The ISS Water System

The ISS water system is a complex integrated recycling architecture that is designed to process all waste water to potable water. The water recovery may ultimately exceed 90 percent, approaching full closure. The ISS life support and water system architecture is shown in Figure 1.

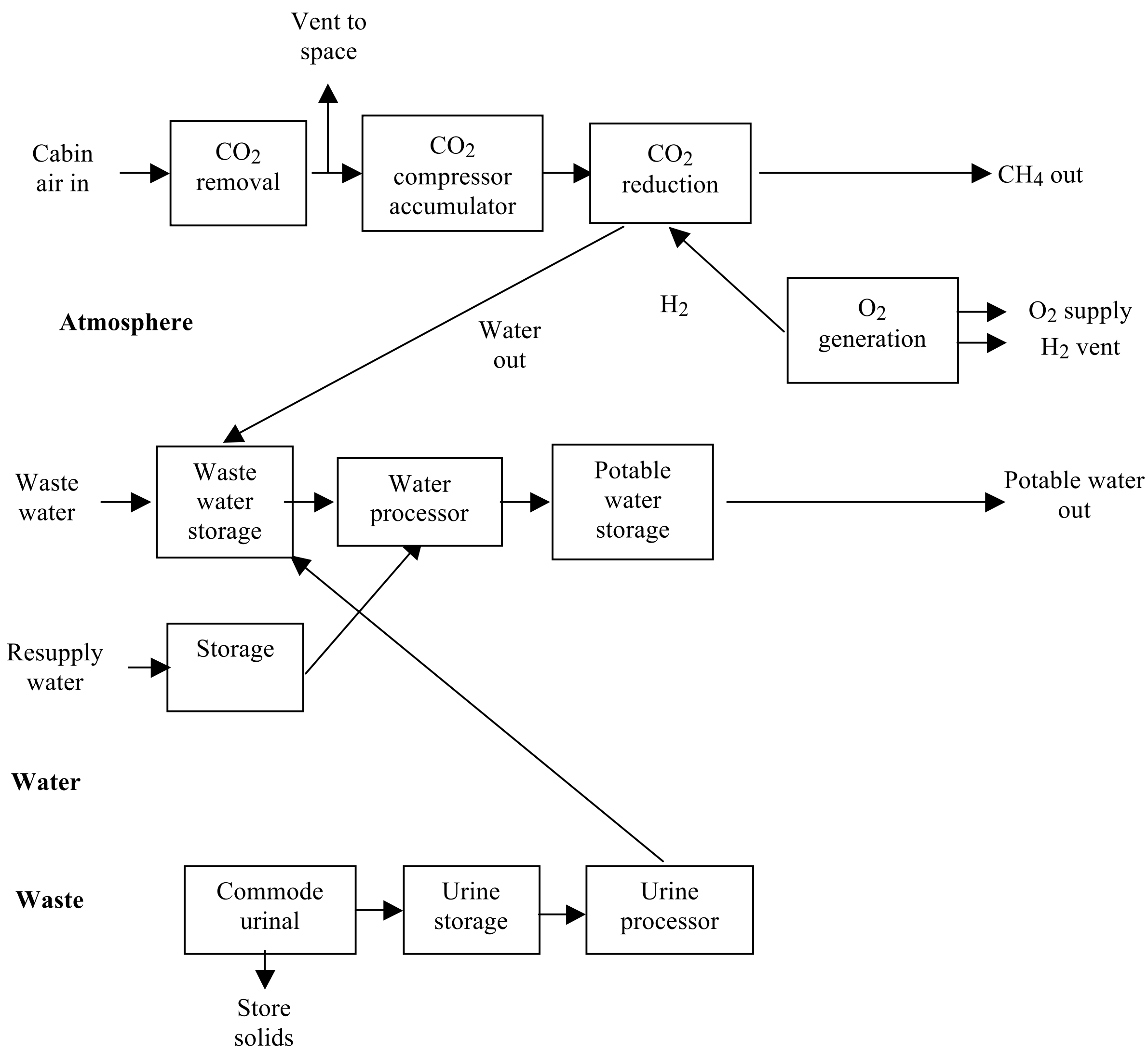

Figure 1. The ISS life support and water system architecture

As shown in Figure 1, the ISS life support system contains atmosphere, water, and waste recycling processors. The carbon dioxide removal system is designed to allow the carbon dioxide to be vented to space or to be delivered to the Sabatier carbon dioxide reduction system. The electrolysis oxygen generator provides oxygen directly to the cabin atmosphere. The hydrogen can be vented overboard or used for carbon dioxide reduction.

Cabin atmosphere condensate is derived from respiration, perspiration, and evaporated hygiene water. Cabin condensate is collected, delivered to waste water storage, processed by the potable water processor, and sent to a potable storage tank. Resupply water delivered by Progress or other resupply vehicles is usually run through the water processor before potable use. Urine and flush water is pumped from the urinal to the urine processor and the distillate is combined with other wastewater. The commode bags and compacts feces. Solid wastes and feces are usually loaded into Progress and burned up during Earth reentry. (Diamant and Humphries, 1990, 901210) (Carrasquillo and Bertotto, 1999-01-2146) (Bagdigian and Ogle, 2001-01-2387)

B. The Three Loop Water System

The ISS water system is fully integrated. It would be desirable for a Mars base to reduce the cost and complexity and improve the reliability and maintainability of water recycling. One thing that can be done is using a three separate loop water recycling system architecture, as shown in Figure 2.

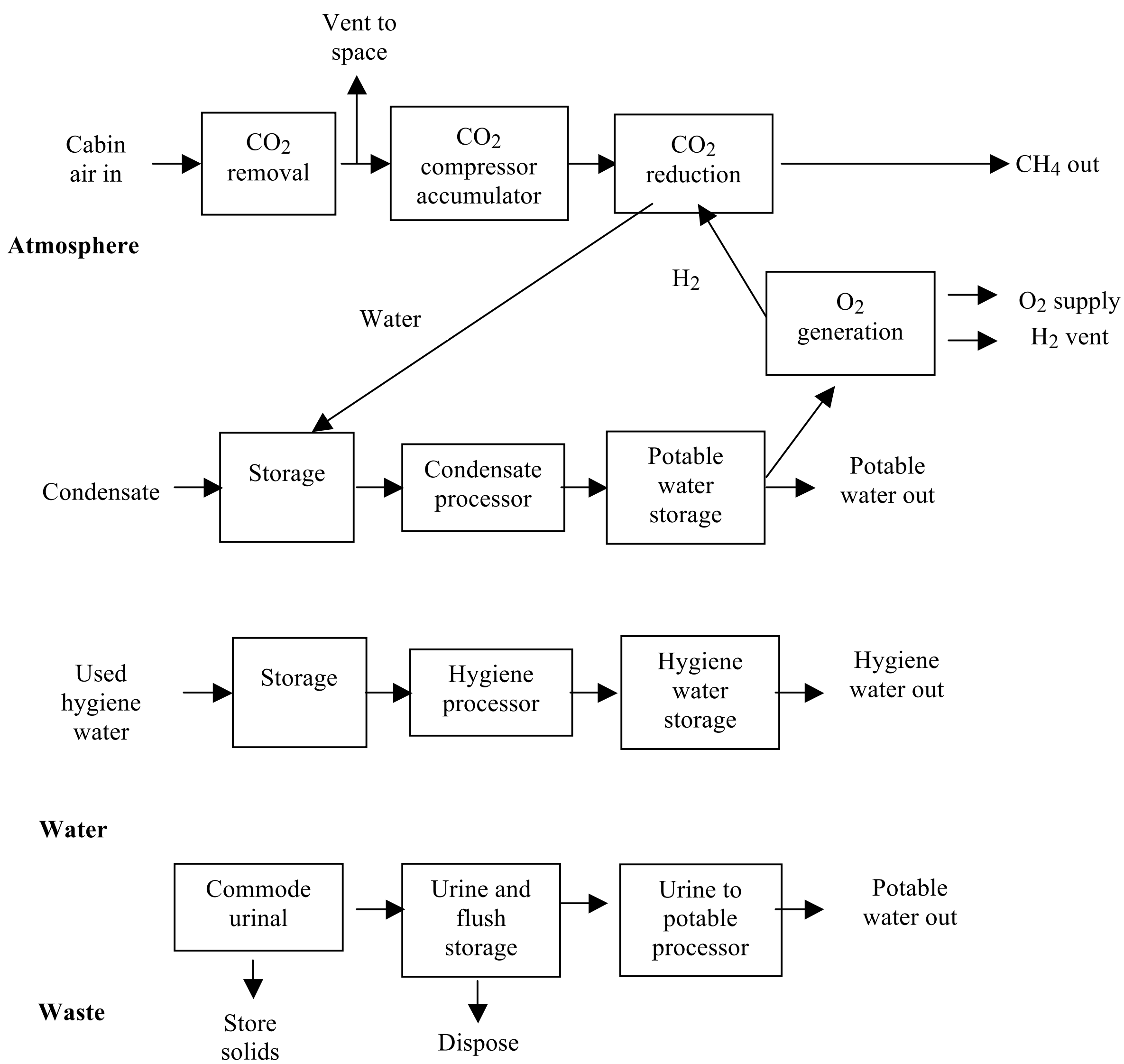

Figure 2. The three loop life support and water system architecture

Condensate water, used hygiene water, and urine and flush water would be processed in three separately implemented loops. Condensate water is derived from respiration, perspiration, and evaporation of hygiene water. Some makeup water must be provided for hygiene water evaporation. The urine and flush loop has more input waste water than is needed to provide flush water, and the remainder can be processed to potable if needed or disposed of unprocessed if not needed.

Separating the input waste water streams will allow less difficult processing of the less contaminated sources. The three separate loops are not closed or independent. Water must be transferred between them.

C. Three Loop Water Recycling System Water Balance

The nominal water balance for the three loop water recycling system architecture is shown in Table 5.

Table 5. The three loop water recycling system architecture water balance.

Water sources		Water uses	
Makeup	0.10 kg/CM-d	2.38 kg/CM-d	Drinking and food preparation water
Respiration and perspiration condensate	2.28 kg/CM-d		
Used wash water	1.29 kg/CM-d	1.29 kg/CM-d	Wash water
Urine and flush water	2.00 kg/CM-d	0.50 kg/CM-d	Urine flush water
		1.50 kg/CM-d	Potable or dispose
Total sources	5.67 kg/CM-d	5.67 kg/CM-d	Total uses

Respiration and condensate is recycled into potable water for drinking and food preparation. There is a small deficit of 0.10 kg/CM-d that must be supplied as makeup water, ultimately derived from processed urine and flush water. The used wash water is recycled to less than potable standards for reuse as wash water. 0.5 kg/CM-d of urine and flush water would be processed for use as urine flush water. Because of the water in the food and produced by food metabolism, the water system has a net positive water balance. The excess water appears as 1.5 kg/CM-d of urine and flush water that is not needed for recycling into urine flush water and could be processed into potable water if needed.

Table 5 presents a theoretical water balance, showing the three loops as separate for mathematical accounting. There will be unavoidable transfers of water between the three loops, notably by evaporation of wash and flush water. Water must be transferred between uses to compensate. The evaporation of wash water may remove the requirement of 0.10 kg/CM-d of makeup water for drinking and food preparation. Urine and flush processing could then be limited to providing flush and wash water, rather than makeup potable water.

Since the water system has a throughput of 5.67 kg/CM-d and a net allowed loss of 1.4 kg/CM-d, the overall recycling efficiency need be only 75%. Losses in the wash water loop would be supplied from storage or processed urine. The 1.4 kg/CM-d is the net positive water balance shown in Table 1 and is due to the use of hydrated food and the metabolism of food into water. The use of dehydrated food would require much higher recycling efficiency.

D. Implementation of the Three Loop Water Recycling System

The three loop Mars surface base water nominal water balance has four water sources, makeup, condensate, wash water, and urine and flush water. Different water processor technologies may be better suited for the different waste streams. MIR used a similar three loop system.

1. Makeup

The amount of makeup water needed for crew consumption could be quite small if the condensate processor is highly efficient, and might not be needed at all if there is significant wash water evaporation. The makeup water could increase to 0.5 kg/CM-d if condensate loop closure is only 90%.

Additional makeup water is required for oxygen generation. The crew requires 0.84 kg/CM-d of oxygen, which can be produced from 0.95 kg/CM-d of water. The crew produces 1.00 kg/CM-d of carbon dioxide, which, if all the oxygen is recovered as water and then converted to oxygen, would yield only 0.73 kg/CM-d of oxygen. The shortage of 0.11 kg/CM-d of oxygen requires an additional 0.12 kg/CM-d of water, in addition to the 0.83 kg/CM-water provided by the reduction of carbon dioxide. However, the carbon dioxide reduction process loses half the input hydrogen as methane. Unless additional hydrogen is supplied or the methane converted to hydrogen and carbon by pyrolysis, only half the oxygen in carbon dioxide can be recovered. The total shortage of water would then be 0.54 kg/CM-d. (Jones, 2008-01-2193) (Reed and Coulter, 2000) (Wieland, 1994)

The makeup water if required should be produced by processing the plentiful excess urine and flush water to potable. This would provide an additional source of water and could improve water dependability in the event of accidents, failures, or downtime. If it is desired to avoid urine and flush processing, the makeup water could be provided from Earth and stored.

2. Condensate

Respiration and perspiration condensate is water removed from the Mars base atmosphere to control humidity. Evaporation from wash water and urine and flush water will increase the amount of condensate. It is cleaner than used wash water and is far less contaminated and difficult to purify than urine and urine flush water. Processing condensate into potable water requires collecting it, separating it from atmosphere, purifying it, removing volatile contaminants, and adding a biocide to preserve it. An automated condensate water recovery system that used a sorption-catalytic technology was operated on MIR and met most of the crew's needs for drinking and food preparation water. (Eckart, 1996) Several condensate systems could operate in parallel for increased reliability.

3. Wash Water

Much of the wash water used on a Mars base will evaporate and be recovered as humidity condensate. The wash water processing loop will not be closed and will require makeup water. On ISS, wash water is not collected. Wash cloths used by the crew for hygiene are hung to dry. In a future Mars mission, the wash water budget could be increased to provide for equipment cleaning and showers. Gravity drainage would allow collection of used wash water and direct processing of the used wash water remaining after evaporation.

Closed loop recirculating showers have been developed on Earth and presumably similar systems for more limited hygiene would perform well in gravity on Mars. The recirculating system would not have to remove all surfactants as would be needed for full potable quality. Another benefit of a closed loop wash system is that the other loops would not have to deal with hygiene product contaminants. The ISS uses multifiltration for both hygiene and condensate processing and also considered reverse osmosis. The MIR implemented a separate automated loop for hand washing and showering. (Eckart, 1996)

4. Urine and Flush Water

Urine processing to produce potable water for drinking and food preparation must use evaporation and condensation. The ISS employs a Vapor Compression Distillation (VCD) system for urine and flush processing. The VCD uses rotation for operation in zero gravity, but this additional complexity would not be required on Mars. (Eckart, 1996) Of the total 2 kg/CM-d urine and flush waste stream, only 0.5 kg/CM-d is required to provide flush water. 1.5 kg/CM-d more of the urine and flush water is available for processing into potable water, but much less may be needed. However, if the water balance is close to neutral, which is possible if there is extensive use of dehydrated food, it would be necessary to process most of the urine and flush water to potable.

A MIR urine recovery system produced water for urine flush and water electrolysis. (Eckart, 1996) Urine flush water and even wash water can be held to less difficult requirements than potable water, so possibly a less difficult purification process could be used. If only small amounts of urine and flush water had to be processed to potable water, possibly a slower rate air evaporation system could be used. It would benefit from gravity and be simpler and easier to maintain and repair.

Urine and flush water can be processed differently to meet different requirements. It can be purified into potable water as on ISS, used to produce flush and technical water as on MIR, or if all is not needed, some may be left unprocessed. The choice to be able to process all urine and flush water to potable, as shown in Figure 2, has the advantage of increasing water system reliability, as discussed below.

E. Relative Performance of a Recycling Three Loop Water Recycling Architecture for Mars

The suggested implementation of the three loop water recycling architecture for Mars is intended to improve the cost-reliability trade-off by allowing less difficult processing of lesser amounts of waste water, but simply providing separate parallel processing paths creates a reliability improvement. The above analysis of reliability and cost started with a water recycling system that had a Pr(recycling fails) $\leq$ 0.3 over the eighteen months Mars base mission. Its reference Life Cycle Cost (LCC) was CR.

Suppose this reference system was divided into three parallel water processing paths as in Figure 2. The cost and failure probability will be allocated to the parallel recycling paths proportionally to their output as shown in Table 6.

Table 6. The three loop water recycling system architecture water balance.

Water path	Output	Allocated cost, fraction of CR	Allocated failure probability, 0.3 total
Condensate	2.38 kg/CM-d	0.42	0.126
Wash water	1.29 kg/CM-d	0.23	0.068
Urine and flush water	2.00 kg/CM-d	0.35	0.106

As before, the reliability design goal is Pr(LOC) $\leq$ 0.001 and Pr(LOM) $\leq$ 0.1. Previously it was assumed that the failure of the water system would cause loss of crew. With three loop system, the crew could survive if wash and urine and flush processing were lost as long as condensate was still purified. But if all the urine was processed into potable water, the crew could also survive if condensate and wash water processing was lost. Thus the Pr(LOC) of a single string three loop recycling system is Pr(LOC) = 0.126 * 0.106 = 0.013, far better than the Pr(LOC) = 0.3 of a single integrated system. If identical dual redundant units are used for both the condensate and urine and flush processors, Pr(LOC) = 0.0002, far in excess of the requirement, and the cost is 1 ½ * (0.42 + 0.35) CR = 1.16 CR = 0.58 CS. This is significantly less expensive than the least expensive Mars base water system designs in Table 3. It is 42% less than full storage, no recycling, or two identical redundant recycling systems, ¼ storage. Pr(LOM) occurs if both condensate, or both urine and flush, or the single wash water processor fail. Pr(LOM) = 0.095, within specification.

This result shows that a three loop water recycling system architecture can easily achieve high required reliability at greatly reduced cost, just by providing parallel paths. Possible simplifications in hardware implementation could make three loop water recycling even less expensive for a Mars base.

F. Advantages of Developing the Three Loop Water Recycling Architecture for Mars

A three loop water system architecture specifically designed for a Mars surface base would have many advantages, even though an upgraded ISS water system could be suitable for a moon base. The Mars three loop design architecture advantages include:

1. Gravity assisted operation for improved performance and reliability at lower cost
2. Testing in Earth gravity is more realistic for a Mars base than for ISS.
3. Less difficult processing by lower required efficiency and closure
4. Less difficult processing by not mixing condensate, wash water, and processed urine and flush
5. Less difficult processing by not bringing all waste water to potable specifications
6. Less complex system for easier design and better maintainability and reliability
7. Less systems integration, allowing independent or sequential subsystem development, test, and upgrade
8. Independent separate parallel path water processing for better reliability

ISS water system design had to cope with the lack of gravity and local resources, but a Mars base system design should take advantage of their presence. The complex integrated ISS water system impressively uses high technology to take all waste water sources to potable water with the goal of high closure, but this approach seems more difficult than using separate processors to meet the higher reliability requirements of a Mars base.

VI. Conclusion

This work considered how cost and reliability considerations affect the water system designs for the moon and Mars. Because both the ISS and a moon base allow the crew to return to earth in a few days if the water system fails and cannot be repaired, similar recycling systems with the same reliability can be used for ISS and a moon base.

If a crew cannot return from a Mars base before the scheduled departure, the water necessary for crew survival over the mission duration must be provided with high reliability. This problem led to the consideration of several alternate water system architectures, including full storage, highly redundant recycling, and recycling with survival water storage. Using previous results that the cost of recycling-only life support is roughly two times the cost of full storage, it was found that a dual recycling system with one-quarter storage would have cost as low as a full storage system.

A water recycling architecture with three separate processors was conceived that improved the cost-reliability trade-off for a Mars base. Condensate, wash water, and urine and flush are separately recycled. Three loop water recycling has significantly less cost than a dual recycling system with one-quarter storage or a full storage system.

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