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Impact of Water Integration on Space Station Freedom Propellant Availability

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Water is an important resource on the Freedom Space Station and is essential for life support, laboratory, and general spacecraft operations. Overall distribution is provided by the integrated water system (IWS), which uses water collected from the environmental control and life support system (ECLSS) and Shuttle Orbiter to support extravehicular activity (EVA) and laboratory experiment requirements. Typically, this integrated approach to water handling yields an available excess that can be electrolyzed into gaseous oxygen and hydrogen propellants. In fact, recognition of this potentially "free" resources was the major reason for selecting an electrolysis propulsion system and integrated water distribution for the Freedom Station. This approach also eliminates redundant hardware and reduces operations costs associated with propellant resupply and disposal of waste water. The availability of excess water strongly depends on the operational, design, and performance characteristics of the systems that interface with the IWS. This paper describes the water usage of these systems, identifies the key parameters influencing the overall water balance, and assesses their impact on propellant availability for the propulsion system.

Introduction

THE cumulative cost of resupplying propellant is a primary consideration in selecting a propulsion system for a permanent orbital facility such as Space Station Freedom. Of all the options studied,[1] one that uses gaseous oxygen and hydrogen produced by water electrolysis potentially offers the lowest life-cycle costs, because it uses a fluid that is readily produced and discarded by many Station systems. Use of water collected on-orbit not only reduces the resupply of propellant[2] but also lowers logistics requirements and operations costs for other systems.

These benefits are realized by implementing an integrated water system (IWS)[3] to collect, store, and distribute water among the systems that either consume or discard the fluid. The IWS usage hierarchy illustrated in the functional schematic of Fig. 1 offers several advantages, namely:

1) Reduction of water resupply costs for Station consumers.

2) Use of common storage and distribution hardware, and elimination of redundant, system-dedicated equipment.

3) Infusion of pristine Orbiter water into the environmental control and life support system (ECLSS) water supply to lower contaminant levels and reduce the technical risk of ECLSS water reclamation.

Table 1 defines the nominal quantities transferred across each interface in Fig. 1. The following sections present more fully the derivation of these values and describe their sensitivity to key system design and operational characteristics. The paper concludes by defining the upper and lower bounds of water availability and describing the associated effects on resupply requirements for water.

ECLSS and Crew Support

The ECLSS is the only onboard system that nominally produces a net excess of water. The ECLSS water balance is highly dependent on the efficiencies and types of chemical processes for CO_2 recovery, urine reclamation, oxygen generation, and overall water recovery. This balance essentially consists of the inputs and outputs shown for nominal subsystem characteristics in Fig. 2.

Water Inputs and Outputs

The primary source of water is food consumed by the crew. The nominal quantity, 1.1 lbm/man-day, is derived from assuming the extremely dry diet used for the Skylab program and represents a lower bound for food water content. It is conceivable that a more normal, water-enriched diet will be implemented for psychological reasons. This would increase the supplied quantity to about 2.0 lbm/man-day and nearly double the total excess generated by the ECLSS.

Another input is from the chemical reduction of CO_2. In order to maintain CO_2 levels within acceptable limits, excess

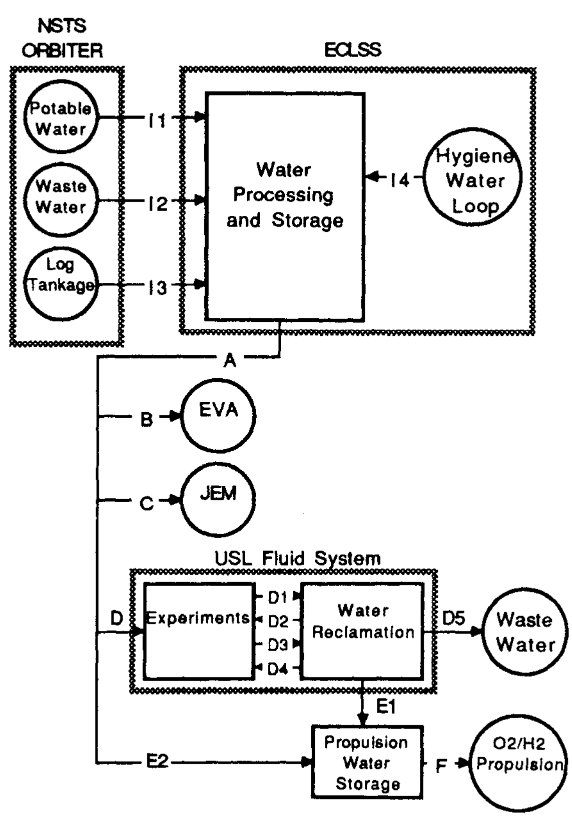

Fig. 1 IWS water usage hierarchy.

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Table 1 IWS hierarchy interface description

Interface Designation	Description	Quantity derived from	Nominal value lbm/90 days
11	Potable water available from Shuttle Orbiter water scavenging	•Stay time •Station to Shuttle power cord •Resupply interval •Orbiter power level	1330
12	Waste water available from Orbiter water scavenging	•Number of crew using Orbiter facilities •Stay time	0
14	Excess hygiene water produced by ECLSS	•Food water content •Number of crew •Urine reclamation capability	700
A	Total water supply on Space Station	$A = 11 + 12 + 14$	2030
B	Water supply for EVA servicing	•Space suit (EMU) type •Number of EVA's per operation interval	0
C	Water resupply for JEM[a] experiments	Assumed constant	60
D	Total USL water resupply requirement	•Crew time allocated for experiments •Type of experiments	539
D1 and D2	CFES water transferred to and recovered from USL reclamation system	•D1 = CFES waste water •D2 = Reclamation efficiency of CFES water × D1	1676 1425
D3 and D4	Remaining water transferred to and recovered from USL reclamation system	•D3 = Total waste water − D1 •D4 = Standard reclamation efficiency × D3	822 53
D5	USL waste water unusable to propulsion	•D5 = (D1 − D2) + (D3 − D4) (with reclamation) •D5 = D3 − D4 (without reclamation)	539
E1	USL waste water compatible with electrolysis units, tanks, and thrusters	•E1 = 0 (with reclamation) •E1 = D1 − D2 (without reclamation)	0
E2	Excess hygiene water	E2 = A − (B + C + D)	1431
F	Total water available to propulsion	E2 = E1 + E2	1431
13	Makeup water provided by logistics	13 = Propulsion water requirement − F	0

[a]Japanese experiment module.

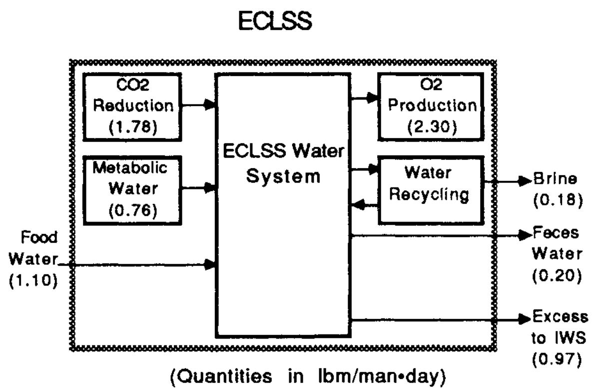


Fig. 2 Nominal ECLSS water balance.

hydrogen produced from oxygen generation (i.e., water electrolysis) is combined over a catalyst with CO_2 recovered from the pressurized module atmosphere. The resultant reaction (i.e., Bosch CO_2 reduction process) produces water and a solid carbon by-product that must be collected and returned to Earth. A third input is water generated metabolically by the crew. This relatively small quantity, nominally 0.76 lbm/man-day, is recovered from urine and crew respiration, and is roughly proportional to crew activity levels.

Most of the water that is truly consumed by the ECLSS is electrolyzed to compensate for loss of atmospheric oxygen due to module leakage, airlock depressurization, and crew respiration. A portion is also lost from the reclamation of urine and hygiene water, and recovery of atmospheric condensate. The efficiency for recovery of water form crew urine, the primary constituent of this term, can vary between 90–96% depending on the type of reclamation system used. Currently, the most efficient candidate process employs reverse osmosis and can recover up to 96% of the water contained in the urine. The remaining 4% of concentrated water and solid water products is collected as brine and returned to Earth.

Unlike urine, water contained in the feces is considered completely lost. Cost-effective extraction of water from this product is unlikely due to its high bacterial content and relatively low water content. Therefore, all fecal material is collected on-orbit and returned to Earth.

Design and Operational Sensitivities

The amount of water transferred across each interface in Fig. 2 is influenced by several operational and design parameters. Besides food water content and water recovery capability, the most significant driver is the number of crew supported by the ECLSS. Actually, the entire ECLSS materials balance is proportional to the number of crew members supported by the system. For example, periods of reduced occupancy, such as during man-tended operations, require less ECLSS support and consequently reduce the total excess produced by the system. Alternatively, additional crew support while the Shuttle Orbiter is docked or during later growth phases will increase the net excess.

Closure level or the extent of overall fluids recovery influences the ECLSS materials balance and resupply requirements. For instance, eliminating CO_2 reduction, urine reclamation, and/or hygiene water recycling reduces water production and necessitates water resupply for ECLSS. Because lessening the degree of closure greatly increases life-cycle costs, the maximum closed system was retained as the reference for this study.

Crew activity levels also significantly impact ECLSS water availability. Increased activity translates to additional food consumption (food/water input) and metabolic water production. The associated increase in oxygen requirements and resultant loss of water to O_2 production is offset by increased water recovery from the Bosch CO_2 reduction process. The net effect is an increase in available water when a more strenuous regimen is implemented for the crew.

Besides crew respiration, module leakage also influences ECLSS water availability. This is dependent on the design of the module pressure vessel, the effectiveness of the intermodule seals, and the total number of modules on the Station. Anticipated growth scenarios envision the addition of up to four more modules, which would increase the requirement for electrolyzed water and reduce the overall water excess. This effect, however, would be offset by the support of additional crew members.

The key parameters influencing ECLSS water production, in decreasing order of importance, are food water content, urine reclamation capability, and number of crew. These parameters may vary significantly over time, and the sensitivity of excess ECLSS water to changes in their values is shown in Fig. 3.

Parameter (Units)	Sensitivity	Nominal Value of Parameter	Parameter Max & Min Limits	ECLSS 90 Day Production (lbms)
Number of Crew (Men)	87.5 lbm per man	8	10	875
			6	525
Food Water Content (lbm/man•day)	720.0 lbm per lbm/man•day	1.1	2.0	1420
			1.1	700
Urine Reclamation (Percent)	34.7 lbm per percent	96	96	700
			90	492

Fig. 3 ECLSS water sensitivities.

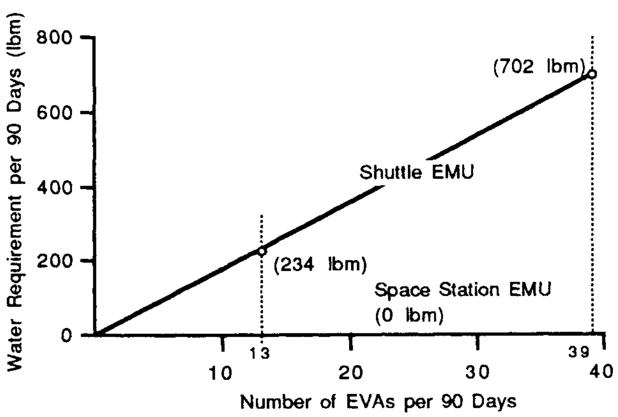


Fig. 4 Water balance sensitivity for EVA servicing.

Extravehicular Activity Servicing

The quantities of fluids consumed in support of manned extravehiclular activity (EVA) depend on the degree of closure in the space suit life support and thermal control processes and the frequency of EVA's. Although oxygen and water are both typically provided by ECLSS, this study separated out the water supply interface in order to highlight its significance to the overall balance.

Of the two types of space suits considered for use on S.S. Freedom, the current Shuttle suit represents the option requiring the least development. The suit employs an open-loop extravehicular mobility unit (EMU) for life support and relies on an open-loop water sublimator for transport of heat to the external environment. The latter thermal control function consumes almost all of the water used, expending it at a rate of 1.3 lbm/h. For a single, 6-h EVA, and extra 1.2 lbm of drinking water is included, thus bringing the total requirement to 9.0 lbm per EMU or 18.0 lbm when two men are considered. With these quantities, the total requirement is a function of the frequency or number of EVA's executed over each 90-day operations interval. This study assumed a nominal frequency of 1 per week or 13 for every 90 days, although a higher rate of 3 per week is possible. With nominal conditions, this equates to a requirement of 234 lbm per 90 days.

A more advanced space suit option is currently being developed to minimize operational impacts to the Freedom Station. Its higher pressure operation of 8 psi, as opposed to the Shuttle suit's 4 psi, eliminates the need for a lengthy prebreath cycle, thereby reducing the time allotted for EVA preparation. The heat removal system in the suit's EMU is closed-loop and obviates the need to makeup water. In addition, CO_2 and urine produced during EVA are collected and at least partially recovered by the station ECLSS. For this study, it was assumed that no water or CO_2 was lost during EVA. Consequently, the water balance with the advanced suit is not influenced by EVA frequency.

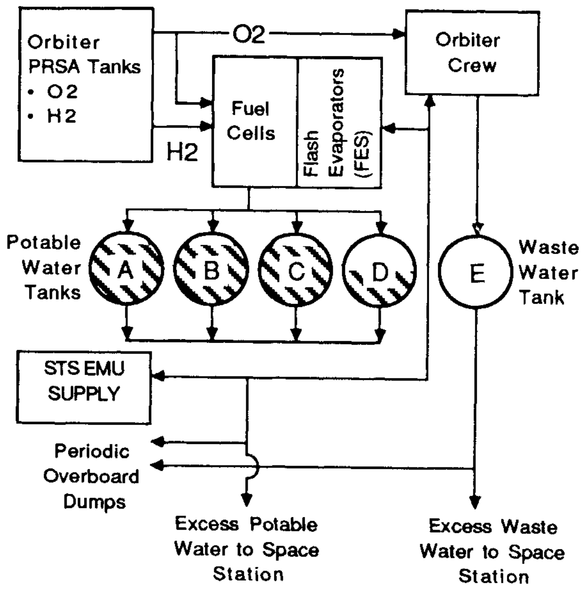


Fig. 5 Orbiter water/fuel cell schematic.

Although the high-pressure suit with advanced EMU will eventually be used to support steady-state operations, it is conceivable that the Shuttle EMU will be used during the early phases of the program. This, coupled with extensive outside activity during assembly, will significantly impact overall water availability, as shown by the sensitivity curves in Fig. 4.

Shuttle Orbiter

During a typical mission, the Shuttle Orbiter produces 1200 to 1600 lbm of water from the nominal operation of its oxygen/hydrogen fuel cells. Except for the 330 lbm retained onboard as contingency for life support and payload bay door coolant, most of this excess water is periodically dumped to accomodate the limited Orbiter storage capabity of 660 lbm. For Station-servicing missions, collection and transfer (i.e., scavenging) of this water to the IWS may be necessary to prevent the severe contamination to the immediate external environment that would otherwise occur from Orbiter water dumps.

Orbiter water scavenging also offers several advantages.[4] The chief benefit is that it provides an access to an inexpensive source of high-quality (i.e., potable) water for Station consumers. Because it does not have to be paid for in terms of resupply, this water represents an essentially "free" resource to the Station. A more subtle benefit from scavenging is the reduction of technical risk associated with the development of ECLSS water reclamation processes. The anticipated processes can maintain a total organic carbon (TOC) content of 0.10%, twice as high as the maximum permitted 0.05%. Flushing ECLSS water loops with pristine Orbiter water, which has a TOC content of 0.001%, will lower TOC to acceptable levels and thereby reduce ECLSS development costs.

A general schematic of the Orbiter water/fuel cell system is shown in Fig. 5. Oxygen and hydrogen are stored cryogenically in four power reactant supply assembly (PRSA) dewars, which employ internal heaters to expand and transfer these gases from the tanks. A major portion of the oxygen and hydrogen is distributed to three fuel cells (FCP's), where it is converted into water and transferred to an assembly consisting of four 164-lbm-capacity storage tanks. From this assembly, it is eventually distributed to either the flash evaporators, the onboard environmental control and life support system, an external dump nozzle, or an EMU access panel in the airlock.

The rate of water production from the fuel cells is a function of power output and fuel cell integrity (or age) as shown in Fig. 6. The amount of water generated increases linearly with power level at 0.80 lbm/kW-h for a newer, more efficient

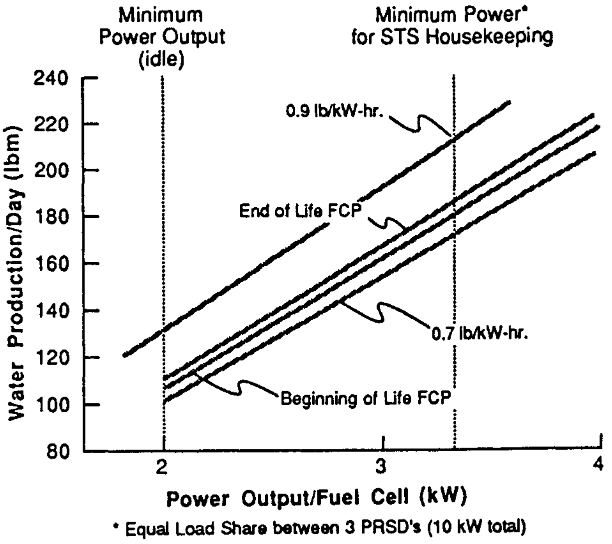


Fig. 6 Fuel cell water generation rates.

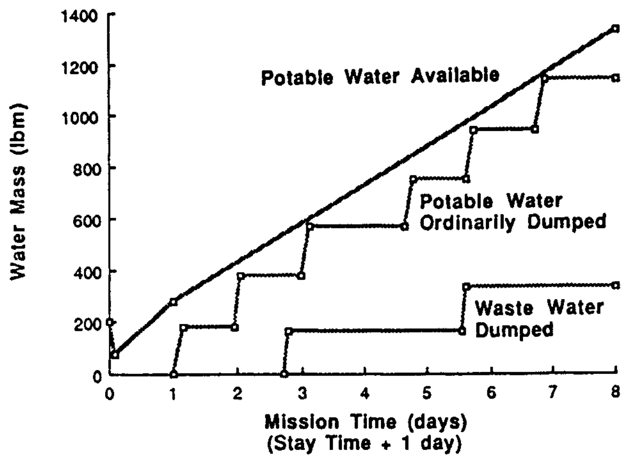


Fig. 7 Orbiter water production and disposal time-line.

FCP and at 0.86 lbm/kW-h for an older cell. The average total output for a typical mission varies between 15–18 kW and can exceed 22 kW to support extra control and contingency power requirements during launch and return. However, while docked to the Station, a power level of only 10 kW is required to sustain housekeeping and maintenance operations. This value was selected because it reduces the number of periodic water dumps to the Station and decreases wear on the Orbiter fuel cells.

For a constant power output, the total amount of available fuel cell water varies linearly with time. Figure 7 illustrates this relationship for a power level of 10 kW and shows that available fuel cell water closely approximates the quantity that would otherwise be dumped without scavenging. For a stay time of 7 days, the total scavengeable amount is 1330 lbm.

The water that accumulates in the waste tank (tank E in Fig. 5) is independent from the fuel cell output and can be separately scavenged and purified by the Station ECLSS. This option has not been seriously considered, primarily because the small quantities of available water do not warrant the additional plumbing required for access. Approximately 53% of the 7.46 lbm/man-day produced comprises condensate from respiration and perspiration, while the remaining fraction consists of urine. Because all of these represent human products, the total rate of production is proportional to crew size. An alternative to scavenging this water directly is to encourage Orbiter crew use of Station toilet facilities while docked to S.S. Freedom. Almost 80% of the waste water that would normally go to Tank E can be recovered this way for Station use.

Design and Operational Characteristics		Orbiter Staytime (days)		
		5	7	9
90 Day Resupply Interval	Without Power Cord	1,033	1,330	1,627
	With Power Cord	538	637	736
45 Day Resupply Interval	Without Power Cord	2,066	2,660	3,254
	With Power Cord	1,076	1,274	1,472

Quantities in lbm/ 90 days

Fig. 8 Orbiter water sensitivities.

The total amount of water recovered from the Orbiter is also influenced by the frequency of resupply flights. The nominal 90-day resupply cycle is based on a Shuttle mission frequency of four Station dedicated launches per year. In order to satisfy current logistics projections for cargo launch and return, the frequency may be as high as eight missions per year, which means a resupply cycle of 45 days and a doubling of the water supplied to the IWS over a 90-day period.

Because oxygen and hydrogen must be carried by the Orbiter for power production, water generated by the fuel cells can be considered as an essentially free resource. When the Orbiter is docked, however, many Station experiments are shut down and extra power may be available. If the 10 kW required by the Shuttle can be accessed from the Station, then approximately 67% of cryogenic oxygen and hydrogen (and associated tankage) can be off-loaded, thus increasing Shuttle lift capability by 2000 lbm. This is a significant advantage to overall logisitics, but reduces scavangeable water to about 640 lbm per mission.

This procedure requires an interface for power transfer (i.e., power cord) from the Station to the Orbiter and is contingent on shutting down and restarting two of the three fuel cells on-orbit (one unit is left on to provide conditioning for the cryogen tanks). Although these units are qualified for on-orbit restart capability, this operation has never been performed on a Shuttle mission.

The sensitivities of excess Shuttle water to variations in stay time, mission frequency, and Orbiter power access are summarized in Fig. 8.

United States Laboratory

The United States Laboratory (USL) module contains facilities that accommodate various types of materials processing and life sciences research. A baseline set of 14 experiments, representing a cross section of the user community's needs, was used to derive water and other fluid requirements for the lab. Since most of these experiments require pyrogen-free (ultrapure) water, a hyperfiltration process is applied to all water cycled within the USL's fluid distribution system (PMMS). Regardless of the source, the degree of pretreatment is essentially the same. Because there are no unique restrictions imposed on incoming water quality, the lab water supply is readily integrable with the IWS.

The amount of time and water required to perform a single cycle for each experiment is shown in Table 2. With these values, total lab water usage is a function of the number of crew hours dedicated to the laboratory and the allocation of these hours among the different experiments. Total water requirements for crew time allotments of 10, 20, and 30 h per day are shown in Table 3.

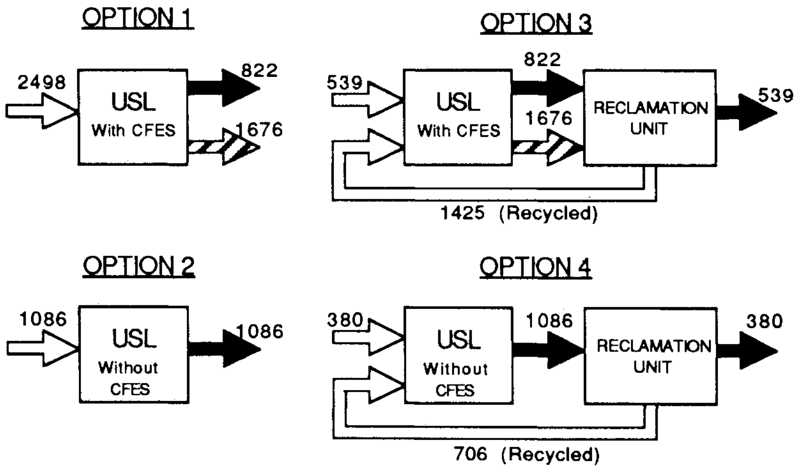
A major driver in the USL water balance is the Continuous Flow Electrophoresis System (CFES). This experiment has a cycle requirement (335 lbm) that is almost an order of magnitude higher than the next greatest experiment user. Removing CFES from the experiment complement increases the amount of time available to run other experiments and reduces the total 90-day usage from 2498 lbm to 1086 lbm, with the assumed crew time allotment of 20 man-h/day.

Table 2 USL experiment requirements

			With CFES		Without CFES	
Experiment	Crew hours per cycle	Water per cycle, lbm	Cycles per 90 days	Water per 90 days, lbm	Cycles per 90 days	Water per 90 days, lbm
Acoustic cont.	13.3	9.46	6	56.8	9	85.1
Cont. flow (CFES)	35.2	335.20	5	1676.0	0	0.0
Directional solid	75.5	1.10	2	2.2	2	2.2
Droplet burn	11.5	8.38	10	83.8	12	100.6
Electroepitaxial	29.8	1.54	1	1.5	1	1.5
Electromagnetic cont.	8.2	5.05	10	50.5	10	50.5
Free surf. membrane	7.9	3.31	18	59.6	24	79.4
Membrane production	20.7	45.86	8	366.9	12	550.3
Mono latex	24.8	1.76	2	3.5	3	5.3
Protein crystal growth	123.9	48.73	2	97.5	2	97.5
Solid immed.	14.8	7.94	2	15.9	2	15.9
SS flame	9.5	7.06	10	70.6	11	77.7
Solid crystal	34.0	3.31	2	6.6	2	6.6
Vapor phase	73.7	6.73	1	6.7	2	13.5
Total				2498.1		1086.7

Table 3 USL water crew sensitivities

	With CFES			Without CFES
Number of crew hours per day	CFES reqmt., lbm	Other exps., lbm	Total, lbm	Total, lbm
10	670.4	298.4	968.8	405.6
20	1676.0	822.1	2498.1	1086.1
30	2011.2	1322.1	3333.3	1696.9



OPTION	Total Resupply (lbm)	Available to Prop (lbm)	Unusable Quantity (lbm)
1	2498	1676	822
2	1086	-	1086
3	539	-	539
4	380	-	380

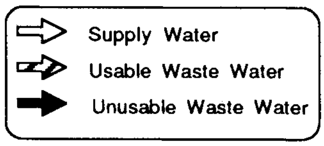


Fig. 9 USL water processing options.

Another factor is the degree of reclamation performed within the USL. Reclamation reduces resupply requirements by purifying a fraction of the waste water and mixing it with fresh, makeup water to meet total user requirements during the next operation interval. For most lab waste water, a 65% reclamation efficiency (water recovered/water processed) appears feasible. However, some experiments, such as CFES, contain mostly organic contaminants and their waste water can be reclaimed at a higher efficiency (about 85%). Consideration of these different reclamation capabilities yields the four options for USL water usage shown in Fig. 9. Using these cases as bounds, resupply requirements can range from 380 lbm to 2498 lbm.

With reclamation (options 3 and 4), the impact of including CFES is small due to the high degree of waste water recovery from this experiment. Without reclamation, however, IWS water handling is significantly influenced by incorporation of CFES. Unlike the waste water from other experiments, unreclaimed waste water from CFES can be fed directly to propulsion static feed electrolysis units. For this reason, the total availability of pure and usable waste water to propulsion is fairly insensitive to CFES requirements, particularly when no reclamation is implemented. With CFES (option 1), IWS logistics requirements are driven by USL water requirements, because CFES waste can be used by propulsion. This yields a condition where logistics makeup is required, although there is more than sufficient water available to propulsion. Without CFES (option 2), the condition is similar to the cases employing reclamation.

Water Availability

The effectiveness of integrated water handling depends on both the quantity available from onboard systems and propulsion total impulse requirements. The criteria used to assess the impact of integration on propellant availability is the extent of logistics support necessary to accommodate the water requirments of all Station users. For example, a balance in which the total impulse available from water collected on-orbit is less than propulsion requirements penalizes the Station by necessitating additional resupply of water. Alternatively, an availa-

Table 4 On-orbit water availability

	Maximum availability per 90 days		$I_{Tot} < 543.6 \times 10^3$ lbf·s		$I_{Tot} > 543.6 \times 10^3$ lbf·s	
Parameter	Value	ΔWater, lbm	Value	ΔWater, lbm	Value	ΔWater, lbm
Resupply interval, days	45		90		90	
Power cord incorporation	None	3,254	Yes	538	Yes	538
Orbiter stay time, days	9		5		5	
Urine reclamation efficiency	96%	1,348	90%	492	90%	492
Food water content	2.0		1.1		1.1	
Space suit type	Advanced	0	Shuttle	(234)	Shuttle	(234)
USL CFES incorporation	No	(380)	Yes	(2,498)	No	(1,086)
USL reclamation incorporation	Yes		No		No	
JEM water requirement		(60)		(60)		(60)
Usable CFES waste water available to propulsion		0		1,676		0
IWS water available to propulsion		4,162		(1,762)		(350)

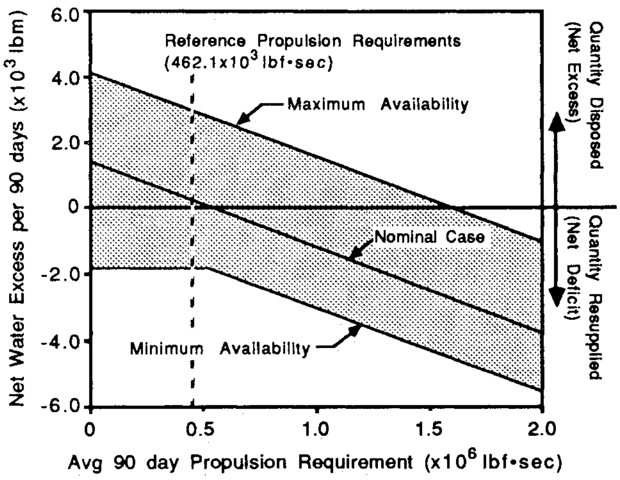


Fig. 10 Range of net water excess.

bility in excess of propulsion requirements is a benefit, since it allows greater margin and flexibility in propulsion operations. Actually, a substantial excess could incur additional costs for the on-orbit disposal or return to Earth of water. However, this study ignores this aspect and focuses on the impact on resupply requirements.

Propulsion total impulse requirments consist of maneuvers for altitude maintenance (reboost), backup attitude control, collision avoidance, and other contingencies. For a constant Shuttle rendezvous altitude, the aggregate of these requirements varies over an 11-yr solar cycle. This is due primarily to continuous variations in atmospheric density and their corresponding influences on drag and reboost requirements.

Overall propulsion requirements are extremely sensitive to spacecraft configuration, flight mode, primary attitude control method, and operational procedures. Consequently, their accepted values have changed considerably with maturation in the definition of Station design and operation. Water availability, therefore, must be examined over the range of projected requirments. However, a point reference of 462.1×10^3 lbf-s was assumed in order to compare directly different combinations of IWS system characteristics. This represents an integrated average over the 11-yr solar cycle and the accepted value when the electrolysis system was selected for the program. Reboost and all other propulsive maneuvers were assumed to occur at 90-day intervals in correspondence with the nominal operations increment. This average requirement translates, with an assumed specific impulse of 385 s, to 1200 lbm of water per 90 days.

The sensitivities presented in the previous sections provide the basis for investigating the effect of different combinations of operational and design characteristics on IWS water availability and resupply requirements. Only parameters that could conceivably vary from their current baseline values were considered. For instance, the independent parameters considered for ECLSS were restricted to urine reclamation capability and food water content. Although other parameters such as crew number, metabolic rate, module leakage, and closure level have a significant influence on the water balance, their values are closely coupled to high-level program requirements and were assumed constant. The following parameters and bounds were considered for the final analysis:

1) Resupply interval (90 vs 45 days)
2) Implementation of Orbiter/Station power cord
3) Orbiter stay time (5 vs 9 days)
4) Urine reclamation efficiency (96% vs 90%)
5) Food water content (1.1 vs 2.0 lbm)
6) Space suit (advanced vs Shuttle EMU)
7) USL CFES incorporation
8) USL water reclamation

The parameter combinations that yield the maximum and minimum values for water availability are shown in Table 4. The case representing the upper limit maximizes the amount of water scavenged from the Orbiter and collected from the ECLSS. Because of the negligible requirements for EVA with the advanced EMU, the only major nonpropulsive consumer is the USL. By implementing water reclamation and no CFES, makeup requirement are kept to a minimum of 380 lbm, thus yielding a total of 4160 lbm for propulsion usage. This translates to an average 90-day total impulse capability of 1601.6×10^3 lbf-s, which is nearly 3.5 times greater than the reference requirement of 462.1×10^3 lbf-s.

With reference requirements, logistics resupply is unnecessary, since available water far exceeds the amount required for propulsion. In fact, an additional method of disposal is necessary to accommodate the extra 2962 lbm remaining after propulsion requirements have been satisfied. This condition warrants some form of nonexpulsive disposal in order to avoid contamination to the Station's external environment. Favored approaches include tanking the excess for subsequent return to Earth or deorbit and aeroincineration in the atmosphere. Other operational solutions, such as orbiting at a lower altitude or a variable altitude flight path, reduce the excess by increasing reboost requirments, but would result in more rapid deterioration of Station external surfaces by atomic oxygen in the upper atmosphere.

In the event that average total impulse requirements exceed 1601.6×10^3 lbf-s, resupply of water will be required. Even with requirements above this value, access to 4162 lbm of essentially free water still substantially reduces the quantity of propellant resupplied from Earth and Station operations costs.

The cases in Table 4 that result in minimum water availability always incur a net deficit in the water balance and require the greatest resupply. Unlike the maximum case, two sets of conditions must be considered. both of these minimize water collected from the Orbiter and ECLSS and implement no reclamation within the USL. The feature that distinguishes the two is incorporation of CFES in the experiment complement. Propulsion requirements dictate which option requires the most water resupply.

For requirements less than 543.6×10^3 lbf-s, inclusion of CFES results in minimum availability by yielding a water deficit of 1762 lbm. Because the 1676 lbm of waste water from this experiment can be used directly by propulsion, resupply remains at a constant 1762 lbm for impulse requirements less than 645.3×10^3 lbf-s. However, the total impulse value of 543.6×10^3 lbf-s represents the crossover point where exclusion of CFES with the same characteristics minimizes availability. Because lab waste water cannot be used by propulsion, logistics resupply increases proportionally with total impulse requirements.

Water resupply is summarized as a function of average propulsion requirements in Fig. 10. This figure defines the maximum and minimum amounts of water that remain after consideration of propulsion requirements. Positive values indicate a net excess that must be handled with a alternative disposal mechanism. Negative values represent the amount that must be provided by logistics. This figure shows that for requirements below 1602.4×10^3 lbf-s, either a net deficit or excess is possible, depending on system design and operational parameters. Above this value, all possible IWS scenarios will require resupply.

With the assumed nominal design and operational characteristics, the crossover point between excess and deficit occurs at 550.9×10^3 lbf-s. Water availability for this case, namely 1430 lbm, is 230 lbm greater than the referenced average propulsion requirements.

Conclusions

Water availability and the likelihood of logistics resupply depend on the design and operational characteristics of systems that interface with the IWS. Ultimately, water resupply is driven by propulsion requirements, which are extremely sensitive to spacecraft configuration, solar activity, and flight modes.

With the assumed nominal characteristics and reference propulsion requirements, there will be sufficient water collected on-orbit to eliminate the need for logistics resupply. However, these values could change significantly as the Station design becomes more definite. Consequently, basing the overall handling approach on any assumed set of reference values is premature. Even if an approach could be justified, unanticipated modifications to the spacecraft's configuration or flight modes during the 10 years after initiation of steady-state operations could significantly alter the preferred approach.

By examining propellant availability over a range of IWS characteristics and propulsion requirements, this study has shown that both operational approaches are possible with the current program concept. In order to accommodate this inherent uncertainty in system characteristics, propulsion requirements, and spacecraft evolution, overall water handling should incorporate features to accommodate either a net deficit or excess in the water balance. Although implementing this flexibility will increase initial costs for water transportation hardware, it will inevitably minimize operational impacts to the propulsion system and other water users on the Station.

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References

[1]Wilkinson, C. L. and Brennan, S. M., "Space Station Propulsion Options," AIAA Paper 85-1155, July 1985.

[2]Brennan, S. M. and Donovan, R. M., "Space Station Benefits from ECLS – Propulsion System Synergism," AIAA Paper 86-1487, June 1986.

[3]NASA, "Fluid Management System Architecture Control Document," NASA Johnson Space Center, Space Station Program, JSC-30264, Dec. 1986.

[4]NASA, "Payload Integration Plan," NASA Johnson Space Center, Space Station Program, JSC-21053, July 1986.