

# Clarifying Objectives and Results of Equivalent System Mass Analyses for Advanced Life Support

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## ABSTRACT

This paper discusses some of the analytical decisions that an investigator must make during the course of a life support system trade study.

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 requirements are most likely to have lowest cost. It can also be used to identify which of the many interacting parts of a life support system have the greatest impact and sensitivity to assumptions.

This paper summarizes recommendations made in the newly developed ALS ESM Guidelines Document and expands on some of the issues relating to trade studies that involve ESM. In particular, the following three points are expounded:

- 1) *The importance of objectives:* Analysis objectives drive the approach to any trade study, including identification of assumptions, selection of characteristics to compare in the analysis, and the most appropriate techniques for reflecting those characteristics.
- 2) *The importance of results interpretation:* The accuracy desired in the results depends upon the analysis objectives, whereas the realized accuracy is determined by the data quality and degree of detail in analysis methods.
- 3) *The importance of analysis documentation:* Documentation of assumptions and data modifications is critical for effective peer evaluation of any trade study. 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.

## INTRODUCTION

The ALS ESM Guidelines document (Levri *et al.*, 2003) was drafted to provide detailed instructional material for researchers who are performing ESM evaluations. The document was developed under the Systems Integration, Modeling and Analysis (SIMA) Element of the ALS Program. It provides a definition of ESM, describes how to calculate ESM, and discusses interpretation of ESM results.

ESM is used as a measure of transportation cost in ALS trade studies. An ESM trade study may be performed to compare various technologies, hardware devices, hardware configurations and/or control approaches. Because the cost to transport a payload is proportional to the mass of that payload, a mass-based measure such as ESM is often used to quantify the cost of the life support system and associated infrastructure. An ESM value is the sum of the life support system mass and appropriate fractions of supporting system masses, including pressurized volume, power generation, cooling, and crewtime, for maintaining a specified crew over the duration of a specified mission.

This paper does not discuss the ESM equation and parameter definition. (For the reader's interest, the ESM equation and parameter definitions are provided in Levri *et al.*, 2003.) Rather, this paper addresses three issues of interest that are considered in the ESM Guidelines Document: the importance of objectives, the importance of results interpretation, and the importance of analysis documentation. Clear objectives are necessary for identification of the questions of interest and related assumptions, identification of system characteristics to reflect in the analysis, and definition of the system to the appropriate extent and level of detail. Results interpretation and analysis documentation is critical because the author of the study is the person in the best position to evaluate the results, and the only one in full knowledge of all the details. Although these are

important issues for all trade studies, this paper discusses that importance as it applies to trade studies that involve ESM in some manner.

When it is feasible and appropriate, single metrics, such as ESM, can facilitate comparison. For ESM to be applied appropriately, the trade study options must first meet some common prerequisites. Only options that satisfy those prerequisites should be included in the study. After the trade options have been identified, some characteristics may require comparison, using ESM. However, it may not be possible to normalize all parameters in a study to a single ESM value. For example, when buying a car, most considerations can be reduced to some metric like cost per passenger mile; however, issues such as aesthetic appearance and safety may not be easily lumped into that same metric. Thus, some characteristics can either be examined as prerequisites, or compared in some other manner.

## THE IMPORTANCE OF OBJECTIVES

Analysis objectives should drive all facets of the ESM computation. Objectives should be clearly defined in order for the investigator to determine the mission of interest and system characteristics to capture in the study, to define the appropriate system, and to appropriately apply data.

Analyses should address important questions. Important questions are generally ones that make a difference to decisions that need to be made in the near future. Currently, there is a lot of interest in technology selection, thus that is an appropriate area to investigate. However, the technologies must be significantly different for the answer to be of much value. For example, if two technologies make a difference to the overall mission cost of 1%, it makes little difference which one is selected.

The 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 involves defining the system of interest to the appropriate extent and level of detail to *comprehensively* capture cost impacts of trade options. In order to capture the cost impacts of the trade options on the entire life support system, the analyst must consider the important interfaces to the system of interest. This concept applies to all systems involved in a mission, even if some costs are traditionally considered to be out of the scope of the life support system.

Although technically not illustrative of ESM, some computations other than the total system impact can be interesting. For example, it may be useful to know that the equipment mass of one trade study option is 30% heavier than an alternative, even if that computation does not reflect the total system impact.

Ideally, analysis objectives are defined at the inception of the study, in an appropriate level of detail. However, the need for further clarification of the objectives often arises during the course of the research. Consequently, a trade study can be iterative. With experience, an analyst can gain foresight into the proper level of detail that is required in defining the study objectives. As the details of trade options emerge during the study, the objectives of the study may require re-clarification.

Study objectives drive decisions on the mission of interest, selecting characteristics to reflect in the analysis, defining the appropriate system, and applying data appropriately, as discussed below.

## IDENTIFYING 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 Reference Missions Document (Stafford *et al.*, 2001) 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 ALS Reference Missions Document (RMD), it is recommended that the RMD assumptions be used in the study baseline. If not, these missions can be used as a starting point and changes to that mission can be documented.

When making trade comparisons, the analyst must consider the suitability of each trade study option in a mission. For example, if comparing two technologies, the functions that the technology performs should be desirable for that mission scenario. As an explicit (and relatively obvious) example, it would be inappropriate to compare two soybean-processing devices in reference to a mission in which food is entirely prepackaged and ready to eat. (In such a scenario, a food-processing device would never be needed.) However, the suitability of trade options in particular missions is not always clear. In fact, the objectives of a trade study may actually be to identify the appropriateness of a trade option to a particular mission, based upon the total system impact of that option. For example, a valid study could consider the cost of growing soybeans to provide the crew with soybean-based fresh foods on a mission, compared to not growing soybeans and providing the crew with other food types.

Top-level assumptions related to the missions in the ALS Reference Missions Document are documented in the ALS Baseline Values and Assumptions Document (BVAD) (Hanford 2002). The BVAD also identifies possible assumptions for missions that are not included in the RMD. Such assumptions include, for example, 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. (One motivation for developing the BVAD is to provide guidance to the ALS Community on reasonable assumptions for various missions. Use of a common set of assumptions facilitates identification of the reasons for differences in trade study results.)

In particular, infrastructure costs, or "equivalency factors" drive the relative impacts of mass, volume, power, cooling and crewtime needs on the computed cost. As a result, the analyst should make efforts to use the most appropriate and reliable information for the equivalency factors. With continued research, collection of more accurate data will hopefully result in equivalency factors of greater accuracy in the BVAD.

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. As the analyst gains knowledge of the details of operation of the various subsystems within the system of interest, initial assumptions may require revision. All assumptions (both top-level and more detailed) should be described (and well organized) throughout the trade study documentation. As this can be quite arduous, effort should be focused on the issues that most affect the results.

#### SELECTING SYSTEM CHARACTERISTICS TO REFLECT IN THE ANALYSIS

Based upon the analysis objectives, the analyst must determine which characteristics should be captured in the trade study. Characteristics of interest might be based upon function, availability, safety, gravity dependence, radiation susceptibility, noise levels, or a variety of other attributes. This determination will depend on the particular study, and often an initial trade study needs to be made in order to develop a methodology and identify what assumptions or data are needed. Thus, it can be necessary to iterate analysis steps to appropriately represent the most significant characteristics.

The investigator must then determine the methods by which those characteristics will be reflected. Characteristics of interest may be considered *prerequisites* for inclusion in the study, and/or they may be *compared* (quantitatively and/or qualitatively) between trade study options. 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.

For an example of prerequisite characteristics, consider an analysis whose objective is to identify the lowest ESM technology that provides a certain level of moisture content reduction (water activity) in wasted food materials. Thus, only technologies that can provide that specific function, at the required level of moisture removal (or greater) should be considered in the analysis.

Notice that the objective in the prior example strongly drives the analysis approach. For example, if the reason for removing the water from the wasted food is to stabilize the food materials before being stored as wastes, then the important prerequisite is that the water be removed down to a certain water activity from that material. However, consider the case where water removal from the wasted food was intended to not only stabilize the waste but also to recover water for later consumption by the crew. In that case, the objectives of the study may be to determine the lowest ESM option that removes water to a certain level *and at a certain purity*. Also notice that the objectives of the prior example were to "identify the lowest ESM technology...". By declaring this in the objective, the study considers power needs, logistics, crewtime, etc., not just moisture content removal, and may address issues such as alternative sources of water, such as availability of water from local materials.

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 low-Earth orbit mission, then any implementations<sup>1</sup> of technologies that are incompatible with microgravity should be eliminated from the study. Similar prerequisites may exist for performance, availability, safety, radiation susceptibility, noise levels and other characteristics, depending on the analysis objectives and the investigator's judgement.

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

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<sup>1</sup> Most technologies are not microgravity sensitive. However, particular implementations of technologies are often microgravity sensitive. For example, a hardware device that uses gravity flow might be fitted with appropriate pumps to make it microgravity compatible. Thus, it may be important for an analyst to consider alternative implementations of a technology in a trade study.

analysis, by some other quantitative means, or in a qualitative manner in the study.

Some characteristics that are not prerequisites in the trade study may also require comparison. 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 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 compared in the study.

For any characteristics that will be compared, the analyst must decide upon a means of comparison. For a general example, 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.

#### DEFINING THE SYSTEM TO THE APPROPRIATE EXTENT AND LEVEL OF DETAIL

The analyst should define the system to the extent and level of detail necessary to capture the total system impact of the trade options. However, quantification of the "total" system impact often requires more resources (time and money) than are available for an analysis. In such cases, the analyst must use judgement to determine the most important characteristics to reflect, by the most effective and appropriate means. Again, the decisions made by the analyst must be driven by the specific study objectives.

In general, the ESM for the entire life support system should be calculated. It may, however, only be necessary to calculate ESM for a portion of the life support system, if the rest of the system remains identical, for all ESM-quantified characteristics, between trade study options. Thus, the analyst must determine the characteristics that will be reflected by an ESM

computation, and define the system accordingly, so that the system can be sized appropriately. Care should be taken that a significant interface has not been neglected.

This section presents brief examples to illustrate system definition for ESM purposes. For the purposes of Advanced Life Support, the system extent may range from the entire life support system and interfaces 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, consider a comparison between the total system impacts of growing 20m<sup>2</sup> of salad crop versus growing 20m<sup>2</sup> of potato crop. In addition to the differences in crop production specifics, the evaluation should include differences outside of the biomass production system that have a significant impact on study results. A proper comparison of the two options, would involve development of an entire dietary concept, and specification of how all parts of the diet would be satisfied. The potato 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. Additionally, different quantities and compositions of nutrient solution may be needed for the different crop options, which may impact requirements for shipping or recycling of nutrients. Depending on the analyst's assumptions about the role and operation of the water recovery system (WRS), the WRS may require resizing between trade options. The analyst's decision of which subsystems to include when defining the system for study depends on the analysis objectives and the investigator's judgement.

The system should be defined to the appropriate level of detail. In the comparison of salad and potato crops, issues such as 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 quantifying critical differences between options, then those differences should be discussed qualitatively in some other manner in the study. In order to minimize the number of characteristics that require investigation, a preliminary sensitivity analysis to identify the change in outcome per change in parameter values can aid in identifying the most critical study parameters.

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. Such choices should be in harmony with the objectives of the analysis.

## APPROPRIATE 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, adjustment for a different development state (notably flight ready), adjustment for environment, 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.

### Adjustment for Development State

Depending upon the objectives of the analysis, some data may require adjustment for the appropriate development state. In ALS trade studies, the flight-ready development state is typically of greatest interest for ESM evaluations. 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.

For trade study comparisons, all equipment data should be representative of comparable development states. For example, equipment in the infancy of development should not be compared with equipment for a different<sup>2</sup> technology at a flight-ready state. Adjusting 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, other critical 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.

For example, launch forces and 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. As another example, for a Mars surface mission, equipment exposed to the Mars surface may require modification for radiation conditions and operation during dust storms. Trade option assumptions may also need to accommodate constraints on the release of materials to the Martian environment due to planetary protection concerns. Additionally, in order to satisfy a requirement on the degree of risk to the crew equivalent to that of Shuttle or International Space Station missions, equipment for a Mars surface (or any longer-term, more distant mission) may require greater system reliability.

Probably the most difficult issue in comparing flight ready options with developmental options is the amount of detail 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.

The analyst must judge the importance of development state adjustments in the reflection of trade study options against the availability of data and the analysis resources needed to make such modifications. Requirements of future missions are (by definition) uncertain, and the information needed to make data adjustments is often unavailable. For example, if a failure modes and effects analysis has not been conducted on a system, then the analyst will have little knowledge of the types of modifications needed to bring a system to a certain level of reliability. The analyst may also not have knowledge of the degree of reliability/availability that will be required for future missions. As time progresses and future missions come closer in time, some mission requirements will be developed. However, in the current state of mission uncertainty, an analyst must anticipate the requirements of future missions. Thus, an investigator may choose to qualitatively discuss necessary data alterations, rather than attempt to quantify the modifications. Regardless of the approach, all data modifications deemed appropriate for the study should be clearly explained in the analysis documentation.

### System Sizing and Data Scaling

The analyst must determine the proper hardware sizes for the mission scenario of interest for the system that

<sup>2</sup> However, for the purposes of forecasting changes in characteristics for a particular piece of equipment, it is valid to compare data for an early development state with data for a later development state.

has been deemed appropriate for the study. Hardware is commonly sized according to a characteristic parameter. Lacking other information, throughput, or mass flowrate 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 system-sizing effort. In this respect, the investigator's judgement should be used to determine which material compounds should be included in the sizing effort. For example, if the analyst deems it necessary to compare mineral requirement differences in biological systems, then the sizing effort must consider the minerals of interest. However, 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.

Depending on the objectives of the analysis, the approach to system sizing may range from steady-state to transient conditions. In other words, system sizing efforts may lie anywhere in between (or include) these two approaches. A steady-state mass balance requires less analysis effort but is less realistic than the more effort-intensive transient mass balance. Steady-state mass balances can be easily implemented using spreadsheet software, whereas transient mass balances are most easily performed through the use of transient simulation tools. 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. Thus, if a steady-state mass balance is used but the analyst knows that an incinerator (for example) will actually be operating in semi-batch mode, then the analyst may modify the mass balance results for the incinerator to reflect that knowledge. This may mean estimating modifications for the mass flowrate of materials into the semi-batch mode incinerator and for the material containment that is needed prior to incineration.

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 sizing with nominal operation, 2) steady-state sizing with off-nominal events, 3) transient sizing with nominal operation, and 4) transient sizing 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 calculations of daily loads, under nominal operation.

Once the appropriate sizing parameter values have been determined, the investigator should scale the hardware raw data to those values. For example, a technology developer may provide hardware raw data for a laboratory prototype that processes only a fraction of the flow that would require processing in an actual mission or test bed. Thus the hardware data must be scaled up to accommodate the desired mass flowrate (the sizing parameter). An industrial process, on the other hand, is likely to be much larger than needed for space missions and must be scaled down. If an objective of the analysis is to compare functionally similar processors for a specific mass throughput (or other sizing parameter), raw data scaling is necessary.

A simple approach is to scale raw data linearly with respect to the sizing parameter. However, more accurate scaling 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 Engineering Industry.)

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

## THE IMPORTANCE OF RESULTS INTERPRETATION

To legitimately implement ESM results in a selection process, the 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. 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 (such as TRL, robustness and/or simplicity/complexity) are likely to drive technology selection.

The desirable degree of results accuracy can depend upon the analysis objectives. Because of the compounding nature of error in analyses, if study objectives necessitate a very detailed analysis involving large amounts of data, then a high degree of accuracy in data and methods is necessary. However, if the



objectives necessitate an analysis of a low level of detail, then the required degree of data and methods accuracy might be reduced.

Researchers that provide data for an ESM evaluation may execute various levels of rigor in the data collection process. In addition, if 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 data feeds into the confidence of ESM results, the investigator should have at least a basic impression of data quality. Confidence in results is also affected by decisions affecting the rigor of development state adjustments and scaling efforts. The analyst should balance the degree of effort needed for adequate results confidence with resource availability during each step of the ESM evaluation process.

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 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. 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.

## THE IMPORTANCE OF ANALYSIS DOCUMENTATION

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. As this can be quite arduous, effort should be focused on the issues that most affect the results and add value to the final report.

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.

Some of the decisions that must be explained in the results documentation 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 and other evaluations.
5. Input data values, their sources, and a brief explanation of those values implemented.
6. Justification of development state adjustments, sizing methods, and scaling factors, including quantification and references.
7. A discussion of the expected accuracy of ESM (and other) results and associated interpretation.

## CONCLUSION

This paper discussed the importance of some of the analytical decisions that an investigator must make during the course of a trade study. When applied appropriately, an ESM analysis can be a useful tool for making choices between trade study options. However, in cases where no conclusive decision can be drawn from an ESM analysis, the results may be useful in determining the most important cost drivers (mass, volume, power, cooling or crewtime) for a trade study option. The analysis effort can also draw attention to the need for possibly critical data that needs to be collected and/or verified.

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## DEFINITIONS, ACRONYMS, ABBREVIATIONS

**ALS:** Advanced Life Support

**BVAD:** Baseline Values and Assumptions Document

**ESM:** Equivalent System Mass

**RMD:** Reference Missions Document

**R&TD:** Research and Technology Development

**SIMA:** Systems, Integration, Modeling and Analysis

**WRS:** Water Recovery System