Life Support Goals Including High Closure and Low Mass Should Be Reconsidered Using Systems Analysis

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Recycling space life support systems have been built and tested since the 1960's and have operated on the International Space Station (ISS) since the mid 2000's. The development of space life support has been guided by a general consensus focused on two important related goals, increasing system closure and reducing launch mass. High closure is achieved by recycling crew waste products such as carbon dioxide and condensed humidity. Recycling directly reduces the mass of oxygen and water for the crew that must be launched from Earth. The launch mass of life support can be further reduced by developing recycling systems with lower hardware mass and reduced power. The life support consensus has also favored using biological systems. The goal of increasing closure using biological systems suggests that food should be grown in space and that biological processors be used for air, water, and waste recycling. The goal of reducing launch mass led to use of Equivalent System Mass (ESM) in life support advocacy and technology selection. The recent consensus assumes that the recycling systems architecture developed in the 1960's and implemented on ISS will be used on all future long missions.

NASA and other project organizations use the standard systems engineering process to guide hardware development. The systems process was used to develop ISS life support, but it has been less emphasized in planning future systems for the moon and Mars. Since such missions are far in the future, there has been less immediate need for systems engineering analysis to consider trade-offs, reliability, and Life Cycle Cost (LCC). Preliminary systems analysis suggests that the life support consensus concepts should be revised to reflect systems engineering requirements.

Nomenclature

AES	=	Advanced Exploration Systems
ALS	=	Advanced Life Support
BVAD	=	Baseline Values and Assumptions Document
CELSS	=	Controlled Ecological Life Support System
CM-d	=	Crew Member per day
ESM	=	Equivalent System Mass
EVA	=	ExtraVehicular Activity
ISS	=	International Space Station
LCC	=	Life Cycle Cost
LEO	=	Low Earth Orbit
P/C	=	Physical/Chemical
Pr(LOC)	=	Probability of Loss of Crew
TRL	=	Technology Readiness Level

I. Introduction

THE space life support program has long operated under a widely shared consensus that describes the correct goals and approaches for developing life support for future missions. This consensus has guided life support advocacy, program planning, and project selection. The life support consensus is described and its justification and implications for future life support development are discussed.

Near term missions usually develop their needed systems using the familiar project management approach guided by systems engineering and analysis. The intent of systems analysis is to consider issues relevant to the

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current system's design, development, and operation. Some major systems engineering considerations are discussed and their implications for future life support development are examined.

It seems evident that some reconsideration of the life support consensus is needed and that trade-offs of its goals and methods are required. Different goals such as high closure and low hardware mass and contrasting methods such as biological, chemical, and material storage are in conflict. Systems engineering considerations add further complications.

II. The space life support consensus goals and methods

Some of the major life support consensus concepts are listed in Table 1.

Table 1. Life support goals and methods.

A	High closure, sustainability, is a major goal of life support.
B	Biological systems are needed for high closure and sustainability
C	Food should ultimately be grown in space using crop plants.
D	Biological water and waste processors should replace physical-chemical processors.
E	Equivalent System Mass (ESM) is a good advocacy and planning metric for life support.
F	Reliability analysis is not a major current need.
G	Cost analysis is to be avoided.
H	The ISS life support systems can be refined and used for Mars.

The listed life support goals and methods are simplified for the sake of clarity. Some contributors in life support would frame them less strongly or point out that they are no longer operative. However, the concepts form a fairly complete and largely consistent world view that was held by many for decades and still can exert a strong influence. They are assessed to consider what effect using these concepts would have on life support research and development.

There is some conflict between the consensus goals and methods. The goal of increasing closure is compatible with reducing ESM if it is done by reducing material resupply. However, increasing closure may increase ESM due to the additional systems needed to recycle the less abundant and more difficult wastes. The ISS systems have reasonably high closure, and improvements such as recycling brine are planned to increase it. One obvious conflict is between using biological systems or physical-chemical systems similar to those on ISS. Biological systems may improve greatly in the future and be suitable for larger, longer missions.

There have been changes over time, but these goals and methods have been accepted and have influenced life support decisions. Each of the entries in Table 1 is discussed.

A. High closure, sustainability, is a major goal of life support.

The system closure metric that was long used in life support is equal to the percentage of all life support material - oxygen, water, food, and other supplies for the crew - that is provided by recycling rather than supplied from Earth. Because the mass of oxygen, water, and other supplies increases directly with mission length, more recycling and higher closure is needed for long duration missions.

The stated goal of life support research and development was to approach a totally closed human ecosystem, independent from Earth. The future life support system for the Moon and Mars was expected to include food production, waste recycling, and ultimately to be "totally closed except for losses due to leaks, EVA's, etc.," and to approach "complete closure of the food and solid waste loops." (Wieland, 90-3728) (Bilardo, 90-3729) "The goal for these (Moon and Mars) missions is a higher level of mass recovery, perhaps achieving 95% closure." (Wieland, 90-3728) Percent closure was replaced by ESM as the major metric for life support research and development in the late 1990's.

B. Biological systems are needed for high closure and sustainability.

NASA Administrator Goldin in the 1990s' redirected NASA toward biological systems. "In the future we want our systems to be biologically-based …. We also want to exploit biology to build life support systems for our astronauts that minimize re-supply." (Goldin, 1999) Significant efforts were made in plant growth and bioreactor research, discussed in the next sections.

C. Food should ultimately be grown in space using crop plants.

Hydroponically growing plants for astronaut food was extensively researched in NASA's CELSS program. CELLS originally stood for Closed Ecological Life Support System, but the more realistic term Controlled was substituted for Closed by the late 1980's, to reflect the hydroponic system's need for energy, maintenance, and other inputs. Food must be grown in space if space habitats are to be independent of Earth, and popular depictions of space habitats often include hydroponic crop systems. Hydroponic plants not only produce food, they generate oxygen by photosynthesis and recycle water by transpiration, with the humidity recovered as easily processed humidity condensate.

D. Biological water and waste processors should replace physical-chemical processors.

NASA research on water and other biological processors began in the 1990's and continues. The ultimate goal was to develop life support systems that were highly reliant on biological systems for food production, water purification, solid and liquid waste processing, soil production, and air contaminant treatment. (Flynn et al., 981538) (Hogan et al., 981535)

E. ESM is a good advocacy and planning metric for life support.

ESM is the total launch mass needed to provide and support a system, including its mass, volume, power, cooling, and materials and spares logistics. The mass equivalent of the crew time needed to operate and maintain the hardware was added. (Levri et al., 2000-01-2395) ESM was made the basis for life support technology selection. (Maxwell and Drysdale, 2001-01-2365). Reducing ESM directly reduces the launch cost. Considering ESM adds a cost-benefit consideration to system design.

The use of ESM favors recycling systems over resupply of materials from Earth. Supplying all materials has very high launch mass and ESM, while recycling systems have much lower launch mass and ESM. The use of ESM is encouraged and sometimes required by NASA for systems analysis and technology development proposals.

F. Reliability analysis is not a major current need.

While the need for reliable life support is acknowledged, it seems reasonable to minimize or postpone intensive efforts. Within life support, most analysis uses ESM, which assumes that all the systems compared will be designed to meet the same reliability requirement. The ISS has been kept safely operating with spare parts even though some systems have much less reliability than expected. Based on this ISS experience, it is assumed that all life support system failures can be repaired using spares. (Bagdigian et al., 2015-094) Attempts to understand life support reliability issues have not been pushed to resolution. "(N)o consensus has been reached on what is meant by improving on reliability, or on how to assess reliability within the AES (Advanced Exploration Systems) projects." (Sargusingh and Nelson, 2014-180)

G. Cost analysis is to be avoided.

One of the reasons for establishing ESM was to institutionalize a method to avoid cost analysis in life support. To quote the NASA ESM guidelines, NASA/TM-2003-212278, "ESM is typically used as a transportation cost measure in ALS (Advanced Life Support) trade studies, to avoid the complications, both technical and political, of using dollar costs for comparisons." (Levri et al., 2003) ESM is the favored alternative to cost. "Cost would be a superior metric if we had the data, but flight hardware cost estimates are typically derived from mass during early development. Furthermore, dollar cost is overly dependent on timeframe and fiscal issues, such as the cost of money, and rapidly becomes politicized." (Drysdale, 981746) The high cost of human space exploration is probably the major reason that new missions are not approved. The cost of developing and operating life support systems is not usually considered.

H. The ISS life support systems can be refined and used for Mars.

It has been assumed that space station life support systems can be refined to be used for future long duration exploration missions. (Bagdigian et al., 2015-094) "The current ISS regenerative air and water systems form the basis for these future architectures." (Bagdigian et al., 2014-19) "(E)volving systems used successfully aboard the International Space Station (ISS) … is a leading technical approach." (Howard et al., 2015-4456)

The current ISS life support system is similar to the original recycling architecture developed in the 1960's. Most technology research and development has been focused on developing improved subsystems that might replace others within the same overall system concept. Some work has aimed to provide additional recycling, such as brine processing. The current ISS systems have a long development and operational history and are a known quantity. The thought of developing a new and different approach is unattractive.

III. NASA project management, systems engineering, and technology selection

NASA is traditionally a project organization, developing space systems using a phased approach which is supported by systems engineering. An important early step in system design is technology selection.

A. NASA project management

The NASA project process starts with mission-derived system requirements and proceeds through analysis (phase A), preliminary design (B), detailed design (C), development (D), and operations (phase E). The development of the ISS life support system was a phased project, but other life support activity conducted under the general consensus described above has not been a single coherent project. Much work has been focused on improving the ISS systems. The investigations into future systems seem more like pre-phase A work, which emphasizes advanced studies to develop and examine alternate technologies for future missions.

B. Systems engineering

The systems engineering that supports a project typically includes requirements analysis, technology readiness assessment, trade-offs and optimization, reliability and maintainability, logistics planning, test planning, risk analysis, hazard and safety analysis, and Life Cycle Cost (LCC). (NPR 7120.5B, 2002) (NASA/SP-2016-6105) (Blanchard and Fabrycky, 1990) The systems development process is better if it is guided by clear requirements and honest communication. There are usually conflicting requirements and competing design alternatives, so compromises and trade-offs are inevitable. Life support has been concerned with requirements, technology readiness, and especially logistics, but there has been less investigation of reliability, risk, safety, and cost.

C. Technology selection

After the system architecture is defined, technology selection determines the system detailed design. Some of the top level life support technology selection factors are performance, safety, readiness, operability, and cost. Table 2 shows these top level considerations and some of their more detailed aspects.

Table 2. Life support technology selection factors.

Performance
Percent closure, self-sufficiency
Quantity of product
Quality of product
Microgravity capability
Contamination potential
Noise
Safety
Number of critical failure modes
Reliability
Probability of Loss of Crew [Pr(LOC)]
Readiness
Technology Readiness Level (TRL)
Operability
Crew time
Maintainability
Complexity
Cost
Equivalent System Mass (ESM)
Logistics, resupply, spares
Life Cycle Cost (LCC)

Most of the selection factors and criteria are well known. Percent closure has been mentioned. Failure modes analysis classifies failures according to criticality and counts them. System reliability affects safety, but spares and redundancy can counteract hardware failures. The Probability of Loss of Crew, Pr(LOC), is a required metric that is computed using Probabilistic Risk Analysis. Technology Readiness Level (TRL) is defined on a scale from concept through prototype to flight. The higher TRL systems have had more development and testing and are often

the leading candidates for selection. ESM, as mentioned, is the total launch mass needed to provide and support a system, including its hardware mass, volume, power, cooling, and its materials and spares logistics. Life Cycle Cost (LCC) also counts the cost of system development, launch, and operations, and so is more inclusive than ESM.

The list of Table 2 is intended to aid discussion of life support development. It is not suitable to guide actual technology selection because of overlaps, conflicts, and lack of criteria weighting and prioritization. Logistics are included in ESM and much of ESM is reflected in LCC. Pr(LOC) reflects the crew safety aspects of failures and reliability, but they also have impact on ESM and LCC. All of the technology selection factors can be important, but sometimes a serious problem with a single factor is sufficient to eliminate a candidate technology.

The systems engineering considerations and technology selection factors are used here as a checklist. They are used to help reconsider the space life support consensus goals and methods.

IV. Systems consideration of the life support goals and methods

NASA currently has no defined missions beyond ISS and the human exploration of Mars seems always to be twenty years in the future. This allows time, an indefinite open-ended period, to investigate potentially useful technologies without prematurely limiting the options. New game changing technologies may appear. Designing the life support systems now for future missions would require clearer mission requirements and more funding than seems available. Future oriented research is needed to achieve the space life support consensus goals and methods.

Nevertheless, it seems useful to assume that future life support systems will be developed and to assess what they might be like. What systems would we build and test now if the life support community wanted to demonstrate systems suitable for the anticipated future missions? The methods of NASA project management, systems engineering, and technology selection would guide this effort.

There are three major alternatives suggested by earlier and current life support consensus goals and methods; maximally biological systems, physical-chemical systems similar to ISS, and direct material resupply from Earth, as used on short missions. An initial investigation of future life support systems can begin by reconsidering the consensus life support goals and methods using the approaches of systems engineering analysis.

A. High closure, sustainability, is a major goal of life support.

High closure and sustainability are desirable system properties. Spending resources to increase closure and independence may be justified, especially if future systems will benefit. However, any requirement that impacts a design will have some cost. If the most cost-effective design is selected from some mix of the options of biological production, recycling, and resupply from Earth, the system will have some resulting percentage of mass closure. And it will use the most cost-effective selection of production, recycling, and resupply.

The most abundant and easiest to treat wastes would be recycled first by preference and the smaller and more difficult to treat wastes would be disposed of and their mass replaced by resupplied materials. The highest mass consumable, water, and the most easily recycled waste, humidity condensate, would be recycled before urine, a lower mass and more difficult waste product. Methane produced from Sabatier processing of exhaled carbon dioxide, and also human solid waste, are much more difficult to recycle and are a much smaller part of the recyclable mass. Since the most cost-effective waste resources will probably be exploited first, increasing closure by recycling more material usually faces diminishing returns.

If closure is increased beyond the level that minimizes cost, the higher closure systems will have higher cost than systems that simply discard the less cost-effective wastes and resupply makeup materials. This is true whether the cost metric is ESM or LCC, but since ESM counts only mass launch as cost while LCC includes development and operations costs, ESM tends to justify a much higher level of closure than LCC.

Closure and sustainability can be used to advocate projects with lower cost-benefit, such as difficult and costly recycling efforts to recover minor wastes. Such projects often have research value and future potential, but they are unlikely to be used in a near term systems design. From a systems analysis and cost-benefit point of view, high or increased system closure should not be a system design requirement for near term systems.

B. Biological systems are needed for high closure and sustainability.

The advance of biochemical engineering has been impressive in recent decades and holds great promise for the future. However, as with recent advances in computers and communication, benefits to space exploration seem more likely to result from academic and industrial rather than government research.

Investments in biological systems, like investments in higher closure and sustainability, have research value and future potential. The use of biological systems in space life support should be decided by current cost-benefit

analysis, possibly modified to include demonstrating future technologies. Crop plants and biological processors are the salient options.

C. Food should ultimately be grown in space using plants.

Growing plants for astronaut food has been extensively researched, but is clearly not economical now. The large mass and power of plant growth chambers makes growing food much more expensive than supplying food from Earth, even for a decade-long mission. In an initial assessment in 1983, it was specifically stated for a Mars surface mission that "it does not appear that CELSS would benefit this mission." (Gustan et al., 831149) Eckart's detailed bioregenerative system modeling for his 1997 PhD dissertation found that "a break-even point between regenerable P/C systems and hybrid/CELSS systems is unlikely, because they save only a little mass from food resupply while requiring much more resupply mass to keep the hardware systems for plant growth operating." (Doll and Eckart, 2000, p. 566)

Future plant growth developments and more efficient lighting and power supplies may make growing food more cost-effective. Full system mass closure would require growing all the food. The most cost-effective option is probably growing half of the crew's food. Growing all the food requires using calorie inefficient, higher protein and fat producing crops such as soybeans and peanuts. Growing about half of the food would provide all the oxygen and water recycling needed by the crew, so physical/chemical air and water recycling systems would not be needed.

There is some physiological and psychological benefit in growing and consuming fresh food, but in the absence of a specific new requirement, further development of the current ISS food system for longer missions may be the most cost-effective approach. If shelf life of stored food cannot be increased for longer missions, food growing may be needed.

D. Biological water and waste processors should replace physical-chemical processors.

In the 1990's, NASA became interested in applying biology in space systems, including life support water recycling. This seemed reasonable when increasing closure was the accepted life support goal but later ESM analysis produced conflicting results. The first, optimistic, in-house assessment favored a bioreactor water processor. A later analysis found that the bioreactor water processor has ESM similar to the ISS water system, but was about seven times more massive than two alternate non-biological systems. (Flynn et al., 981538)

E. ESM is a good advocacy and planning metric for life support.

The life support consensus goal of increasing closure is achieved directly by reducing logistics, but reducing logistics will decrease ESM only if the ESM of the additional recycling systems is sufficiently low. Reducing ESM directly reduces the launch cost, which makes ESM a more reasonable life support goal than reducing closure.

ESM includes only launch mass, but launch mass is expanded to include the mass required to supply the required pressurized volume, the power and cooling systems, and the logistics for materials and spares. ESM is a limited cost metric since it does not include hardware development cost and operations cost, except for a mass penalty for the use of crew time.

NASA systems analysis uses Life Cycle Cost (LCC), which includes development, launch, and operations costs. The use of ESM seems to suggest that the launch cost is the largest or most important cost, but this is not necessarily so. For recycling life support systems, the development and operations costs may be much larger than the launch cost.

Using ESM suggests that recycling systems should be preferred to both biological systems and directly resupplied materials. Plant growth systems and biological processors have high ESM due to very high hardware mass, volume, and sometimes power, even though they reduce logistics mass. Resupply has high ESM due to very high logistics mass, materials and tankage, even though the additional resupply hardware is minimal. Thus ESM is a good advocacy metric for recycling, but not for life support in general. However, ESM is probably too simple for effective advocacy, since it is an easily deconstructed sum of masses and it omits the sometimes larger cost factors of development and operations. Life support advocacy should depend on a more general assessment of needs and benefits.

ESM is also misleading as a planning and technology selection metric. The major reduction in ESM is obtained when resupply is replaced by recycling. If further reductions in ESM are desired, the only method is to reduce the mass, volume, and power of the recycling equipment. This is difficult, costly, and can produce only small incremental gains in ESM, since most of the ESM of resupply has already been saved. Systems engineering analysis suggests that it would be much better to use life support research efforts to improve some of the other technology selection factors in Table 2, such as noise, reliability, crew time, and maintainability, rather than to achieve small decreases in ESM.

The main reason not to use ESM is that LCC is a more accurate, useful, and accepted cost metric. LCC is further discussed under cost analysis.

F. Reliability analysis is not a major current need.

If Mars is the future mission, life support reliability must be much higher than needed for ISS. A higher failure rate can be accepted on ISS since life support materials and parts can be replaced relatively quickly and the crew can return in an emergency. A mission to Mars must take along all the materials and spares that will be needed for maintenance and repair. The Mars crew cannot return before the schedule set by the planetary orbits. For Mars, reliability must not only be better but must be accurately quantified so that the needed number of spare systems can be precisely determined. A moon base, like ISS, can rely on quick resupply and emergency crew return, which allows lower life support reliability than for Mars.

Reliability analysis suggests the need for further work. Logistics planning uses reliability estimates to determine the number of spares, but it is assumed that all failures can be repaired using spares. Unfortunately, new systems often have design flaws that cause all of the allocated spares to fail rapidly.

The common life support approach is to design for two fault tolerance rather than for a target reliability. A typical requirement is to "Have life-critical systems that are two-fault tolerant." (Connelly, 2000) But increasing fault tolerance can actually reduce reliability. "However, redundancy can also decrease spacecraft safety by 1) adding additional failure modes to the system, 2) increasing design "opaqueness", 3) encouraging operational risk, and 4) masking or "normalizing" design flaws." (Ocampo, 2014-248) There is no substitute for calculating the expected reliability.

A paper that considered the potential of ISS life support for Mars assessed reliability but set too low a goal. (Bagdigian et al., 2015-094) It was considered acceptable that, "With several readily apparent exceptions, …. equipment has been shown to be capable of achieving operational lifetimes on the order of those needed to support such missions." The fact that most equipment can probably last through the mission is no substitute for estimating reliability and the spares requirement.

Reliability analysis is needed to plan to develop the highly reliable life support needed for Mars. Limited knowledge of reliability makes going to the moon more attractive than Mars, since moon base life support can be designed for less difficult reliability requirements.

G. Cost analysis is to be avoided.

Cost analysis using LCC can compare life support systems more effectively than using ESM. LCC includes development, launch, and operations costs. For manned space systems, the development and operations cost can exceed the launch cost. The operations cost is typically about 10% of the development cost per year, so the operations cost would roughly equal the development cost after a ten-year mission. (Guerra and Shishko, 2000, p. 938) The total cost of the ISS recycling life support is about 2 billion current dollars, one billion for hardware development, and one billion for launch and operations over roughly ten years. (Jones, 2016-111) Since it supports four crew members, ISS recycling life support costs about one-half billion dollars per crewmember.

The mass and cost of resupply can be roughly estimated for comparison. Each crewmember requires about 10 kg of resupply per crewmember per day (kg/CM-d) of water, oxygen, and LiOH including tanks and canisters. The crew water need is 4.16 kg/CM-d, and tanks add 0.83 kg/CM-d, for a total of 4.99 kg/CM-d. (Wieland, 1994, p. 6) (Carrasquillo, Reuter and Philistine, 1997) The crew required oxygen is 0.84 kg/CM-d in a tank mass of 0.30 kg/CM-d, for a total of 1.14 kg/CM-d. (Wieland, 1994, p. 6) (BVAD, 2004, p. 31) The mass of LiOH plus canister is 1.75 kg/CM-d. (Eckart, 1996, p. 192) The total of 7.88 kg/CM-d is rounded up to 10 kg/CM-d to simplify the rough calculation. The ten-year resupply mass would then be 36,500 kg/CM.

The shuttle launch cost was about 75 $k/kg. This corresponds to the actual cost per launch of 1.2 billion dollars for 16,000 kg to Low Earth Orbit (LEO). (Pielke and Byerly, 2011) The total ten-year launch cost for resupply would be 2.74 billion dollars per crewmember. Considering only the launch cost, shuttle resupply would have been about five times more expensive than recycling. In the shuttle era, recycling did save considerable mass and cost. An ESM or mass based decision to use recycling would have been justified.

However, for the last decade or so, the shuttle has been retired and Space X has provided significantly lower launch cost to LEO and ISS. A SpaceX Falcon 9 launch costs 62 million dollars and can place 22,800 kg in LEO. (Spacex.com, 2017) The SpaceX Falcon 9 launch cost is 2.72 $k/kg. The total ten-year launch cost for resupply would now be only 0.1 billion dollars per crewmember, only one-fifth of the 0.5 billion dollar cost of developing and operating the recycling system.

High launch cost has long been recognized as a major problem for space exploration. (Wertz and Larson, 1996) Now that the hoped-for drastic reduction in launch cost has occurred, achieving a factor of nearly 30, some formerly

accepted ideas should be reconsidered. Launch cost is no longer always a major cost factor. It follows that ESM is no longer a useful cost substitute. LCC is clearly needed to compare life support approaches. The development and operations cost of complex space hardware such as recycling systems can far exceed the launch cost, significantly affecting system comparisons. Very high mass systems, such as water resupply tanks, that were unthinkable for long missions now seem more affordable than recycling systems. Of course, many other systems engineering considerations and technology selection factors such as in Table 2 will affect design decisions.

H. The ISS life support systems can be refined and used for Mars.

Although it has been assumed that equipment derived from space station life support can be used for Mars, earlier analysis advocated developing alternates for ISS and future missions. (Carrasquillo, Bagdigian, et al., 2004)

The space station life support was designed for space station requirements, which can differ significantly from Mars transit and Mars surface requirements. The primary difference is that life support for Mars must be considerably more reliable than for ISS, which can rely on quick resupply and emergency crew return. A Mars transit system would require radiation hardening and the ability for quiescent waiting while the crew is on the surface. A Mars surface system could take advantage of gravity and planetary resources such as atmospheric carbon dioxide.

Another problem with using space station life support for Mars is that the mass payback of recycling systems for Mars will be much less than for space station, because the Mars mission is much shorter. Space station had a planned ten-year life and will go longer, so the amount of water and oxygen that the crew will consume is very large. This allows the recycling systems to be fairly large but still pay back ten times their mass in water or oxygen over a ten-year mission. The ISS water and oxygen systems have each taken about one year to pay back their own mass in water or oxygen. (Bagdigian et al., 2015-094) But Mars transit round trip and Mars surface missions are only about a year and a quarter long. The ISS recycling systems would not save much mass on a Mars mission. Including the mass of tanks and containers for resupply would increase the mass payback of recycling by about 30%. ESM computations add mass penalties for volume, power, and cooling to the hardware mass and would penalize recycling much more than resupply. Mass and ESM based comparisons do not justify using systems similar to ISS life support for Mars. The previous LCC estimates based on current low launch costs also favor resupply over recycling.

The life support systems engineering and technology selection factors so far mentioned, requirements, reliability, mass, ESM, and LCC all favor resupply over recycling, but many other factors are pertinent. Many of these also favor resupply. Storage can easily operate in microgravity and does not tend to produce contamination or noise. Tanks can fail but recycling has many more failure modes. Tanks used in space have never failed and overall supply availability can be increased with a few spares, producing low Pr(LOC). Resupply has been used on all missions other than ISS and tanks and containers have high flight proven TRL. Resupply requires little crew time and maintenance and is very simple.

Recycling does have some major advantages. Recycling increases closure and self-sufficiency. While it has been argued that high closure is desirable but should not be a specific requirement, increased closure does help solve the problem of waste. Using pure resupply produces many wastes, some difficult to handle. The cost of waste management should be added to the cost of resupply for a fair comparison to recycling. Some wastes, such as humidity condensate, could be used for purposes requiring less quality than crew consumption or stored as emergency reserves. Carbon dioxide could simply be vented. Human wastes require containment and perhaps sterilization. Both resupply and recycling can provide the required quantity of product, but recycling can provide an increased quantity if a mission is unexpectedly extended, while resupply has a strictly fixed quantity. Both resupply and recycling may have difficulties in achieving the desired quality of product, resupply due to long storage and recycling due to processing difficulty.

The most obvious disadvantage of resupply is that it requires a very large logistics mass. A decision to use resupply rather than recycling requires accepting this large mass and the cost to launch it. The new era of much lower launch costs has changed the cost-benefit calculation and challenges the previous life support consensus goals of high closure and low mass.

V. Conclusion

It has long been reasonably assumed that space life support should strive for high mass closure and low launch mass. Life support thinking extended these concepts to endorse food growing, biological processors, and the ESM metric. The decades-long development of recycling systems clearly pointed to their further development for Mars.

The actual implementation of Mars life support is far in the future, which leaves time for research and progress in these areas.

Beginning to consider the details of project management, systems engineering, and technology selection has not seemed urgent. However, investigating how life support would be implemented when needed provides a viewpoint to reconsider the life support goals and methods that have been used to guide research.

It was expected that the standard project and systems approach could provide insight, but the results have been surprising. The long standing fundamental problem that has made space exploration very difficult, the very high cost of launch, has nearly disappeared. There is no longer a dominating need for life support to increase system closure and reduce launch mass. Using resupply rather than recycling is now a plausible and in some ways attractive option for the long missions that, until recently, were generally understood to require recycling to reduce launch mass.

Life support research and development can be guided by considering the design and systems engineering analysis of the planned future life support systems. The choice between resupply and recycling is probably the major concern. The high resupply mass for a long mission favors recycling and was long thought to be decisive, but now much lower launch cost allows resupply to be considered. Research can usefully pursue a few attractive ways to cut costs or add benefits, but systems analysis must consider all the relevant costs and benefits. The system design may be selected to minimize one major problem, such as mass, cost, or risk.

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