Parametric Analysis of Life Support Systems for Future Space Exploration Missions

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The National Aeronautics and Space Administration is in a process of evaluating future targets for space exploration. In order to maintain the welfare of a crew during future missions, a suite of life support technology is responsible for oxygen and water generation, carbon dioxide control, the removal of trace concentrations of organic contaminants, processing and recovery of water, and the storage and reclamation of solid waste. For each particular life support subsystem, a variety competing technologies either exist or are under aggressive development efforts. Each individual technology has strengths and weaknesses with regard to launch mass, power and cooling requirements, volume of hardware and consumables, and crew time requirements for operation. However, from a system level perspective, the favorability of each life support architecture is better assessed when the sub-system technologies are analyzed in aggregate. In order to evaluate each specific life support system architecture, the measure of equivalent system mass (ESM) was employed to benchmark system favorability. Moreover, the results discussed herein will be from the context of loop-closure with respect to the air, water, and waste sub-systems. Specifically, closure relates to the amount of consumables mass that crosses the boundary of the vehicle over the lifetime of a mission. As will be demonstrated in this manuscript, the optimal level of loop closure is heavily dependent upon mission requirements such as duration and the level of extra-vehicular activity (EVA) performed. Sub-system level trades were also considered as a function of mission duration to assess when increased loop closure is practical. Although many additional factors will likely merit consideration in designing life support systems for future missions, the ESM results described herein provide a context for future architecture design decisions toward a flexible path program.

Nomenclature

ALS	Advanced Life Support
ALSSAT	Advanced Life Support Sizing & Analysis Tool
CAMRAS	Carbon dioxide and moisture removal amine swing bed
CDS	Cascade distillation system
c_i	Cost equivalency for parameter i
CM	Consumables mass
CT	Crew time requirement
ESM	Equivalent system mass
ISS	International Space Station
LEO	Low-Earth orbit

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LPCOR	Low-power carbon dioxide removal technology
LSS	Life support system
NCM	Non-consumables mass
P	Power requirement
Q	Cooling requirement
TRL	Technology readiness level
V	Volume requirement
4BMS	Four-bed molecular sieve CO_2 removal technology

I. Introduction

The National Aeronautics and Space Administration is currently in the process of defining new missions. A number of potential destinations under consideration for these missions include near-Earth objects and asteroids, comets, Lagrange points, the Moon, and ultimately Mars. Such destinations require the capacity to travel beyond low-Earth orbit (LEO). As a result, an entirely new ensemble of technological requirements are imposed in order to successfully accomplish these missions.

Decades of developmental efforts by NASA, the contractor community, and academic partners, have resulted in the advent of a life support system (LSS) for the International Space Station capable of revitalizing air, remediating water, and processing waste materials, among other tasks. Although the advent of the ISS life support system is a remarkable achievement, the new mission constraints dictate design modifications to existing LSS configurations. Such constraints and the associated implications were astutely summarized by Jones and Kliss.[1] In particular, the design of the ISS life support system was predicated on the assumptions that: (1) re-supply would be regular and frequent, and (2) an emergency return to Earth is a possibility should the LSS undergo an indefinite failure. Both capabilities are made possible due to the proximity of LEO destinations.

Deep space mission constraints conflict with some of the previously discussed aspects of traveling to LEO targets. From an economical and logistics perspective, re-supply becomes increasingly prohibitive for flexible path missions. Some recent estimates indicate that on a per kilogram basis, deep space targets may cost \$1250k/kg versus \$25k/kg for shuttle launch costs.[1,2] Consequently, mass reduction begins driving design decisions for flexible path missions. In particular, one strategy to reduce launch mass is to increase the regenerative capabilities of the spacecraft. This requires the implementation of closed-loop life support technologies. Some of these technologies exist while other are under aggressive development. As a result, the introduction of advanced life support equipment may serve to increase system complexity or uncertainty with regard to the failure modes for immature technologies. Furthermore, the degree of loop closure that is necessary, or even practical, is mission dependent.

Moreover, mission duration may exceed the storage capacity and usage rate of consumables rendering emergency return impossible under worst case conditions. As a result, LSS for flexible path targets necessitate superior reliability to ensure crew safety. Jones and Kliss[1] remark reliability can be augmented via two paths. First, iterative design serves to identify and reduce failure modes through manufacturing prototypes, performance characterization, failure analysis, design modification, and subsequent re-prototyping. As much of the technology to fulfill NASA's objectives is custom made, performing *a priori* reliability optimization is not a straightforward task and can only be facilitated through the iterative design process. This process typically comes with a great budget and time commitment generating data for analytical models at a slow rate. Secondly, reliability can be increased by providing a spacecraft design with redundant hardware, spare parts, and contingency consumables to assist a crew through instances of hardware failure. The disadvantage of this approach is that launch mass is increased. However, the mass-cost of increasing redundancy or supplementing with consumables can be readily interrogated with predictive models.

These observations in aggregate provide ample motivation to re-visit LSS architecture design for flexible path missions. In particular, the authors of this manuscript seek to address the following questions: (1) What degree of loop closure is practical for deep space missions of varying duration? (2) How can the mass-cost be reduced via employing advanced LSS technologies? and (3) What is the mass-cost of increasing reliability through hardware redundancy and contingency consumables? Under initial consideration, it might seem counter-intuitive to increase system complexity while seeking to increase reliability -or- to add additional hardware/consumables mass while seeking to reduce launch mass. However, the supposition of this work is that the risk increase through employing low technology readiness level (TRL) hardware to increase loop closure can be mitigated with additional hardware and consumables. Moreover, so long as an advanced LSS with redundancy and contingency has a lower predicted mass-cost to implement than the current state-of-the-art LSS of the ISS, then the individual low TRL hardware comprising that system still merit consideration for iterative design efforts until additional data exists suggesting otherwise. Hardware redundancy and contingency consumables are not presented as a long term strategy to achieve reliability but instead are used as a means to offset increased risk with the consideration of low TRL advanced technologies under development. In this process, the development efforts for the options capable of promoting high reliability and low mass-cost will not be prematurely eliminated from consideration in future spacecraft.

II. Analytical & Computational Methods

In this analysis, a variety of LSS architecture options and implementations were exhaustively considered. The subsequent sections serve to expound upon the analytical techniques, accompanying assumptions, and computational tools employed in this investigation.

A. Equivalent System Mass Analysis

For this analysis, the efficacy of competing life support architectures were comparatively assessed using the measure of equivalent system mass (ESM). The metric of equivalent system mass was developed through the pioneering efforts of Levri and colleagues[3,4] as a means to benchmark advances in life support technology versus current state-of-the-art equipment. ESM quantifies the mass of LSS hardware, consumables, and associated infrastructure, along with mass penalties based on power, volume, cooling, and crew time requirements to operate the life support hardware. The mass penalties are applied using cost factors attributed to spacecraft-specific properties (*e.g.* power generation technology under consideration or radiation shielding panels required to enclose the habitat module). Thus, an ESM analysis is an effort to comprehensively value the favorability of an architecture. ESM is calculated according to eq. (1) and is a summation of mass M, along with mass equivalencies $c_i I$, where I and i represent power (P, p), volume (V, v), cooling (Q, q), and crew-time requirements (CT, t), respectively.

$$\text{ESM} = M + c_p P + c_v V + c_q Q + c_t CT \tag{1}$$

As indicated elsewhere, ESM as a measure of attractiveness is not without disadvantages. For example, Jones[5] notes that as it relies on the implicit assumption that competing technologies always achieve nominal performance and equivalent degrees of safety and reliability. For this reason, in one of the first attempts to formalize ESM and its application, Levri indicates ESM should rarely be the only metric applied in trade study due to the inability to accurately compare safety, reliability, and performance capabilities.[3] As a result, the application of ESM in the current work serves as an indicator as to draw broad conclusions regarding what type of loop closure is optimal for specific mission constraints and to provide a measure of the margin in mass that exists between current state-of-the-art and advanced LSS technologies in which increased system complexity can be abated through redundancy and additional consumables.

B. Mission Specification & Cost Equivalencies

A number of deep space missions were considered of varying mission duration ranging from 40-900 days in duration assuming a crew-size of three personnel. The habitat of the spacecraft was assumed to include a hard shell similar to an ISS module. Although light weight inflatable modules are under consideration for deep space missions, all life support components would need to be launched in a hard shell prior to inflation. As a result, a hard shell cost equivalency was employed for these calculations. Power was assumed to be generated through solar voltaics with fuel cell storage. Heat rejection was presumably facilitated through flow through radiators. Crew time cost equivalencies were architecture specific and calculated based on the mass of the specific LSS hardware mass divided by a nominal estimated crew time projections for prolonged duration missions. The product of this cost equivalency and the estimated crew time requirement for the specific architecture provides the ESM contribution attributed to a specific LSS configuration. As a result of these assumptions, cost equivalencies were identified and summarized in table 1. These particular values are characteristic of a deep space exploration vehicle such as the Mars transit vehicle as documented elsewhere.[6]

Table 1. **Cost equivalencies applied in this investigation.**

Cost factor attribute	Value	Units
Volume, ISS-type hard shell	66.7	kg/m^3
Power, solar voltaic with fuel cell storage	237.0	kg/kW
Thermal, flow-through radiators	40.0	kg/kW
Crew-time, architecture specific	–	kg/CM·hr

In addition, it is worth mentioning that for these deep space missions, extra-vehicular activity was considered to be minimal. In some cases, for missions exceeding 365 days, one week of heavy extra-vehicular activity was assumed. In those studies, overall ESM values for all systems tended to be increased by similar amounts and did not produce any interesting trade results since the activity time was dramatically less than transit time. For the remainder of the results in this manuscript, the reader can presume EVA was neglected.

C. Technology Options Considered in this Analysis

For the current investigation, several candidate subsystem technologies were considered. All options were selected on the basis of either equivalent or increased loop closure capabilities to the current ISS state-of-the-art LSS. Asterisks indicate the current ISS subsystem technology utilized as a basis for comparison*. For the water sub-system, the ISS basis for comparison was specified as ISS waste recovery system assuming 70% water recovery from urine through vapor compression distillation and 100% recover for condensate.

- Water sub-system (7 options):
  1. ISS-WRS with VCD assuming 90% water recovery and 100% condensate recovery*.
  2. ISS-WRS with VCD assuming 90% water recovery, 100% condensate recovery, and brine reclamation.
  3. ISS-WRS with CDS assuming 90% water recovery.
  4. VPCAR assuming 90% water recovery and brine processing with an air evaporator system.
  5. VPCAR assuming 90% water recovery and brine processing with lyophilization.
  6. VPCAR assuming 90% water recovery without brine processing (brines sent to solid-waste treatment).
  7. CDS as a primary processor assuming 90% water recovery.
- Air sub-system (8 unique combinations from 3 option sets):
  1. Carbon dioxide reduction: Sabatier* -or- Bosch CO_2 reduction.
  2. Degree of reduction: Stoichiometric proportional reduction with available hydrogen commodities* -or- complete reduction (requires launch of excess hydrogen commodities).
  3. Carbon dioxide removal: four-bed molecular sieve* (4BMS) -or- low-power carbon dioxide removal (LPCOR).
- Waste sub-system (4 options):
  1. Waste storage*.
  2. Lyophilization.
  3. Warm-air drying.
  4. Heat-melt waste compaction.
- Trace contaminant control system (2 options):

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*Denotes the current state-of-the-art sub-system technology as employed on the ISS

    1. ISS trace contaminant control*.
    2. Advanced trace contaminant control.
- Menu Options (2 options):
    1. Shuttle training menu*.
    2. Low-moisture content food.

For all sub-systems under consideration, calculations were performed with and without varying hardware redundancy and contingency consumables. In cases where consumables were considered, consumables were supplied at a rate of 10 days worth of contingency food, water, air commodities, and carbon dioxide removal for every 180 days of mission duration. For redundancy considerations, all LSS hardware was supplied in replicate creating a dual-string life support architecture. Calculations were performed for four separate contingency-redundancy scenarios: (1) no redundancy or contingency, (2) redundancy supplied without contingency, (3) contingency supplied without redundancy, and (4) both redundancy and contingency were supplied. Durations considered included 40, 100, 365, 600, and 900 days. Consequently, 896 unique LSS permutations exist plus the ISS case for comparison reasons, 4 scenarios were considered for redundancy/contingency, and 5 discretized durations were analyzed. This combination of options results in the requirement of 17,940 individual ESM calculations.

D. Computational Automation

In order to accommodate the multitude of ESM calculations required in this analysis, the Advanced Life Support Sizing and Analysis Tool (ALSSAT) version 10.0 was utilized. ALSSAT is generalized spreadsheet tool that performs comprehensive mass balance calculations for a given life support architecture and mission specifications. The results of the mass and energy balance requirements are converted back to an equivalent system mass. Operational capabilities and sizing calculations for particular subsystem technologies were collected from annually-updated laboratory and operational data. In addition to performing the ESM calculations for a user-specified scenario, ALSSAT has the ability to write-out input files for use at a later time. Noting the input files have a defined structure, the structure of the ALSSAT output files can be exploited for the rapid generation of thousands of input files for a given mission specification. In particular, custom code was generated using the MATLAB® programming language to rapidly generate input files. The MATLAB® code uses the '`fgetl`' function and a series of '`switch`' statements to scan an input file line-by-line and perform modifications for system specification. An alternative open source computing language such as GNU Octave could be employed for this task if attaining access to a MATLAB® license is problematic.

After a multitude of input files have been generated via the MATLAB® code, the files were passed back to ALSSAT for ESM calculations. In order to automate the calculations, the Visual Basic code that drives the graphical user interface of ALSSAT was modified in order to loop over all of the generated configuration files residing in a user-specified directory. The MATLAB® code and modified ALSSAT tool provided the ability to explore tens of thousands of life support configurations in a matter of hours. As a result, a large multi-variate configuration space could be thoroughly interrogated to find all ESM minima for a given mission specification. As calculation were performed in sets of 897, all architectures could be characterized in a reasonable amount of time. If the trade space increases to the point this is not possible, then intelligent optimization techniques such as genetic algorithms could be employed.[7]

III. Results & Discussion

As previously discussed in this work, a flexible path approach to space exploration significantly alters the approach to spacecraft design. Some of the assumptions largely relied upon to design the LSS architecture of LEO spacecraft no longer hold. Most notably, frequent re-supply may no longer be pragmatic and emergency return to Earth might not be feasible. The new mission constraints create a necessity for increased loop closure and increased reliability or maintainability. As a result, spacecraft design constraints need revisited when developing spacecraft for long term deep space missions.

To address the LSS architecture modification amenable to these types of missions, a few individual investigations were performed. (A) Major contributions to overall ESM were assessed for this long-duration, low-EVA load missions. (B) Loop closure was systematically increased in order to establish when closure is practicable. (C) Contingency and redundancy was considered as means to determine whether the increased risk of implementing non-ISS technologies for future missions could be mitigated while maintaining a lower overall ESM than current state-of-the-art ISS LSS.

A. Comparison of Architecture ESM Contributions

In order to perform architecture optimization under the new mission requirements, it is first worth determining the factors contributing most significantly to ESM. To perform this analysis, a set of 897 ESM calculations were performed for each advanced life support (ALS) architecture plus the baseline current ISS configuration. This was performed for all mission durations and contingency/redundancy scenarios. Each set of calculations demonstrated similar results with respect to the significant ESM contributions which tend to be a result of the cost factors imposed for a specific mission. Fig. 1 shows the results for a 900-day mission without contingency and redundancy and illustrates the typical trends observed for long duration missions.

In fig. 1, individual ESM contributions were calculated, along with the sum of these contributions, and the 897 systems were ranked from lowest to highest ESM. As is demonstrated by fig. 1, the non-consumables mass (NCM) tended to be the most significant contributor to ESM. This is the mass associated with life support hardware, consumables storage tanks, and other supporting infrastructure. The second most significant contributor was the consumables mass (CM) including drinking and hygiene water, food and packaging, and gas commodities. Consumables mass would plausibly be expected to provide a more significant contribution for missions where heavy extra-vehicular activity would be performed. Volume was often the third most significant contributor to ESM indicating that as mission duration increases, it becomes important to consider strategies to conserve volume such as waste processing and laundry. Power was the fourth largest contributor for these missions. Cooling and crew time only contributed in a minor way to ESM.

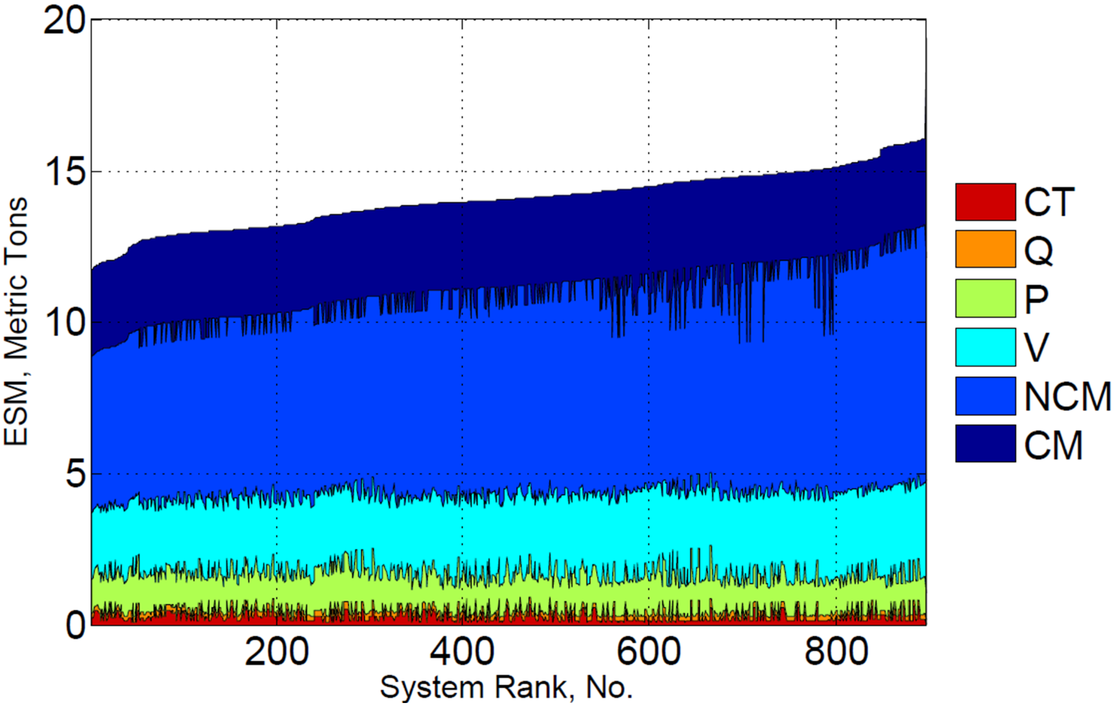

Figure 1. 900-Day ESM contributions for 897 competing life support architectures ranked from lowest to highest ESM. NCM - non-consumables mass, CM - consumables mass, P - power, CT - crew-time, V - volume, and Q cooling.

Upon considering the significant contributions to ESM in aggregate, it becomes apparent that employing technology to minimize mass, volume, and power requirements will produce the most significant decrease in ESM. Consumables mass can be lowered through increased capabilities to recycle water and gas commodities. Volume can be decreased via waste processing and laundry. Both strategies are associated with an increase in loop closure. The disadvantage of these strategies is that they might come with an increase in power requirements or hardware mass to implement. This presents an optimization challenge in order to find the greatest degree of system closure providing the lowest ESM. The results thereof are likely to be heavily dependent upon mission specification and duration.

In order to explore the necessary level of loop closure for varying duration, color grouping plots were compiled for multiple durations. Each specific color is attributed to a certain level of loop closure. These results are represented by fig. 2. ISS configurations have equal loop closure to the current state-of-the-art ISS life support system. ALS-1/2/3 have at least one, two, or three, advanced technologies with increased loop closure for the air, water, or waste sub-systems. As is indicated in fig. 2, for the short 40-day mission, it is not significantly advantageous to have high degree of loop closure. In fact, green dots indicating maximum loop closure tended to aggregate toward the highest system rank side of the figure. On the low system rank side of the figure, a group of yellow dots indicates that minimal closure is more favorable for the short 40-day mission. As mission duration is increased to 365 and then 900 days, the yellow dots begin trending toward the high system rank side of the figure. For the 900-day mission in particular, a distinct grouping of blue and green dots are observed at the low ESM side of the figure.

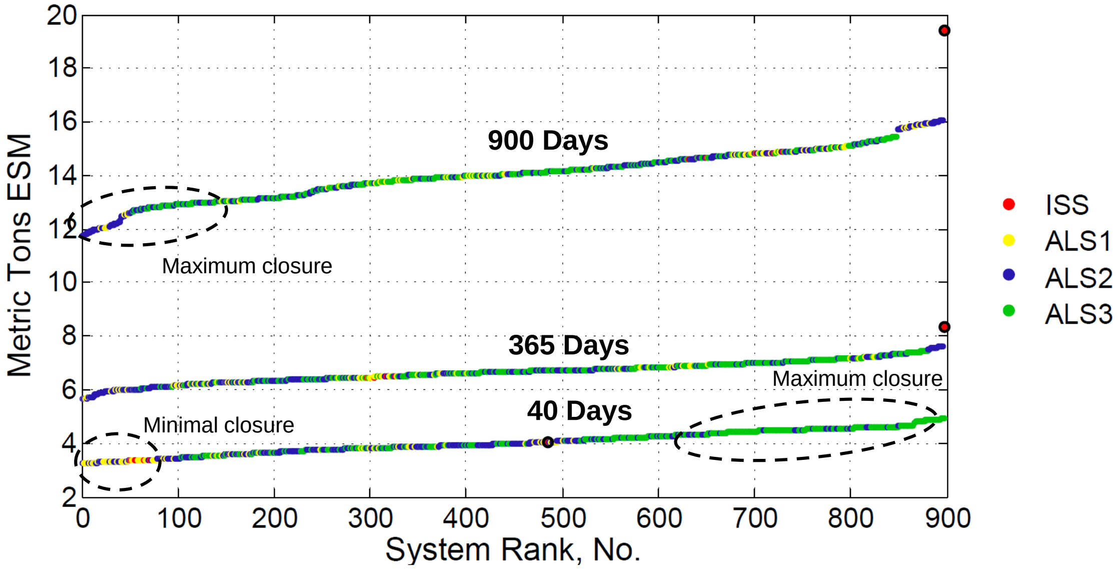

Figure 2. Demonstration of the ESM ranking of various architectures versus mission duration and number of ALS components for air, water, and waste subsystems. ISS - ISS-style air, water, and waste subsystems. ALS1 - includes one advanced technology for air/water/waste processing. ALS2 - includes two advanced technologies for air/water/waste processing. ALS3 - includes three advanced technologies for air/water/waste processing.

The results in fig. 2 illustrate increasing loop closure can provide, although not guarantee, a lower architecture ESM. However, these results say little with regard to how the advanced life support suites compare directly against the current state-of-the-art ISS configuration. For that analysis, it might be useful to find where the ISS configuration lies in the ESM distribution for the ALS configurations. These results are displayed in fig. 3.

Fig. 3 demonstrates the distribution in ESM for the missions of various durations. The vertical dashed line indicates the position at which the current ISS configuration lies in comparison to ALS technologies currently under development. For all mission duration, when either equal or greater loop closure is considered, an ALS system can be configured in ALSSAT that predicts a lower ESM value than what the ISS is already implementing. For short durations, the ISS life support configuration is located around the middle of the distribution. Although several ALS suites exist with lower ESM than the ISS architecture, the ISS configuration has the added advantage of having a higher system-level TRL. As duration increases a systematic movement of the ISS configuration toward the tail-end of the distribution is observed. This result is even more pronounced as duration tends to 1000 days (not shown). As all configurations explored in this analysis have similar to greater loop closure than the ISS configuration, this is attributed to the fact that as mission duration increases, it becomes favorable to pay the non-consumables mass and power costs to implement

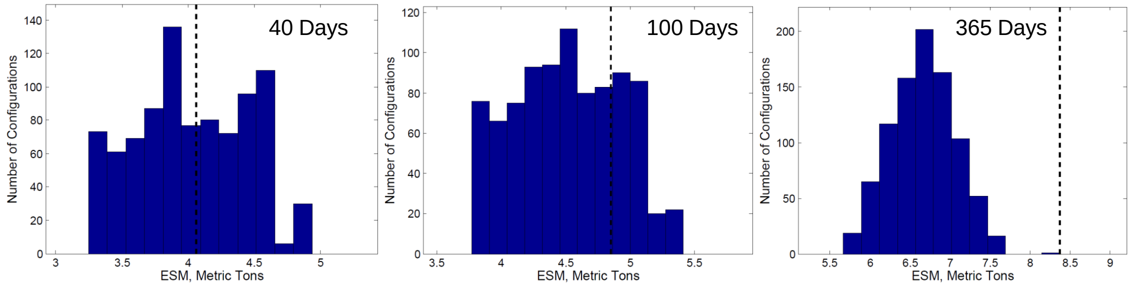

Figure 3. Distributions in ESM for missions of vary duration. The vertical dashed line indicates where the current state-of-the-art configuration as implemented on the ISS falls with respect to the ALS architectures.

more regenerative technologies reducing the consumables mass requirement at launch. This result merits further investigation.

B. Break-even Analysis for Increasing Loop Closure

As previously discussed, the flexible path mission requirements present an opportunity for optimization through balancing power, consumables, and non-consumables mass demands through the use of ALS technologies. Greater air and water loop closure reduce consumables mass at the expense of increased non-consumables mass and power requirements.

To assess when increased closure becomes practical, a trade study on ESM versus mission duration was performed for 5 candidate architectures representing increasing regenerative capacities. These architectures are summarized in tab. 2. The options under investigation were not necessarily selected as an endorsement for any particular subsystem technology but instead to represent a cross-section of technologies enabling increased sub-system closure.

In the study summarized by tab. 2, suite 1 neglects water recovery, carbon dioxide reduction, and waste processing. The carbon dioxide reduction technology for suite 1 was assumed to be a carbon dioxide and moisture removal amine swing (CAMRAS) bed type of technology. Within ALSSAT, air and water save options are not considered for CAMRAS so that CAMRAS is equivalent to an open air loop within ALSSAT. Suite 2 is analogous to the current ISS life support system implementing more efficient processing of gas and water commodities while storing solid waste. Suite 3 implements a slight increase in water loop closure and exchanges a low power carbon dioxide removal (LPCOR) assembly for the more power intensive four-bed molecular sieve (4BMS) carbon dioxide removal technology. Suite 4 utilizes a heat-melt compactor (HMC) for solid waste processing while suite 5 combines lyophilization with HMC. For all suites under consideration, ESM calculations were performed for 40-1000 day duration missions. These results are included in fig. 4.

Table 2. Life support systems implementing a systematic increase in regenerative capacity considered for a trade study on ESM with increasing mission duration.

Suite	Architecture Summary:	Significance of Architecture:
1	CAMRAS, No Water Recovery, No CO_2 Reduction, Stored Waste	Open loop specification in ALSSAT
2	4BMS, Sabatier Reduction, ISS Water Recovery, Stored Waste	Current ISS configuration
3	LPCOR, Sabatier Reduction, ISS with CDS, Stored Waste	Increased closure for the water loop
4	LPCOR, Sabatier Reduction, ISS with CDS, HMC	Increased closure for water/waste
5	LPCOR, Sabatier Reduction, ISS with CDS, Lyophilization + HMC	Further increase water recovery

The top panel of fig. 4 demonstrates break-even results for this analysis. The thickened-lines for each suite represent the ESM predictions from ALSSAT plus and added 10% to account for uncertainty in ESM predictions for technologies still under development. For missions up to around 100 days, an open loop configuration is favorable. Although the open loop configuration does not reclaim resources, the consumables mass and associated storage infrastructure is not prohibitive in comparison to the hardware and power costs

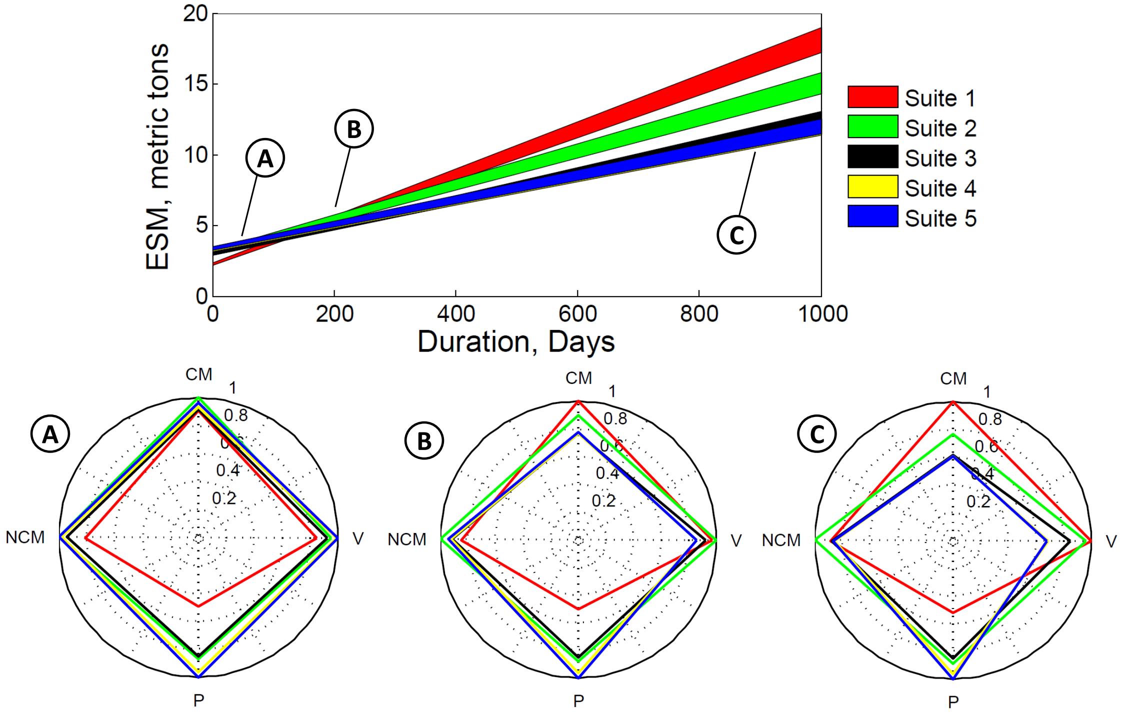

Figure 4. Closure trade study for extended duration deep-space missions along with accompanying radar charts. (A) 40-day radar chart, (B) 200-day radar chart, and (C) 900-day radar chart. Radar chart axes are normalized to provide relative indication of how ESM contributions are influenced in comparison to one another with increasing mission duration. These factors include: consumable mass (North axis - CM), non-consumable mass (West axis - NCM), power ESM (South axis - P), and volume ESM (East axis - V).

to implement advanced technologies. Beyond 100 days in duration, closed loop life support begins to become attractive. In these cases, suites 3-5 always had lower ESM values than the ISS analog (suite 2). In particular, suite 4 implementing HMC for solid waste storage demonstrates the lowest ESM as predicted by ALSSAT. Suite 5 exhibited a marginal increase in ESM through the implementation of lyophilization in combination to HMC. Although the combination technology comes with an increase in ESM, the lyophilized waste is less amenable to bacterial contamination improving system safety. This is an example of an additional factor that would need to be considered in design down-selection. As displayed by the 10% uncertainty in the plot, increased loop closure is important for long duration missions although the exact architecture configuration will most likely need to be assessed after the mission has been comprehensively defined and subsystem technologies under consideration reach equivalent TRLs.

As ESM is an amalgam of subsystem technology contributions, the underlying attributes driving an increase in ESM can sometimes be disguised unless considered independently. In order to concisely organize some of these attributes, the consumables mass, non-consumables mass, power, and volume contributions to ESM were plotted for 40, 200, and 900 days on radar charts similar to what has been previously presented by Jones.[5] The use of radar charts enables several criteria to be organized in a concise manner to better understand the major contributors. The ESM contributions were normalized by the maximum contributor for each data set. In this manner, all contributing factors can be analyzed for their relative magnitude against one another. For the short duration mission in fig. 4A, all configurations had similar consumables mass and volume contributions to ESM while the regenerative architectures had a high non-consumables mass and power. The increase in non-consumables mass (*i.e.* life support hardware and infrastructure mass) and power is the cost paid to recover consumables. For short duration missions, this cost is not necessarily practical. As mission duration increases in 4B&C, consumables mass requirements decrease for the more closed loop systems, the power requirements and non-consumable mass for the life support systems stay relatively constant, and the volume contribution to ESM is decreased significantly for the systems implementing waste processing. The results indicate that for deep space missions, effort to close the air/waste/water loops pays dividends for 100 days onward with a pronounced reduction in consumables mass and a reduction in volume associated ESM when waste treatment with HMC and lyophilization are employed. For moderate to long duration missions, spacecraft design efforts necessitate consideration of advanced life support technologies.

C. Hardware Redundancy & Contingency Consumables Considerations

As indicated in the previous section, moderate to long missions in deep space stand to benefit through increased loop closure provided through advanced life support technologies. However, advanced life support technologies do not have the operational history of technologies currently employed on ISS. Failure modes and countermeasures have not been fully characterized for low TRL ALS equipment. Moreover, most of these technologies are comprised of custom components adding uncertainty to *a priori* reliability analyses. However, data collected in laboratory testing indicate these technologies provide the capacity for increased loop closure.

These concerns raise some questions with regard to strategizing for flexible path missions. Should immature but promising technologies be eliminated from consideration in favor of more mature technologies with operational history? In some cases, this may be the best approach. In other cases, it could serve to stifle the development of truly game-changing technologies. This suggests non-mature technologies should still receive consideration but perhaps the less mature technologies should be penalized for a more fair comparison. The subsequent question then becomes: How can reliability risks associated with less mature technologies be mitigated while the iterative design process continues and data sets become more complete? A short term possibility, but by no means an indefinite strategy would be to consider some of these technologies with either hardware redundancy or contingency consumables to maintain safety/operability in the event of equipment failure. This provides a context through which ALS technologies could be compared against ISS life support technologies with operational history. In the following analysis, the most competitive ALS technologies with varying degrees of contingency consumables and hardware redundancy were compared against the baseline ISS architecture. If a competitive ALS architecture with the added mass penalty imposed for contingency consumables and hardware redundancy achieves a lower system ESM than the ISS architecture, then the implementation of such ALS technologies might be worthy of strong consideration.

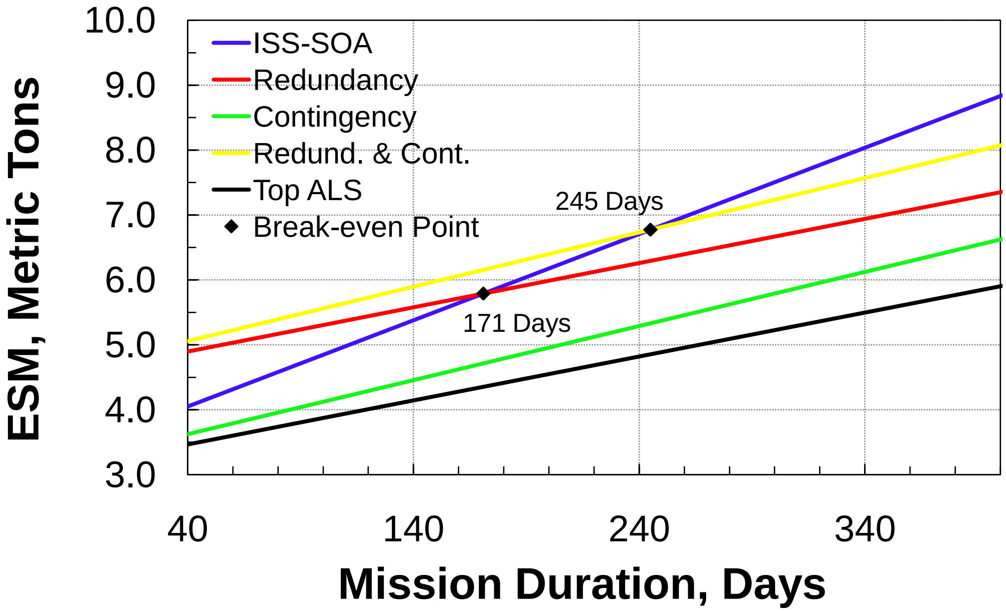

Figure 5. Break-even analysis for contingency and redundancy considerations for advanced life support (ALS) technologies in comparison to the current state-of-the-art ISS architecture.

In this analysis, the ISS architecture was compared against the top ALS suite of technology (1) with hardware redundancy but no contingency consumables, (2) with contingency consumables but no hardware redundancy, and (3) with hardware redundancy and contingency consumables. Contingency consumables were assumed to be provided at a rate of 10 days worth of gas, water, food, and CO_2 removal for every 180 days of mission length (*i.e* 5.6% mission duration). With regard to hardware redundancy, all ALS technology and associated infrastructure was supplied in duplicate. The results of this analysis are illustrated in fig. 5.

As indicated in fig. 5, the top ALS suite of technologies with contingency consumables has a lower ESM than the ISS architecture for all times investigated in this study. This suggests the risk of utilizing lower TRL equipment can be somewhat abated and still achieve a lower ESM than the current state-of-the-art. At approximately 170 days of mission duration, a break-even point exists where a dual-string life support architecture comprised of ALS technologies attains a lower ESM than the ISS configuration. Moreover, at approximately 250 days of mission duration, an ALS architecture with complete hardware redundancy and contingency consumables has a lower ESM than the ISS architecture without contingency consumables or redundancy. These results indicate that even if the ISS technologies are considered perfectly reliable, an assumption history bares inaccurate, ALS technologies with contingency consumables and hardware redundancy can still potentially provide a lower ESM cost for deep space missions. This provides ample motivation to continue pursuing ALS technologies for future missions.

IV. Conclusions

Deep space missions associated with a flexible path approach to space exploration impose new challenges previously not designed around in the development of LSS for LEO destination. Such challenges prohibit frequent re-supply and unplanned return trips to Earth. This result necessitates increased loop closure and high reliability from the life support architecture. These ambitions are seemingly at odds. Increased closure can be achieved with more advanced but lower TRL life support equipment. This comes at the expense of a risk to reliability since final designs and life cycle testing are still underway for the ALS equipment. The results discussed in this work explore these issues.

First, major ESM contributors for this type of a mission were established. These include non-consumables mass, consumables mass, volume, and power. For these mission constraints, consumables mass was lower than what would be expected for a high extra-vehicular activity mission such as long term habitation of a Lunar outpost. Results of this analysis also demonstrate that as mission duration increases from around 100 days and beyond, increasing the regenerative capabilities of the spacecraft through implemented advanced life support begins to become practical. Moreover, at these durations, an ESM analysis alone indicates ALS architecture configurations may be more favorable than what is already implemented in the closed-loop life support system of the ISS. In particular, a break-even analysis indicates that augmenting water, air, and waste processing closure provides the greatest benefit.

The disadvantage of the ESM analysis is that it circumvents reliability concerns implicitly assuming all equipment always achieves nominal performance without instances of failure. Making the change to ALS technologies serves to increase system complexity and/or eliminate operational history of the LSS components. This creates uncertainty with regard to reliability. Consequently, to provide a more fair comparison, the ALS architectures were penalized with additional mass for contingency consumables and redundant life support hardware while the ISS suite was assumed to achieve perfect reliability. In this analysis, the ALS architecture with contingency consumables always attained a lower ESM than the competing ISS suite. At 170 days, a dual-string life support system comprised of ALS technology achieved a lower ESM than the current state-of-the-art. Lastly, at 250 days in mission duration, the ALS architecture with hardware redundancy and contingency consumables obtains a lower ESM than the ISS configuration. As a caveat, adding contingency and redundancy to achieve reliability is not a long term strategy. It is employed here instead used as a mass penalty to demonstrate the ALS technologies still merit strong consideration for deep space missions. As development efforts continue and more thorough data is generated, break-even points will be predicted with greater precision and the efficacy of ALS technologies to enable these missions will become more clear.

Future work toward better understanding the trade between current state-of-the-art versus ALS technology includes a multi-faceted approach. The ALSSAT repository of operational data and mission objectives will continually be updated to achieve higher fidelity in ESM predictions. Alternative assumptions on levels of redundancy and contingency rates warrant further investigation. Finally, the ALSSAT program provides a good perspective on the mass economics for individual life support architectures under provided mission constraints; however, probing system reliability is equally as important. Adding a dynamic component to the ALSSAT software would enable researchers to begin approaching system- and subsystem-level failure analyses as published elsewhere.[7]

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