Planetary Water Recycling Systems Trade Study

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Long-term planetary space missions present new and unique challenges in life-support systems. Water constitutes the majority of the mass required to sustain human life in space and it follows that efficient water recycling has the potential to lower mission costs. The effect of partial gravity in planetary missions mean that terrestrial systems could be applicable. This trade study evaluates terrestrial and NASA developed water recycling technologies on the basis of applicability as a planetary base water recycling systems. Various bioreactors, membrane reactors, filtration, and district water reclamation systems are investigated and rated based on several standardized parameters. A customer-oriented Quality Function Deployment (QFD) is utilized to analyze the ratings of the technologies for the tasks required. The trade study aims to rank the various systems based on their Equivalent System Mass (ESM), Technology Readiness Level (TRL), scalability, crew time, and overall logistics requirements, among others. The results of the study can serve as a basis for future inquiries and studies by NASA and other interested parties. The results of this study provide a down selection from 24 systems to 5 systems that trade very close to each other. The results provide a context and justification for a future comparative hardware test program to determine which of these systems offer the best solution.

Nomenclature

BLSS = Biological Life Support System
DOC = Direct Osmotic Concentration
ESM = Equivalent System Mass
FO = Forward Osmosis
ISS = International Space Station
ISS WPA = International Space Station Water Processing Assembly
kg/L cap = kg of equipment mass per liter of equipment capacity
kg/L total = kg of mass per liter of water processed during a 1095 day mission
MTBF = Mean Time Between Failures
O_2 = Oxygen generation penalty assessed based on ISS oxygen generation unit
OCT = Operational Crew Time
OD = Osmotic Distillation
QFD = Quality Function Deployment
SBM = Synthetic Biological Membrane
TIMES = Thermoelectric Integrated Membrane Evaporation
TRL = Technology Readiness Level
VPCAR = Vapor Phase Catalytic Ammonia Reduction
VRA = Volatile Removal Assembly

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I. Introduction

THIS trade study investigates water recycling systems based on their applicability for future planetary space missions. Current space water reclamation technologies, such as those found on the International Space Station (ISS), are primarily designed for microgravity environments. Development costs and the complexity of microgravity systems tends to run high and their applicability for long-term planetary missions, where partial gravity exists, is questionable. Many gravity-based earth water treatment systems are commercially available and used today in distributed water recycling applications.

This paper takes a customer-oriented trade study ranking approach to understand the applicability of commercially available and NASA developed water treatment systems on future planetary missions. Systems were primarily chosen for study based on their commercial and industrial availabilities and underlying technology readiness. Engineering judgment was used when necessary to provide a common basis for evaluation.

II. Quality Function Deployment (QFD)

The method used in this study is quality function deployment (QFD). QFD is a mathematical multi-dimensional analysis tool used to reduce a multitude of qualitative and quantitative parameter ratings into a single additive score. QFD works by first identifying aspects of a system that may be desirable (the 'whats') and assigning them an importance level (for this project, the average from a management survey). These are then correlated to a set of parameters (the 'hows') which are used to rate each system. By determining the relative importance of each 'what' and the strength of their correlation to each 'how', the ratings can be scaled appropriately, summed, and thus used to rank the systems.[1, 2]

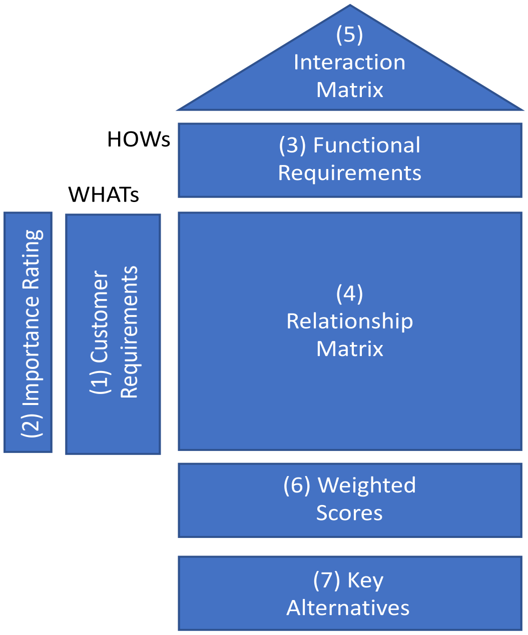


Figure 1. QFD computational matrix

The QFD computational matrix is provided in Figure 1. This matrix is a mathematical spreadsheet model. In this matrix region (1) is used to identify decision criteria (WHATs). Region (2) is used to input the importance rating derived from the customer survey for each of the decision criteria. Region (3) is used to identify quantitatively or qualitatively measurable engineering parameters (HOWs). Region (4) is used to determine how alternatives satisfy each of the customer requirements (• = strong; o = medium; Δ = weak; lll = no relationship). Region (5) is used to determine interaction or dependencies of alternatives with each other. Region (6) is where the weighted scores for each of the critical parameters are calculated. Region (7) is the calculated weighted scores for all alternatives. An example of a completed QFD matrix for this study is provided in Figure 2. The entire QFD matrix is designed to be an easy way to perform sensitivity analysis of importance ratings and relationship scores.

The project consisted of finding and researching technologies on the basis of potential suitability of purpose, and then analyzing these technologies in a structured and methodical way to determine the systems which are most promising. The overall structure of the project, in order, was as follows:

- Initial technology discovery and research.
- Development of a survey for industry experts to assess importance of several characteristics of a water recycling system to be used on a planetary space mission (the WHATs).
- Development of a list of critical parameters by which to judge each technology (the HOWs).
- Rating of each technology by the critical parameters.
- Scaling of all technologies to a common basis (4 person crew on 1,095 day mission).
- Complete Quality Functional Deployment (QFD) to determine top performing technologies.

Certain parameters such as water quality and water recovery ratio were normalized for all technologies by adding post treatment system for those systems that produced water that does not meet NASA specification or had low water recovery ratios. Brine treatment and dead volume were not included in this study but will be included in subsequent analysis. The following sections describe each of the methods used to develop the data for the QFD analysis. These methods provide for both qualitive and quantitative scores and the scaling used to format them for the additive approach of the QFD trade study. Any qualitive inputs were verified and assigned by six person panel.

III. Trade study description

The water recycling trade study is described next. The customer aspects, technologies, and functional requirements are discussed.

A. Survey of customer aspects

Using Google Forms, a customer survey was generated to find out which aspects of a water recycling technology are most important to industry and NASA experts. In the survey, participants were asked to consider several characteristics of a system, and rate each from 1-9 based on overall importance (with 9 being most important). The responses were averaged and input into region 2 of the QFD matrix in Figure 1. The aspects of the system which were rated in the survey and the average values of respondents can be seen in Table 1**.** Of the ten customers solicited with the survey five responded.

Table 1. List of survey questions sent to industry experts and their average responses.

Question	Average (0-9)
Utilization of Batch System	3.5
Continuous Flow System	3.5
Potential for Scaling Error	7
Handles Variable Feed	7
Development Risk	5
Energy Recovery from Byproducts	1
Ability to Treat Solids	6
High Water Recovery	7.75
Low Energy Use	5
Low Consumption of Material Resources	7.25
High Confidence in System	8.5
Low Maintenance	7
Simple Operation	7.75
Safety	6.5
Low Financial Cost	3.75
Risk Recovered Water is not Potable	6.25
TRL of at least 5	5
Ability to be Scaled Up	5.75
Utilization of Gravity	4.5
Single Technology System	3.5
Short Start-Up Time	3.75

B. Overview of Technologies

One of the first tasks of the trade study was to find technologies which may possess the required characteristics of a water recycling system for use on a planetary space mission. A literature review was conducted to identify potential technologies and screen them for applicability to a planetary mission. When possible technology developers were contacted to discuss optimal performance parameters for use in this trade study. Of a total of 24 systems evaluated 18 had data available that was appropriate for evaluation. Table 2 lists all of the technologies that were fully evaluated in the study.

Table 2. List of technologies included in this study.

Water Recycling Technology	***Description***	***Reference***
Aquacell S-Series	Collection, screening, aerobic biological treatment, ultrafiltration, ultraviolet disinfection, nutrient removal, chlorination, and storage	3
LEAP MBR	Aerobic membrane bioreactor where air is pumped in the bottom of the apparatus to scour the membranes, keeping them clean.	4

Living Machine	Trash tank and a settling tank, equalization tank, recirculation tank, tidal flow wetlands, lightweight expanded shale aggregate that is filled and drained, flooded flow wetlands, disinfected with micron filters, an ultraviolet unit, and chlorination.	5
BioBarrier Membrane Bioreactor	Aerobic membrane bioreactor with aerated distribution system submerged in water within the primary tank, which forces air bubbles upward through the membrane plates, cleaning the membrane. The flat sheet membrane (0.03 to 1.3-micron pore sizes) within the aerated distribution system facilitates micro- and ultrafiltration.	6, 7
Staged Anaerobic Fluidized Membrane Bioreactor	Anaerobic Fluidized Bioreactor (AFBR), and Anaerobic Fluidized Membrane Bioreactor (AFMBR), fluidized granular activated carbon to provide surface area for biological growth and clean membranes	8
Omni processor	De-watering of biosolids in a dryer system. The evaporated water is treated through filtration, and condensation, ozone injection, micro, and ultra-filtration. The dry biosolids are fed to a controlled fire for combustion where the heat generated is used for a boiler system. A pathogen free ash byproduct is produced from the burned biosolids.	9
AdvanTex® Treatment System	Multiple-pass, packed-bed aerobic wastewater treatment that uses a collection septic tank, "Biotube" filter, AX-RT anerobic reactor and a textile filter media.	10
siClaro®Submerged membrane bioreactor	Aerobic bioreactor connected to submerged membrane filter.	11-13
Orange County Water District	Aerobic bioreactor, filtration, microfiltration, reverse osmosis, and ultraviolet light with hydrogen peroxide.	14
Thermoelectric Integrated Membrane Evaporation (TIMES)	Membrane distillation system that uses thermoelectric modules to recycle heat of vaporization.	15
International Space Station (ISS) Water processing System (WPA)	Vapor compression distillation to treat urine and multi-filtration beds to treat humidity condensate, wet oxidation to post treat both product streams.	16
Vapor Phase Catalytic Ammonia Reduction (VPCAR)	Vapor compression distillation with catalytic oxidation reactor in vapor stream.	17, 18
Forward Osmosis (FO)	Forward osmosis coupled with reverse osmosis	19
Osmotic Distillation (OD)	Forward osmosis vapor/liquid separation using osmotic forces.	20
Direct Osmotic Concentration (DOC)	Membrane evaporator for urine, forward osmosis for hygiene and wet oxidation for prost treatment of both product streams.	21
Synthetic Biological Membrane (SBM)	Forward osmosis with regenerative FO membrane.	22
Biological Life support System (BLSS)	Plant based water recycling	23
COMMANDER	Membrane aerated bioreactor. Microgravity compatible.	24

C. Equivalent System Mass (ESM)

Initial economic analysis was done using NASA's Equivalent System Mass (ESM) approach. ESM is a measurement of the overall launch mass required for any system and its components. It incorporates the mass, volume, and power consumption of the system as shown in equation 1 below.

Equation 1: $ESM (m, v, p, c, r) = m + v * me(v) + p * me(p) + c * me(c) + r * me(r)$ [25]

The ESM was calculated from the system mass, m; volume, v; power, p; cooling, c and resupply, r.[25] "Me(v) is the mass charged for a cubic meter of volume in kg/m3, me(p) is the mass charged for a kilowatt of power in kg/kW, me(c) is the mass charged for a kilowatt of cooling in kg/kW" and me(r) is the mass of any resupply requirement.[25] The mass equivalents shown in Table 4 below were obtained from a previous Mars transit study[26] and confirmed for a surface mission in the NASA Baseline Values and Assumptions Document (BVAD).[27]

Table 4. Mass Equivalents used for ESM calculations.[27]

	Mass	Volume	Power Required	Cooling	Resupply
Mass equivalents	1	215.5	327	60	1

For initial comparison purposes the estimated system ESM values were used. A value level scale was established as shown in Table 5 below.

The following assumptions were used to calculate ESM values:

- Sizing of different systems was linear. Raw data was collected from systems sized as close to a 4 person system as possible. Then it was normalized to a per-liter (L) value. All trades are calculated using these per-liter values. To scale to any desired larger flow rate multiply results by the flow rate of feed (in L/hr).
- Oxygen demand for biological systems was assumed to be 3.3 g/L. This represents an estimation of the best value possible for the treatment of a combined wastewater composed of urine, hygiene water and humidity condensate.[24]
- ESM values for oxygen consumption were calculated using the ISS Oxygen Generation Assembly.[3, 28] This is a water electrolysis system that splits water into oxygen and hydrogen.
- Product water from biological systems was assumed to require post treatment using membranes to remove inorganics and microbes. A forward osmosis membrane system was assumed to be used to do this. The FO system was selected because NASA has tested FO as a post treatment system to a bioreactor in the past and therefore it has a higher TRL.[29]
- The ISS Volatile Removal Assembly (VRA) was assumed in all cases to remove trace organics and insure sterility of the product water. The VRA is used in both biological and physical chemical systems. The VRA was selected because it has been tested in a similar configuration previously by NASA so the TRL is high.[16]

ESM was calculated and the results grouped together into ranges and assigned values from 1 to 9 using Table 5. Note that the magnitude of the ESM benefit is inverted, with high ESM mass values generating low QFD ESM ratings. This was done to make ESM an additive value.

Table 5. ESM level to value description.

ESM Level	***Description***
1	ESM Value between 1297 and 1089
2	ESM Value between 1089 and 931
3	ESM Value between 931 and 790
4	ESM Value between 790 and 632
5	ESM Value between 632 and 474
6	ESM Value between 474 and 316
7	ESM Value between 316 and 158
8	ESM Value between 158 and 30
9	ESM Value between 30 and 0

The calculated ESM values and supporting data for each technology are provided in Table 6. Note that all systems that did not produce potable water were modified using engineering judgment to meet NASA potable standards. This was done by adding a membrane post treatment system to remove organics and/or a wet oxidation reactor to sterilize the product and oxidize any trace organic contaminates. Aerobic biological systems that consume large quantities of oxygen were assigned a penalty for the generation of oxygen. Data from the ISS oxygen generation system was used to do this. The second, third and fourth columns of Table 6 identify which engineering assumptions are used for each technology, FO (membrane post treatment), VRA (wet oxidation post treatment), or O_2 (oxygen generation).

Table 6. ESM values with supporting data

Technology	*FO*	*VRA*	*O_2*	*Mass (kg/L cap)*	*Volume (m^3/L cap)*	*Power (kW/L cap)*	*Cooling (kW/L cap)*	*Resupply (Kg/L-total)*	*ESM*
AquaCell		x	x	32.5	0.063	0.145	0.145	0.2628	93.5
LEAP MBR	x	x	x	331.	0.128	0.096	0.096	0.5475	98.4
AdvanTex	x	x	x	35.7	0.241	0.060	0.060	0.5475	111.4
Omniprocessor		x	x	222	1.437	1.999	1.999		1305
Orange County			x	318.9	0.670	0.476	0.476		647.7
Living Machine	x	x	x	231.9	1.275	0.298	0.298	0.5475	622.0
SAF-MBR	x	x	x	27.17	0.0815	0.043	0.043	0.5475	61.7
BioBarrier		x	x	29.4	0.204	0.071	0.071		100.8
siClaro SMBR	x	x	x	116.43	0.742	1.088	1.088	0.5475	643.8
TIMES		x		209.8	1.904	0.295	0.295	0.047	785.8
VPCAR				95.25	0.242	0.327	0.327	0.009	293.8
FO		x		23.0	0.072	0.026	0.026	0.0171	49.1
SBM		x		23.03	0.072	0.026	0.026	0.0005	49.2
OD		x		375.4	4.194	0.425	0.425	0.0001	1443.8
DOC				70.8	0.473	0.650	0.650	0.258	424.6
BLSS		x		538.7	4.3	1.14	1.14		1935.3
COMMANDER	x	x		54.23	0.192	0.034	0.034	0.5475	114.2
ISS WPA				143.5	0.170	0.087	0.087	39.42	254.1

(kg/L cap) = kg of equipment mass per liter of equipment capacity
(kg/L total) = kg of mass per liter of water processed during a 1095 day mission.
FO = Forward Osmosis membrane post treatment to remove salts
VRA = Volatile Removal Assembly ISS wet oxidation post treatment to remove trace organics and sterilize
O_2 = Oxygen generation penalty assessed based on ISS oxygen generation unit

D. Technology Readiness Level (TRL)

Each system was assessed using Technology Readiness Level (TRL) definitions used by NASA[25]. TRL levels and definitions are provided in Table 7. Technology TRL levels were assessed using Table 7 and then fit into ranges from a low score of 1 up to a high score of 9 and are presented in Table 8.

Table 7. Technology Readiness Level definitions.[25]

Technology Readiness Level	*Description*
1. Basic principles observed and reported	This is the lowest "level" of technology maturation. At this level, scientific research begins to be translated into applied research and development.
2. Technology concept and/or application formulated	Once basic physical principles are observed, then at the next level of maturation, practical applications of those characteristics can be 'invented' or identified. At this level, the application is still speculative: there is not experimental proof or detailed analysis to support the conjecture.
3. Analytical and experimental critical function and/or characteristic proof of	At this step in the maturation process, active research and development (R&D) is initiated. This must include both analytical studies to set the technology into an appropriate context and laboratory-based studies to physically validate that the analytical predictions are correct. These studies and experiments should constitute

concept	"proof-of-concept" validation of the applications/concepts formulated at TRL 2.
4. Component and/or breadboard validation in laboratory environment	Following successful "proof-of-concept" work, basic technological elements must be integrated to establish that the "pieces" will work together to achieve concept-enabling levels of performance for a component and/or breadboard. This validation must be devised to support the concept that was formulated earlier, and should also be consistent with the requirements of potential system applications. The validation is "low-fidelity" compared to the eventual system: it could be composed of ad hoc discrete components in a laboratory.
5. Component and/or breadboard validation in relevant environment	At this level, the fidelity of the component and/or breadboard being tested has to increase significantly. The basic technological elements must be integrated with reasonably realistic supporting elements so that the total applications (component-level, sub-system level, or system-level) can be tested in a 'simulated' or somewhat realistic environment.
6. System/subsystem model or prototype demonstration in a relevant environment (ground or space)	A major step in the level of fidelity of the technology demonstration follows the completion of TRL 5. At TRL 6, a representative model or prototype system or system - which would go well beyond ad hoc, 'patch-cord' or discrete component level bread boarding - would be tested in a relevant environment. At this level, if the only 'relevant environment' is the environment of space, then the model/prototype must be demonstrated in space.
7. System prototype demonstration in a space environment	TRL 7 is a significant step beyond TRL 6, requiring an actual system prototype demonstration in a space environment. The prototype should be near or at the scale of the planned operational system and the demonstration must take place in space.
8. Actual system completed and 'flight qualified' through test and demonstration (ground or space)	In almost all cases, this level is the end of true 'system development' for most technology elements. This might include integration of new technology into an existing system.
9. Actual system 'flight proven' through successful mission operations	In almost all cases, the end of last 'bug fixing' aspects of true 'system development.' This might include integration of new technology into an existing system. This TRL does not include planned product improvement of ongoing or reusable systems.

Table 8. TRL scores of all systems.

Technology	*Score*	*Explanation*
Aquacell	6	Used in a planetary environment with many available prototypes.
LEAP	6	Used in a planetary environment with many available prototypes.
AdvanTex	6	Used in a planetary environment and commercially available.
Omniprocessor	5	Only a single prototype available in a planetary environment. Limited model information.
Orange County	6	Used in a planetary environment with many available prototypes.
Living Machine	6	Used in a planetary environment with many available prototypes.
SAF-MBR	6	Used in a planetary environment with many available prototypes.
Biobarrier	6	Used in a planetary environment with many available prototypes.
SMBR	6	Used in a planetary environment with many available prototypes.
TIMES	6	Used in a planetary environment with many available prototypes.
VPCAR	6	System prototype demonstration in a relevant environment (ground or space).
FO	6	System prototype demonstration in a relevant environment (ground or space).
SBM	4	Component and/or breadboard validation in laboratory environment.
OD	6	System prototype demonstration in a relevant environment (ground or space).
DOC	6	System prototype demonstration in a relevant environment (ground or space).
BLISS	4	Component and/or breadboard validation in laboratory environment.
COMMANDER	6	System prototype demonstration in a relevant environment (ground or space).
ISS WPA	9	Actual system 'flight proven' through successful mission operations.

E. Scalability

Many of the systems being examined are produced with specific target markets dictating the flow rate and size of the unit. For example, some systems are more suited towards small residential units, whereas others are marketed towards large skyscrapers. To be considered for a planetary space mission, it is important that the technology be scalable for both small and large uses, depending on the crew size. To account for this, a scalability parameter was made to rate the technologies by as outlined in Table 9. The definitions in Table 9 were then used to rate all the technologies as presented in Table 10.

Table 9. Scalability levels and definitions.

Scalability Score	*Description*
1	System produced in only one size.
2	System produced in more than one discrete size.
3	System is custom built for specific use. Once built, system size is fixed.
4	System is modular, and as such can either shrink or grow depending on the needs of the mission as it changes.

Table 10. Summary of scalability scores for each technology.

Technology	*Score*	*Explanation*
Aquacell	3	The S-Series is a custom solution and therefore can be scaled for many sized projects.[3]
LEAP	4	Unit is modular and can be grown and shrunk as needed to accommodate more or less water.[4]
AdvanTex	2	System exists in discrete sizes, but does have scaling documents available.[30]
Omniprocessor	1	System exists in a single industrial scale size.
Orange County	1	At the moment, there is only one size of the system.[31]
Living Machine	2	Several different models and discrete sizes in use.[5]
SAF-MBR	2	The system exists in multiple sizes such as that of the pilot-scale tested in Korea and the model at the Codiga Resource Recovery Center at Stanford University.[8]
Biobarrier	3	Custom solution and therefore can be scaled for many sized applications.[33]
SMBR	3	Custom solution and therefore can be scaled for many sized systems.[12]
TIMES	2	Thermal systems are surface area to volume limited.
VPCAR	2	Thermal systems are surface area to volume limited.
FO	4	Exist in size very close to requirement Scales linearly.
SBM	4	Scales linearly. Low TRL to evaluate scaling.
OD	4	Exist in size very close to requirement. Scales linearly.
DOC	4	Exist in size very close to requirement. Scales linearly.
BLISS	4	Assume scales linearly. Little data on scaling.
COMMANDER	4	Assume scales linearly. Little data on scaling.
ISS WPA	3	UPA - Thermal systems are surface area to volume limited.

F. Mean Time Between Failures

Mean Time Between Failure (MTBF) is a measurement of system reliability and service requirements. As such it is a key parameter for choosing which technology to move forward. This parameter considers only failures; it is simply the expected time between each failure occurrence. Table 11 below summarizes the range and definition based on MTBF. This parameter indicates an initial reliability assessment of the technology. After evaluating each technology and its MTBF, Table 12 presents the results for each technology.

Table 11. Rankings of MTBF parameters and respected description.

MTBF Score	*Description*
1	System is operational 3,500 Hours or less between failures.
2	System is operational 3,500 to 7,000 Hours or less between failures.
3	System is operational 7,000 to 10,000 Hours or less between failures.
4	System is operational 10,000 to 13,000 Hours or less between failures.
5	System is operational above 13,000 Hours between failures.

Table 12. All technologies and their rankings on MTBF parameter.

Technology	*Score*	*Explanation*
Aquacell	4	Assumption based on technologies that the Aquacell uses (bioreactor, aerobic screening).
LEAP	4	Assumption based on technology being used (membrane bioreactor).
AdvanTex	5	Life cycle of pump is 15 years, float switches 5-10 years, overall system >20 years.[36]
Omniprocessor	2	Assumption based on the high temperature system environments.
Orange County	3	Based on Orange County's experimental test data sheets around 1 failure every year. 8,640 hours between failures.[31]
Living Machine	4	Based on Living machine experimental test data sheets 11,000 hours between failures have been recorded.[5]
SAF-MBR	2	Calculation based on two system failure incidents during 485-day pilot-scale testing in Korea.[8]
Biobarrier	3	Estimation based on expected lifespan of a typical septic air pump.[37]
SMBR	4	Assumption based on membrane bioreactor being used.
TIMES	2	Assumption based on technology being used (multi-media filtration) .
VPCAR	2	Complicated specially designed rotating parts.
FO	4	Commercial off the shelf components. Extensive pilot scale testing.
SBM	5	System is designed to extend MTBF to 3 years.
OD	4	Commercial off the shelf components. Pilot scale testing.
DOC	4	Commercial off the shelf components. Some pilot scale testing.
BLISS	4	Commercial off the shelf components. Engineering judgment.
COMMANDER	4	Commercial off the shelf components. Extensive pilot scale testing.
ISS WPA	3	Complicated specially designed rotating parts. Has 90 day resupply specification and 3 year life.

Many of our technologies had no record of failure times, thus similar technologies' data of failure times in hours were used. For example, LEAP and Aquacell followed a similar ranking as other membrane bioreactors. The lowest scored used was a 2, since systems like the omniprocessor had failure times of at least once a year. The highest score was 5 from AdvanTex having failure times of once every 5 years.

G. Start-up Time

Given that crew members can only last for so long without water resources, it is important to consider the amount of time it would take to start up systems that could provide those resources. Most of the systems being examined use unique water recycling techniques that differ from the others and, therefore the systems have various start-up times as well. For example, while some technologies can be setup and used on the same day, others require extensive amounts of time to pass so that biological processes can occur and aid in water treatment. Such a case, however, makes those technologies less practical in space mission applications, making it necessary to create a start time parameter to rate the technologies by. The start time levels and definitions are outlined in Table 13 below. As with all critical parameters, start time was used to judge each technology that the group set out to rate. Using the scale as a guideline, the results can be seen below in Table 14.

Table 13. Start time levels and definitions.

Start Time Score	*Description*
1	At this level, the system will take at least a month (30+ days) to start up, given that start-up begins at assembly of the system.
2	At this level, the system will start up within a month or less (15-30 days), given that start-up begins at assembly of the system.
3	At this level, the system will start up within 2 weeks (8-14 days), given that start-up begins at assembly of the system.
4	At this level, the system can start up within a week (2-7 days), given that start-up begins at assembly of the system.
5	At this level, the system can start up within a day, given that start-up begins at assembly of the system.

Table 14. Summary of start time scores for each technology.

Technology	*Score*	*Explanation*
Aquacell	3	Assumption. There is a bioreactor in the S-Series unit, so the system requires basic start-up time associated with typical bioreactor.
LEAP	4	Assumption based on technology being used (bioreactor).
AdvanTex	5	The system can start up in a day assuming it will be above surface.[38]
Omniprocessor	3	Assumption. Precautionary safety measures should be taken, but the system will take 2 weeks to start up.
Orange County	4	Assumption. No record of start-up has been found. System may take a week to start, as such is expected of similar city plant systems.[31]
Living Machine	3	The system will take 2 weeks to start up, according to previous facilities data.[5]
SAF-MBR	4	Assumption based on underlying technology being used (bioreactor).
Biobarrier	5	The system is shipped installation-ready, entailing short setup and start times.[6]
SMBR	5	The system comes with pre-assembled filtration units and can start up in less than a day.[12]
TIMES	5	Minutes to start.
VPCAR	5	Hour to start.
FO	5	Minutes to start.
SBM	4	Hour to start.
OD	5	Minutes to start.
DOC	5	Minutes to start.
BLISS	1	Months to start.
COMMANDER	2	Weeks to start, biological system. Has tested rapid startup.
ISS WPA	5	Minutes to start.

H. Operational Crew Time

Given that crew members aboard a planetary space mission will already have multiple responsibilities, tasks related to the water recycling system integrated within their habitat should not take up too much more of their time. While it would be ideal for the water recycling system chosen for such a mission to maintain itself throughout the day, it is understandable if a system would need to be checked periodically to ensure that it is functioning smoothly. To determine whether or not the systems being examined are practical in terms of the time they require for crew members to operate the system or perform system-related tasks throughout the day, a crew time parameter was created as outlined in Table 15 below. As with all critical parameters, Operational Crew Time (OCT) was used to judge each technology that the group set out to rate. Using the scale as a guideline, the results can be seen below in Table 16.

Table 15. Crew time levels and definitions.

Crew Time Score	*Description*
1	At this level, the system requires an OCT (starting-up, resetting cycles, checking on system) of 18-24 hours in total per day.
2	At this level, the system requires an OCT (starting-up, resetting cycles, checking on system) of 6-18 hours in total per day.
3	At this level, the system requires an OCT (starting-up, resetting cycles, checking on system) of 1-6 hours in total per day.
4	At this level, the system requires an OCT (starting-up, resetting cycles, checking on system) of 30 minutes to 1 hour in total per day.
5	At this level, the system requires an OCT (starting-up, resetting cycles, checking on system) of 30 minutes in total per day.

Table 16. Summary of operational crew time scores for each technology.

Technology	*Score*	*Explanation*
Aquacell	5	Assumption. The system is marketed as being passive technology and requires very little oversight required by crew members.
LEAP	5	The system is marketed as being passive technology with very little oversight required by crew members.[38]
AdvanTex	5	The system is marketed as being passive technology with very little oversight required by crew members.[40]
Omniprocessor	3	Operational time ties in with precautionary safety measures that need to be taken to ensure system integrity, entailing approximately 1-6 hours of crew time per day.
Orange County	4	The system requires approximately 1 hour of crew time per week.[14]
Living Machine	3	The system requires approximately 1 hour of crew time per day, since biological system needs daily attention.[5]
SAF-MBR	5	Assumption. The system is marketed as being passive technology and requires very little oversight required by crew members.
Biobarrier	5	The system is marketed as being passive technology and requires very little oversight required by crew members.[38]
SMBR	5	The system is marketed as being passive technology and requires very little oversight required by crew members.[12]
TIMES	5	Little to no daily crew requirements. No data, engineering judgment.
VPCAR	5	Little to no daily crew requirements. Based on pilot scale testing.
FO	5	Little to no daily crew requirements. Based on pilot scale testing.
SBM	5	Little to no daily crew requirements. Low TRL poorly defined.
OD	5	Little to no daily crew requirements. Based on pilot scale testing.
DOC	5	Little to no daily crew requirements. Based on pilot scale testing.
BLISS	4	Time required for startup, harvesting and replanting.
COMMANDER	4	Time required for startup and monitoring.
ISS WPA	5	Little to no daily crew requirements.

I. Logistics Risk

Many of the logistics or resupply mass values used in the ESM calculations were taken from technologies with varying levels of development. In some cases, such as the ISS WRS, were derived from operational fight data. Others, such and TIMES, were derived from bench scale configurations and engineering judgment. The Logistics Risk parameter encompasses the risk that logistics data will increase as TRL increases. A qualitive scale, shown in Figure 17, was defined where data derived from operation flight or commercial applications is given the highest score and data derived from engineering judgment is given the lowest score. All values are based on a per liter of feed water for a 1095 day mission. Using the scale as a guideline, the results can be seen below in Table 18.

Table 17. Logistics levels and definitions.

Logistics Score	*Description*
1	Data derived from engineering judgment.
2	Data derived from bench scale testing .
3	Data derived from pilot testing .
4	Data derived from ground based commercial operations.
5	Data derived from flight operational data.

Table 18. Summary of logistics scores for each technology.

Technology	*Score*	*Explanation*
Aquacell	1	Data derived from engineering judgment
LEAP	1	Data derived from engineering judgment
Advantex	1	Data derived from engineering judgment
Omniprocessor	1	Data derived from engineering judgment
Orange County	1	Data derived from engineering judgment
Living Machine	1	Data derived from engineering judgment
SAF-MBR	1	Data derived from engineering judgment
Biobarrier	1	Data derived from engineering judgment
SMBR	4	Data derived from engineering judgment
TIMES	2	Data derived from bench scale testing
VPCAR	3	Data derived from pilot testing
FO	3	Data derived from pilot testing
SBM	2	Data derived from bench scale testing
OD	3	Data derived from pilot testing
DOC	2	Data derived from bench scale testing
BLISS	1	Data derived from engineering judgment
COMMANDER	3	Data derived from pilot testing
ISS WPA	5	Data from flight operations

J. Maintainability

Maintenance of any system is crucial to the lifespan of the equipment and maximizes efficiency, reliability and safety; however, frequent preventative maintenance (PM) adds additional burden on the crew. A maintainability score was developed as shown in Table 19 below. The score range is directly correlated to how often a system needs to be maintained. Common PM intervals of weekly, bi-weekly, semi-annually, and annually were used. As with all critical parameters, scalability was used to judge each technology that the group set out to rate. Using the scale as a guideline, the results can be seen below in Table 20**.**

Table 19. Maintainability levels and definitions.

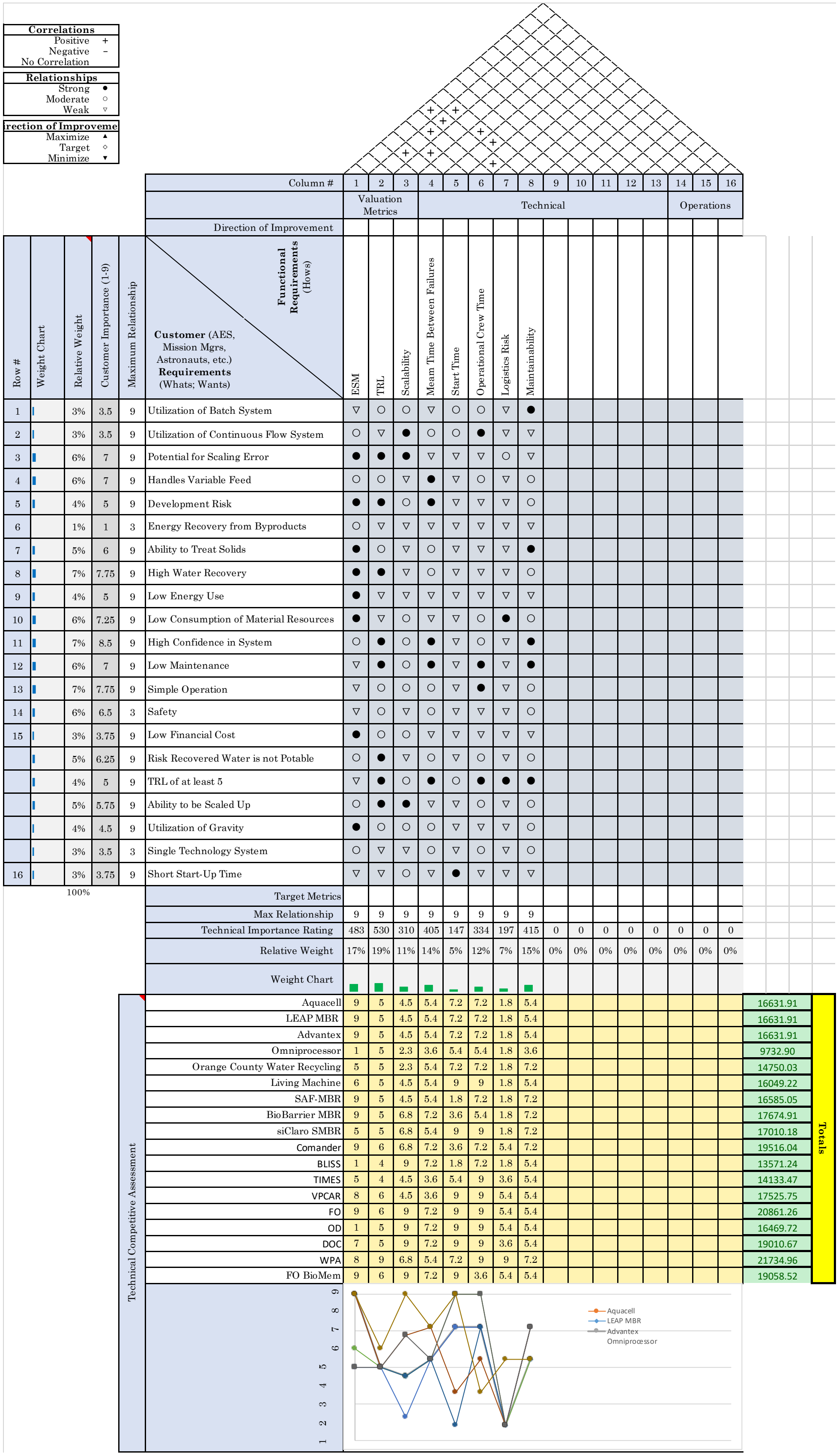
Maintainability Score	*Description (hours/3 years)*
1	At this level, the system needs to be diagnosed weekly. (1152 hours)
2	At this level, the system needs to be diagnosed every 2 weeks. (576 hours)
3	At this level, the system needs to be diagnosed monthly. (288 hours)
4	At this level, the system needs to be diagnosed every 6 months. (48 hours)
5	At this level, the system needs to be diagnosed annually. (24 hours)

Table 20. Summary of maintainability scores for each technology.

Technology	*Score*	*Explanation*
Aquacell	3	Assumption. Bioreactor, must be monitored relatively often to ensure health of biotics.
LEAP	3	Assumption. Bioreactor, must be monitored relatively often to ensure health of biotics
AdvanTex	5	Manufacturer recommended annual inspection only.[34, 35]
Omniprocessor	2	Maintenance for the omniprocessor is not well understood or defined, but one can assume a weekly or bi-weekly preventative maintenance for this high stress system would be expected; hence, a maintainability score of 2 was assigned.
Orange County	4	Orange county facility has a quarterly cleanup scheduled for their technology.[31]
Living Machine	4	System needs to be diagnosed every 6 months.[5]
SAF-MBR	4	Assumption. Granular activated carbon, membranes, and pumps should be checked and/or replaced every 6-12 months.
Biobarrier	4	Assumption. Septic tank effluent filter and membranes should be checked.
SMBR	3	siClaro BMA10 is a custom solution and therefore can be scaled for many sized systems[12].
TIMES	3	At this level, the system needs to be diagnosed monthly (288 hours).
VPCAR	3	At this level, the system needs to be diagnosed monthly (288 hours).
FO	3	At this level, the system needs to be diagnosed monthly (288 hours).
SBM	3	At this level, the system needs to be diagnosed monthly (288 hours).
OD	3	At this level, the system needs to be diagnosed monthly (288 hours).
DOC	3	At this level, the system needs to be diagnosed monthly (288 hours).
BLISS	3	At this level, the system needs to be diagnosed monthly (288 hours).
COMMANDER	3	At this level, the system needs to be diagnosed monthly (288 hours).
ISS WPA	3	At this level, the system needs to be diagnosed monthly (288 hours).

IV. Results

Figure 2 presents the results of the QFD analysis. QFD is a multi-dimensional analysis tool used to reduce several individual parameter ratings into a single score which may help when comparing two or more separate systems. QFD works by first identifying the customer requirements that are desirable (the ‘Whats’) and assigning them an importance level (for this project, the average from the customer survey responses). These are then correlated to a set of functional requirements (the 'Hows'). In general “hows” that impact many ‘whats’ have the most impact on the trade. By determining the relative importance of each 'what' and the strength of their correlation to each 'how', the ratings can be scaled appropriately, summed, and thus used to rank the systems. The 'whats' are located on the left hand side, the 'hows' are on the top of the matrix, and the correlation is in the center. The correlations are mapped graphically to week, medium, and strong. For example, as shown in Figure 2, ESM has the most relationship correlations to customer requirements. The black dots indicate a strong correlation to a customer requirement. Many of these customer requirements have high customer importance ratings. This means that ESM can be expected to have an important influence on the results of the trade study. The numeric rating results are presented in green squares at the bottom right. The higher the score the better. Figure 3 presents the results for this trade study.



Correlations	
Positive	+
Negative	−
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

rection of Improveme	
Maximize	▲
Target	◇
Minimize	▼

					Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
						Valuation Metrics			Technical										Operations		
					Direction of Improvement																
Row #	Weight Chart	Relative Weight	Customer Importance (1-9)	Maximum Relationship	**Functional Requirements** (Hows) **Customer** (AES, Mission Mgrs, Astronauts, etc.) **Requirements** (Whats; Wants)	ESM	TRL	Scalability	Meam Time Between Failures	Start Time	Operational Crew Time	Logistics Risk	Maintainability								
1		3%	3.5	9	Utilization of Batch System	▽	○	○	▽	○	○	▽	●								
2		3%	3.5	9	Utilization of Continuous Flow System	○	▽	●	○	○	●	▽	▽								
3		6%	7	9	Potential for Scaling Error	●	●	●	▽	▽	▽	○	▽								
4		6%	7	9	Handles Variable Feed	○	○	▽	●	▽	○	▽	○								
5		4%	5	9	Development Risk	●	●	○	●	▽	▽	▽	○								
6		1%	1	3	Energy Recovery from Byproducts	○	▽	▽	▽	▽	▽	▽	▽								
7		5%	6	9	Ability to Treat Solids	●	○	▽	○	▽	▽	▽	●								
8		7%	7.75	9	High Water Recovery	●	●	▽	○	▽	▽	▽	○								
9		4%	5	9	Low Energy Use	●	▽	▽	▽	▽	▽	▽	▽								
10		6%	7.25	9	Low Consumption of Material Resources	●	▽	○	▽	▽	○	●	○								
11		7%	8.5	9	High Confidence in System	○	●	○	●	▽	○	▽	●								
12		6%	7	9	Low Maintenance	▽	●	○	●	▽	●	▽	●								
13		7%	7.75	9	Simple Operation	▽	○	○	○	▽	●	▽	○								
14		6%	6.5	3	Safety	▽	○	▽	○	▽	▽	▽	○								
15		3%	3.75	9	Low Financial Cost	●	○	○	▽	▽	▽	▽	▽								
		5%	6.25	9	Risk Recovered Water is not Potable	○	●	▽	○	▽	○	▽	○								
		4%	5	9	TRL of at least 5	▽	●	○	●	○	●	●	●								
		5%	5.75	9	Ability to be Scaled Up	○	●	●	▽	▽	○	▽	○								
		4%	4.5	9	Utilization of Gravity	●	○	○	○	▽	▽	▽	○								
		3%	3.5	3	Single Technology System	○	▽	▽	○	▽	○	▽	○								
16		3%	3.75	9	Short Start-Up Time	▽	▽	○	▽	●	▽	▽	▽								
		100%																			
					Target Metrics																
					Max Relationship	9	9	9	9	9	9	9	9								
					Technical Importance Rating	483	530	310	405	147	334	197	415	0	0	0	0	0	0	0	0
					Relative Weight	17%	19%	11%	14%	5%	12%	7%	15%	0%	0%	0%	0%	0%	0%	0%	0%
					Weight Chart																

Technical Competitive Assessment	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Totals
Aquacell	9	5	4.5	5.4	7.2	7.2	1.8	5.4									16631.91
LEAP MBR	9	5	4.5	5.4	7.2	7.2	1.8	5.4									16631.91
Advantex	9	5	4.5	5.4	7.2	7.2	1.8	5.4									16631.91
Omniprocessor	1	5	2.3	3.6	5.4	5.4	1.8	3.6									9732.90
Orange County Water Recycling	5	5	2.3	5.4	7.2	7.2	1.8	7.2									14750.03
Living Machine	6	5	4.5	5.4	9	9	1.8	5.4									16049.22
SAF-MBR	9	5	4.5	5.4	1.8	7.2	1.8	7.2									16585.05
BioBarrier MBR	9	5	6.8	7.2	3.6	5.4	1.8	7.2									17674.91
siClaro SMBR	5	5	6.8	5.4	9	9	1.8	7.2									17010.18
Comander	9	6	6.8	7.2	3.6	7.2	5.4	7.2									19516.04
BLISS	1	4	9	7.2	1.8	7.2	1.8	5.4									13571.24
TIMES	5	4	4.5	3.6	5.4	9	3.6	5.4									14133.47
VPCAR	8	6	4.5	3.6	9	9	5.4	5.4									17525.75
FO	9	6	9	7.2	9	9	5.4	5.4									20861.26
OD	1	5	9	7.2	9	9	5.4	5.4									16469.72
DOC	7	5	9	7.2	9	9	3.6	5.4									19010.67
WPA	8	9	6.8	5.4	7.2	9	9	7.2									21734.96
FO BioMem	9	6	9	7.2	9	3.6	5.4	5.4									19058.52

Figure 2. QFD matrix

Figure 3 shows that there are two groupings of technologies. The best scoring technologies are SBM, WPA, DOC, FO, and COMANDER. The second best scoring group includes OD, VPCAR, siClaro, SAF, and BioBarrier. The current version of the study does not have the resolution to rank each technology within each group.

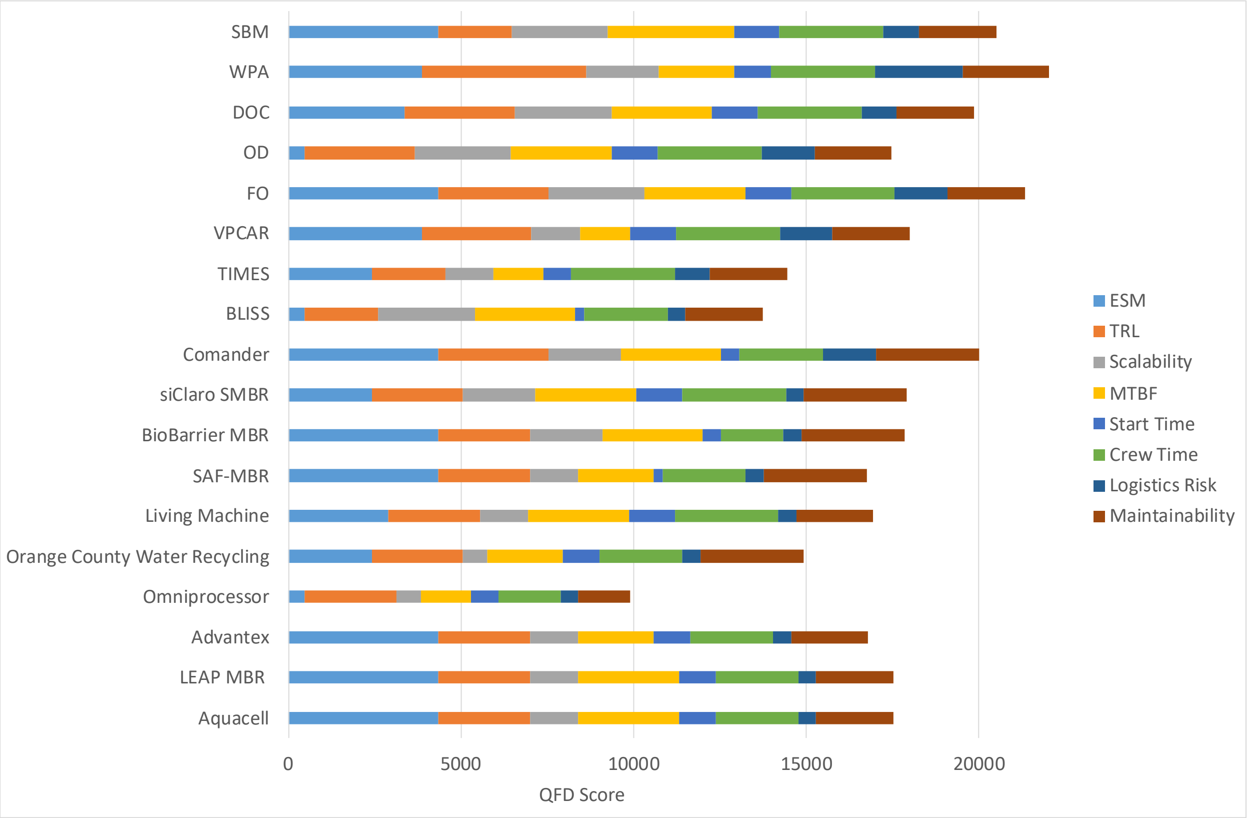


Figure 3. Total results from first QFD, separated by score per parameter.

Figure 3 shows the relative contribution of each parameter to the total score. It also shows how closely the parameters for each technology compare to each other. Note that in Figure 3 all parameters have been normalized so that the higher the score the better the ranking. For example, having a high ESM is better than having a low one, which is counter intuitive. The ESM has been normalized and then inverted so that all parameters are additive.

V. Discussion

The five highest ranked technologies shown in Figure 3 are SBM, WPA, DOC, FO, and COMANDER. All of these technologies have been developed by NASA specifically for exploration missions so it is not unexpected that they trade well. A sensitivity analysis evaluating which parameters shown in Figure 3 had the highest impact in the trade has shown that ESM, Scalability, and MTBF parameters have the largest variability from system to system. This means that these parameters impact the final ranking the most. The standard deviation for all parameters is provided in Table 21. Figure 4 shows ESM values for each of the systems evaluated. Bars in red indicate the 5 high ranked systems. As shown in the figure, there is only a weak correlation between ESM of the 5 highest ranked systems with several of the biological systems having the lowest ESM values. Figure 5 shows the ranked score for Scalability for each of the technologies. Bars in red are again the highest ranked systems. Here there appears to be a stronger relationship between the top 5. Figure 6 shows the ranked score of MTBF for each of the systems. In this case again

Table 21. Standard deviation of selection parameters

Parameter	Standard Deviation
ESM	1446
TRL	603
Scalability	718
MTBF	625
Start Time	372
Crew Time	420
Logistics Risk	588
Maintainability	429

there again appears to be a strong correlation between MTBF and technology ranking. Of the 3 parameters ESM has the biggest impact with a standard deviation double that of Scalability or MTBF.

An analysis of the impact of mission duration has shown that doubling it has an impact on the trade but it is not large enough to change the top five ranking. Figure 6 shows the results of a recalculation of the QFD matrix with the mission duration extended from 3 to 6 years and the assumption that all of the physical chemical technologies have to be replaced once for a 6 year mission. As shown in Figure 6 the Commander and SBM systems competitiveness is improved and the physical chemical systems decreased. In general it can be concluded that as mission durations increase biological technologies improve and physical chemical technologies do not trade as well.

The accuracy and resolution of this study is dependent upon the quality of the data utilized. Some is hard engineering data from peer reviewed sources, others is product literature provided by manufacturers and some is engineering judgment. Whenever possible the most optimistic data was used. This disparity in data quality could have an impact on the final rankings of the technologies. Future work will be directed at improving the quality of the non-peer reviewed data. This should include working with manufacturers to verify data and in cases where this cannot be done, testing to verify the validity of engineering judgment assumptions.

The data is also impacted by scaling. Many of the biological system were significantly scaled down. Some were scaled down 90% which could be considered excessive considered a linear scaling was used. In some cases to get more accurate data, smaller scale systems will need to be developed and tested to verify performance data. Most of the physical chemical systems were sized approximately correctly, with the exception of the Omniprocessor.

Resupply requirement data quality disparities will also have an impact on the validity of this study. Some of the technologies such as the ISS WPA and FO systems have well documented resupply requirements. Others have no resupply estimates. Although a correction factor was used to address this, additional work is required to improve data quality. Other issues such as water dead volume requirements and brine drying will also need to be evaluated before the study can be finalized.

VI. Conclusions

With these critical limitations in mind, this study has identified five technologies for further development by NASA. They are SBM, WPA, DOC, FO, and COMANDER. A sensitivity analysis has determined that ESM, Scalability, and MTBF parameters have the biggest influence on winners and losers. ESM has the largest impact. A mission duration sensitivity analysis has determined that extending the mission duration from 3 to 6 years does not change the winners. However, extending the mission duration does improve the competitiveness of biological system with respect to physical chemical systems. Future work will focus on adding new technologies to this study and improving the resolution to make a down selection to just four technologies by the end of the year. Then these 4 technologies will be considered for development by NASA in order to conduct a side by side comparison test program to further down select to just one or two technologies for future development.

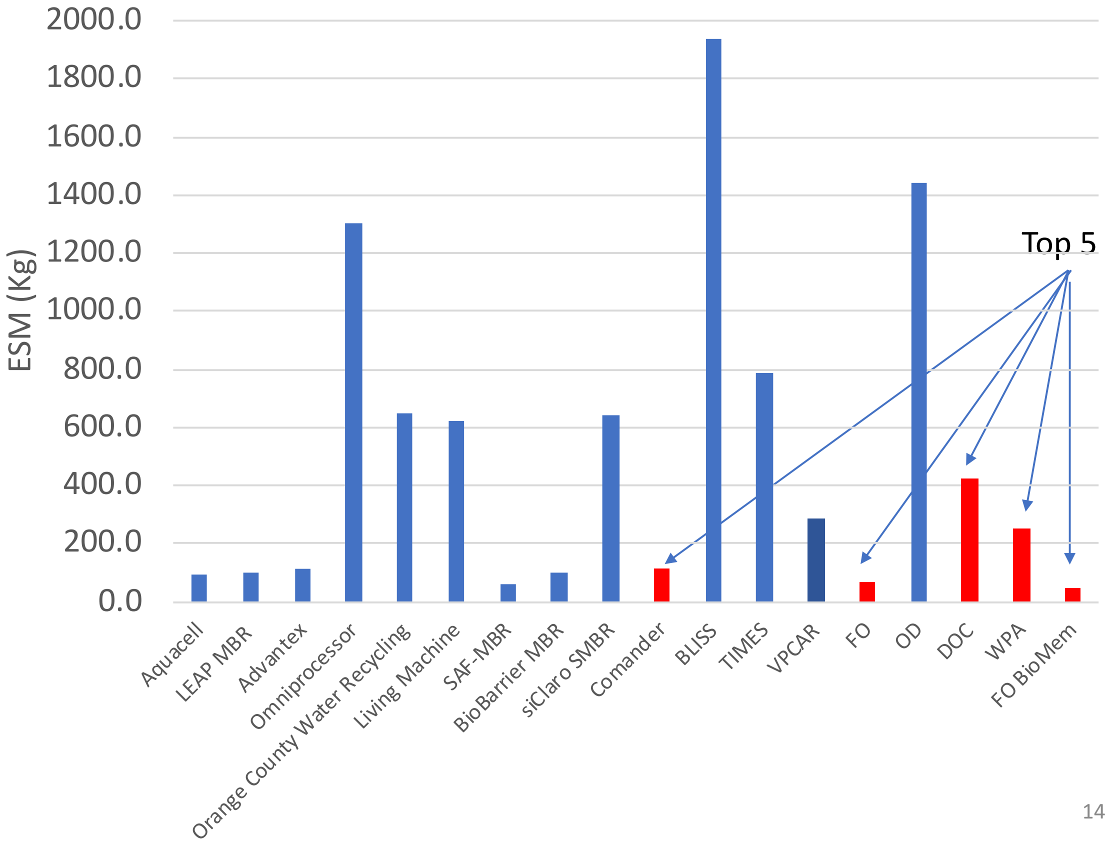


Figure 4 Equivalent System Mass.

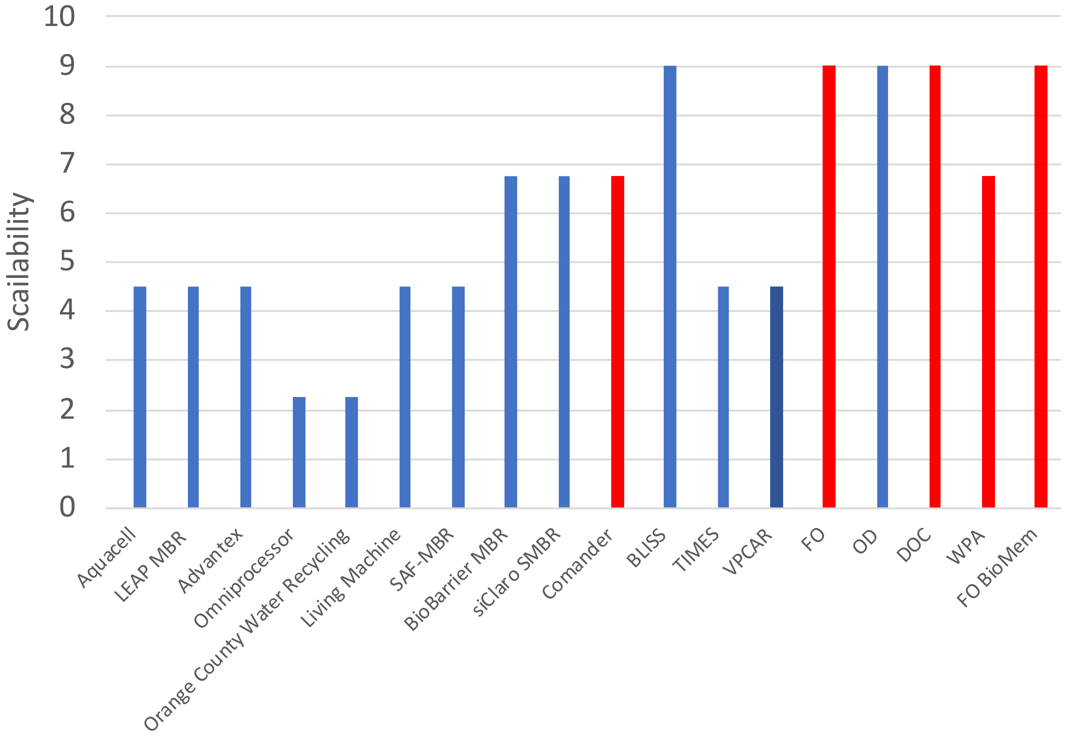


Figure 5. Scalability.

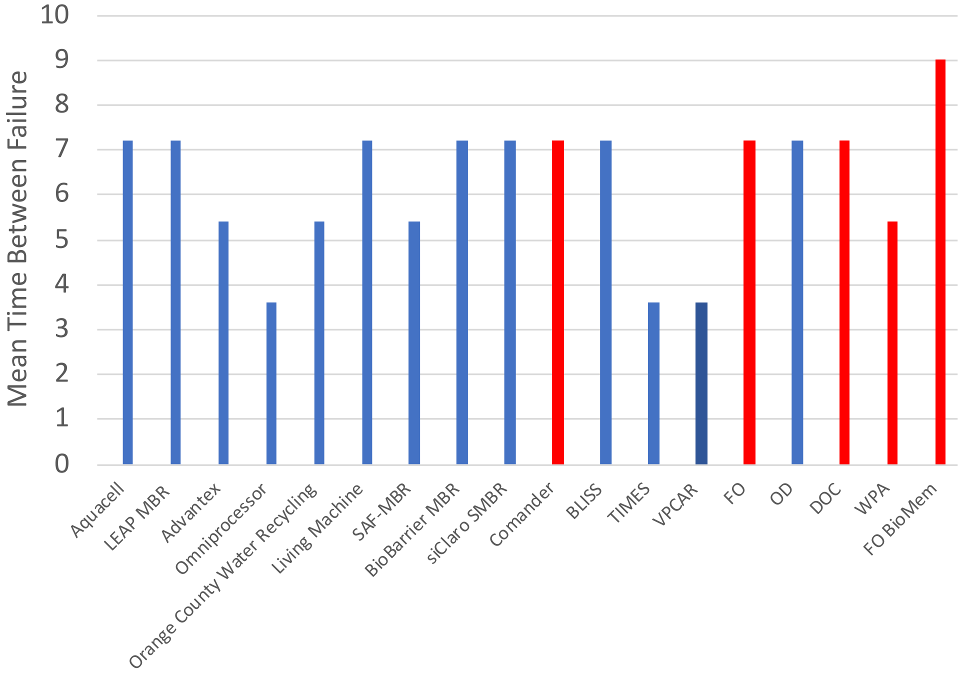


Figure 6. Mean time between Failure (MTBF).

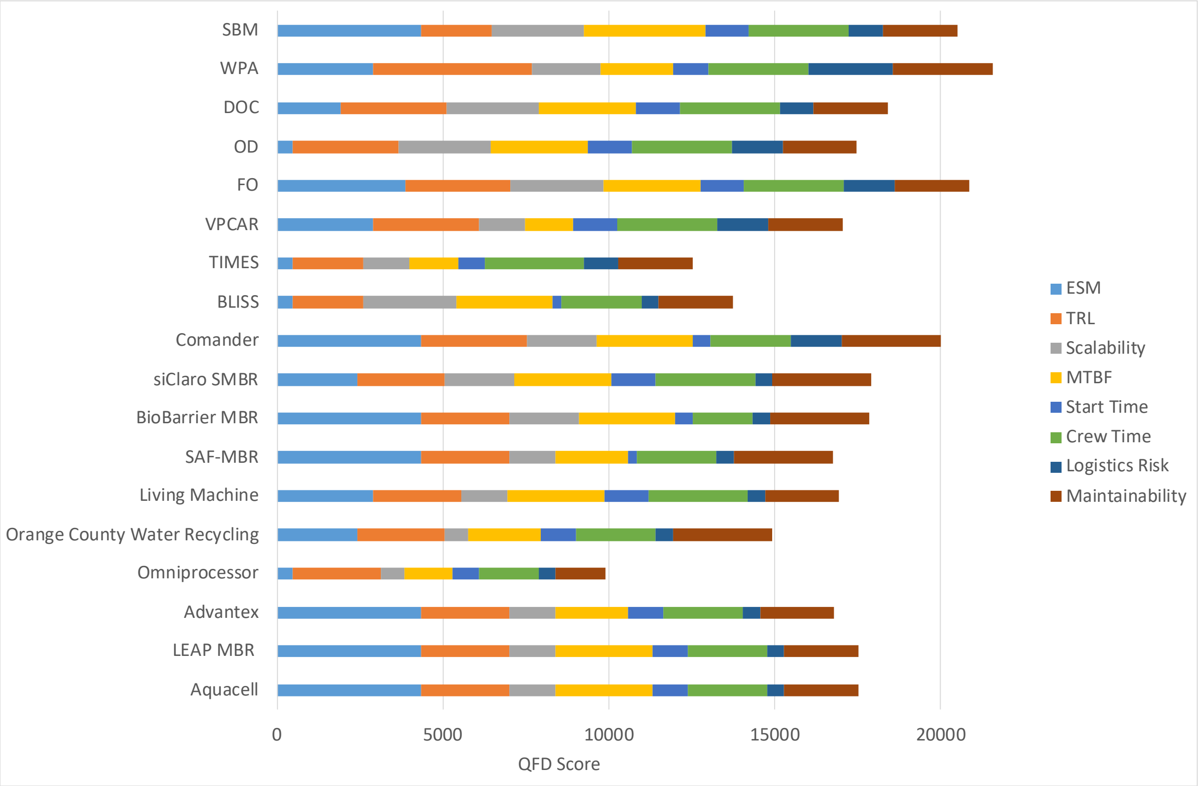


Figure 7. QFD results for 6 year mission.

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