ECLSS Does Not Exist in a Vacuum: Integrated Analysis is Necessary to Inform System Architecture Decisions

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Environmental Control and Life Support System (ECLSS) architecture selection has profound implications for mission cost and mass extending far beyond the ECLSS itself. Similarly, other mission architecture decisions – particularly involving transportation systems – can influence optimal ECLSS architectures. Loop closure influences requirements for water, oxygen, and other consumables. System maintainability and reliability influences spares mass and risk. System, consumables, and spares mass interact with transportation system architectures and propellant demands and propulsion element sizing. All these interactions with other systems must be considered when evaluating ECLSS options. Analyses that focus only on maximizing ECLSS loop closure – or minimizing ECLSS mass, or minimizing ECLSS life cycle cost – may lead to sub-optimal or even counterproductive system architecture and investment decisions at the mission level. For example, an ECLSS architecture that minimizes ECLSS lifecycle cost but results in excessively high logistics mass could lead to significantly increased transportation system costs or make interplanetary transportation infeasible. Increased loop closure could result in higher development costs and higher mass if system/spares mass increases outweigh consumables reduction. In addition, systems mass and consumables mass are not directly comparable and have different impacts on propellant requirements, as consumables mass changes over the course of the mission. This paper presents an integrated analysis examining the overall impact of different ECLSS and transportation architectures on mass for a crewed Mars mission, including the habitat and transportation systems as well as consumables, spares, and propellant. Key observations are discussed, along with opportunities for further sensitivity analysis and model development. Overall, ECLSS development activities must consider their impacts at the mission level, as part of an integrated system, rather than in isolation.

Nomenclature

<table>
<thead>
<tr>
<th>CCAA</th>
<th>Common Cabin Air Assembly</th>
<th>OGA</th>
<th>Oxygen Generation Assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDRA</td>
<td>Carbon Dioxide Removal Assembly</td>
<td>ORU</td>
<td>Orbital Replacement Unit</td>
</tr>
<tr>
<td>CH4</td>
<td>Methane</td>
<td>POS</td>
<td>Probability of Sufficiency</td>
</tr>
<tr>
<td>CTB</td>
<td>Crew Transfer Bag</td>
<td>PPA</td>
<td>Plasma Pyrolysis Assembly</td>
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<tr>
<td>ECLSS</td>
<td>Environmental Control and Life Support Systems</td>
<td>SEP</td>
<td>Solar Electric Propulsion</td>
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<tr>
<td>EOI</td>
<td>Earth Orbit Insertion</td>
<td>SLS</td>
<td>Space Launch System</td>
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<td>EVA</td>
<td>Extravehicular Activity</td>
<td>TCCS</td>
<td>Trace Contaminant Control System</td>
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<tr>
<td>H2O</td>
<td>Water</td>
<td>TEI</td>
<td>Trans Earth Injection</td>
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<tr>
<td>HPS</td>
<td>Hybrid Propulsion System</td>
<td>TMI</td>
<td>Trans Mars Injection</td>
</tr>
<tr>
<td>LOx</td>
<td>Liquid Oxygen</td>
<td>UPA</td>
<td>Urine Processor Assembly</td>
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I. Introduction

Environmental Control and Life Support System (ECLSS) architecture selection has profound implications for mission cost and mass extending far beyond the ECLSS itself. Similarly, other mission architecture decisions – particularly involving transportation systems – can influence optimal ECLSS architectures. Loop closure influences requirements for water (H2O), oxygen (O2), and other consumables. System maintainability and reliability influences spares mass and risk. System, consumables, and spares mass interact with transportation system architectures and propellant demands and propulsion element sizing. All these interactions with other systems must be considered when evaluating ECLSS options. Analyses that focus only on maximizing ECLSS loop closure – or minimizing ECLSS mass, or minimizing ECLSS life cycle cost – may lead to sub-optimal or even counterproductive system architecture and investment decisions at the mission level. For example, an ECLSS architecture that minimizes ECLSS lifecycle cost but results in excessively high logistics mass could lead to significantly increased transportation system costs or make interplanetary transportation infeasible. Increased loop closure could result in higher development costs and higher mass if system/spares mass increases outweigh consumables reduction. In addition, systems mass and consumables mass are not directly comparable and have different impacts on propellant requirements, as consumables mass changes over the course of the mission.

This paper presents an integrated analysis examining the overall impact of different ECLSS and transportation architectures on mass for a crewed Mars mission, including the habitat and transportation systems as well as consumables, spares, and propellant. It is important to note that the results presented here represent a series of exploratory analyses executed to understand fundamental relationships between key mission drivers. They are notional, and do not represent actual implementation plans of any kind. Key observations are discussed, along with opportunities for further sensitivity analysis and model development. Overall, ECLSS development activities must consider their impacts at the mission level, as part of an integrated system, rather than in isolation.

II. Methodology

This paper examines eight ECLSS architecture cases, representing a range of loop closure levels. The set of technologies used in each case define an ECLSS resource recovery capability, as well as a set of Orbital Replacement Units (ORUs) characterized by mass, failure rate, and other key parameters. These systems are evaluated against a notional conjunction-class Mars mission in order to calculate logistics and transportation system requirements and determine the mass of the integrated system – the habitat mass, transportation system mass, and their constituents – over the course of the mission, including the mass at departure. Development, production, and launch costs are also estimated. This integrated analysis approach allows insight into the relationships between different systems, and highlights how decisions made in one system affect the entire mission. The specific case definitions, assumptions, and modeling approaches are described in the following sections.

A. Baseline Case and Sensitivity Analysis Descriptions

Each ECLSS architecture is defined by the set of regenerative technologies that are included in the architecture, including the Oxygen Generation Assembly (OGA), Water Processor Assembly (WPA), Urine Processor Assembly (UPA), Sabatier, Brine Drying, Plasma Pyrolysis Assembly (PPA), and Bosch systems, as summarized in Table 1. All cases also include the Carbon Dioxide Removal Assembly (CDRA), Waste and Hygiene Compartment (WHC), Common Cabin Air Assembly (CCAA), Trace Contaminant Control System (TCCS), O2 and nitrogen (N2) supply.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Open Loop</th>
<th>+OGA</th>
<th>+WPA</th>
<th>+UPA</th>
<th>+Sabatier</th>
<th>+Brine Drying</th>
<th>+PPA</th>
<th>Bosch</th>
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</thead>
<tbody>
<tr>
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<td>X</td>
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<td>X</td>
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<td>X</td>
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<tr>
<td>WPA</td>
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<td>X</td>
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<td>X</td>
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<td>X</td>
<td>X</td>
</tr>
<tr>
<td>UPA</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Sabatier</td>
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<td>X</td>
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<td>X</td>
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<td>X</td>
<td></td>
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<tr>
<td>Brine Drying</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
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<td>X</td>
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<tr>
<td>PPA</td>
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<td>Bosch</td>
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Table 1: Summary of ECLSS architecture cases.
and distribution, pressure control and relief, air circulation and ventilation, atmospheric constituent monitoring, active thermal control, electrical power, communications and tracking, command and data handling, and attitude and rate determination systems, as well as fixed habitat mass, including structures and other equipment that is assumed to not fail during the mission. All cases assume an approximately 1,000-day conjunction-class mission with 4 crew. Consumables are budgeted to account for losses from 4 docking events. The baseline analysis assumes food hydration is 50% (i.e. the food is 50% water by mass), consumables are budgeted for 12 Extravehicular Activities (EVAs), and spares are supplied to achieve a Probability of Sufficiency (POS) of 0.98. It also assumes the 2035 mission opportunity is used for trajectory analysis, and current failure rate estimates for supportability analysis (i.e. no additional testing). A sensitivity analysis is also conducted to examine different food hydration levels, EVAs, and POS levels, as well as the impact of changing to a different mission opportunity and implementing 10 years of passive testing on all systems.

B. Metrics and Analysis Outputs
The outputs of this analysis are system mass and cost estimates under the different circumstances described above. Habitat mass is calculated at each major propulsive maneuver – Trans-Mars Injection (TMI), Mars Orbit Insertion (MOI), Trans-Earth Injection (TEI), and Earth Orbit Insertion (EOI) – since the mass at each burn, not just the mass at departure, is a significant driver of transportation system mass. Trash and other waste products are jettisoned before each of these burns in order to reduce mass. The model does not currently include the jettisoning of spares during the mission, though that approach is being investigated as future work. These mass estimates are used to size a transportation system, determine propellant requirements, and calculate total system mass at departure (i.e. TMI). Mass is divided into several categories, shown in a hierarchy in Figure 1. Each category is equal to the sum of its subcategories, which provides a mass breakdown ontology that can be examined at the desired level of detail. In addition, each mass category is associated with a particular color, which is used in the results to provide consistent, easy comparison between cases. In addition to mass results, this analysis assesses the development, production, and launch costs for the habitat and transportation system, including propellant and logistics. Cost results are presented in terms of percent change in cost relative to the baseline open loop case.

C. Logistics, Supportability, Transportation, and Cost Assessment
As indicated in Figure 1, logistics consists of three major categories: consumables, spares and maintenance items, and gas & liquids. Consumables include food, clothing, towels, fecal containers, and other items that are consumed at a fixed rate over the course of the mission. Gasses & liquids include water, oxygen, and nitrogen, also consumed at a fixed rate. Spares and maintenance items are replacement parts used to repair random failures or implement scheduled maintenance, respectively. Packaging overhead is also calculated for each category, in the form of carriers for consumables, spares, and maintenance items in the form of Crew Transfer Bag (CTB) liners, as well as tanks for water, oxygen, and nitrogen. Additional CTB and tank mass required for launch is included in the launch cost analysis. Spare parts and maintenance requirements are calculated using the supportability model described in depth by Owens, which has been applied in several previous analyses. The set of systems included in the habitat for each

![Figure 1: Mass breakdown hierarchy used for this analysis. Each of these mass categories are evaluated for all cases at each of the four major propulsive maneuvers.](image-url)
case define a list of ORUs, each of which has an associated mass, quantity, duty cycle, life limit, and failure rate estimate. These data are based on current ISS systems, and have not been resized to account for changes in crew size. Spares allocations are optimized to achieve the specified POS requirement, accounting for uncertainty in failure rate estimates, while minimizing total mass. The number of maintenance items required for each ORU is calculated using the ORU’s life limit. Maintenance items are used on a regular schedule, and the number of items spent before major burns is calculated to determine the mass carried at those maneuvers. This analysis currently assumes that spares are not jettisoned during the mission; this capability is a planned extension of the model, described in Section V.

Consumables, gasses, and liquids are allocated to meet the demand of 4 astronauts for the duration of the mission, and nitrogen is provided to account for pressurization requirements, using the model described by Ewert and Strongren. Water and oxygen requirements account for the recycling capability of any regenerative ECLSS present in each case, as well as water in stored food. Any excess water generated during the mission is vented, and trash products are jettisoned before major burns. In order to reduce tank mass, water, oxygen, and nitrogen are assumed to be stored in large tanks that are integral to the habitat structure.

The transportation system is sized for a conjunction-class trajectory using the model described by Chai et al. and is assumed to be a Hybrid Propulsion System (HPS) consisting of a liquid oxygen / methane (LOX/CH4) chemical propulsion system and a 400kW low-thrust xenon Solar Electric Propulsion (SEP) system with a 675kW solar array. The trajectory, HPS size, and propellant loads are optimized as a function of the mass of the habitat at the four major propulsive maneuvers (TMI, MOI, TEI, and EOI) using the results of the logistics model.

Development and production costs were estimated at the component level using PRICE H, an industry standard parametric cost estimating model. Launch costs were modeled using parametric cost estimates for the Space Launch System (SLS) and a representative heavy-lift commercial launch capability, as has been used in previous work. The dry mass of the habitat and HPS were each assumed to be launched on an SLS with a capacity of 45t to cis-lunar space, at a cost of $1 billion per launch. For each launch, the remaining mass capacity was filled with either logistics (for the habitat) or propellant (for the HPS). The remaining logistics and propellant masses were launched on a series of commercial launches with a capacity of 12t to cis-lunar space. (Although the notional vehicle could deliver as much as 15t to cis-lunar space, this capacity was reduced by 20% to account for the cargo vehicle carrying the logistics and/or propellant.) Logistics and propellant masses were not mixed on the same flight. The commercial launch vehicle was assumed to have a cost of $200 million per launch, including the cargo vehicle.

It is important to note that, while this analysis examines a wide range of system configurations and sensitivities, it only represents specific points in the very large ECLSS-transportation system tradespace. As noted in Section I, this analysis is an exploratory analysis executed to understand key system drivers, not a final assessment.

III. Results

A. Baseline Case

Figure 2 shows the mass of the habitat at each major burn for all 8 ECLSS architectures in the Baseline case (i.e. 50% food hydration, 12 EVAs, 0.98 POS, no additional testing). These results show how the mass of the habitat and logistics change significantly over the course of the mission, and how ECLSS loop closure affects those changes. The Open Loop architecture has the highest mass at departure. However, because it relies on stored consumables more than the other cases, the mass of the habitat at EOI is less than half of the mass at the start of the mission. In contrast, architectures with higher loop closure start at lower mass, but less of that mass is consumed and expended over the course of the mission, and the mass at EOI is typically higher. Jettisoning of trash and other logistics items that are no longer required is a critical strategy for reducing total departure mass, as described below. In general, cases with loop closure beyond UPA exhibit an approximately 18t (26%) reduction in habitat departure mass from the Open Loop case. In this baseline case, which assumes the food is 50% water by mass, additional loop closure beyond that point does not produce significant mass reduction.

Figure 4 shows the total departure mass in each case for the 2035 mission opportunity, which is calculated by adding the HPS and propellant masses to the habitat mass at TMI. As expected, values follow the same general trend as habitat mass at TMI. Loop closure beyond UPA results in an approximately 44t (26%) reduction in departure mass, and at the food hydration level assumed here (50%) higher levels of loop closure do not continue to decrease that mass. Sensitivity to food hydration level is examined in Section B. As noted above, the departure masses shown here take advantage of reductions in habitat mass during the mission as trash is dumped overboard. Every kilogram of trash stored on the habitat during a propulsive maneuver results in an unnecessary increase in the amount of propellant required for that maneuver. As an example, if the Open Loop architecture were used without jettisoning trash during the mission, the total departure mass would increase by nearly 22t (13%), even though the habitat mass at departure would be the same. For the Brine Drying case, the mass at departure would increase by over 10t (8%). If there are
reasons to store trash during the mission, those reasons should be carefully weighed against the resulting multi-ton increase in mission mass.

Figure 3 shows the percent change in cost of each ECLSS architecture in the baseline case, relative to the Open Loop architecture. The total cost is shown alongside the habitat, HPS, and launch costs to highlight changes in different contributions. The cost for the habitat and HPS includes development and procurement. Each value is calculated as the difference between the cost in that architecture and the Open Loop architecture. This figure clearly shows one of the key tradeoffs in ECLSS loop closure: increased loop closure reduces launch cost and HPS cost by lowering the amount of mass that must be transported between planets, but it increases the cost of the habitat itself. This increase in habitat cost comes from the development and procurement of new systems as well as their associated spares and maintenance items. In general, under the modeling assumptions used here, loop closure at or beyond WPA results in approximately 5% reduction in the total cost to develop, procure, and launch one mission. Again, these results are only for the baseline case, which assumes 50% food hydration, 12 EVAs, 0.98 POS, 2035 opportunity, and no additional testing. Each of these factors will impact the mass and cost associated with each ECLSS architecture to some degree and these results should not be considered final. Rather, they are a starting point for this exploratory analysis intended to help understand the impact of different decisions on the mass and cost associated with a Mars mission.

![Habitat Mass at Major Burns - Baseline](image1)

**Figure 2: Habitat mass at major propulsive maneuvers for the baseline case.**

![Total Departure Mass - Baseline](image2)

**Figure 3: Change in cost for the baseline case, showing changes in the cost of the habitat, the HPS, and launch, as well as changes in total cost. All values are shown as a percentage of the total cost of the Open Loop architecture.**

![Total Departure Mass for the baseline case.](image3)

**Figure 4: Total departure mass for the baseline case.**

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B. Sensitivity Analysis

The results in Section A are associated with one set of assumptions regarding food hydration, number of EVAs, POS, mission opportunity, and amount of testing. This section presents the results of a sensitivity analysis examining a range of values for each of these parameters. Unless otherwise noted, each parameter is examined independently—that is, these analyses vary one parameter at a time while holding all others constant at their baseline values. Figure 5 shows the results of sensitivity analysis on food hydration levels, number of EVAs, and POS.

Lower food hydration levels have the potential to reduce mass for higher loop closure systems, as those systems can use recycled water to hydrate food, and thus reduce stored food mass without requiring an increase in stored water mass. This trend is highlighted in Figure 7, which highlights the impact of food hydration levels on ECLSS mass, including water, oxygen, tanks, food, and ECLSS systems, spares, and maintenance items. Lower food hydration has two direct effects: reduction in stored food mass (due to reduced water content), and an increase in the amount of water required to hydrate the food for crew consumption. For open loop systems, these effectively cancel out, as the reduction in food mass is equivalent to the increase in water mass. Depending on storage overhead associated with food and water, this change may result in a net mass increase. However, when water recycling is available, the water used to hydrate the food can be recycled. As a result, lower food hydration levels coupled with water recycling can enable lower stored food mass without the corresponding increase in stored water requirements if the recycling capability is able to make up for the increased water demand. However, if food hydration levels are high, then the water stored in the food may reduce or even negate the value of water recycling capabilities. For example, at 50% food hydration, the level of loop closure provided in the Sabatier case is sufficient to reduce stored water requirements down to their minimum levels (i.e. a small

Figure 5: Results of sensitivity analysis, showing the impacts of changes in food hydration (top), EVAs (middle), and POS (bottom) on total departure mass. Parameters not being examined are held at baseline values in each case.

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contingency amount). Additional loop closure does not provide additional value at those high food hydration levels, as stored water is already reduced to its minimum value. In fact, high loop closure coupled with high food hydration may be counterproductive, as excess water will be generated as the crew consumes water in the food and it is recycled by the ECLSS. Collecting and storing this excess water would result in increased transportation system mass, and therefore it is simply vented overboard and provides no value.

EVA count does not have a significant impact in the range examined here. For context, 6, 12, and 18 EVAs correspond to a rate of approximately 1 EVA every 6 months, 3 months, and 2 months, respectively. Each EVA results in lost consumables due to airlock cycling and other factors, and as a result a larger number of EVAs results in a higher logistics requirement. While this effect is small for this range, it is expected that increased EVA frequency (e.g., once per month or once per week) could result in larger increases in logistics requirements.

Changes in POS result in changes of mass of spares required to achieve that POS level. The baseline POS level examined here, 0.98, corresponds to a 1 in 50 chance of insufficient spares during the mission – that is, a 1 in 50 chance that an ORU fails during the mission and there are no remaining spares available to replace it. The two other POS levels examined here, 0.99 and 0.995, correspond to a 1 in 100 and 1 in 200 chance of insufficient spares, respectively. Higher POS requirements result in higher spares mass, and ECLSS architectures with higher levels of loop closure (which are typically correlated to more complex systems with higher parts counts) are more sensitive to changes in POS.

Figure 6 shows the combined impacts of food hydration, EVA count, and POS by examining two cases: an “aggressive” case that uses the lowest values of each factor (30% food hydration, 6 EVAs, 0.98 POS) and a “conservative” case uses the highest values (50% food hydration, 12 EVAs, 0.995 POS) cases to the baseline. Both cases assume a 2035 mission opportunity and no additional testing. These results, along with the individual sensitivity results shown in Figure 5, show that these three factors alone can result in a more than 12 t change in departure mass for high loop closure cases. In addition, these factors can change the relative value of different investments. For example, in the conservative case (under the modeling assumptions used here), Brine Drying results in the lowest total departure mass. However, in the aggressive case additional loop closure beyond this point produces additional benefits, with Bosch providing the lowest mass.
Figure 8 shows the impacts of testing and changes in mission opportunity. As noted in previous work,3,4 testing and operational experience are key activities that are required to improve and validate failure rate estimates, and can significantly reduce the spares mass required for Mars missions. This analysis examined the potential change in mass resulting from 10 years of testing. Future ORU failure rate estimates are projected by performing a Bayesian update under the assumption that the number of failures that occur during the test period is the most likely (i.e. modal) number of failures, given current estimates. It is important to emphasize that there is no way to know the outcome of a test until the test is completed. This analysis assumes a test outcome in order to examine potential impacts; it is not a prediction of a specific test benefit. Actual test results should be used to track progress and continue to update forecasts. These results indicate that testing provides value in all cases, and that more complex systems with higher loop closure tend to see greater benefits from testing. This is largely because spares mass is greater in these cases, and therefore there is more potential for savings via failure rate uncertainty reduction. Under the modeling assumptions used here, testing reduced the total mass associated with the Bosch architecture by nearly 10 t (8%).

All mission opportunities are not created equal. Different mission opportunities have different delta-V requirements, resulting in different transportation system mass and cost. The baseline case and sensitivities examined above assumed a mission during the 2035 opportunity (i.e. the system departs Earth in 2035). Figure 8 also shows the impact of a change to the 2041 opportunity for the baseline case. However, due to the different energy requirements of the 2041 trajectory, the HPS and propellant mass are significantly increased in all cases, by approximately 20 t to 27 t. More closed-loop architectures experience a larger increase in mass from this change, largely because (as shown in Figure 2) these architectures do not shed as much mass over the course of the mission and thus tend to have higher EOI masses. These results indicate that total departure mass is very sensitive to the particular mission opportunity being examined. System designers and mission planners must carefully consider which opportunity or set of opportunities that a system is meant to be used for to ensure that it achieves required performance in all cases. A system optimized for one mission opportunity may not be effective for another opportunity.

Figure 9 shows the sensitivity of total mission cost to changes in the above parameters, as a percentage of the total cost of the baseline Open Loop architecture. The cost for the baseline case is shown alongside the aggressive and conservative cases from Figure 6, as well as the testing case and 2041 case. Note that the cost model does not currently include the cost of changing the food hydration levels and verifying that different food hydration levels meet crew nutritional needs, nor does it include the testing costs. These numbers only include the production, development, and launch of the habitat and HPS (including spares and maintenance items) as well as launch costs associated with other logistics and propellant. The aggressive case shows a similar cost trend to the baseline case until the three ECLSS...
architectures with highest loop closure, at which point the combination of reduced food hydration and increased loop closure enable mass reductions. The conservative case shows higher costs for all ELCSS architectures, partly as a result of increased mass and partly due to increased procurement quantities for ORUs due to increased spares requirements to meet higher POS targets. Larger cost changes are shown in the test and 2041 cases. Additional testing enables a reduction in mass as well as a reduction in spares quantity, lowering costs in two ways; however, as noted previously this cost model does not include the cost of testing, so these cost changes should be considered only the potential benefits of testing, not the total value of testing.

IV. Discussion

Three key findings emerge from the results above. The first is that choice of the objective by which a decision on degree of ECLSS closure is made impacts the resulting choice; thus, the identification of the relevant metric to stakeholders will impact resulting decisions in ECLSS selection. The second is that there are interdependencies between the ECLSS systems and other systems (in this study, particularly the transportation system) that prevent any single system from being optimized in isolation. The choice of degree of ECLSS closure is strongly coupled with the requirements on the transportation system, which in turn impacts the demands on the ECLSS system. The third is that mission, architecture, or campaign level assumptions and requirements can override the impact of any decision made on the degree of ECLSS closure. Only at the integrated level of the system architecture can ECLSS choices be fully evaluated. Each of these findings in discussed in further detail below.

A. Choice of Objective Impacts Architecture Preferences

As in any decision problem, different stakeholders have different value systems, which manifest in different priorities in making a decision. Different priorities may also be implemented at different levels of scope within the system. When propagated up to full system- and mission-level metrics, these priorities may not have the intended effect. Integrated systems analysis, however, directly connects system and subsystem decisions to high-level metrics, enabling informed optimization of system architecture and design.

For example, a performance-oriented ECLSS designer may select loop closure as a metric to be maximized. Under that objective, the Bosch case would be the “best” system, as it provides the highest loop closure. However, maximizing loop closure is not equivalent to minimizing mass, as it typically results in higher system and spares mass and can lead to sub-optimal design as has been shown by Do et al. and Lange and Anderson, among others. This analysis finds that the loop closure level that minimizes mass is strongly dependent upon the food hydration level, as shown in Figure 5 and Figure 8. At 50% food hydration, maximum loop closure does not minimize mass; when hydration levels are reduced to 30% (a significant change), the highest loop closure does result in the lowest mass. However, it also results in maximum system complexity, as more systems are required to enable that loop closure. Testing also has the potential to significantly lower the spares mass associated with these more complex systems, and has the potential to make the more attractive solutions from a mass perspective. At the other end of the spectrum, the simplest and least expensive ECLSS solution would be an open-loop system. This may be attractive from the perspective of minimizing ECLSS cost, but it results in significantly higher logistics mass. This in turn places a significant burden on the transportation system, which likely increases transportation cost as well as increases overall departure mass.

At the level of the system engineer responsible for the integrated vehicle going to Mars, minimizing the total payload mass (consisting of the ECLSS system, the logistics and spares, and the habitat itself) at departure may be the...
objective by which they evaluate their different options. Toward that objective, the Brine Drying case is the preferred option, as the total payload mass at Earth departure is minimized. An alternative objective would be to minimize the total departure mass of the system, as illustrated in Figure 8. Toward that objective, Brine Drying remains the preferred option in 2035, but Sabatier is the preferred option in 2041. Thus, even two similar and highly related objectives (minimizing total payload mass and minimizing total departure mass) can yield different preferred options, particularly when considering sensitivity to other variables.

At the level of the program manager responsible for the investments made in developing a capability to send humans to Mars, minimizing the total cost of the integrated vehicle may be the objective by which they evaluate their different options. As seen in Figure 3, the costs of the integrated vehicle do not vary monotonically with degree of ECLSS closure. Transportation system cost is proportional to transportation system mass, however, and the change between cases result in shifts in the HPS mass (see Figure 4), which correspond to a decrease in total cost. Thus, while ECLSS system, spares, and maintenance costs increase as degree of closure increases, logistics and transportation system costs decrease. The relative magnitudes of those costs and the changes they experience determine which case has the lowest overall cost. In addition, changes to underlying parameters – particularly food hydration, POS, testing, and mission opportunity – can significantly shift the estimated system cost as well as the relative costs between different levels of loop closure.

The objective by which ECLSS architectures are evaluated will impact what option is preferred. Preferences will also be different between evaluations focused on ECLSS, habitat, transportation system, or integrated system performance. It is therefore vital that the relevant stakeholders, and the objective(s) they value, be identified to inform design choices in the ECLSS system. The choice of ECLSS architecture cannot be made without knowing whose values will drive that choice.

B. Isolated System Optimization May Not Lead to Optimal Integrated Systems

Space systems architecture and design is a highly coupled activity. Decisions made in one system, such as ECLSS, can strongly impact the requirements levied on other systems, such as transportation. Optimization requires an objective (or multiple objectives) to be optimized, and this choice itself may have a variety of impacts as discussed in Section A. However, optimization also requires a selection of the scope over which to optimize – that is, the set of systems and impacts that are considered during optimization. Decisions that improve the characteristics of a single system in isolation may have unintended negative effects on other systems, and therefore optimization of systems in isolation may not lead to an optimal integrated system.

The degree of ECLSS loop closure directly impacts the requirements levied on the transportation system. A decision to optimize based on minimizing ECLSS cost and/or complexity, for example, would likely select a low loop closure option, such as the ones represented in the Open Loop case. However, that decision would increase the mass that must be pushed by the transportation system by approximately 20t. This results in greater power and propulsion needs for the transportation system. As the power needs for the transportation system increase, more arrays are required for the electric propulsion system, which increases the complexity of packaging the vehicle in a single launch, and may even necessitate in-space assembly. In addition, a larger payload requires greater quantities of propellant to perform the same maneuvers, and thus the vehicle’s propellant tanks (and the resulting vehicle) must increase in mass and volume. This larger design increases the cost of the transportation system. Potential changes in the number of launches required to deploy the transportation system have impacts on the schedule of the entire Mars mission, requiring either an accelerated cadence of launches or a delay in the Earth departure date. Thus, the ECLSS architecture decision impacts not only the design and operation of the crew’s habitat, but likely has consequences that ripple through the entire mission architecture.

C. ECLSS Decisions are Driven by Mission Assumptions

Assumptions and choices at the mission level may also constrain the options for ECLSS closure, or may be so impactful on the integrated vehicle mass or cost that the choice of ECLSS closure becomes trivial by comparison. The mission may call for additional EVAs that necessitate greater degrees of ECLSS closure to makeup EVA losses. Changes in the proportion of hydrated to dehydrated food provided to the astronauts lead to changes in the amount of water carried in the food, which impacts the value of water recycling and may change the optimal level of loop closure. However, it is important to note that such changes in the food mixture have nutritional and psychological impacts on the crew during the multi-year mission. There is currently insufficient information to determine if a diet with different hydration proportions will still meet the nutritional and psychological needs of the crew on the three-year mission, and further research may be required to determine if such changes in food hydration are feasible. The synodic period of Mars missions is such that the trajectory requirements in one opportunity are not identical to those in subsequent opportunities; some opportunities may require more delta-V during the outbound portion of the mission, while others may require more delta-V on the return trip. These shifts in propulsion needs can favor options that have less mass at
the beginning of the mission (cases with higher degree of ECLSS closure) or options that have less mass at the end of the mission (cases with minimal ECLSS closure). Further, if there is a desire to reduce the total mission time in space by flying non-minimal energy trajectories, the costs of the associated transportation system may dominate the costs of the payload regardless of the choice for ECLSS closure.\textsuperscript{12} Thus, mission or architecture factors that exist independent of the ECLSS system design may impact or override the preference for the degree of ECLSS closure.

V. Future Work

The analysis presented above includes a detailed evaluation of ECLSS architectures, their impacts on logistics and spares requirements, and the resulting impacts on transportation systems. However, there are several factors that are not currently included in the model but are planned for future updates. The size of the habitat itself is currently assumed to be the same in all cases. However, changes in system, spares, and logistics loads will result in changes to stowage requirements, which may impact habitat sizing. In addition, power and thermal systems will be modeled to account for the increased power demand resulting from additional systems added to increase loop closure. The current model assumes that spares are kept on board throughout the entire mission; however, there are potentially significant benefits to jettisoning spares throughout the mission to reduce mass at later burns. Future iterations of the model will include this factor and assess its impact on risk. Finally, this analysis discussed cost indirectly, but future iterations will include more sophisticated cost estimation in order to enable more direct comparison between options on ECLSS, habitat, transportation system, and launch costs.

Food hydration level has been identified as a key driver of overall logistics mass and ECLSS architecture. While this model evaluated the impacts of changing food hydration on these metrics, further research is required to understand the impact of these changes on nutrition, palatability, psychology, and other crew health factors. The integrated system modeling presented here will help provide insight into the potential benefits of changing food hydration, but additional research and testing may be required to determine if those changes are feasible.

In addition, testing and reliability growth can have a significant impact on spares mass requirements\textsuperscript{3-5} which may result in more favorable trades for the cases that have larger spares masses. However, testing also impacts program schedules and cost. Further research will investigate these impacts and develop a model to include the cost and schedule impacts of testing in integrated system evaluation.

Finally, while the sensitivity analysis presented here examined a wide range of factors, there are many others that are likely to have a significant impact on results. For example, the transportation system analysis assumed that all cases had the same SEP power level. However, given that the payload mass (i.e. habitat mass) changes significantly between different cases, it may be that a different SEP power level leads to a more optimal solution. In addition, this analysis assumed a conjunction-class mission. Other, higher-energy trajectories may enable shorter missions (reducing logistics requirements) at the expense of higher delta-V (increasing propellant requirements and HPS size). Future analysis will include further exploration of the impact of different trajectories on architecture decisions, along with other factors associated with habitat and transportation system design and concept of operations.

VI. Conclusions

The preferred degree of ECLSS closure depends on the objective(s) by which that decision is being made, and cannot be made in absence of consideration of other systems within a space mission architecture. Minimizations of mass, complexity, and cost each have the potential to yield different preferences in the choice of ECLSS approach; thus, it is the identity of the decision-maker and their associated value system that determines that preference. The additional mass of a less closed ECLSS system can significantly increase the burden on the transportation system, necessitating additional launches and an impacted schedule to accomplish a mission. However, further degrees of closure may have only minimal impact on the transportation system at the expense of additional spares and added complexity; hence, the choice of ECLSS closure likely lies not at one extreme or the other, but instead depends on the interrelationships between multiple systems within an architecture. ECLSS, like all other spacecraft systems, does not exist in isolation. ECLSS architecture decisions ripple through the entire spacecraft and mission design, and these impacts should be carefully considered throughout the design and development process.

References
