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Need for Cost Optimization of Space Life Support Systems

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As the nation plans manned missions that go far beyond Earth orbit to Mars, there is an urgent need for a robust, disciplined systems engineering methodology that can identify a cost optimized Environmental Control and Life Support (ECLSS) architecture for long duration deep space missions. The commonly used Equivalent System Mass (ESM) reflects only the system launch cost, including the mass of the hardware, spares, and logistics and of the power and cooling supporting systems. Unlike ESM, an effective cost optimization method should include all the important ECLSS cost elements. The key parameter for the economic analysis of life support system design is Life Cycle Cost (LCC). LCC takes into account the cost for development and qualification of the system, launch costs, operational costs, maintenance costs and all other relevant and associated costs. Additionally, an effective methodology must consider system technical performance, safety, reliability, maintainability, crew time, and other factors that could affect the overall merit of the life support system.

Nomenclature

4BMS = Four Bed Molecular Sieve
ARS = Atmosphere Revitalization System
BEO = Beyond Earth Orbit
CDRA = Carbon Dioxide Removal Assembly
DDT&E = Design, Development, Test, and Evaluation
EAM = Exploration Augmentation Module
ECLSS = Environmental Control and Life Support
ESM = Equivalent System Mass
ISRU = In-Situ Resource Utilization
ISS = International Space Station
LCC = Life Cycle Cost
LEO = Low Earth Orbit
OGA = Oxygen Generation Assembly
ORU = Orbital Replacement Unit
Pr(LOC) = Probability of Loss of Crew
Pr(LOM) = Probability of Loss of Mission
PRA = Probabilistic Risk Analysis
SPWE = Solid Polymer Water Electrolysis
SRS = Sabatier Reactor Subassembly
UPA = Urine Processor Assembly
VCD = Vapor Compression Distillation
WPA = Water Processor Assembly
WBS = Work Breakdown Structure
WRS = Water Recovery System

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I. Introduction

THIS paper outlines a structured methodology to evaluate and optimize life support systems for unsupported, long duration, deep space human missions. Given the large costs associated with manned deep space missions and the limited budgets expected to be allocated for them, this selection method must emphasize Life Cycle Cost (LCC) rather than Equivalent System Mass (ESM). (Levri et al., 2003) (Jones, 2003-01-2635) Other key parameters including performance, maintainability, spares, safety, and reliability must be related to life cycle cost to ensure the optimum system is obtained. The proposed new methodology will allow optimized life support system development for future missions.

II. Overview

NASA is currently in the early stages of planning a bold and sustained human space exploration program that ventures beyond earth orbit (BEO) for the first time since the Apollo program ended. These new missions will take people to potential locations as diverse as the moon, an asteroid, Lagrange points, the moons of Mars and ultimately to the surface of Mars itself. With people on board, the Environmental Control and Life Support System (ECLSS) becomes one of the most critical systems for mission success. While many life support systems have been developed over the history of human spaceflight, none are specifically designed for the demanding requirements that long duration deep space exploration will impose.

Given the limited budgetary resources available to the space program, it is imperative that the development of any new ECLSS must consider the overall cost. Unlike other spacecraft systems, the merits of life support systems are typically judged using the Equivalent System Mass (ESM) concept. This methodology emphasizes the system launch mass plus equivalent mass allowances for the pressurized volume, electrical power, cooling and crew time required to operate the system. This approach may have been appropriate for the ECLSS used on the International Space Station (ISS), since it was always intended to be serviced by regular space shuttle missions. However, as regular re-supply from Earth will not be possible for a BEO mission, placing the emphasis on ESM could distort decision making when developing the ECLSS required for long duration BEO missions.

The objective of this paper is to outline a disciplined systems engineering methodology that is inclusive of all driving parameters and that when fully implemented results in an optimized ECLSS architecture for long duration deep space missions. In order to emphasize the economic analysis of life support design, Life Cycle Cost (LCC) should be used. LCC includes development and test costs, launch cost as reflected by ESM, and operational and maintenance costs. The technical performance, safety, reliability, maintainability, crew time, and other factors all affect the overall cost and benefit of a life support system design.

Such an improved decision making methodology will allow considering not only what is best for each potential mission, but rather what makes sense for the entire BEO space program. A system that might not be technically optimized for any one mission may be economically advantageous compared to multiple different systems that are each optimized for an individual mission. This “big picture” approach can ultimately save considerable money, helping to improve the budgetary viability of the overall BEO space program.

III. ECLSS background

Propulsion, reentry, and life support systems are the three biggest challenges on the journey to Mars, but life support has received very much less than its due emphasis. We can easily recall the tragic accidents during launch and reentry, but life support has been equally risky, with fatalities due to fire (Apollo 1) and decompression (Soyuz 11) and a close call with carbon dioxide build up (Apollo 13). Both short and long missions have only a single launch and reentry, but the risk of a life support failure increases with every day a mission continues. Long missions require secure water and food as well as atmosphere. Launch and reentry systems can be tested in a day, but the required life support reliability, and the efforts to maintain the system, can only be established by long duration testing, that should exceed the planned mission length.

Technology development for life support systems incorporating recycling has been astonishingly stagnant. The first and only operational US recycling system is the International Space Station (ISS) ECLSS. But these systems and most of the subsystems were tested with humans in closed chambers back in the 1960’s. The current ISS water and oxygen subsystems were prototyped and compared to alternates in the early 1990’s and have been flying since the mid 2000’s. Many of these systems have had failures that required redesigns or operational accommodations. The ISS ECLSS and other systems were designed to be maintained by the crew using Orbital Replacement Units (ORUs) that are typically comprised of a dozen or more components that are not maintainable during flight. It was thought to be more cost effective to use the crew’s capability and the space shuttle’s launch capacity rather than to design and proof test higher reliability systems that would require little or no servicing. This ORU approach has proved difficult on ISS, requiring much more of the crew's limited and valuable time than anticipated. (Russell et al., 2006) (Russell and Klaus, 2007) The ORU approach is considered impractical for deep space missions. All the ORUs would have to be launched with the mission, since resupply during a deep space mission would be practically impossible. The cost of launching multiple large ORUs would be high. Even with the shuttle and the available ORUs, the major reason that ISS life support has remained secure is the presence of an equally capable Russian system of completely different design.

There is a clear need to technically and economically evaluate the integrated performance of ECLSS technologies and subsystems from the overall system impact perspective rather than just individual subsystem technical performance (e.g., total system mass efficiency and closure versus individual subsystem optimization). For example, some ECLSS developers think that simply improving ISS ECLSS reliability is the best way to develop future exploration life support. (Bagdigian, et al., 2015-094) Others question this, noting that the ISS ECLSS was inherently designed for maintainability by ORUs rather than the high reliability needed for deep space. (Jones et al., 2014-074) They also find that our confidence in the current life support system is directly tied to having the totally redundant, separate and dissimilar Russian system. (Jones et al., 2014-074) It is likely that the reliability improvement approach may be better for some future missions that are moderately extensible from the ISS mission, whereas the needs of other missions may be better met by developing a totally new approach.

The new methodology suggested in this paper can also be used at a higher level to determine whether it makes more sense to develop multiple systems optimized for each mission or to develop one system for all missions, knowing that the resulting system may not be optimized for any mission. If one compares long term surface missions to the moon and Mars, the needs of each mission will be different. While both may take advantage of in-situ resource utilization (ISRU) to meet the surface demands for oxygen and water, the resources available will be markedly different. The journey to each location will also drive requirements for the transport spacecraft. For a lunar mission, it likely makes sense to bring along the water and oxygen required during transit, but that becomes onerous for a multi-month Mars transit, so recycling will be needed. A lunar mission may be able to depend on an emergency delivery of spare parts from Earth. A Mars mission cannot. Does it make sense to develop two different ISRU systems? Does it make sense to develop both a storage system and a recycling system? Does it make sense to develop a lower cost, lower reliability system for the Moon when you will have to develop a high cost, high reliability system for Mars anyway? By applying a cost optimizing methodology over the entire deep space program, it would be possible to realize major cost savings over the course of the program.

Previous and current ECLSS analysis methods and tools are inadequate to consider the upcoming ECLSS design and integration challenges. Changing the 50-year old ISS ECLSS architecture to meet the needs of tomorrow's spaceships will be difficult. Suggested improvements are limited to exchanging one subsystem for a familiar, physically compatible alternative, or adding some minor additional recycling to improve closure. The concept of "Closing the loop," or pushing material closure to approach 100%, has long been the sacred goal of recycling, regardless of its diminishing returns and increasing costs. (Wieland, 90-3728) (Bilardo, 90-3729) Closure was used to propose growing food crops hydroponically, regardless of the high costs and critical reliability/maintainability problems. The emphasis on closure has since been replaced by ESM, which is focused on launch mass impacts. The use of ESM was justified by the belief that the cost to launch a given mass was the largest and most important cost in providing life support. ESM, which is still in use today, de-emphasized reliability, maintainability and total life cycle cost. However, these parameters are often of greater importance to many potential mission customers and highly important to long-duration missions where launch costs are a substantially lower fraction of the total program costs. Many models intended to optimize design merely minimize ESM or launch mass. Hence, past ECLSS analyses do not necessarily provide good guidance for future ECLSS development.

Today there is an urgent need to bring structured and thorough systems engineering into the planning and design of life support for our nation's future manned exploration goals. Short term missions can get by with stored oxygen and water. Longer missions such as the space station can save launch mass and launch cost by recycling these commodities, but this requires designing and developing costly systems. A space station system in low Earth orbit does not require very high reliability since materials and spare parts can be easily supplied from Earth, or the crew can return if systems cannot be repaired. A deep space mission, such as to Mars or an asteroid, will require very high reliability since materials and spare parts cannot easily be supplied and the crew cannot return quickly if systems cannot be repaired. Nothing would discourage people more from expanding human activity into space than a crew perishing for lack of air, water or food.

But the development of true space-faring technologies must also be cost effective. Technology development, and engineering in general, is the economic application of science. A workable approach for the cost optimization for space life support system is urgently needed.

IV. The suggested cost optimizing approach

Recycling life support engineering design and operations data and the systems engineering approach can be used to develop the needed new methodology to optimize future life support system design and development. We have life support data that was produced the hard way, by ISS ECLSS design and operations.

A. The ISS ECLSS development history

The ISS ECLSS was originally the Space Station Freedom (SSF) ECLSS utilizing the highly capable Space Transportation System (Shuttle) as a "de-facto" resource that drove sizing, ORU choices, and human-presence maintainability. Its development followed the usual systems engineering process of requirements, design, development, test, and operations, but compromises were needed. The cold war ended and the SSF was drastically downsized and combined with an ex-Soviet space station design to form most of the ISS. Rather than system wide ECLSS optimization, two prototypes of the oxygen, water and other subsystems were simply compared head to head. (Carasquillo et al., 1992) (Carasquillo and Bertollo, 1999-01-2146) (Carasquillo et al, 2004-01-2385)

Planned subsystem and integrated system testing had to be drastically reduced, typically to a mere few tens of hours of ground testing for systems expected to work for ten or more years in space. Inevitably, early problems occurred during ISS operations due to unanticipated microgravity effects and to design oversights that could with luck have been anticipated. Many redesigns and work-arounds have been implemented and more are still needed.

The operational history of the ISS ECLSS provides useful detailed information on the failure modes, repairs and maintenance record of the ECLSS systems. This data can be used to develop a list of the general parameters that drive the true operability of the units. For example, the Carbon Dioxide Removal Assembly (CDRA) has had failures of a filter, seals and valves, some of which are common cause failures. (Jones, 2012-3602) This data will help quantify the ranges of parameters of "generic" technology that must be analyzed across all technologies to produce adequate system cost comparisons. Moving parts, sizes of ORUs, time-to-maintain and time-to-repair parameters will all affect the optimum cost-effective systems trade of the "best" technology and technology implementation. The methodology is needed to establish the rationale for the top level requirements related to maintainability, reliability, and cost. This in turn should drive technology development toward true operability over a long duration mission.

B. Need for a cost optimizing methodology to go beyond ISS

NASA's plans for deep space human exploration, with the ultimate goal of reaching Mars, require a coherent logical methodology to develop the necessary life support without the de-facto assumptions of the ISS designed systems. The missions are not currently defined, but there are many interesting possibilities and adequate "design reference missions" do exist. Possible long duration exploration missions include an upgraded ISS, a new space station like ISS in Low Earth Orbit (LEO), a moon base, a space station in lunar orbit, an asteroid visit, a Mars fly by, a Mars moon visit, a short stay (but long transit) Mars surface mission, and a long stay Mars surface mission. All of these long duration missions are expected to require recycling life support.

C. Approach to the cost optimizing methodology

How can systems engineering produce the proposed and needed rigorous optimization methodology? It must be stretched to reach a wider capability. Missions are established at the highest level, inspired systems architects then conceptualize the design, and systems engineers attend to the details - requirements, subsystem interfaces, design documentation, change control, integration, test, operations planning, etc. But systems engineering is where concept meets reality, and reality rules. Different proposed design and integration approaches achieve the requirements and goals in different ways and to different degrees. Real world goals and requirements always conflict, so trade-offs must be made. The essence of systems engineering is pragmatism and compromise for a higher cause, to develop the best possible system. The optimized system is never a political compromise, never a design by committee. The clash of implementations and goals can only be overcome by invoking the overall mission goal to deploy resources in the most economically effective way. Good systems engineering is always top down, based on the driving overall mission goal, and economical with resources. System engineering limits subordinate managers' tendency to optimize their own individual subsystems or project phases at the expense of the overall system (known as "Sub-Optimization by Work Breakdown Structure - WBS"). Subsystem managers do this by usurping resources or off-loading difficult requirements and negative impacts to other subsystems.

Going forward it is vital that system level economic optimization be considered along with technical optimization and this may require modifying the design architecture at the expense of some technical performance.

The proposed methodology can be developed by applying top down system engineering to life support for any potential sequence of long duration human space missions.

D. Systems engineering to economically optimize life support for long duration missions

This new economic optimization methodology would be based on cost-centered, anticipatory systems engineering of the life support systems for a future series of long duration missions. The planned early stage high level methodology will do the basic systems engineering needed to inform high level budget, schedule and system design decisions. For example, the methodology would be used to develop the ECLSS architecture, technology suite, and proposed designs for the "Exploration Augmentation Module" (EAM) sometimes known as the "Habitat" and help ensure that the technologies funded are ones that, in the systems context, have the best value and not just the best functional performance.

The crucial step in this process is to define the fundamental life support system goals and the trade-offs between them. The three key aspects of a life support system are its performance, cost, and risk, including maintainability, spares and safety. These must be economically traded and optimized.

The object is not to minimize cost or maximize performance or minimize risk, but rather to appropriately optimize cost while considering performance and risk to ensure that functional performance (e.g., percent loop closure) does not trump overall life cycle costs. We need to understand the relationships between these parameters. The first step is to break performance, cost, and risk down into related subcomponents and include similar parameters. The system parameters and representative subcategories are listed in Table 1.

Table 1. System parameters and subcategories.

Life Cycle Cost (LCC)	Design, Development, Test, and Evaluation (DDT&E) cost
	Launch cost
	Operations cost
Other cost measures	Equivalent System Mass (ESM)
	Mass, volume, and power
	Launch size and number of launches
	Crew time
	Logistics and resupply
	"Free" materials and services (e.g., ISS water resupply by the Space Shuttle)
Performance	Life support material quantities
	Life support material qualities
Other performance parameters	Reliability (and effect on spares)
	Maintainability (and effect on spares and time)
	Operability
	Microgravity compatiblity
	Noise
	Commonality (and effect on spares)
	Complexity
	Self-sufficiency, percent closure
Risk and safety	Probability of Loss of Crew [Pr(LOC)]
	Probability of Loss of Mission [Pr(LOM)]
	Probabilistic Risk Analysis (PRA)
	Safety and hazards analysis

Table 1 includes most of the system parameters considered in life support design analysis. (Jones, 1999-01-2079) (Jones, 2010-6015) The usual approach to producing a design is analysis of individual criteria, discussion, and the use of engineering and management judgment. The design is defined and then it is justified. The most common human decision heuristic is called elimination by aspects, which is ranking all the designs or competing subsystems according to the most important decision parameter, then eliminating the lower scoring ones, and so on through the decision parameters until only one choice is left. Elimination by aspects can produce clearly suboptimal choices. (Tversky, 1972) For example, a rhetorical overemphasis on one particular justification can be used to force the choice. If the shuttle provides the ISS with free water, water recycling need not be flown, but then water is critically short if the shuttle is grounded. If the mission planning and costing is constrained to a single launch, then recycling life support may not pay.

The proposed optimization methodology must organize this array, identify the key trade-off parameters and establish mathematical trade-off interrelations that allow parametric economic optimization. Some of this can be suggested now.

E. Developing the structured methodology for cost optimizing

Life Cycle Cost includes Design, Development, Test, and Evaluation (DDT&E) cost, launch cost and operations cost. DDT&E cost can be estimated based on system mass, design heritage and other factors. Launch cost depends on the system mass (including spares and tools for maintenance), the cost to launch a kilogram to LEO, and the total mass to payload mass ratio. Operations cost depends on development cost and mission duration effects such as maintenance and repair. The cost metrics most often used in life support have been either the system wet launch mass or the Equivalent System Mass, which is the system launch mass plus mass allowances for the pressurized volume, power, cooling, and crew time required to operate the system. LCC better reflects the total space mission cost, but usually does not include costs for volume, power and cooling, which should be added. A major variable for future missions is the launch cost to LEO. Launch cost was ignored for shuttle launch of ISS components. The actual shuttle costs were sometimes quoted as very high, including development cost in addition to operations cost. Commercial launches have become much less expensive. The launch size and number of launches may be limited in reality. This can be added as a hard constraint on the optimization, and may or may not produce a less favorable optimum design point. The cost of crew time can be difficult to assess. (Jones, 2001-01-2359) There are certainly limits to available crew time, but conversely it will be important for long duration missions to have adequate crew activities to keep them mentally occupied (for example US submarines have historically been designed to require crew maintenance in order to occupy the crew during long periods of otherwise inactivity). The ISS astronauts are severely time constrained due to maintenance requirements, which limits science and engineering experiments. Possibly a crew on the way to Mars will have little better to do than work on life support systems. Unplanned logistics support and resupply will probably be unavailable due to distance, time and the physical constraints of orbital mechanics.

By quantifying the costs to improve performance or improve risk and safety, system wide and multi-mission trade-offs can be made. Life support system development costs are proportional to system mass, which is proportional to the mass of material produced, according to scaling laws. The cost of reliability depends on the approach chosen to increase reliability. For detailed redesign and test, costs increase exponentially. (Jones, 2012-3618) Adding redundant systems simply adds the cost and mass of the additional hardware. (Jones, 2011-5094) Maintainability is related to reliability and involves costs for logistics (including tools), resupply and crew time. Commonality is tricky. In a world of well designed, well tested, well understood systems, using identical pumps, valves, filters, etc. can reduce the spares requirement. But for new untried designs, components may have common cause failures that would disable whole groups of systems. In space, diversity trumps commonality, but increases DDT&E costs. Complexity is usually bad, adding to cost and reducing reliability. Self-sufficiency and a higher percentage of oxygen and water closure are good because they reduce dependency on Earth, but increasing closure has increasing costs and diminishing returns or even negative returns that are lost in traditional performance trade-offs. The most cost effective and lowest risk design could include substantial material transport from Earth.

The risk to the crew is usually measured by the Probability of Loss of Crew, Pr(LOC). The risk of losing the mission is measured by the Probability of Loss of Mission, Pr(LOM). For this methodology, it should be assumed that each system will need to meet the same Pr(LOM) and Pr(LOC) requirements. These driving requirements must be met by any design solution and will have effect on the designs chosen (e.g., redundancy, robustness, etc.) and their costs.

V. The life support system

The systems engineering trade-off parameters must be developed for all recycling ECLSS subsystems. For reference, the block diagram of the ISS ECLSS is shown in Figure 1. (Carasquillo et al., 1992)

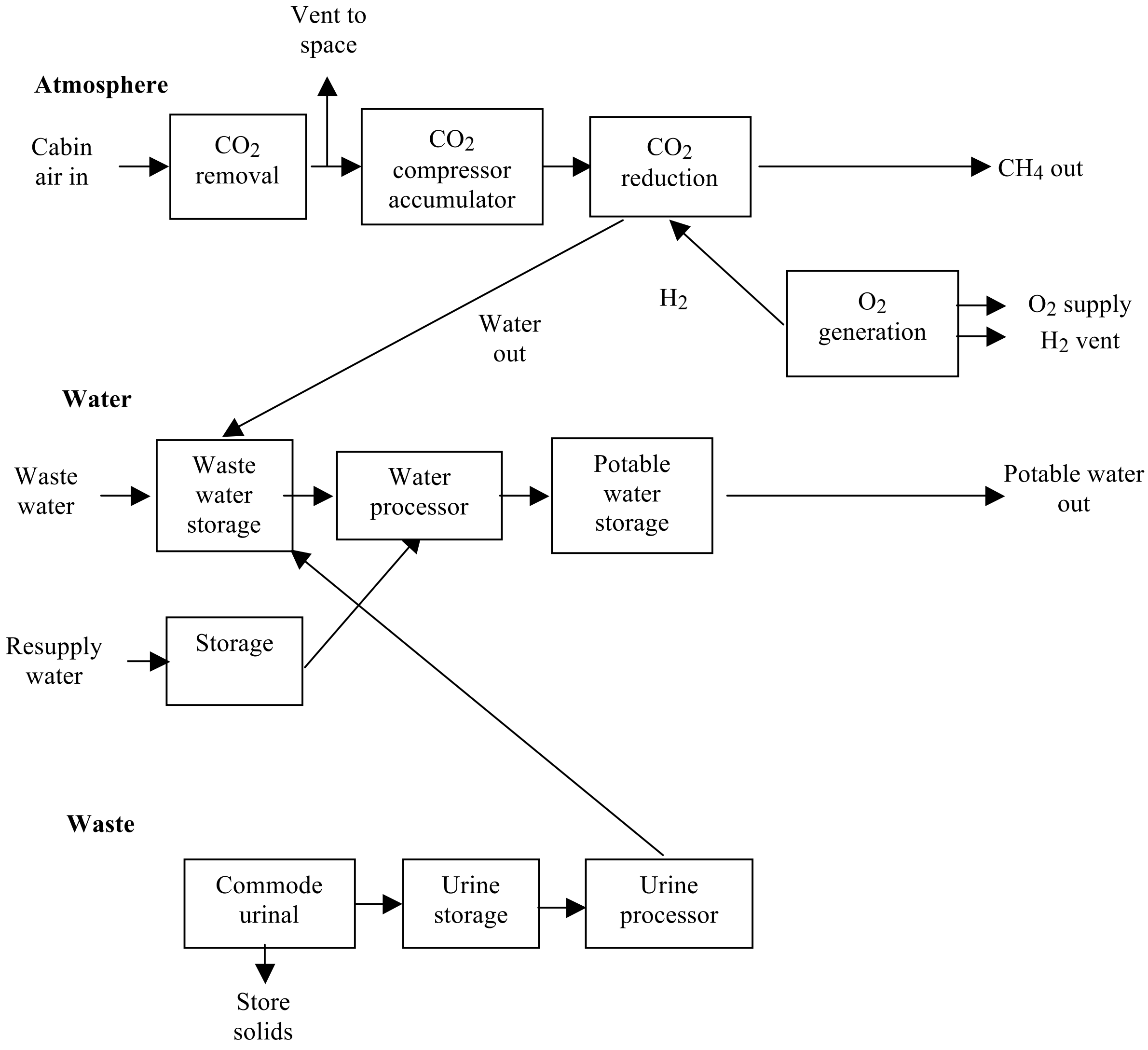

Figure 1. The ISS ECLSS.

Figure 1 shows the eleven major subsystems in the standard recycling life support system architecture. Cost, performance and risk must be optimized throughout the system, requiring system-wide trade-offs.

The ISS life support system contains atmosphere, water and waste recycling processors. The four bed molecular sieve (4BMS) 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. Waste hygiene water and cabin condensate are stored and routed through the potable water processor 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 is pumped from the urinal to the urine processor and the distillate is combined with other wastewater. The commode compacts and bags feces. Solid wastes and feces are usually loaded into Progress and burned up during Earth reentry. The major ISS ECLSS technologies are listed in Table 2. (Carasquillo et al., 1992)

Table 2. ISS ECLSS technologies.

ISS assembly	ISS technology
Atmosphere Revitalization System (ARS)	
Carbon Dioxide Removal Assembly (CDRA)	Four Bed Molecular Sieve (4BMS)
Sabatier Reactor Subassembly (SRS)	Sabatier
Oxygen Generation Assembly (OGA)	Solid Polymer Water Electrolysis (SPWE)
Water Recovery System (WRS)	
Water Processor Assembly (WPA)	Multifiltration
Urine Processor Assembly (UPA)	Vapor Compression Distillation (VCD)

Designing for long duration missions has a profound effect on the relative importance of two design parameters that have, before now, been second priorities: maintainability and spares logistics planning. Maintainability takes into account the ability to replace components that have the potential to wear out or otherwise be consumed. Spares philosophy takes into account not only the commonality and size of the parts, but also the lowest level of spares that are defined. The current ORUs may be replaced by smaller parts. If not inherently designed into the technology, the maintainability and spares approach can profoundly affect the operability and eventual success of the subsystem and entire ECLSS.

An ultimate cost optimization methodology would include a mathematical model of the potential design that would be able to predict and influence the design toward the long-duration-driven considerations. The maintainability and spares philosophy will allow for a prediction of the volume, mass and cost of the subsystem and its impact on the entire ECLSS. Compared to propulsion, power, and automation, the ECLSS technology area is less defined for long duration (conversely, unmanned probes have been designed and operated continuously for years and decades). However, a cost optimization approach developed for ECLSS can be adapted for almost any space system, and even be extended to hard-to-maintain isolated terrestrial applications.

The suggested structured methodology to assess and optimize life support must be applied from the lowest to the highest levels of the life support systems hierarchy. The design of the lowest level subsystems can be optimized, subsystem technology can be compared, and the system level impacts of the subsystem interactions can be identified and enhanced. The system level performance can be assessed and improved. At the highest systems level, possible architectural changes, such as adjustments or alternates to the system schematic of Figure 1, can be considered. At the subsystem level, the engineering parameters such as mass and failure rate are used, while the overall system is better optimized using such high level metrics as cost and risk.

VI. Conclusion

As we turn our attention to manned missions that go beyond Earth orbit, there is an urgent need to develop a robust methodology that will allow our nation's space program decision makers to technically and programmatically assess the new ECLSS architectures that will be required. Given the large costs associated with these new missions and the ever-limited budgets allocated to space exploration, this selection method needs to place greater emphasis on life cycle cost as opposed to Equivalent System Mass. Balancing life cycle cost along with mass, technical performance, reliability and maintainability will ensure the optimum value is obtained. The effort planned in this paper will lay the groundwork needed to fully develop this optimization methodology. Ultimately it is hoped that this method can be used to optimize not just for one particular mission, but for the overall long term exploration initiative, thereby helping to ensure sufficient resources are available to achieve all of our manned exploration goals.

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