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Advanced Life Support Equivalent System Mass Guidelines Document

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SYMBOLS

C	cooling requirement of subsystem i [kW$_{th}$]
C_{eq}	the mass equivalency factor for the cooling infrastructure of subsystem i [kg/kW$_{th}$]
CT	crewtime requirement of subsystem i [CM-h/y]
CT_{eq}	mass equivalency factor for the crewtime of subsystem i [kg/CM-h]
D	duration of the mission segment of interest [y]
ESM	ESM value of the entire life support system (the sum of the crewtime and non-crewtime portions of ESM) [kg]
ESM_{CT}	crewtime portion of ESM [kg]
ESM_{NCT}	non-crewtime portion (considers mass, volume, power, and cooling only) of ESM [kg]
ESM_{TOTAL}	ESM value of the entire life support system (the sum of the crewtime and non-crewtime portions of ESM) [kg]
L_{eq}	location factor for the segment of interest [kg/kg]
M_I	initial mass of subsystem i [kg]
M_{TD}	time- or event-dependent mass of subsystem i [kg/y]
P	power requirement of subsystem i [kW$_e$]
P_{eq}	mass equivalency factor for the power generation support infrastructure of subsystem i [kg/kW$_e$]
SF_I	initial mass stowage factor for subsystem i [kg/kg]
SF_{TD}	time- or event-dependent mass stowage factor for subsystem i [kg/kg]
SIMA	Systems Integration, Modeling and Analysis
t_{LSS}	crewtime that is required to maintain the life support system (a subset of t_{WORK}) [CM-h/y]

$t_{MISSION}$	crewtime that is used in performing scientific, mission-oriented work (a subset of t_{WORK}) [CM-h/y]
t_{WORK}	total crewtime allotted for work (not devoted to time such as eating, sleeping, exercising, personal time, etc.) [CM-h/y]
V_{eq}	mass equivalency factor for the pressurized volume support infrastructure of subsystem i [kg/m^3]
V_I	initial volume of subsystem i [m^3]
V_{TD}	time- or event-dependent volume of subsystem i [m^3]

ACRONYMS

ALS	Advanced Life Support
AU	Astronomical Unit
BVAD	Baseline Values and Assumptions Document
ESM	Equivalent System Mass
ETCS	External Thermal Control System
ITCS	Internal Thermal Control System
LEO	Low-Earth Orbit
NASA	National Aeronautics and Space Administration
RMD	Reference Missions Document
R&TD	Research and Technology Development

1   ABSTRACT

Equivalent System Mass (ESM) is often applied to evaluate trade study options in the Advanced Life Support (ALS) Program. ESM can be used to identify which of several options that meet all specified requirements have the lowest launch cost, as related to the mass, volume, power, cooling and crewtime needs.

This document provides an introduction to the ESM concept, an explanation of the computational method, and a discussion of results interpretation and reporting. Any researcher with a basic understanding of the integration issues of an Advanced Life Support system may apply the methods in this document to perform an effective ESM-based trade analysis.

2 INTRODUCTION

2.1 Purpose of this Document

This document provides a definition of Equivalent System Mass (ESM), describes how to calculate ESM, and discusses interpretation of ESM results, in the interests of the Advanced Life Support (ALS) Project. The ESM computational method described in this document has evolved over several years and is consistent with the method used in the Advanced Life Support Project 2001 Metric Document (Drysdale and Hanford, 2002).

This document provides guidelines for performing an ESM evaluation for trade study[1] purposes. The document is designed to provide detailed instructive material for researchers who are performing ESM evaluations for the first time. It documents the ALS Systems Integration, Modeling and Analysis (SIMA) Element position on ESM, to provide consistency in ESM evaluations. This document also addresses ESM issues that have been frequently raised by ALS researchers.

2.2 Document Control

This document was created under the SIMA Element of the ALS Project. Thus, the final document will be under the control of the SIMA Lead. Please send document comments to the primary author and the SIMA Lead.

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[1] It is critical to note the difference between a "trade study" and an "ESM evaluation". An ESM evaluation is one of several possible tools that may be used in a trade study. A trade study may include various quantitative and qualitative criteria in evaluating technology options. In this document, the words "study" and "analysis" are used interchangeably. A trade study is a comparison of trade-offs for various options. A an ESM value for a single technology may be computed, but the value can only be compared to other options that are evaluated under identical assumptions. Moreover, an ESM value should never be "unconditionally" assigned to a technology, since most ESM values are scenario-specific.

2.3 ESM Definition, Rationale and Application

ESM is typically used as a transportation cost measure in ALS trade studies, to avoid the complications, both technical and political, of using dollar costs for comparisons. Because the cost to transport a payload is proportional to the mass of that payload, a mass-based measure such as ESM is used to quantify the launch cost of the life support system and associated infrastructure. An ESM value represents the sum of the life support system[2] mass and appropriate fractions of supporting system masses, including pressurized[3] volume, power generation, cooling, and crewtime, for maintaining a crew over the duration of a specified mission.

ESM should rarely be the only metric applied in a trade study. As a cost metric, ESM may not be capable of capturing reliability, safety and performance differences between trade study options. Thus, for ESM to be applied appropriately, the trade study options must meet some common prerequisites, and some characteristics might require comparison by means other than ESM. (This issue is discussed in Section 3.1.)

2.4 The Elementary ESM Equation and a Simple Example

ESM could include any aspect of the system that exerts an effect on system mass, but in practice the parameters of interest[4] are typically narrowed down to the following:

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[2] As it is used here, "system" may pertain to a complete life support system, or any subset of a complete life support system and supportive infrastructure.

[3] In reality, all volume in the habitat will be pressurized unless there are some materials or equipment that don't require pressurization (or possibly require less pressurization, such as a large plant chamber). However, if it is necessary for the crew to access materials and equipment that are unpressurized or pressurized below that of human requirements, an EVA expedition or temporary repressurization of that chamber would be required. Because of this, in typical missions, life support system equipment to which the crew might require access is pressurized. However, the possibility for alternative scenarios exists, which is the reason for the "pressurized" qualifier in this sentence.

[4] As with all aspects of a trade study, the parameters to include in an ESM analysis are subject to scrutiny by the analyst. If there is low confidence in a particular data value or equivalency factor, then the analyst should judge whether to include that parameter in the ESM evaluation or to qualify the issue in some other manner. In particular, crewtime data tends to be uncertain at low stages of technology development, although crewtime is a very critical and decisive part of typical human-rated space missions. (For example, EVA crewtime drove a major redesign of the International Space Station when it was determined that the crew could not support as much EVA as the design required.)

- Mass[5]
- Volume[5]
- Power
- Cooling
- Crewtime

Although these five parameters could be related to one another in a variety of ways, ESM is calculated as the sum of the mass equivalencies of these parameters.

Equation 1 is provided as a simplified version of the complete ESM equation (presented in Section 3.2). Equation 1 is provided for explanatory purposes only, for simple expression of the ESM concept for first-time ESM users. If an actual ESM computation is performed, the analyst should understand the complete ESM equation in Section 3.2.

$$ESM = M + (V \cdot V_{eq}) + (P \cdot P_{eq}) + (C \cdot C_{eq}) + (CT \cdot D \cdot CT_{eq})$$ Equation 1

where ESM = the equivalent system mass value of the system of interest [kg],

M = the total mass of the system [kg],

V = the total pressurized volume of system [m^3],

V_{eq} = the mass equivalency factor for the pressurized volume infrastructure [kg/m^3],

P = the total power requirement of the system [kW$_e$][6],

P_{eq} = the mass equivalency factor for the power generation infrastructure [kg/kW$_e$],

C = the total cooling requirement of the system [kW$_{th}$][7],

C_{eq} = the mass equivalency factor for the cooling infrastructure [kg/kW$_{th}$],

CT = the total crewtime requirement of the system[CM-h/y],

D = the duration of the mission segment of interest [y],

CT_{eq} = the mass equivalency factor for the crewtime support [kg/CM-h].

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[5] This parameter may have both initial and time-dependent components. See Equation 2.

[6] kW$_e$ = kW electrical

[7] kW$_{th}$ = kW thermal

Mass equivalency factors (V_{eq}, P_{eq}, C_{eq}, and CT_{eq}) are used to convert the non-mass parameters (V, P, C and CT) to mass equivalencies. Equivalency factors are determined by computing the ratio of the unit mass of infrastructure required per unit of resource. For example, consider a structure used for pressurized volume that is based upon a design that has a total volume capacity at launch of 300 m³ and a total empty mass of 30,000 kg. Such a design has a mass equivalency factor for volume of: V_{eq} = (30,000 kg/300 m³) = 100 kg/m³. Thus, if a subsystem in the ESM evaluation requires 4 m³ of pressurized volume at launch, it would have a *volume* cost ($V \cdot V_{eq}$) of (4 m³ * 100 kg/m³), or 400 kg.

Mass equivalency factor values may be obtained from the ALS Baseline Values and Assumptions Document (BVAD) (Hanford, 2002). However, it is also acceptable for a researcher to develop mass equivalency factors that are more appropriate for a particular investigation. In such a case, an explanation of the equivalency factor values and references should be provided in the analysis final report.

Each distinct segment of a mission should be considered individually in ESM evaluations. Quantifying the benefits of off-loading (e.g. venting, dumping) mass in between propulsion events requires segment-specific ESM computations. For example, consider two technologies that are being evaluated for the transit habitat of a Mars mission. If one of the technologies is able to off-load expended mass before launching from Mars orbit to Low-Earth Orbit (LEO), that advantage will only appear if the ESM for each mission segment is computed separately. Location factors may be required for segment-specific ESM values if those values are to be summed linearly or compared. This topic is discussed in Section 3.3.

The following *simple* ESM calculation is meant to serve as an example for conveying basic concepts to first-time ESM users. The example is not a trade study comparison, as only one technology option is evaluated. Some values in the example are based upon values provided in Doll and Eckart (1999).

Assume that the system of interest[8] is a carbon dioxide scrubbing device being rated for a Mars outbound transit mission (duration, D = 0.49 y). The investigator sizes the device for the appropriate processing rate, based upon assumptions about the mission of interest, and determines the following values. The hardware, expendables, and spares[9] required

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[8] Recall that in this document, "system" may pertain to a complete life support system, or any subset of a complete life support system and supportive infrastructure. For explanatory purposes, the system in this example is purposely restricted to a single hardware device. The appropriate system to define depends upon the objectives of the analysis and the extent and detail of the system necessary to reflect the total cost impact of each trade option. This issue is discussed further in Section 3.1.

[9] In the ESM descriptions after this section, most hardware is accounted under an "initial mass" term, and most expendables and spares are accounted under a "time-dependent mass" term. However, for simplicity in this example, initial and time-dependent mass (and initial and time-dependent volume) are not distinguished.

over the entire duration of the mission weigh 91.6 kg (M). The volume of the system is 0.45 m^3 (V). The power requirement of the system is 0.9 kW$_e$ (P), thus the cooling requirement of the system is 0.9 kW$_{th}$ (C). The crewtime requirement is 4 CM-h/y (CT).

Assume that the investigator chooses to apply equivalency factors provided in the ALS BVAD (Hanford, 2002) for a Mars transit mission. Thus, V_{eq} = 215.5 kg/m^3, P_{eq} = 237 kg/kW$_e$, C_{eq} = 60 kg/kW$_{th}$, and CT_{eq} = 1.14 kg/CM-h in Equation 1.

Applying the above values, the computation of *ESM* according to Equation 1 is:

$$ESM = 91.6 \text{ kg} + (0.45 \text{ m}^3 \cdot 215.5 \text{ kg/m}^3) + (0.9 \text{ kW}_e \cdot 237 \text{ kg/kW}_e) + \ldots$$
$$\ldots + (0.9 \text{ kW}_{th} \cdot 60 \text{ kg/kW}_{th}) + (4 \text{ CM-h/y} \cdot 0.49 \text{ y} \cdot 1.14 \text{ kg/CM-h}) = \underline{458 \text{ kg}}$$

Every piece of hardware in the system of interest may have mass, volume, power, cooling and crewtime requirements. However, in ALS trade studies the real quantity of interest in an ESM analysis is comparison of the *total system impact* of trade options, which is often more complicated than simple accounting of hardware items. Determination of the total system impact often involves determining the quantities of working materials in the system that are necessary to maintain crew health over the entire mission duration. To do this, the investigator should define the system to the appropriate extent and level of detail to *comprehensively* capture cost impacts of trade options. These issues are explained further in Section 3.1.

2.5   Purposes of the ESM Concept

The primary purpose of ESM is to serve as one of the tools used in life support trade studies of ALS system options[10] for space missions or ground-based test beds. Examination of transportation cost impacts using ESM, in conjunction with evaluation of other pertinent issues not addressed by ESM, can facilitate decisions on research and technology development. ESM also currently serves as a tool for computing the ALS Metric[11] that is reported to NASA Headquarters and, ultimately, Congress.

ESM evaluations can also be used to evaluate test-bed design and performance. In planning for post-test-bed ESM evaluations, data collected during the test should include mass, volume, power, cooling, and crewtime information. After a test-bed run, ESM evaluations may be used to provide an assessment of mission transportation cost for the particular system hardware, configuration and control approach used in the test bed.

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[10] The word "option" is used here to represent technology, hardware, configuration and/or control approach options.

[11] The ALS Metric is based upon ESM evaluations of candidate, future long-duration mission scenarios. The ALS Metric concept and computational method is documented in detail in Drysdale and Hanford (2002).

Similarly, ESM can be calculated for particular implementations of potential reference missions, such as missions in the ALS Reference Missions Document (RMD) (Stafford *et al.*, 2001). The effects of variations on life support system designs or transportation architectures for a reference mission can be considered using ESM, in conjunction with evaluation of other important features, to rank various options for that mission.

2.6   Users

Users of ESM can include:

- System Analysts
- Researchers
- Technology Developers
- Managers

Typically, the role of computing ESM is assigned to life support system analysts, who obtain technology data from researchers and technology developers as well as from historical documents, reports and databases. The results from ESM analyses are then presented and explained to various members of the community, including researchers, technology developers, and managers. Community members may use the results of ESM evaluations, along with other important criteria, to make decisions about research and technology development (R&TD) direction, and/or test bed and reference mission technology options.

However, analysts are not necessarily the only individuals that compute ESM. In some cases, researchers, technology developers, and managers may perform ESM evaluations. This document is designed to guide any individual in performing meaningful and consistent ESM evaluations.

3   ESM COMPUTATIONAL METHOD

ESM calculations involve significant amounts of data and assumptions, and the calculations should be performed in a consistent fashion if the results are to be comparable and useful for trade study purposes. This section of the document discusses decisions and assumptions about the analysis, as well as application of the ESM equation.

3.1   Decisions and Assumptions about the Analysis

An analysis requires consideration of the following six interconnected facets, while documenting all critical assumptions.

1)   Determination of analysis objectives

2)   Determination of the mission of interest and related assumptions

3)   Determination of the system characteristics that should be captured in the analysis

4)   Definition of the system extent and level of detail

5)   Application of data

6)   Interpretation of results

As illustrated in Figure 1, because knowledge is gained during the analysis process, the analysis steps may be iterative[12]. At any point in the analysis process, it may be necessary to reiterate a previous step. As the process is iterated, the investigator should take the opportunity to review the analysis objectives, critical characteristics, system definition and data application and change them if necessary. Because ALS inherently deals with missions that are incompletely defined, the analyst should also make an effort to document all design assumptions during the course of the study.

3.1.1 Determination of Analysis Objectives - Analysis objectives drive all facets of the ESM computation. Objectives should be thoroughly defined in order for the investigator to determine the mission of interest and system characteristics to capture in the study, define the extent and detail of the system, and apply data.

Ideally, analysis objectives are defined at the inception of the study, in an appropriate level of detail. However, in reality, the need for further clarification of the objectives often arises during the course of the research. This document provides examples that

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[12] One commonly useful iteration approach is to compute rough estimates of ESM values at the inception of the study, in order to identify critical issues, before embarking on study details.

portray the need for clear, appropriately detailed analysis objectives. With experience, an analyst can gain foresight into the proper level of detail that is required in defining the study objectives.

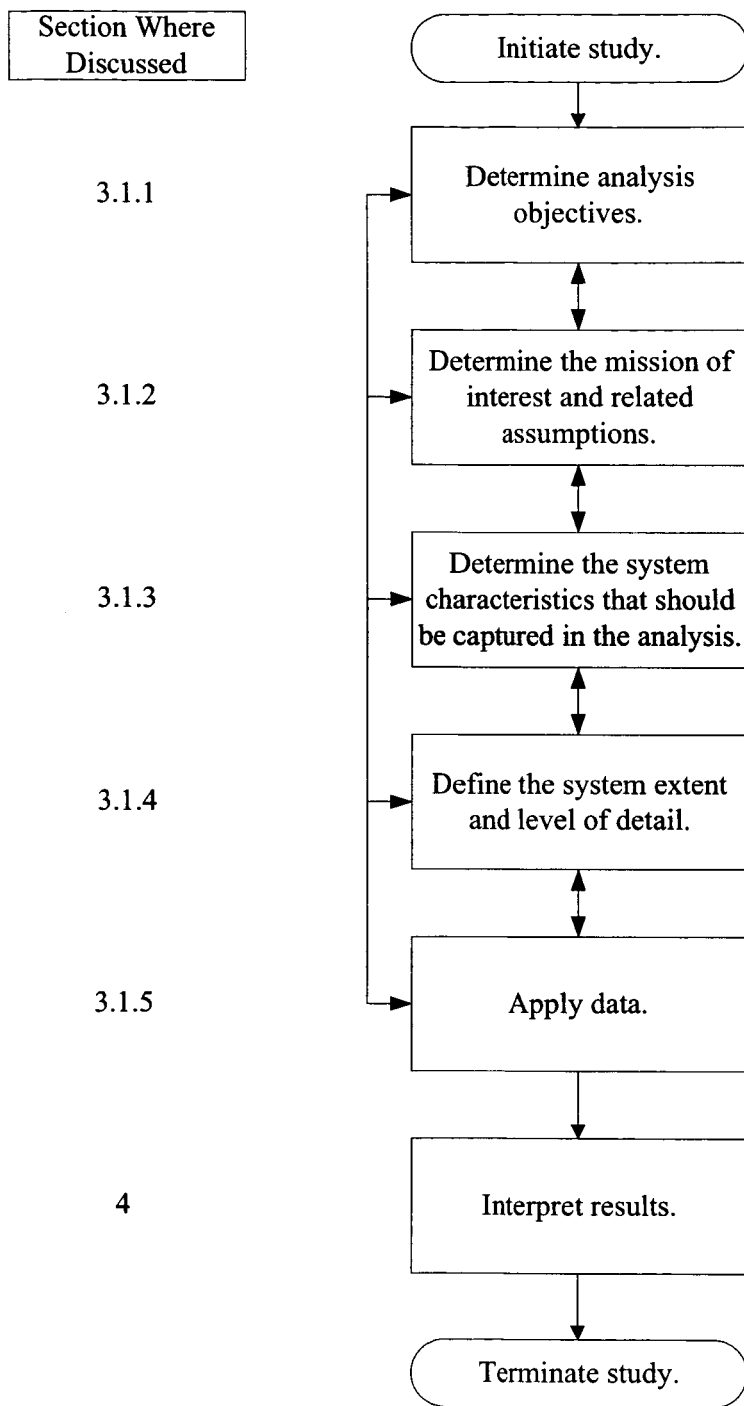| Section Where Discussed	
	Initiate study.
3.1.1	Determine analysis objectives.
3.1.2	Determine the mission of interest and related assumptions.
3.1.3	Determine the system characteristics that should be captured in the analysis.
3.1.4	Define the system extent and level of detail.
3.1.5	Apply data.
4	Interpret results.
	Terminate study.

Figure 1. Flowchart for the ESM analysis process.

3.1.2 Determination of the Mission of Interest and Related Assumptions - The results of an ESM analysis depend on the assumptions made about the operating environment, the subsystem of interest, and the surrounding system. Consequently, an ESM analysis must be done with a particular mission and set of assumptions in mind.

The ALS RMD is one source that analysts can use for selection of a particular reference mission for consideration in a trade study. Indeed, if the mission of interest is addressed in the RMD, it is recommend that the RMD assumptions be used in the study baseline. If not, RMD missions can possibly be used as a starting point, and mission changes can be documented.

Top-level assumptions that are related to RMD missions are documented in the ALS BVAD. Such assumptions include, for example, mission-specific[13] mass equivalency factor values, the number of crew members, number of visits to each site, mission duration, habitable volume, infrastructure costs, crewmember body mass, and typical metabolic loads. When deemed applicable by the analyst, the values provided in the BVAD may be applied to trade studies. If other estimates are applied in lieu of BVAD values, the investigator should provide appropriate documentation[14] for those values.

In addition to the top-level mission assumptions, notions about the details of system hardware, configuration and control are inherently made throughout a trade study. All top-level and system detail assumptions should be well described, referenced and organized throughout the trade study documentation.

3.1.3 Determination of the Characteristics of Interest and the Means by Which to Capture those Characteristics in the Study - Based upon the analysis objectives, the investigator determines which characteristics should be captured in the trade study. The investigator must then determine the means by which those characteristics will be captured in the trade study.

Characteristics of interest may be considered *prerequisites* for inclusion in the study, or they may be *compared* (quantitatively[15] and/or qualitatively[16]) between trade study

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[13] An equivalency factor only has value in the context of an actual mission scenario from which analysts can assess the infrastructure costs.

[14] If the documentation is well-known and reliable, a simple reference is adequate. Otherwise, derivation of the values should be provided in the analysis documentation.

[15] Other methods of quantitative comparison that are deemed appropriate by the analyst for the study might be unrelated to ESM, or they might be some modification of ESM. For an example of a comparative measure that is a modification of ESM for evaluation of food systems, see Cruthirds (2001).

options. For characteristics that will be compared, the analyst must decide upon a means of comparison. If the investigator judges that ESM is the best approach to take in comparing that particular characteristic and if the necessary data is available for an ESM comparison, then characteristics should be compared by the ESM method. If the analyst determines that a non-ESM means is required for a characteristic comparison[17], that characteristic can be compared by some other quantitative or qualitative method.

Characteristics of interest might be based upon function, availability, safety, gravity dependence, radiation susceptibility, noise levels, or a variety of other attributes. Evaluation of characteristics requires that the investigator have a comprehensive understanding of each trade study option.

As mentioned above, some characteristics may be considered prerequisites for including a technology in the study. For example, if an analysis objective is to identify the lowest ESM technology that provides a specified degree of water recovery from wasted food, then only technologies that can provide that specific function[18] should be considered in the analysis. However, comparable function might not be the only required characteristic. For example, if the analysis is being done to evaluate technologies for water recovery from wasted food for a LEO mission, then any technologies that are incompatible with microgravity should be eliminated from the study[19]. Similar prerequisites may exist for

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[16] Note that qualitative comparisons should only be used when there is inadequate data available for a quantitative comparison. There is a danger in making biased decisions based on qualitative comparisons of critical issues.

[17] Often, the possibility of quantifying significant option differences depends largely on the data availability and the degree of confidence in that data. The analyst must sometimes make judgements, based upon degree of conversion difficulty, of whether to convert non-ESM quantities into ESM values.

[18] The word "function" in this document pertains to the general role of a system. For example, the function of a laundry system is to clean clothes; the function of a four-bed molecular sieve is to remove carbon dioxide from an atmosphere. A system may have more than one function. For example, an incinerator may have functions that include recovering carbon dioxide from waste material, recovering water from waste material, and biologically stabilizing waste materials. "Function" should not be confused with "performance", which is a descriptor of the ability of a system to execute a particular function.

[19] The analyst should consider whether the technology concept itself is incompatible with microgravity, or if a particular implementation (i.e. design) of the technology is incompatible with microgravity. In the former case, the technology might be eliminated from the study if microgravity compatibility is a prerequisite. In the latter case, projections can be made on the change in ESM that would be associated with making the technology design microgravity compatible. However, design change estimates for microgravity compatibility are best done directly by the technology developer.

performance, availability, safety, radiation susceptibility, noise levels and other characteristics, depending on the analysis objectives and the investigator's judgement[20].

The prerequisites for some characteristics may be exceeded in some trade options. Generally, there is no value in exceeding the performance requirements. However, depending on the objectives of the study, in some cases, the benefits (or detriments) of exceeding those prerequisites should be quantified or qualified. In the example in the previous paragraph, the water recovery efficiency (percentage of water recovered) may be greater in one trade option than in another. The difference (if in fact beneficial or detrimental) of exceeding this requirement might be reflected in an ESM analysis, by some other quantitative means, or in a qualitative manner in the study.

As discussed in the first paragraph of this section, some characteristics that are not considered prerequisites may require quantitative or qualitative evaluation. For example, assume that an analyst decides that comparable functionality is the only prerequisite for including a technology in an evaluation for a Mars surface mission. If the specific function required is water recovery from inedible plant materials, then many different technologies, including heat-drying, freeze-drying, composting, and incineration may be included in the analysis. However, the above-mentioned options may be very different in terms of performance, availability, safety, radiation susceptibility, noise levels, waste stabilization capabilities, and other characteristics. If such differences are expected by the investigator to be important in selection between trade options, then those differences should be either quantified or qualified in the study.

After considering the type and quality of analysis data that is available, the analyst may conclude that an ESM evaluation would reflect differences in launch costs between two trade options, given functional and performance requirements. However, the analyst might conclude that availability, safety and other differences should not or cannot be reflected in the ESM evaluation. Such a decision may be made for reasons of data inadequacy, uncertainty about flight requirements for those characteristics, or the availability of a more appropriate quantification method.

After determining the characteristics of interest and the means by which to capture those characteristics in the study, the system may be defined to the appropriate extent and level of detail.

3.1.4 Definition of the System Extent and Level of Detail - The analyst should define the system to the extent and level of detail necessary to compare characteristics of interest in trade options. ESM can often be calculated for a portion of the life support system, if

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[20] If the differences between ESM values in accounting for a characteristic difference is expected to be insignificant, then it may not be worth the analysis resources (time and money) to investigate that particular issue. However, if a characteristic difference is expected to be significant, but data is unavailable to quantify that distinction, then the analyst might qualitatively discuss the difference.

the rest of the system remains identical between trade study options. This section presents two brief examples to illustrate these concepts: 1) comparison of $10m^2$ of salad crop to $10m^2$ of wheat crop, and 2) comparison of oxygen generation via bioregeneration (green plants) to oxygen generation via water electrolysis. For the purposes of Advanced Life Support, the system extent may range from the entire life support system and interfaces[21] to any subset thereof.

The system should be defined to the appropriate extent. The analyst should consider any portion of the life support system that has a significant effect upon, or is significantly affected by the trade options. For example, if a comparison is being made between growing $10m^2$ of salad crop versus growing $10m^2$ of wheat crop, in addition to the differences in crop production specifics, the evaluation should include significant differences outside of the biomass production system. For example, the wheat crop option may require significantly more food processing resources (equipment mass, volume, power, cooling and crewtime) than the salad crop option. The wheat crop option may also be more effective in generating oxygen, removing carbon dioxide and producing food energy than the salad crop option, resulting in sizing differences in air revitalization equipment and prepackaged food stores. The different crops may also result in different types and quantities of wastes, resulting in differences in the necessary waste subsystem. Depending on the analysis objectives and the investigator's judgement, it may be necessary to include such subsystems when defining the system for study.

The system should be defined to the appropriate level of detail. In the comparison of $10m^2$ of salad crop and $10m^2$ of wheat crop, issues such as nutritional (macro- and micro-nutrient) differences, palatability differences and differences in crew psychological benefits between the two options may be difficult to reflect in the ESM computation. In that case, if considered by the analyst to be important, such differences should be addressed, qualitatively and/or quantitatively, elsewhere in the study. Some differences, such as the sensitivity of the different crop types to system perturbations, may be, in theory, quantifiable in the ESM computation. However, the data necessary for such quantification may not be available. If inadequate data exists for revealing critical differences between options, or if the ESM method is unable to reflect the differences, then those differences should be discussed quantitatively and/or qualitatively in some other manner in the study.

Identification of the appropriate system extent and level of detail for an ESM evaluation may be complicated by major functional differences between options. In some cases, technologies of interest might have some overlapping functionality and some non-

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[21] The reader is referred to the ALS Baseline Values and Assumptions Document (Hanford, 2002), Table 2.4.1 and Table 2.4.2, for descriptions of ALS Subsystems and Interfaces. ALS Subsystems include Air, Biomass, Food, Thermal, Waste and Water. ALS Interfaces include Crew, Cooling, Extravehicular Activity Support, Human Accommodations, In-Situ Resource Utilization, Integrated Control, Power and Radiation Protection.

overlapping functionality. For example, oxygen generation via bioregeneration (green plants) may be compared to oxygen generation via water electrolysis, because there is some overlapping functionality (oxygen generation). However, because green plants also provide other critical functions, such as carbon dioxide scrubbing and water purification, the investigator should make an effort to define at least functionally comparable systems. For example, a carbon dioxide scrubber and water purification system may be added to the water electrolysis option. Food processing and waste systems may also be modified for comparable functionality. However, the two options may still differ in *degree* of water purification (quality of the output water). Depending on the objectives of the analysis, the analyst may choose to either further modify the options to achieve an even greater degree of commonality or to qualitatively discuss the purification differences. The appropriate approach depends on the potential impact on analysis results and the degree of resources (i.e. time and money) that have been assigned for the investigation.

Regardless of the system definition approach, a justification of the system extent and level of detail should be provided in the analysis report, so that the analysis choices can be scrutinized.

3.1.5 Application of Data - Raw data provided by researchers and technology developers may require some modification in order to fit into the context of a particular ESM evaluation. Data modifications may include, but are not limited to, development state adjustment, and/or system scaling. Although development state adjustment and system scaling are the most common types of data modification in an ESM analysis, other types of modification may be necessary. All data modifications should be explained and quantified in the analysis report.

3.1.5.1 Development State Adjustment: Depending upon the objectives of the analysis, some data may require adjustment for the appropriate development state[22]. In ALS trade studies, the flight-ready development state is typically of greatest interest for ESM evaluations[23]. However, because there is no official definition of the flight-ready development state, the analysts judgement must be used to determine the modifications that are appropriate for the particular analysis.

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[22] "Development state" is analogous, in some situations, to Technology Readiness Level (TRL). TRL is a scale of nine technology development increments that is often used within NASA to characterize the development status of a technology. Although the ALS Program is typically interested in the flight-ready development state, other states, such as the current state or ground-based test-ready state could potentially be of interest.

[23] In predicting the efficiency of flight-ready technology, the theoretical best performance may be of interest. Particularly, flight-ready performance may be difficult to predict for a technology in the early stages of research and development (TRL 1). In such a case, the researcher may choose to base performance predictions on the theoretical best performance that could be achieved. If the theoretical best performance is assumed in a study, this should be clarified in the analysis documentation.

For trade study comparisons, all equipment data should be "normalized" to the same development state[24]. Normalizing data to a future development state often requires that the investigator make assumptions in order to modify values or to estimate missing values. All such assumptions and their reasoning should be thoroughly documented so that the analysis results can be understood in the appropriate context.

For example, in determining a flight-ready development state ESM, the analyst may predict that advances through R&TD will result in improved design sophistication such as material types, automation, and processor efficiency, thereby reducing the flight-ready ESM. Similarly, critical system characteristics may necessitate modification of the raw data to appropriately capture those qualities in the analysis.

To adjust raw data for a flight-ready development state, in addition to improvements in the technology during development, the investigator should account for the environment of the mission and any other anticipated mission requirements. A list of possible motivations for data adjustment to flight-ready status are listed in Table 1. As there are currently no official guidelines for quantifying such factors in an analysis, the analyst should judge the importance of such adjustments against the availability of data and the analysis resources needed to make the modifications.

Requirements of future missions are (by definition) uncertain, and the information needed to make data adjustments is often unavailable. Probably the most difficult issue in comparing flight ready options with developmental options is the amount of detailed data available. Flight equipment is by definition complete, thus necessary data is available. Developmental equipment, however, might have no data on maintenance costs or crew time, and may not have all the pieces necessary for safely operating the equipment in a space environment. For example, a bench-top electrolysis unit might not have all of the sensors and safety equipment required to prevent a hydrogen explosion. It might not have been run long enough to know the lifetime of the consumables and spares. As an alternative to modifying data for a flight-ready development state, an analyst may state assumptions that flight equipment is similar to some earlier design stage. Such assumptions are often necessary, since the data needed for development state adjustments is often unavailable. An investigator may choose to qualitatively discuss necessary data alterations, rather than attempt to quantify the modifications. Regardless of the approach,

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[24] Whatever the development state of interest, proper comparisons should be made **in trade studies**. For example, it is inappropriate to compare an ESM value for the current development state of one carbon dioxide scrubber to the ESM value for the flight-ready development state of another carbon dioxide scrubber. The analyst should make a decision of which development state is appropriate for the trade study and normalize the data to that chosen state. In some **non-trade-study** cases of ESM computations, it may be necessary to compute ESM values for different development states for one set of hardware. For example, both the current development state ESM and the flight-ready development state ESM of one set of hardware may be of interest to project managers to estimate the ESM change between those two states.

all development state data modifications deemed appropriate for the study should be clearly explained in the analysis documentation.

Motivation	Example
Technology improvements during research and development	The analyst may predict that equipment may be better automated for a flight, thereby reducing the crewtime requirement.
Gravity conditions	The level of gravity during different phases of a mission will affect equipment structural strength requirements, and may drive modification of processes to accommodate differences in phase separation, convection and other characteristics.
Dust conditions	Equipment exposed to the Mars surface may require modification to enable operation during dust storms.
Sunlight conditions	A Mars greenhouse may require some degree of artificial lighting in order for plants (that have evolved in Earth conditions) to acceptably thrive.
Planetary protection requirements	If implemented on the Mars surface, technologies that vent gas to the external environment may require modification to prevent the release of possible biomarkers (in interest of the integrity of the search for life on the Mars surface).
Radiation conditions	It may be necessary to modify hardware materials to those which are less susceptible to radiation damage.
Launch forces	Equipment might be required to survive 3 g during launch from Earth. Parts of a technology (brittle materials, delicate instruments, fragile connections, etc.) may also be susceptible to launch vibratory forces, therefore requiring modification.
Noise level & associated frequency requirements	Locations without an atmosphere external to the habitat (e.g. LEO) will have more stringent constraints on noise levels and associated noise frequencies.
Safety requirements	Safety devices may be needed to bring equipment to a greater (i.e. flight-ready) safety level or to bring options in a trade study to comparable safety levels.
Availability requirements	Redundant equipment may be necessary to increase equipment availability or to bring options in a trade study to comparable availability levels.

Table 1. Some Possible Motivations for Data Adjustment to Flight-Ready Status

3.1.5.2 System Sizing and Data Scaling: Raw data received from researchers may require scaling for representation of the appropriately-sized system. For example, a technology developer may provide processor hardware parameters[25] for a laboratory prototype that processes only a fraction of the flow that would require processing in an actual mission or test bed. If the objective of the analysis is to compare functionally similar processors for a specific mass throughput, system sizing and data scaling is necessary.

Hardware is commonly sized according to a characteristic parameter. Lacking other information, throughput, or mass flowrate[26] through the equipment, is often a good correlating parameter. For example, in sizing an oxygen generation device, a typical approach is to multiply the number of crewmembers by the historical, individual, average oxygen demand.

The level of detail necessary for defining the system of interest determines the level of detail necessary in the sizing effort. In this respect, the investigator's judgement should be used to determine which material compounds should be included in the sizing effort. If a material compound has a relatively minor effect on system sizing, then it may be appropriate to exclude that particular compound from the sizing effort, in the interest of analysis time and funding. However, it is critical that the analyst contemplates the entire system of interest in the sizing effort, to include any non-intuitive yet significant sizing impacts. Sizing efforts often require that the investigator make assumptions about the hardware, configuration, and control approaches in the system. These assumptions should be clearly stated in reporting the evaluation results, so that the results can be considered in context of those assumptions.

Depending on the objectives of the analysis, the sizing effort may *range* from steady-state to transient[27] conditions[28]. In other words, system sizing efforts may lie anywhere in

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[25] In this document, "hardware parameters" pertain to the mass, volume, power, cooling and crewtime requirements of the hardware, which are inputs to the ESM equation, as shown in Section 3.2.

[26] In some cases, processor mass flowrate is directly proportional to the number of crewmembers in a mission scenario, thus hardware parameters may be scaled proportionally to the number of crewmembers. Such an approach may also be acceptable when the range of scale is small between raw data hardware parameters and those implemented in an analysis.

[27] "Transient" is often considered to be synonymous with "dynamic".

[28] Power generation system sizing approaches also range in complexity. The simplest approach is to sum the daily-average power draw of each subsystem to size the power generation system. The most complex approach is to simulate the mission to identify peak power needs for sizing the power generation system. Sizing approaches may lie anywhere in between (or include) these two extremes.

between (or include) these two approaches[29]. A steady-state sizing effort requires less analysis effort but is less realistic than the more effort-intensive transient sizing effort[30]. Steady-state sizing efforts can be easily implemented using spreadsheet software, whereas transient sizing efforts are most easily performed through the use of transient simulation tools[31]. If batch or semi-batch processors exist in the system, an alternative between resource-intensive transient simulation and (possibly) inaccurate steady-state estimates may be necessary. In such a case, the analyst might choose to modify steady-state flowrates to agree with the batch or semi-batch nature of the processors.

In this same vein, the investigator should decide whether to size the system for solely nominal (no fault) operation, or if the system should be sized for specific off-nominal events (faults). Thus, system sizing possibilities span a space bounded by 1) steady-state with nominal operation, 2) steady-state with off-nominal events, 3) transient with nominal operation, and 4) transient with off-nominal events. For each individual study, the analyst's judgement should be used to determine the most appropriate sizing tactics. The most common approach to date for system sizing efforts has been steady-state mass flow calculations of daily loads, under nominal operation.

Once the appropriate sizing parameter values through hardware have been determined, the investigator should implement factors to scale the hardware parameters to those values. A simple approach is to scale hardware parameters linearly with respect to the sizing parameters. However, more accurate hardware parameters might be obtained by using scaling factors (which are not necessarily linear) provided by the technology developer or by using component-specific scaling factors that are standard to the chemical industry. (The reader is referred to Yeh, *et. al.*, 2001, for examples of scaling factors used in the Chemical Industry.) As a simplification, the entire piece of hardware

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[29] For example, if a steady-state sizing effort is performed, the analyst may choose apply "corrections" to the results in order to reflect known sizing characteristics of the system.

[30] The easiest design to size is one that provides a processor with steady-state flow. However, when necessary, transient system sizing allows for more accurate processor sizing for peak flows and/or the necessary buffers to bring flows as close as possible to steady-state.

[31] To clarify, if a transient simulation (i.e. dynamic simulation) is performed, the analyst uses the results of that simulation to size processors as well as any necessary buffers (e.g. greywater tanks and potable water tanks in the case of water processor sizing). In some simulation cases, processors may require sizing for the maximum or minimum flowrate that is needed during the simulation in order to satisfy some other conditions, such as requirements on the supply rate of a resource or constraints on holding tank capacity of a resource. Also, in some simuulation cases, buffer tanks may require sizing according to specified conditions such as requirements on the receiving rate of a resource or constraints on the processing rate of a resource. Whatever the requirements and constraints on the simulation, the processors should be sized to the maximum flowrate and buffers should be sized to the maximum capacity seen during the simulation. Such "maximums" are the parameters that feed into the ESM equation (M, V, P, C and CT).

can be scaled to one sizing parameter. However, because there can be components (e.g. controls) of a piece of hardware that are not size-dependent on sizing parameters (such as mass flowrate), more accurate sizing parameters should be used for those components, if readily available. Whatever the approach, sizing parameters, scaling factors and associated assumptions should be adequately explained in the analysis documentation.

3.2   ESM Equation

The equation[32] for the ESM[33] of a given system is:

$$ESM = \sum_{i=1}^{n}\left[\left(M_{I_i} \cdot SF_{I_i}\right)+\left(V_{I_i} \cdot V_{eq_i}\right)+\left(P_i \cdot P_{eq_i}\right)+\left(C_i \cdot C_{eq_i}\right)+\left(CT_i \cdot D \cdot CT_{eq_i}\right)+\ldots\right.$$

$$\left.\ldots+\left(M_{TD_i} \cdot D \cdot SF_{TD_i}\right)+\left(V_{TD_i} \cdot D \cdot V_{eq_i}\right)\right]$$ Equation 2

where ESM = the equivalent system mass value of the system of interest [kg],

M_{I_i} = initial mass of subsystem i [kg],

SF_{I_i} = initial mass stowage factor for subsystem i [kg/kg],

V_{I_i} = initial volume of subsystem i [m^3],

V_{eq_i} = mass equivalency factor for the pressurized volume support infrastructure of subsystem i [kg/m^3],

P_i = power requirement of subsystem i [kW$_e$],

r_{eq_i} = mass equivalency factor for the power generation support infrastructure of subsystem i [kg/kW$_e$],

C_i = cooling requirement of subsystem i [kW$_{th}$],

C_{eq_i} = mass equivalency factor for the cooling infrastructure of subsystem i [kg/kW$_{th}$],

CT_i = crewtime requirement of subsystem i [CM-h/y],

D = duration of the mission segment of interest [y],

CT_{eq_i} = mass equivalency factor for the crewtime of subsystem i [kg/CM-h],

M_{TD_i} = time- or event-dependent mass of subsystem i [kg/y],

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[32] Equation 2 is oriented toward spreadsheet accounting of commodity use by subsystem parameters. In some cases (such as when transient simulation is used to determine the size of the power generation system), assignment of commodity use to specific subsystems is not straightforward, and a modified accounting method should be used. Specific examples of such situations are provided later in this document.

[33] Italics are used to denote symbols used in equations in this document.

SF_{TD_i} = time- or event-dependent mass stowage factor for subsystem i [kg/kg], and

V_{TD_i} = time- or event-dependent volume of subsystem i [m^3].

The terms in the ESM equation are summed over $i = 1$ to n subsystems. A "subsystem" as written in this document pertains to any subset of the system that was defined for the study. A spreadsheet example is included with this document, as a possible template for itemizing ESM subsystems. Figure 2 shows the main view of the ESM Template. In the ESM Template, a separate row is provided for each subsystem, divided as deemed appropriate by the analyst. Currently, only three rows are provided for data entry (Item 1, Item 2, and Item3), so the investigator should add rows as necessary, while assuring that the "Total" row correctly sums the values for each parameter in the spreadsheet.

The most common approach to date for defining subsystems has been at the hardware level. Generally, the system should at least be divided into subsystems as necessary to reflect subsystem-specific stowage and equivalency factors and to allow for straightforward critique by others. Typically, subsystem-specific equivalencies (V_{eq}, P_{eq}, C_{eq}, and CT_{eq}) are not necessary; one equivalency factor value is applied to all subsystems for a particular mission segment[34]. Therefore, the ESM Template has been designed so that "System-Applicable Equivalency Factors" can be entered and used as the default values for all subsystems in the results documentation.

The spreadsheet nature of the ESM Template makes it most suited to system sizing via steady-state sizing. The template should be modified, or other reporting methods should be used if regarded necessary by the analyst. For example, if an investigator chooses to size a system according to transient simulation results, it may be difficult to assign portions of the peak power and cooling needs to specific subsystems[35]. Thus, the analyst

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[34] As a specific counter-example, one subsystem may be relatively impervious to environmental radiation, while another subsystem may be relatively vulnerable to environmental radiation. If the necessary radiation shielding is not built onto the hardware itself and counted as initial mass (M_I), then the latter technology would require a larger volume equivalency factor to account for the additional radiation protection. Additionally, one subsystem could associate resource needs to multiple infrastructure sources. For example, both solar and nuclear power could, in theory, be utilized during a Mars surface mission. In such a case, a particular piece of hardware could obtain part of it's power needs from the solar power generation system and the remainder of it's power needs from the nuclear power generation system. In such a case, an analyst performing an ESM computation should take care to assign appropriate mass equivalency factors for power use to the distinct resource needs, without "double-booking" the hardware power requirements.

[35] One approach to such a dilemma to allocating portions of the total power "peak" to the different subsystems may be to assign the necessary mass of the power system according to the particular hardware's influence on the *overall* power system design. Thus, if a particular piece of hardware requires 4 kW at the design point (peak) of the power system design simulation, thereby driving the size of the power system from 16kW to 20kW, then those 4kW might be "billed" to that specific hardware.

might choose to use only the mass, volume and crewtime portions of the template and specify the peak power and cooling demands in a different manner. In such a case, the assumptions behind the simulation configuration that lead to that peak power and cooling needs should be explained.

The goal of an ESM trade study evaluation is to size the system *differences* between trade options. Thus, even though this document goes to great lengths to detail all types of materials that might be accounted in a system, the analyst only needs to consider the things that differ between options for a particular analysis. Additionally, categorization of materials according to ESM parameters is not clear-cut. For example, some analysts may choose to categorize the mass of cabin atmospheric gases under the initial mass term (M_I), while other analysts choose to categorize those gases under the time-dependent mass term (M_{TD}). In fact, the exact means of materials categorization is inconsequential, as long as all critical materials are quantified correctly over the entire mission duration.

In the ESM Template, cells are provided for each of the parameters in Equation 2. The columns for each parameter can be "unscrolled" to reveal background information that may be necessary for proper referencing and explanation of data. The unscrolled columns include sub-columns for:

- Original Data Value, Source and Description;

- Development State Adjustment Explanations, Quantifications and Sources; and

- Scaling Explanations, Quantifications and Sources.

Other ALS researchers should be able to understand and critique the data that are applied in the analysis. Thus, it is critical that applied values be appropriately documented, so that the evolution of values (from original to implemented) can be tracked. Figure 3 shows the columns for background information for the initial mass term $(M_I \cdot SF_I)$ of the ESM calculation. Although not shown in the figure, such columns are repeated for the volume, power, cooling, crewtime, time-dependent mass and time-dependent volume terms.

Each parameter, stowage factor, and equivalency factor in Equation 2 will now be discussed in detail.

ESM Template

Mission Segment Name			
XXXX			
Mission Segment Duration (in Terrestrial years) [D]			
0	years		
SUBSYSTEMS			

	Initial Mass			Initial Volume			Power			Cooling			Crewtime			Time-Dependent Mass			Time-Dependent Volume	
	M_i	SF_i	SF_i*M_i	V_i	V_{eq}	V_i*V_{eq}	P_i	P_{eq}	P_i*P_{eq}	C_i	C_{eq}	C_i*C_{eq}	CT_i	CT_{eq}	CT_i*CT_{eq}	M_{TDi}	SF_{TDi}	$SF_{TDi}*M_{TDi}*D$	V_{TDi}	$V_{TDi}*V_{eq}*D$
	kg	kg/kg	kg	m³	kg/m³	kg	kW$_e$	kg/kW$_e$	kg	kW$_{th}$	kg/kW$_{th}$	kg	CM-h/y	kg/CM-h	kg	kg/y	kg/kg	kg	m³/y	kg
Subsystems	number / formula	number / formula	number / formula	number / formula	number	number / formula	number / formula	number	number / formula	number / formula	number	number / formula	number / formula	number	number / formula	number / formula	number / formula	number / formula	number / formula	number / formula
Item 1		1.0	0		0	0		0	0		0	0		0	0		1.0	0		0
Item 2		1.0	0		0	0		0	0		0	0		0	0		1.0	0		0
Item 3		1.0	0		0	0		0	0		0	0		0	0		1.0	0		0
Rows for additional items are entered here, as needed.																				
ESM Subtotals (kg)			0			0			0			0			0			0		0

Total ESM (kg)

System-Applicable Equivalency Factors

Volume Equivalency Factor	Power Equivalency Factor	Cooling Equivalency Factor	Crewtime Equivalency Factor
V_{eq}	P_{eq}	C_{eq}	CT_{eq}
kg/m³	kg/kW$_e$	kg/kW$_{th}$	kg/CM-h
0	0	0	0

Figure 2. ESM Template Main View.

	Original Data			Initial Mass								
					Development State Adjustments				Scaling			
	Value (kg)	Source	Description	M_i	Explanation	Quantification	Source	SF_i	Explanation	Quantification	Source	SF_i*M_i
				kg				kg/kg				kg
Subsystems	number / formula	text	text	number / formula	text	number / formula	text	number / formula	text	number / formula	text	number / formula
Item 1								1.0				0
Item 2								1.0				0
Item 3								1.0				0
Rows for additional items are entered here, as needed.												

Figure 3. "Unscrolled" Initial Mass Data Columns in the ESM Template.

For example, consider the case where a steady-state mass balance is performed to determine the quantities of working fluids. In a steady-state mass balance, working mass may be estimated as the mass of material in storage awaiting processing, plus the amount that occupies the processor at steady-state. Working mass for a particular processor represents the amount of useful material that is "tied up" in the processor and is therefore unavailable to the rest of the system (Levri et al, 2000). Thus, if processing speed is very fast (or residence time is low), the working mass for that processor will be correspondingly low; if the processing speed is very slow (or residence time is high), the working mass for that processor will be correspondingly high.

If a steady-state sizing effort is performed, but the analyst wishes to properly reflect the nature of batch or semi-batch processors, then working mass may be the time-averaged mass contained in the reactors and buffers during one residence time. Additionally, if a steady-state sizing effort is performed but the investigator has further knowledge about the behavior of the system, then the analyst may make corrections to working mass estimates and tank sizes. Such an endeavor may account for some time-driven material quantities without performing a full transient sizing effort.

Sizing a system through transient simulation may require a different approach to accounting for working mass. In the case of a closed or semi-closed life support system, accumulation of a compound in one location necessarily reduces the amount of that compound in another location. Thus, in the case of transient simulation sizing, it is difficult to assign (categorize) working mass to specific subsystems. In such a case, the working mass of a material for the entire system of interest may be accounted as an individual subsystem, by using a separate row of data in the ESM Template.

3.1.6.2 Initial Volume (V_I): Initial volume, V_I in Equation 2, pertains to any pressurized volume required for housing the system of interest that is associated with initial mass quantities, and any space required for crew access to equipment. Thus, initial volume for a complete life support system includes any pressurized volume necessary to support life support hardware.[37].

Care should be taken such that crew access volume is appropriately accounted. In cases where crew access space is strategically planned around unit change-out, the volume required for that change-out may possibly be disregarded. For example, it may be possible to restrict crew access (in addition to the space between the tops of the plants and the lamps) to replace lamps in a plant growth system to the interval between

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[37] Although the mass of gas that occupies crew free space is accounted in the initial mass term, for computation of the ALS Metric, the ALS Project Office has mandated that crew free volume will not be included in the calculation, in order to prevent misleading metric improvement through restriction of cabin volume and associated reduction in habitat structure and radiation shielding mass.

harvesting and replanting[38]. In such a case, space in addition to the plant growth volume is not required.

3.1.6.3 Power (P): Power, P in Equation 2, pertains to the electrical power requirements for sizing the power generation system. The suitability of Equation 2 (and the ESM Template) in accounting for system power requirements depends on the approach that is used to size the power generation system.

Power generation system sizing approaches range in complexity. The simplest approach is to sum the daily-average power draw of each subsystem to size the power generation system. The most complex approach is to simulate the mission to identify power needs for sizing the power generation system. The investigator should determine if the most appropriate approach to power system sizing is 1) summing daily-average power draws, 2) simulating the system power draw, or 3) some intermediate approach. The analyst should understand the system power dynamics in order to incorporate the most appropriate power generation system sizing methods.

If the investigator chooses to sum daily-average power draws, and power availability and cost are not time-dependent, then application of Equation 2 (and the ESM Template) is straightforward. The accuracy of such an approach depends largely on the power storage capacity (i.e. buffering) of the power system, and the behavior and control approach of the life support system. Such an approach is most representative of the power need for a system that runs continuously at steady-state.

If the analyst chooses to simulate the system power draw, application of the power term $(P \cdot P_{eq})$ in Equation 2 (and the ESM Template) is less straightforward. System power draw fluctuates with subsystem transient power requirements[39] and process scheduling[40]. Thus, rather than summing subsystem power requirements, the simulated power draw profile might be examined to determine the most appropriate value to represent the power requirement of the entire system of interest. The peak power requirement during the simulation may be a good value for sizing the power generation system. However, in design of an actual system, processes might be rescheduled to reduce the peak system power needs. Some degree of power storage might also be used (at some cost) to reduce

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[38] This may be a reasonable assumption, given likely lamp sizes and lifetimes

[39] As an example of transient power requirements for a particular hardware item, an incinerator that uses a heat exchanger to heat inflow air and cool outflow air may have a large power draw during start-up of the process, followed by a relatively low power draw once the process has reached steady-state.

[40] As an example of power fluctuation with process scheduling, a system that incorporates crop production may experience the highest power demands during illumination of the crop. Thus, the peak power need might be reduced by illuminating the crop during the crew's night, when there is little power-demanding activity elsewhere in the system.

peak system power requirements. The investigator should select the most appropriate point on a simulated power profile and decide upon adjustments (if any), based upon knowledge of system operation.

If summing daily-average power draws is too inaccurate and simulating the system power draw is too resource-intensive, the analyst may choose to use an intermediate approach to sizing the power generation system. For example, for some subsystems, the investigator might consider the nominal subsystem power draws to be more representative of reality than daily-average power draws. As an example, an incinerator may be run only after every 10-day crop harvest interval, encouraging the use of a value other than the daily average power draw.

3.1.6.4 Cooling (*C*): Cooling, C in Equation 2, pertains to heat rejection requirements for sizing of the internal and external thermal control systems. As with power, the suitability of Equation 2 (and the ESM Template) in accounting for system cooling requirements depends on the approach that is used to size the thermal control system.

Most power that is consumed in the life support system must eventually be rejected as heat[41]. Thus, in the case of direct application of Equation 2 (and the ESM Template) subsystem cooling needs are typically equivalent to the subsystem power needs. Similarly, in the case of power system sizing by transient simulation, the thermal control system may generally be sized according to the system power requirement. However, there are caveats to equating cooling requirements with power requirements. For example, any exothermic reactions (e.g. human metabolism, oxidative waste processes) or endothermic reactions (water e.g. electrolysis, photosynthesis) in the system should be considered in sizing the thermal control system. Another example is the direct use of sunlight for power, such as in a planetary greenhouse. In such a situation, only a small amount of power may be needed for solar power collection and distribution, but a relatively large thermal heat load would ultimately have to be rejected from the system. Thus, the cooling requirement for the direct use of sunlight may be greater than that of the power requirement.

3.1.6.5 Crewtime (*CT*): Crewtime, *CT* in Equation 2, pertains to any time that the crew spends in system operation or maintenance. Operation and maintenance includes any crewtime spent in processing steps that require crew intervention (including start-up and shutdown), monitoring and control, changing out parts, cleaning, and other maintenance. For an ESM evaluation in which only nominal operation of the system is considered, only crewtime spent in scheduled maintenance is included in the analysis. Unscheduled

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[41] There is a caveat to this generalization. The colder the location of the mission, the greater the rate of passive loss of heat from the habitat. Similarly, during environmental temperatures greater than the habitat temperature, heat rejection is required in excess of that generated within the habitat. However, this caveat is generally disregarded for ALS trade studies.

maintenance (troubleshooting and repair) would be included in ESM evaluations that consider off-nominal events.

Crewtime that is spent on mission-oriented or scientific work is not included in the ESM evaluation. Thus, because extra-vehicular activity (EVA) is typically considered mission-oriented work, it has traditionally not been counted as crewtime in ESM evaluations. However, in a case where a life support technology requires that a portion of EVA time be spent in maintaining the life support system, an appropriate quantity of EVA time should be counted in the ESM crewtime term. For example, in a case where noxious wastes are disposed outside of the habitat on a planetary surface[42], any EVA time (e.g. waste transfer, monitoring pressures) spent maintaining that subsystem should be counted in the crewtime term.

3.1.6.6 Time-Dependent Mass (M_{TD}): Time-dependent mass, M_{TD} in Equation 2, pertains to any mass in the system that is dependent upon the mission segment duration. Such items may include, but are not limited to, consumable resources, process expendables and spare parts[43]. Consumable resources may include clothing, prepackaged food and other materials. However, depending on the sizing effort approach, there may not be a clear distinction between consumable resources (included in the time-dependent mass term) and working mass (included in the initial mass term). The categorization of materials is not particularly important, as long as all critical materials in the system are appropriately quantified and included in the analysis.

3.1.6.7 Time-Dependent Volume (V_{TD}): Time-dependent volume, V_{TD} in Equation 2, pertains to any pressurized volume in that is associated with the time-dependent mass (M_{TD}).

The analyst should take care that time-dependent volume isn't doubly booked in an ESM evaluation. Configurations that are prone to volume double booking include those that take advantage of dynamically changing space in the habitat. For example, in a case where emptied food lockers are used to store stabilized waste materials[44], the investigator

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[42] The environmental impact in such a case might be an issue. However, the case is simplified for the purpose of providing a uncomplicated example.

[43] If the ESM evaluation considers only nominal system operation, then only expendables and spares associated with nominal operation and maintenance should be included in the study. If the ESM evaluation considers off-nominal events, then expendables and spares for appropriate contingency should be included in the study.

[44] This example is solely for illustrative purposes. In reality, because of possible safety hazards, storing waste material, even if stabilized, in close proximity to unused food stores may violate mission requirements.

should not to double-book that volume in both the food subsystem and the waste subsystem.

3.1.7 Stowage Factors and Mass Equivalency Factors - In Equation 2, stowage factors (SF_I and SF_{TD}) are applied to initial and time-dependent masses, when necessary, to account for additional hardware, such as racks, needed to fasten down and contain equipment.

Also in Equation 2, subsystem volume (V_I and V_{TD}), power (P), cooling (C) and crewtime (CT) requirements are converted to units of mass by assignment of a fraction of the infrastructure cost, according to the fraction of resource use. The ratio of the resource cost (in units of mass) to resource use is termed a mass equivalency factor.

Numerical values for stowage factors and mass equivalency factors are provided in the ALS BVAD, along with the assumptions that were used to generate those values. In situations where alternative values are more appropriate for a particular ESM evaluation, the reasoning and value derivation[45] should be provided in the study report.

3.1.7.1 Stowage Factors (SF_I and SF_{TD}): Most items must be secured to the inside of the habitat in some manner. Large items may be fastened directly to the primary structure. For many components of hardware, a simple rack, such as those used on the International Space Station, may be used for securing equipment. For small, loose items, such as food packages, packages of hygiene wipes, rolls of toilet paper, etc., some additional equipment, such as a tray, is necessary for containment.

Stowage factors may be applied, if necessary, to a subsystem's initial and time-dependent mass (M_I and M_{TD}), as a relative representation of the item's need for additional holding structure. However, stowage factors should only be used to the degree necessary to compensate for unavailable information on the equipment that is required for stowage. Thus, some initial and time-dependent mass values in an ESM evaluation may require no alteration by stowage factors, and other data values may require significant alteration by stowage factors.

For example, if the mass of rack structure needed for a component of equipment is well documented, that rack mass can be included in the initial mass of the equipment, and the equipment can be given a 1.0 stowage factor[46]. As another example, if the mass of food lockers needed for individual food items is known, but the mass of the rack needed to

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[45] A reference may be provided in lieu of the derivation, if the derivation exists in a readily-available reference.

[46] A value of 1.0 is the minimum value that may be applied as a stowage factor and implies that no modification to the mass data for stowage requirements is necessary.

secure the lockers is unknown, then the time-dependent food and associated lockers can be given a stowage factor that is greater than 1.0.

In the ESM Template, a default stowage factor of 1.0 is assigned to each subsystem. This default value may be changed for each subsystem, as necessary. Each stowage factor column can be unscrolled to provide information on the explanation and source of each stowage factor that is applied.

3.1.7.2 Volume Equivalency Factor (V_{eq}): As mentioned previously, the ratio of the resource cost (in units of mass) to resource use is termed an equivalency factor.

In practice, volume equivalency factors, V_{eq}, are driven by pressure loads, and requirements for radiation protection and meteoroid shielding. Most designs assume that all parts of the system have similar supportive structure and are shielded and pressurized equally. In such cases, the same equivalency factor is applied to all subsystems. (The system-applicable volume equivalency factor in the ESM Template may be employed.) However, if some portions of the habitat are shielded or pressurized differently than others or use a different supportive structure, then subsystem-specific volume equivalency factors should be used. For example, a shielding-intensive "storm shelter" might be designed into a habitat to protect the crew from short periods of high radiation levels. Similarly, plants might be grown in a chamber that is less shielded[47] and at a lower pressure than the crew habitat[48]. In this case, separate volume equivalencies should be used for the crew and plant habitats[49] (and an airlock would be needed between them).

The habitat structure must withstand the stress caused by the internal pressure loads. In addition, during events of internal or external pressure change, the structure must be able to maintain an acceptable form. The habitat may also require thermal shielding such as radiant or ablative coverings[50]. In those cases, the thermal shielding is proportional to the volume enclosed, with larger cabins requiring larger heat shielding.

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[47] Plants are less radiosensitive than humans.

[48] Such an approach may reduce the necessary mass of atmospheric gases and the air leakage rate. Plant growth rates might also be increased.

[49] Alternatively, the lower of the two volume equivalencies could be used in the computation, and the mass of the extra shielding required for the crew could be accounted for in the initial mass term. As another example, if a habitat requires a storm shelter for high-radiation events, the shelter could be accounted for by explicitly adding shielding mass to the initial mass term, rather than by using a different volume equivalency factors for different parts of the habitat.

[50] The tiles on Shuttle are an example of a radiant covering, while the heat shield on the base of earlier crew capsules are an example of ablative shielding.

Requirements on radiation shielding can have a large effect on equivalency factors for pressurized volume. Radiation shielding requirements vary with the age, sex, nutrition, and genetics of the crew, the time in the solar cycle, distance from the Sun, and local effects such as the Van Allen Belts. In free space near 1 Astronomical Unit[51] (AU), a thin aluminum skin may be adequate to protect humans from short exposures to the ultraviolet radiation and the less penetrating solar radiation. During solar particle events and in the Van Allen Belts, radiation levels can be high enough to require additional shielding to prevent acute radiation sickness. It is harder to shield against the more energetic cosmic radiation, making it a concern for long duration missions.

Depending on the mission location, meteoroid shielding could be required for some habitats. Significant quantities of debris particles are found in LEO, so more shielding would be required than during Mars transit or on the Moon. Mars has a thin atmosphere, which would provide some meteoroid protection and possibly some radiation shielding for a Mars surface habitat.

Accepted values for volume equivalency factors for specific mission segments are provided in the BVAD.

3.1.7.3 Power Equivalency Factor (P_{eq}): As with the volume equivalency factor, the power equivalency factor, P_{eq}, is the ratio of the resource cost (in units of mass) to resource use. Thus, the power equivalency factor is determined by dividing the mass of the power generation system by the electrical power output.

The power equivalency factor should reflect all aspects of the power generation system, including any necessary power storage, heat rejection for the power system, and power distribution and control. All of these characteristics vary with the type of power generation system.

Most designs assume that all parts of the system utilize power from the same power generation system. In such cases, the same equivalency factor is applied to all subsystems. (The system-applicable power equivalency factor in the ESM Template may be employed.) However, if portions of the habitat are powered by different power generation systems, then subsystem-specific power equivalency factors should be used. For example, consider the case of using solar power in which power storage is necessary during the nighttime. Such a system would require that the solar power system be sized for the peak daytime load and oversized for constant draw of power to recharge batteries, which are sized for the peak nighttime load. Thus, different power equivalency factors be applied to equipment that require power during the day (solar power system) versus equipment that require power during the night (batteries). If some equipment were used

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[51] 1 AU = 149,597,870.691 kilometers. An Astronomical Unit is the mean distance between the Earth and the Sun. It is a derived constant and used to indicate distances within a solar system. The Earth orbits at a distance of 1 AU from the Sun.

during both the day and night, the larger of the two equivalency factors would be applied to those particular hardware pieces[52].

Currently, the two most commonly assumed approaches to power generation for ALS reference missions are nuclear reactors and solar collectors. Accepted values for power equivalency factors for specific mission segments are provided in the BVAD.

3.1.7.4 Cooling Equivalency Factor (C_{eq}): As with the volume and power equivalency factors, the cooling equivalency factor, C_{eq}, is the ratio of the resource cost (in units of mass) to resource use. Thus, the cooling equivalency factor is determined by dividing the mass of the thermal control system by the heat rejection capacity of that system.

There are three types of thermal control equipment to consider in an ESM analysis:

1)   subsystem thermal control equipment that transports heat from the subsystem hardware to the internal thermal control system (ITCS),

2)   ITCS equipment that transports heat from the subsystem thermal control equipment (or the cabin air in the case of atmospheric cooling) to the external thermal control system (ETCS), and

3)   ETCS equipment that transports heat from the ITCS to the environment.

Subsystem thermal control equipment may include hardware-associated fans, coldplates, heat exchangers, fluids and controls. ITCS hardware may include lines, pumps, heat exchangers, fluids and controls that are inside the habitat but not within the subsystem cooling equipment. The ETCS requires radiators, piping, heat exchangers, pumps, fluids and controls.

Subsystem thermal control equipment should always be accounted in the initial mass term (M_I). ITCS equipment is most easily accounted by applying an ITCS cooling equivalency factor to the subsystem (or system) cooling demand[53]. ETCS equipment is

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[52] Normally, for a solar power system, the BVAD provides power equivalency factor estimates for continuous power usage and for daytime-only power usage. Values for systems that only operate at night are not included.

[53] In the case of an analysis of a complete life support system, the ITCS equipment may be accounted as a separate subsystem (with its own mass, volume, power, cooling and crewtime demands). This can be done if the analyst has the appropriate ITCS knowledge and such an approach is expected increase results accuracy. In such an endeavor, the analyst must be certain not to double-book the subsystem cooling demands as both subsystem and ITCS cooling demands. While this second approach is recommended and encouraged for overall system analysis, SIMA recognizes that even for an overall system analysis it may not be practical in all cases, especially if the analyst is not familiar with thermal control systems.

accounted by applying an ETCS cooling equivalency factor to the subsystem (or system) cooling demand. If the ITCS is accounted via a cooling equivalency factor, the ITCS cooling equivalency factor and the ETCS cooling equivalency factor (both in units of kg/kW_{th}) may be summed and applied as one factor to the subsystem cooling demand. Values for internal and external thermal control system cooling equivalency factors are provided as both combined values and as separate values in the BVAD. Using combined cooling equivalency factors is the recommended approach and the approach that is consistent with Equation 2.

For most space missions, radiation is the only feasible mechanism of ETCS heat rejection. In some locations such as the surface of Mars, during periods of low environmental temperature, significant heat loss may occur simply due to the temperature gradient between the crew habitat and the external environment. However, radiator sizing depends on the difference between the fourth power of the radiator temperature and the fourth power of the heat sink temperature. Thus, even in continuously cold locations, thermal control systems may still be necessary to maintain a continuously comfortable cabin temperature.

3.1.7.5 Crewtime Equivalency Factor (CT_{eq}): The key assumption behind the application of the crewtime equivalency factor is that time occupied in operation and maintenance of the life support system detracts from the time that is available for mission-oriented work (Levri et al., 2000)[54]. If it is assumed that the main goal of the mission is to achieve specific, scientific objectives, then any crew hours spent on the life support system undermine crew hours needed to achieve the mission goals.

For example, if half of the crew's designated work time is consumed by life support maintenance, the size of the crew and associated life support system must (in theory) be approximately doubled in order to achieve the scientific goals of the mission. Likewise, if three-fourths of the crew's available work time were consumed by the life support system, the size of the crew and life support system would have to be multiplied by four in order to achieve the mission goals. Thus, as the amount of time available for scientific work approaches zero, the number of crewmembers and size of the associated life support system would approach infinity.

Levri et al (2000) presents a discussion of the mathematical theory behind the crewtime equivalency factor, which is summarized here. If the total amount of time that is available

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[54] As with all mass equivalency factors, if the analyst finds the underlying assumptions to be inappropriate to the study at hand, then alternative assumptions can be declared and used to compute different equivalency factors. For example, if it is believed that crewtime will be readily available and in low demand during a particular mission, then the analyst may decide to apply a crewtime equivalency factor of zero. Such a decision is perfectly acceptable, as long as the justification is reasonable and clearly documented in the analysis report.

to the crew for work is categorized into mission-oriented (scientific) work and life support-oriented work, the following equation can be written:

$$t_{WORK} = t_{MISSION} + t_{LSS}$$ Equation 3

where t_{WORK} = total crewtime allotted for work (not devoted to time such as eating, sleeping, exercising, personal time, etc.) [CM-h/y],

$t_{MISSION}$ = crewtime that is used in performing scientific, mission-oriented work (a subset of t_{WORK}) [CM-h/y],

t_{LSS} = crewtime that is required to maintain the life support system (a subset of t_{WORK}) [CM-h/y].

Similarly, if the total ESM of a life support system is categorized into crewtime *ESM* and non-crewtime (mass, volume, power and cooling) *ESM*, the following equation can be written:

$$ESM_{TOTAL} = ESM_{NCT} + ESM_{CT}$$ Equation 4

where $ESM_{TOTAL}{}^{55}$ = the *ESM* value of the entire life support system (the sum of the crewtime and non-crewtime portions of *ESM*) [kg],

ESM_{NCT} = the non-crewtime portion (mass, volume, power, and cooling) of *ESM* [kg],

ESM_{CT} = the crewtime portion of *ESM* [kg].

Following the logic that as time for mission work decreases, the number of crew and size of the life support system increases proportionally, the following equation can be written:

$$ESM_{TOTAL} = ESM_{NCT} \left(\frac{t_{WORK}}{t_{MISSION}} \right)$$ Equation 5

If Equation 4 is combined with Equation 5, the following equation is achieved:

$$ESM_{CT} = ESM_{NCT} \left(\frac{t_{WORK}}{t_{MISSION}} - 1 \right)$$ Equation 6

The crewtime cost is the life support system mass that is required per CM-h/y, thus, the crewtime equivalency factor may be written as follows:

$$CT_{eq} = \frac{ESM_{CT}}{t_{LSS}}$$ Equation 7

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[55] ESM$_{TOTAL}$ is synonymous with "ESM" in Equation 1 and Equation 2. ESM$_{TOTAL}$ is used in this document to remain consistent with the BVAD and the original derivation of the crewtime equivalency factor (Levri, *et al.*).

Manipulation of Equation 4 through Equation 7 provides the following equation:

$$CT_{eq} = \frac{ESM_{NCT}}{t_{MISSION}}$$ Equation 8

Equation 8 shows that the crewtime equivalency factor varies as the ratio of the non-crewtime portion of the life support system and the time available for mission-oriented work.

As a simplification to computing the crewtime equivalency factor, assumptions can be made about ESM_{NCT} and $t_{MISSION}$ for various mission segments, based upon past ALS metric calculations, resulting in standard CT_{eq} values for ALS reference missions. Those CT_{eq} values and their associated assumptions are documented in the ALS BVAD. *Application of ALS BVAD crewtime equivalency factors is the most straight-forward approach approach to computing the crewtime portion of ESM.*

Application of standard CT_{eq} values in the ALS BVAD is most appropriate when the life support system of interest has a $ESM_{NCT}/t_{MISSION}$ value similar to the values used to derive the standard CT_{eq} values. However, if the $ESM_{NCT}/t_{MISSION}$ value for the specific life support system of interest *is known and is very different* from the values used to develop the BVAD CT_{eq} values, then analysis-specific crewtime equivalencies should be computed and implemented according to Equation 8. However, the $ESM_{NCT}/t_{MISSION}$ value is typically not known unless one considers the entire life support system, rather than a subset of the life support system.

3.3   Discussion of Location Factors

Accelerating mass to different locations in space can require different amounts of fuel, making transportation cost per unit mass a location-dependent characteristic. Thus, in order to compare the costs of the various segments, ESM should be computed individually for each segment and then "normalized".

Segment-specific ESM values can be normalized by applying location factors (Fisher *et al.* 2003). A location factor represents the cost of transporting mass between one starting location and destination, relative to the cost of transporting that same amount of mass between a reference starting location and destination[56]. Different location factors should be used for different mission segments. A mission segment may be defined as a portion of a mission separated by changes in velocity (i.e. separated by distinct propulsion

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[56] For example, a possible reference starting location and destination might be the Earth's surface and LEO, respectively.

events). For example, a mission to Mars and back might have the following mission segments[57], each of which has a distinct location factor:

1)   Earth to LEO[58]

2)   LEO to Mars orbit

3)   Within Mars Orbit

4)   Mars orbit to Mars surface

5)   On the Mars surface

6)   Mars surface to Mars orbit

7)   Mars orbit to LEO

8)   LEO to Earth

In order to appropriately compare costs of mission segments, each segment's ESM value should first be multiplied by the appropriate location factor. Such "normalized" costs can then be legitimately compared across segments.

Application of a location factor to an ESM computation results in the following equation:

$$ESM = L_{eq} \cdot \sum_{i=1}^{n} [(M_{I_i} \cdot SF_{I_i}) + (V_{I_i} \cdot V_{eq_i}) + (P_i \cdot P_{eq_i}) + (C_i \cdot C_{eq_i}) + \ldots$$

$$\ldots + (CT_i \cdot D \cdot CT_{eq_i}) + (M_{TD_i} \cdot D \cdot SF_{TD_i}) + (V_{TD_i} \cdot D \cdot V_{eq_i})] \qquad \text{Equation 9}$$

where L_{eq} = the location factor for the segment of interest [kg/kg].

Location factors depend on the type of propulsion used. Location factor values are currently being developed for various propulsion options and mission segments for the next revision of the ALS BVAD. See Fisher *et al.* (2003) for a detailed discussion of equivalency factors.

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[57] Other architectures could have different segments. For example, a direct ascent mission might have only two segments: Earth to Mars surface and Mars surface to Earth.

[58] If Earth to LEO were also the reference starting location and destination, then the location factor associated with that segment would have a value of 1.

4   ESM RESULTS

4.1   Results Confidence

The confidence of an ESM value is driven by the accuracy of raw data used in the evaluation as well as the degree of effort put into modifying that data.

Researchers that provide raw data for an ESM evaluation may execute various levels of rigor in the data collection process. In addition, if raw data is obtained from documentation, rather than directly from a researcher, error propagation in data values can be a concern. On the other hand, data from sources with a very rigorous review process can be quite reliable. Consequently, an analyst may be faced with data from a range of sources and various degrees of accuracy. Because the accuracy of raw data feeds into the confidence of ESM results, the investigator should have at least a basic impression of raw data quality[59].

Confidence in results is also affected by decisions affecting the rigor of development state adjustments and scaling efforts. Application of appropriate equivalency factors, storage factors and location factors also affects the quality of ESM results. The analyst should balance the degree of effort needed for adequate results confidence with resource availability during each step of the ESM evaluation process.

To legitimately implement ESM results in a selection process, the ESM results must be more accurate than the degree of separation between option results. Thus, a rough calculation may be adequate to rank two options, if the result values are grossly different from each other. In other cases, a high level of accuracy is required to make comparisons of options that have very similar ESM values[60]. If the results of an ESM comparison are too close to make a judgement, then both options may be equally good from the ESM perspective, and other issues are likely to drive technology selection.

The degree of results separation that is necessary to conclude a significant difference (i.e. judge one option preferable over another) depends upon the degree of confidence in the data used and the degree of accuracy in the analysis methods. Data confidence and analysis accuracy is analysis-specific. Therefore, the degree of results separation that is required to declare one option preferable to another is also analysis-specific. The

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[59] Ideally, error ranges would be supplied with each point of data in an ESM analysis, allowing for computation of the result's confidence limits. However, in reality, error ranges are rarely reported in data obtained for ESM evaluations, impeding estimation of the degree of confidence in results.

[60] However, if the difference between ESM values is small, the trade study selection will most likely be made based on other information, such as the state of the development, or functional differences (though any option must meet the requirements to be considered).

investigator's judgement should be used to determine the analysis-specific necessary degree of results separation.

If data accuracy is uncertain, a reasonable assumption is that an order of magnitude of separation (i.e. factor of 10) between ESM results is adequate to conclude a significant difference between options (Doll and Eckart, 1999). A difference of a few percent is likely to be sensitive to assumptions. However, the degree of confidence in technology data generally improves as the technology is further developed. Thus, ESM comparisons of trade options at advanced development stages may require less of a degree of separation between results in order to declare a significant difference between options.

4.2   Results Reporting

All assumptions (both top-level and more detailed), input data, sources, and analysis methods should be described (and well organized) throughout the trade study documentation.

Sometimes the greatest value of an analysis can be the identification of superior or inferior input data and their sources. In this same vein, unreferenced data values can make a calculation suspect.

ESM results are analysis-specific and should always be reported in context, rather than as solitary values. For this reason, results reporting should be done with adequate rigor to allow for verification by other researchers. All input data, sources, analysis approaches and critical assumptions made on the hardware, configuration, and control approaches in the system should be clearly stated in reporting the evaluation results, so that the results can be considered in context. Even if the ALS BVAD is used to determine values for an analysis, the analysis documentation should identify which values were applied and explain the implied assumptions.

ESM results documentation should include the following material, and all associated assumptions, as a minimum:

1)   Description of analysis objectives.

2)   Explanation of characteristics deemed worthy of examination (e.g. critical characteristics).

3)   Explanations of which (if any) critical characteristics are captured by ESM and which are reflected by some other quantitative or qualitative means.

4)   Justification of the system extent and level of detail chosen for the ESM evaluation.

5)   Raw data values for ESM parameters, their sources, and a brief explanation of those values implemented.

6)   Justification of development state adjustments, sizing methods and scaling approach, including quantification and references.

7)   Justification of stowage factors, equivalency factors and location factors chosen for the ESM evaluation.

8)   A discussion of the expected accuracy of results and associated interpretation.

5   REFERENCES

1)   Cruthirds, J., Perchonok, M. and Kloeris, V. (2002) "Mathematical Modeling of Food Systems for Long-Term Space Missions". 32nd International Conference on Environmental Systems, SAE Technical Paper #2002-01-2290.

2)   Drysdale, A.E. and Hanford, A.J. (2002) "Advanced Life Support Research and Technology Development Metric – Fiscal Year 2001" JSC 47787, CTSD-ADV-482, Crew and Thermal Systems Division, NASA Johnson Space Center, Houston, TX.

3)   Doll, Susan and Eckart, Peter (1999) Environmental Control and Life Support Systems (ECLSS). in Human Spaceflight: Mission Analysis and Design, Larson and Pranke (eds), McGraw-Hill, New York.

4)   Fisher, John W.; Levri, Julie A. and Jones, Harry W. (2003) "The Effect of Mission Location on Mission Costs and Equivalent System Mass". 33rd International Conference on Environmental Systems, SAE Technical Paper #2003-01-2633.

5)   Hanford, A.J. and Ewert, M.K. (2002) "Advanced Life Support Baseline Values and Assumptions Document", CTSD-ADV-484, JSC 47804, NASA Johnson Space Center, Houston, TX.

6)   Levri, J.A.; Vaccari, D.A.; Drysdale, A.E. (2000) "Theory and Application of the Equivalent System Mass Metric". 30th International Conference on Environmental Systems, SAE Technical Paper #2000-01-2395.

7)   Stafford, K.W.; Jerng, L.T.; Drysdale, A.E.; Maxwell, S.; Levri, J.A. (2001) "Advanced Life Support Systems Integration, Modeling, and Analysis Reference Missions Document," edited by Ewert, M.K. and Hanford. A.J., JSC-39502, Revision A, NASA Johnson Space Center, Houston, Texas.

8)   Yeh, H.Y.; Jeng, Frank; Brown, Cheryl; Lin, Chin; and Ewert, Michael (2001) "Advanced Life Support Sizing Analysis Tool". 31st International Conference on Environmental Systems, SAE Technical Paper #2001-01-2304.

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13. ABSTRACT *(Maximum 200 words)*

Equivalent System Mass (ESM) is often applied to evaluate trade study options in the Advanced Life Support (ALS) Program. ESM can be used to identify which of several options that meet all specified requirements have the lowest launch cost, as related to the mass, volume, power, cooling, and crewtime. This document provides an introduction to the ESM concept, an explanation of the computational method, and a discussion of results interpretation and reporting. Any researcher with a basic understanding of the integration issues of an Advanced Life Support system may apply the methods in this document to perform an effective ESM-based trade analysis.

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