A New Vision and A More Rational Process Will Advance Space Life Support Through Better Projects

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Many space life support assumptions are obviously mistaken but they are generally accepted because they mutually support each other and because they advance a mistaken futuristic vision of closed human ecosystems in space. Many projects have been mistakenly selected to increase life support system closure or reduce launch mass in order to implement this impractical vision. Project members rarely challenge their project's assumptions and guiding vision. Systems engineering including cost, reliability, risk, and system trade-offs has been very strongly discouraged to prevent rational criticism of these dubious assumptions, the projects, and the ecosystem vision. A more realistic vision can define better near term life support goals and future aspirations that will improve mission support and increase public interest. Given more realistic goals, it will be possible to develop effective technical alternatives, use open rational project selection methods, conduct professional project management, and make swifter progress in the inevitable human advance into space. The current unworkable human space settlement scenario involves moon visits and permanent bases, zero gravity trips to Mars, Mars visits and bases, all leading to extensive human settlements on the moon and Mars. This is unrealistic because the moon and Mars have less than Earth normal gravity and high radiation that can seriously damage human health. A better alternative would use rotating space colonies that produce Earth gravity and are radiation shielded. The attractive fantasy of reproducing terrestrial ecology in space should be replaced by the idea of building a closed system based on advancing technology such as artificial photosynthesis. Past mistaken projects include growing plants for food to replicate terrestrial food sources, recovering small amounts of water from difficult to process waste to achieve high system closure, and using newly designed, lighter, but unreliable hardware to reduce launch mass. The political process supporting the false assumptions, projects, and vision has deliberately prevented the usual systems engineering and cost-benefit analysis. We are going to do much better.

Nomenclature

ECLSS = Environmentally Controlled Life Support System
ESM = Equivalent System Mass
ICES = International Conference on Environmental Systems
ISS = International Space Station
LCC = Life Cycle Cost
ORU = Orbital Replacement Unit
Pr(LOC) = Probability of Loss of Crew
TRL = Technology Readiness Level

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I. Introduction

THE space life support program essentially operates by obtaining funding and allocating it to different projects that are supposed to advance human space flight. This requires selecting, advocating, and justifying projects based on the purpose and overall vision of life support. Program management is intuitive and political rather than rational and technical.[1] [2] The selected life support projects, their justifications, and even the overall guiding vision are highly questionable. The current largely unchallenged vison of human expansion is first the moon, then Mars via zero gravity transport, leading ultimately to Earth-like ecosystems on the moon and Mars. This vision does not have good solutions for the problems of zero or partial gravity and high radiation and does not consider the better alternative of space colonies.[3]

Life support has many problematic projects, many suspect justifications, and the familiar natural but usually disparaged political process. This paper lists some dubious life support concepts and challenges them. These criticisms do not apply to all life support efforts and life support has many well justified projects. But many other life support projects are easily challenged since they all seem to be misdirected by a coherent but mistaken vision. The life support project selection process is a familiar political method. Management solicits proposals, deliberates privately using unexplained criteria, and then announces its decisions. Management usually provides some brief proforma rationale, which may be startlingly illogical, such as that past sunk cost justifies further commitment, or based on a false assumption such as closure is needed.

Many promising projects run into trouble and it seems necessary to bail them out by increasing their funding. Often the decision to continue a failing project commits more funding regardless of its higher than expected risk. Good management requires knowing when to pull the plug.[4] Management decisions are often made intuitively, using common shorts cuts known as heuristics. One called the sunk cost trap describes the impulse to send good money after bad and ignore the decision rule that all previous costs, sunk costs, should be ignored. Another damaging heuristic is the status quo trap, where people prefer not to make changes that might challenge the current established consensus.[5] [6] A new more realistic guiding vision and planning process is needed to provide better goals and select more realistic projects.

II. Life Support Vision Concepts Currently Used to Justify Projects

The life support consensus vision contains many concepts that help generate and support a wide array of projects. Some concepts are assumptions used to justify projects. This section reviews challengeable concepts that have been used to develop and motivate questionable life support projects.

A. Challengeable Life Support Concepts

Some mistaken life support project concepts are listed in Table 1, along with the direct counter arguments.

Table 1. Life support challengeable concepts and counter arguments.

Challengeable concept	Counter argument
Closure	
High closure is a key goal of life support development. [7] [8] [9] [10]	Increasing closure has diminishing returns and needs cost analysis.[11] [12]
Difficult minor resources should be recycled.[13]	Recycling some waste is not cost-effective. [14] [15]
Recycling is needed for long missions because of large life support resupply masses and high launch costs.[8]	Launch cost has decreased greatly and resupply often saves cost.[16] [17] [18] [19]
Mass and Equivalent System Mass (ESM)	
Equivalent System Mass (ESM) can serve as the metric for life support development.[8] [20] [21] [22] [23]	ESM is a poor indicator of mission cost and omits performance, reliability, risk, etc.[24] [25] [26] [27]
Reducing launch mass should be the sole or main life support objective.[20]	Launch cost is now much lower. Other cost factors are now more important in Life Cycle Cost (LCC). [28] [29]
Food plants and biological processors	
Food plants should be grown in space.[30] [31] [32] [33]	Plant chambers have excessively high mass and cost more than food resupply. [34]
Biological water and waste processors can replace physical-chemical processors. [35]	Biological processors have much higher mass and process times than physical-chemical processors. [36]

Table 1 continued. Life support challengeable concepts and counter arguments.

Challengeable concept	Counter argument
International Space Station (ISS) life support and its reliability and testing	
A system similar to International Space Station (ISS) life support should be used for transit to Mars. [7 37 38 39]	Mars transit has more difficult reliability requirements and a shorter mission. 1 g transit would be better for the crew. [40 41]
The 1960's era system architecture and technologies used on ISS are inevitable. [7 37]	Oxygen, water, carbon dioxide and waste should be treated separately with reconsidered approaches. Past sunk cost should be ignored. [42 43 44]
Spares can repair all failures, even on the way to Mars. [37]	Most failures are system level and interface interactions and not due to component failures. [45 46 47]
Refining the ISS Environmentally Controlled Life Support System (ECLSS) can produce a reliable system. [37]	ISS life support reliability is poor, not designed for, not easy to improve, and not improving. [48 49] Reliability growth, finding-and-fixing failures, is very difficult on ISS. [50]
Component level repair can replace using Orbital Replacement Units (ORU) and save spares mass.[51 52]	Component level repair may fail due to the complexity of diagnosis. [53 54]
Only hours of integrated ISS ECLSS test were needed. [55]	Design and interface errors cause infant mortality and require time to trouble shoot. [56 57]
Long duration ISS ECLSS test was not needed. [55]	Long duration testing is needed to give confidence in failure rates and needed spares. [58 59 60]
Life support management	
Life support should prevent cost, reliability, risk, and trade-offs because they harm the life support vision of a closed space ecosystem.[20]	Professional systems engineering includes cost, reliability, risk, and trade-offs and is proper and expected. [61 62 63 64]
Formal project selection is not needed as management intuition provides good guidance. [65]	Formal project selection methods avoid errors and improve morale. Intuition can be mistaken or biased.[66 67 68 69]
NASA management	
In general, cost, schedule, and reliability estimates are optimistic, bottom-up, and include only known factors.[6 70]	Using past experience produces better estimates, but optimistic estimates are expected and required. [71 72 73 74]
In shuttle, risk analysis was dropped as too pessimistic. 1 in 100,000 risk estimates were directed.[75 76]	Challenger showed what many knew, that the risk was 1 in 100, disproving the mythic vision of shuttle.[1 2 77]

B. Concept Discussion

These challengeable concepts are used in supporting the current preferred system architecture and advocating advanced projects. Most have a purpose in implementing the shared vision of increased closure and reduced dependence on Earth. [7 8 9 10] The goal for these (Moon and Mars) missions is a higher level of mass recovery, perhaps achieving 95% closure. [9] Others such as assuming reliability growth, easy repair with spares, and little need for testing make the vision seem much easier to achieve. People who promote deceptive assumptions for organizational gain "use socially constructed accounts to legitimate the acts in their own eyes."[78] Systems engineering and formal project selection would consider alternatives, do trade-offs, and estimate cost, performance, reliability, risk, etc. Avoiding doing systems engineering prevents critical analysis of the projects, system architecture and guiding vision.

Each of these concepts supporting the current life support vision is easily disproved but still widely accepted. The true believers seem to be unable to face and consider the counter arguments. In general, facts and logic that conflict with a person's world view make no impression. "People have an almost uncanny ability to see only what accords with their beliefs."[4] At the same time, statements that support that world view are simply accepted without examination.[79] The unrealistic life support assumptions are part of a coherent but mistaken world view. The appeal of the closed system mythology and its validation of current life support projects ensure that challenges to them are dismissed without consideration. People are so convinced that their world view is right that they also accept the supporting arguments without analysis. [6 80] In life support, the general vision and its supporting concepts are substantially wrong.

Most people, most of the time, live in a socially constructed reality. [79] New ideas are usually accepted or denied, not based on facts and logic, but on whether or not they support the current world view.[81] When an unusual idea is introduced, the response is often a blank stare and a change of subject. This works well until problems occur. If we are surprised by real world events, this means our world model is not satisfactory. A reality check is called for.

Unrealistic assumptions inevitably produce harm. False visions always mislead. Wrong choices are made and bad things happen. Deceptive assumptions are usually defended on practical grounds, that they produce some good that justifies the bad, such as researching a technology or defending a project or advancing an institutional goal.[77] Organizations make overly favorable and even deceptive assumptions when under pressure to gain funding and support. This has sometimes been done in life support by practical calculation, as in the adoption of ESM, but it is more usually not intentional. The most salient NASA example of making favorable deceptive assumptions was in the design of the space shuttle, where risk was essentially ignored and was assumed to be much lower than obvious engineering estimates.[77] "(T)op NASA administrators … (had) responsibility for the disaster."[82] Given the overwhelming need for space life support to be effective, reliable, and safe, such pragmatic political justifications to avoid engineering analysis cannot be justified. The current life support closure-based mythology is understandable only as advocacy for funding. This is really indefensible. A return to reality is necessary.

III. The Project Selection Process

The natural intuitive project selection process is political, which is usually preferred to a theoretical ideal rational processes. The political process often includes some rational methodology for appearance's sake, but almost always final project selection is made by "gut feel." [67] "Many of the decisions in R&D are still made based on ad hoc methods of 'gut feeling.' " [65]

A. The Natural Political Process

The common, natural, political management process used in life support is essentially that of a primitive tribe or premodern government. Projects and their justifications are announced by authority, adopted by group consensus, and continued by tradition. In a tribe, the commanding virtues are loyalty to authority, conformity to group consensus, and respect for the past. In modern scientific and technological society, careful determination of the facts, open critical reasoning, and an insistence on logic are given the highest respect in theory but are still often neglected in practice. Tribal management is enforced by familiar methods, group pressure, management sanctions, and ultimately expulsion. Tribes are designed for an environment of strong competition for resources. Strategic concealment, deception, and force seem necessary. A tribe's solidarity and dedication depend on a shared vision that is so accepted that it is never examined. Incompatible facts and ideas are simply not noticed. They cannot be mentioned or discussed. An elaborate unrealistic world view is like some complex mythology, with mutually supporting concepts and narratives and pervasive magical thinking. An example of magical thinking in life support is the conviction that requirements must be frozen at the beginning and never changed. This reflects the observation that frequent requirement changes often indicate project problems. The ISS ECLSS still has formal requirements that were abandoned decades ago but still remain in the specifications. Some zombie requirements have been verified in formal preflight reviews by essentially stating, "This was a bad idea. We didn't do it. Therefore the requirement is verified." In most projects, about half the requirements change and the changes are formally approved and tracked.

B. The Ideal Rational Process

Instead of instinctive natural political management, what is needed is a logical approach to achieving a more realistic space vision. Instead of authority, consensus, and tradition supporting a false mythology, we need fact-based logic and open critical reasoning guided by a realistic vision. Project management, systems engineering, and technology selection are intended to keep projects in conformance with reality.

NASA is a project organization, developing space systems using a phased approach which is guided by systems engineering. 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 work has not been a single coherent project. Much effort has been focused on improving the ISS systems. The investigations into future systems seem more like pre-phase A work, which emphasizes advanced studies and research to develop and examine alternate technologies for future missions.

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, scheduling, and Life Cycle Cost (LCC). The system 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 too little investigation of reliability, risk, safety, and cost.

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

Table 2. Life support technology selection factors.

Performance
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
Logistics, resupply, spares
Life Cycle Cost (LCC)

Most of the selection factors and criteria are well known. Percent closure is usually included in performance but has been dropped here. Failure modes analysis classifies failures according to criticality and counts them. System reliability affects safety. 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 usually the leading candidates for selection. ESM is the usual cost metric but has been deleted here. ESM was deliberately designed to favor recycling over resupply. Considering engineering criteria such as cost, reliability, trade-offs, and risk (which all strongly favor resupply) was initially prohibited and long strongly discouraged. Management by a single, simple, easily manipulated, and intentionally misleading metric such as ESM should be avoided.

Complexity is strongly correlated with cost and reliability and maintainability. LCC includes the cost of system development, launch, and operations and is far superior to ESM.

Pr(LOC) reflects the crew safety aspects of failures, but failures also have impact on LCC. All of these technology selection factors can be important, but sometimes a serious problem with a single factor such as cost or risk is sufficient to drive the choice.

Life support research and development should be guided by systems engineering analysis of planned future life support systems. The choice between resupply and recycling or some combination seems to be the major future life support design issue. The high resupply mass for long missions favors recycling and the current life support vision considers mass decisive, but the recent much lower launch cost makes resupply better for fewer crew and shorter missions. Systems engineering must balance all the relevant costs and benefits.

IV. The Life Support Vision

The unavoidable necessity of obtaining funding by developing and advocating projects seems to have forced space life support to act like a self-serving tribe entranced by an irrational mythology. Space life support is involved in a competitive bureaucratic struggle for survival. Space life support has a strong need for money and influence to advance its vision. Space life support hopes to aid human expansion in space but it is misguided by its current concepts and vision. This general process is illustrated by the flawed space shuttle design mentioned previously mentioned. [75] [77] [82]

A. The Current Long Standing Illusory Vision

The space life support vision of future Earth-like human ecosystems on the moon and Mars is the guiding central element of its past false mythology. The vision includes high closure, recycling, food plants, use of ISS-like life support, and independence from Earth. This mistaken vision is shared by Elon Musk and much of the interested public.[83] The problem with this concept is that both the moon and Mars have partial gravity, high radiation, and limited surface areas not much bigger than Earth's uninhabited spaces. A more realistic vision is that of O'Neil's rotating, shielded space colonies that provide Earth gravity, radiation protection, full time solar power, and vastly greater potential living area than the terrestrial planets and moons. Jeff Bezos, Bill Nye, and others prefer space colonies. [84] [85]

Creating complex ecosystems on the moon and Mars is an attractive idea, but is unrealistic because they would be unstable. Fundamental ecosystem theory shows that the more complex a system is, the more species and interactions it has, the more unstable the system becomes.[86] The same is true in engineering design. The most fundamental design principle in systems engineering is, "Keep it simple." Space life support shows a problematic attraction to over complex solutions. Even though most human missions have used simple resupply, nearly all life support research has involved recycling systems that increase closure and add complexity.

Space life support is seriously misled by its tribal eco-mythology. Ecosystems on the moon and Mars are the guiding vision, supported by the key goal of closure, but space life support has many other supporting myths. Plants will be grown for food. Reducing launch mass is the primary design goal. Difficult scarce wastes are really valuable resources that must be recycled. Systems can be repaired and kept operating using on-board spares. Component level repair can be used to reduce the launch mass of spares. Zero gravity and high radiation will not derail the vision.

Acting on unrealistic beliefs inevitably produces serious harm. Most obviously, projects based on unrealistic assumptions and aimed at unnecessary goals can be a waste of resources. They may increase technical knowledge, but probably will not produce useful products. Developing even well justified systems without considering reliability, cost, and risk will produce less effective and perhaps unsuitable systems. The most necessary systems that deal with waste, such as removing carbon dioxide and handling trash, can be made less workable if they must be modified to also recover wastes in order to reduce launch mass. The heat melt trash compactor has been required recover the water in the trash and to produce stable plastic waste disks for radiation protection. Both are impractical and greatly increase design effort, system cost, and complexity.[13] Although unrealistic projects are easily criticized, the project team necessarily supports them. One purpose of supporting the space life support mythology is to defend current projects.

Those who minimize the harm caused by life support folk lore observe that the mythology is inconsistent, changing, and can be subverted. Food plants once strongly competed with physical/chemical systems to process oxygen and water, but now food plant research has been much reduced. The Equivalent System Mass (ESM) metric was imposed specifically to replace closure because increasing closure produces diminishing returns. Closure has somehow returned and is now used with ESM. It is argued that closure is really being optimized rather than maximized as directed, and so does no harm.[39] It seems necessary for a group to work within a shared vision, but an unrealistic vision does damage. The problems include improper goals, misguided projects, willful blindness to reality, suppression of rational critical analysis, and even a perceived necessity to impose clearly mistaken assumptions on doubters and critics.

B. A New Realistic Vision

Life support should adopt a new more realistic vision that provides plausible inspiration and better guidance. The new vision should be implemented by well-known logical processes for technology development, project selection, project management, and mission planning. A basic need is for open honest discussion and the opportunity for rational criticism. Politics is inevitable, but working to toward a shared high ideal produces better outcomes.

The crucial difference between the current illusory vision and the proposed new realistic vision is in the methods used to confirm reality and establish a shared world view. The traditional conservative method now used by life support is to rely on authority, group consensus, and past tradition. The modern scientific and progressive approach should be used instead to rely on verified facts, logic, practical reason, and open critical analysis. Any established organization - government, big business, NASA - naturally tends to be conservative, working to preserve the existing system and the vision that justifies it. Established organizations frequently attempt to avoid change, new ideas, open discussion, independent thinking, and formalized critical review. NASA life support has blocked systems engineering efforts which are intended to keep the program and project in touch with reality. It is time to get back to reality.

Usually people's assumptions and world view are largely subconscious, but sometimes a surprising event raises awareness. Change may be quick, obvious, and easily explained as in the management directed abandonment of closure in favor of ESM. Or change may be gradual and unnoticed, as in the unexpected return of closure. Some claim that facts demolish fantasy, leading to a return to reality, but this may be optimistic. A famous example of how visions change is Thomas Kuhn's description of scientific paradigm shifts.[81] A paradigm is an extensive model of reality, but all models have limits and exceptions which encourage rival paradigms. Kuhn claimed that scientific revolutions were paradigm shifts, changes in a shared world model. How do groups change their paradigms? Paradigm shifts are easier when individuals have intellectual independence than when they are locked in agreement by authority, community, and tradition. The purpose of any current world view is to justify and support the current system. It maintains itself by rewarding supporters and punishing dissenters. In space life support, projects have been funded if they increase closure or reduce launch mass. The flow of funding reinforces its guiding assumptions and builds support for them. Management can thus establish its world view and prevent engineering challenges.

How can a new paradigm gain acceptance? A new vision is usually adopted only if the current vision is seen to fail. Success or failure of a product cannot be judged by the provider, but only by the real customer, the paying customer. For advanced life support, the paying customer has been the research organization management and the desired product a portfolio of attractive projects that advance the space life support vision and justify its funding. The advertised product is technologies that would be used on future missions, usually recycling technologies that conform to the current futuristic space life support vision, but the potential use of many of them is unlikely. A more realistic goal for a new vision is to develop systems that will improve life support on a specific new mission, with better performance, cost, and reliability. The new mission would be the customer, but without the ability to reduce research funding or divert it to more immediate problems. The mission would set requirements, select projects, and develop them to flight ready. The measure of the life support research contribution would be the improvements in performance and cost provided by the new technology it develops.

In a mission-oriented life support vision, the management approach to engineering has to be “ask, don’t tell.” The new objective is to have management help engineering to produce a product that is acceptable to the mission customer, not to research management itself. An acceptable product can be developed only with an accurate assessment of technical reality, which is the responsibility of engineering. When management must produce a product in the real world, management should only “ask” engineering for the real facts. When management wants to produce an favorable impression in an imaginary world, management tends to “tell” engineering alternate facts, such as those in Table 1. Table 3 compares the current illusory vision with a suggested new realistic vision.

Table 3. Vision comparison.

Vision	Current illusory vision	New realistic vision
Space future	Future human exploration and settlement of moon and Mars, life in 0 g, 1/6 g, 1/3 g, and high radiation.	O’Neill space colonies, 1 g, radiation protection Human expansion vastly greater than possible on moon and Mars.
Customer	Research management	Mission developers
Development goal	Innovative, research-based, ideal closed far future ecosystem	Efficient, tested and reliable systems for near term missions, gradually evolving for the future
System design	Closed, integrated, complex	Cost-effective, possibly open and separated, disaggregated, simple
Technology	Recycling, regenerative, and mass conserving emphasized	Undetermined, storage or recycling as appropriate, advanced high potential such as artificial photosynthesis
Source of truth	Authority, consensus, tradition - pre-modern methods	Facts, logic, reason - scientific method
Management approach	Tell, don’t ask Ignore cost, reliability, risk, trade-offs	Ask, don’t tell Top-down systems engineering, alternate designs and trade-offs, focused on current and near missions

V. The Challenges of Partial Gravity and Solar Radiation

The main problems with a human habitat on Mars are partial gravity and solar radiation. Mars habitats may be shielded by regolith or location in a lava tube. Full 1 g gravity could be provided by a large rotating underground wheel. The horizontal artificial gravity provided by centrifugal force would be combined with vertical Mars gravity to produce 1 g at an angle to the Mars surface. The solutions of shielding and spin are similar to those proposed for a space colony.

A. Problems of zero and partial gravity

Astronauts who spend many weeks or months in space in zero g suffer serious health problems including muscle atrophy, cardiovascular deconditioning, bone calcium loss, impaired vision, and immune system change.[87] The debilitating effects of weightlessness were first demonstrated on the longer Skylab, Salyut, and Mir missions, but it was mistakenly believed that in-flight exercise and resistance training would solve the problem.[88] Research has found that, “Partial gravity exposure below 0.4 g seems to be insufficient to maintain musculoskeletal and cardiopulmonary properties in the long-term. To compensate for the anticipated lack of mechanical and metabolic stimuli some form of exercise countermeasure appears to be necessary in order to maintain reasonable astronauts' health.”[89] “It can be anticipated that partial gravity environments as present on the Moon or on Mars are not sufficient to preserve all physiological systems to a 1 g standard if not addressed through adequate countermeasures."[89] Problems of solar radiation

The major radiation hazard in space is Solar Particle Events which are sometimes referred to as solar flares. Solar Particle Events produce electrons, protons, and heavy nuclei. The particles move in all directions away from the sun. Solar flares are unpredictable but are more likely near the maximum of the 11 year sunspot cycle.[90] [91]

Dangerously large flares are rare but the radiation dose can increase a thousand times in minutes and last for hours. During the Apollo program in August 1972, a Solar Particle Event was big enough to have induced radiation sickness in an astronaut on the moon's surface, if one had been present. Very heavy shielding of the entire space platform or of a storm cellar are reasonable mitigations for deep space habitats.[90] [92]

VI. The Life Support Goals

The life support program has particular goals that are needed to implement each challengeable concept. The goals of the current vision are reviewed and more realistic goals based on a new vision are suggested.

A. Current Long Standing Illusory Goals

Working to maintain and improve the ISS ECLSS a necessary and rational goal, but it should not be misrepresented as the only real goal. Suggesting that a refined ISS ECLSS with improved reliability can be used for the transit to Mars is seriously mistaken. While this claim directs needed attention to ISS ECLSS improvements, it also intentionally diverts resources away from different approaches and alternate technologies. High intrinsic system reliability requires designing for reliability and testing to improve and verify it. ISS ECLSS components were selected for low mass at the expense of reliability. The initial shakedown testing to find and fix design errors, usually called the period of infant mortality, was eliminated in favor of having the astronauts diagnose and repair the only existing proto-flight units in space.[55] Repair and redesign in space are exceedingly difficult and reliability has not improved. Solving some complex system level problems has required redesign, which clearly shows that not all failures can be fixed using spare parts alone.

Space life support research has considered possible future technologies but not different overall system architecture approaches. The belief in closure and integrated recycling life support has encouraged work on difficult minor waste resources and required specific technologies dealing with major issues, such as carbon dioxide removal and trash handling, to support uneconomical oxygen and water recovery. The specific project goals supporting the dubious vision of an ecosystem in space include increasing closure, reducing launch mass, and developing 0 g plant growth and biological processors, as noted in Table 1.

B. More Realistic Goals

Different supporting goals are needed to implement a new more realistic vision. In the near term, the ISS astronauts need improved space life support. They must endure the deleterious effects of high carbon dioxide levels, zero gravity, and high radiation. The need for the crew to diagnose and repair the ISS ECLSS consumes excessive crew time. Having the mission and even human life depend on unreliable equipment adds unnecessary risk and stress to the unavoidable hazards of space. Future astronauts, space tourists, and space soldiers will benefit when these problems are solved.

Humans in space require life support with high performance, high quality, and high reliability and maintainability be provided by cost-effective and affordable systems, as suggested by Table 2. Ecosystem closure, reduced launch mass, and biological systems are not user needs for better life support and they are not rational cost-effective methods to achieve better life support.

VII. More Realistic Projects

Now that the cost of launching mass has dropped by a factor of 10 or 20, the long accepted key justification for using recycling is gone.[16] [17] [18] [19] Especially on short missions with few crew, resupplying water and oxygen and using lithium hydroxide to remove carbon dioxide is much cheaper and more reliable than providing recycling systems. Recycling largely replaced resupply on the ISS, but now the lower launch cost and need for higher reliability in deep space have significantly changed the technology selection factors. To beat resupply, future regenerative systems must have better reliability, maintainability and cost than current ones, but do not need lower launch mass or significant recycling capability.

Life support projects should be chosen to advance the goal of providing high performance, cost-effective life support, and to expand mission options. Modern project selection, systems engineering, and project management methods should be used. Many current projects could provide better performance and cost, even if originated under a questionable vision of space life support. Current and future projects' goals, assumptions, and justifications should be subject to open rational analysis. Requirements, assumptions, and cost factors should not be limited to one implausible notional mission, but comprehend potential future missions. This would include missions that are short and long, near and far, 0, 1 or partial gravity, low and high radiation, fulltime or cyclic solar radiation, etc. Alternate approaches for each life support functional requirement should be developed, creating an opportunity to use diverse redundancy to improve reliability.

Projects are needed to improve all the basic life support functions. Lower, more Earth-like carbon dioxide levels are needed in spacecraft, and regenerative carbon dioxide removal has a high mass payback compared to resupply of lithium hydroxide. Cost-effective water recycling should first use easily treated atmosphere condensate and avoid concentrated brines. Water is by far the most massive life support material, so water recycling provides the greatest launch mass savings. A mixed recycling and storage system could provide high reliability by using a stored survival water supply with lower reliability recycling for hygiene and other uses. Providing oxygen by water electrolysis has difficult power and hydrogen containment problems, so oxygen tanks may be more cost-effective. Rockets typically use oxygen and hydrogen or methane as fuel and their mass requirements are much greater than life support's. The moon and Mars have abundant oxygen in moon rocks and the Martian carbon dioxide atmosphere, and both have small amounts of water. A flexible oxygen, hydrogen, and water centered space economy could be based on a mix of Earth supply, spacecraft recycling, and planetary resources. One of the first economically viable activities will be producing propellant derived from water mined on the moon.[93]

The basic recycling life support system architecture and many of the technologies it uses were first tested as an integrated system in a closed chamber with a crew in the 1960's. The revolution in computers, networks, and artificial intelligence that has occurred in the fifty years since seems to have greatly changed everything but life support. System autonomy is currently being designed into the vehicle architecture for Gateway, and ECLSS could be included later. It would be useful to have a carbon dioxide removal system that could be placed anywhere in a spacecraft atmosphere with a power connection and that would sense carbon dioxide levels, turn on when needed, monitor its input, output, and internal operation, and request maintenance and replacement when needed. Automation is not easily achievable by adding it a previously designed system, but requires selecting and designing the operating technology, sensors, actuators, computers, networks, and control algorithms as a fully integrated system. A water recycling system using atmosphere condensate could be similarly independent with multiple units, but a hygiene water recycling system would require interfaces with sinks, showers, and washing machines.

VIII. Conclusion

The current life support vision is not only very far from engineering reality, it deliberately rejects the standard engineering methods needed to investigate the real world. A fantasy world has been established to help advocate a recycling life support program rather than to develop more obviously useful technology. Mistaken life support assumptions have been imposed using improper methods. This traditional life support mythology damages life support projects and should be replaced by a realistic world view with worthwhile goals that lead to more useful projects.

The current space life support world view is a coherent but fantastic belief system that is strongly supported by management, group consensus, and decades-long history. The life support mythology supports impractical research intended to advance autonomous human ecosystems independent of Earth. But such independent human habitats are unnecessary and impractical, since future human expansion in the solar system is easier if integrated with the Earth economy. The traditional plan to settle the moon and Mars seems misguided, since it ignores gravity and radiation problems. Space colonies with artificial gravity and shielding can better support human life. The current life support culture is focused on a false far future rather than realistic near term missions. Many specific assumptions of the life support mythology are easily shown to be false, but the guiding mythology seems impervious to criticism based on facts and logic.

The false life support belief system is upheld by authority, consensus, and tradition, which are pre-modern tribal methods to establish truth, values, and goals. The enforcement of consensus has required the deliberate abandonment of systems engineering and the intentional prohibition of analysis of cost, reliability, and risk. The truth, value, and reasonableness of the consensus assumptions is not allowed to be discussed.

The true goal of NASA's advanced life support research is to develop more cost-effective and reliable life support for astronauts on current and near future missions. For the foreseeable future, humans in space will conduct scientific, commercial, and military activities for very practical ends. To provide high quality life support, engineering reality must rule. Rather than implementing a self-serving management myth designed to compete deceptively for funding, life support should be guided by facts, logic, and supported by open honest cooperation. A new scientific, technical, engineering approach will check assumptions, get the facts, develop alternative designs, and use logical analysis to select life support development projects.

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