Commonality Analysis for Exploration Life Support Systems

by

Phillip M. Cunio

B.S. Aerospace Engineering
B.S. Mechanical Engineering
B.A. German Studies
University of Florida, 2006

SUBMITTED TO THE DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE IN AERONAUTICS AND ASTRONAUTICS
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE 2008

Signature of Author..............................
Phillip M. Cunio
Department of Aeronautics and Astronautics
May 2008

Certified by..............................
Jeffrey A. Hoffman
Professor of the Practice
Aeronautics and Astronautics
Thesis Supervisor

Accepted by..............................
Prof. David L. Darmofal
Associate Department Head
Chair, Committee on Graduate Students

Commonality Analysis for Exploration Life Support Systems

by
Phillip M. Cunio

Submitted to the Department of Aeronautics and Astronautics
on May 22, 2008 in Partial Fulfillment of the
Requirements for the Degree of Master of Science in
Aeronautics and Astronautics
At the Massachusetts Institute of Technology

ABSTRACT

Commonality, defined practically as the use of similar technologies to deliver similar functions across a range of different complex systems, offers opportunities to improve the lifecycle costs of portfolios of complex systems. In this thesis, a proposed methodology for commonality analysis is tested by application to a portfolio of life support systems for planetary surface exploration.

A database of environmental control and life support technology is developed and presented, and sets of system architectures for environmental control and life support systems are generated by models using the Object-Process Network (OPN) meta-language, which integrates information from the database.

System architectures are downselected to a few interesting architectures, from which interesting potential portfolios are created, and commonality analysis is applied to these portfolios of complex environmental control and life support systems. The applied commonality analysis methodology estimates the total equivalent campaign mass to be transported to the planetary surface for exploration, the development cost of the necessary equipment, the mass of spares required by the equipment, and the number of unique items to be developed at various Technology Readiness Levels.

Based on these analyses, recommendations for further technology development and appropriate commonality levels in future portfolios of complex systems are presented, and a summary of desirable future work concludes the thesis.

Thesis Supervisor: Jeffrey A. Hoffman
Title: Professor of the Practice, Aeronautics and Astronautics

ACKNOWLEDGEMENTS

The author wishes to express gratitude to Professor Jeffrey A. Hoffman, whose intellectual support and guidance went a long way toward making this thesis possible.

The author also wishes to acknowledge the contributions of Professor Edward F. Crawley, who funded the author's research and other activities through grants from NASA, and with whose research group the author was privileged to work.

Others whose contributions should be recognized are Wilfried K. Hofstetter, who was always dispensing insightful critiques, and whose advice was occasionally invaluable. Professor Crawley's Space Systems Architecture research group is recognized in its entirety as a source of much advice, insight, and support, although special thanks are extended to the senior members of the group, including Ryan Boas, Paul Wooster, and Bill Simmons, who set particularly helpful examples to follow.

The author also wishes to extend a special thanks to the key members of the MSR project team, with whom he worked on a regular basis on many projects, including Zahra Khan, Jim Keller, Ryan Odegard, and Takuto Ishimatsu. Much of the encouragement needed to complete this thesis stemmed from these.

Finally, the author wishes to thank three people without whom he would not be here: Mrs. Paula Marie Cunio, Mr. Stephen Jeremy Cunio, and most particularly Talitha JoAnn Cunio. The author hopes that the trust and patience displayed by these for many years have been duly rewarded. From Talitha especially has come unending support of all possible kinds, and her tangible and intangible contributions to all the author does cannot be overstated, nor her positive influence on him overestimated. Thank you.

ABBREVIATIONS

2BMS: 2-Bed (Carbon) Molecular Sieve
4BMS: 4-Bed (Zeolite) Molecular Sieve
ACRS: Advanced Carbon-Forming Reactor System
APCOS: Aqueous Phase Catalytic Oxidation Post-Treatment System
CHX: Condensing Heat Exchanger
ECLSS: Environmental Control and Life Support System
EVA: Extra-Vehicular Activity
HSWPA: Hamilton Sundstrand Water Processing Assembly
LiOH: Lithium Hydroxide
MF: Multifiltration
OPN: Object-Process Network
PLSS: Personal Life Support System
RO: Reverse Osmosis
RWGS: Reverse Water-Gas Shift reactor
SAVac: Solid Amine Vacuum desorption (pressure-swing system)
SAWD: Solid Amine Water Desorption
SCWO: Super Critical Wet Oxidation
TCC: Trace Contaminant Control
TIMES: Thermoelectric Integrated Membrane Evaporation System
TRL: Technology Readiness Level
VAPCAR: Vapor Phase Catalytic Ammonia Removal
VCD: Vapor Compression Distillation

TABLE OF CONTENTS

List of Figures

CHAPTER 1. Introduction

1.1 Motivation

The development of complex systems is an expensive and risky task. Yet such development must take place before the implementation of large-scale endeavors, such as the return to the Moon and the crewed exploration of Mars, as proposed by the Vision for Space Exploration (1) and as currently being implemented by NASA. The development of many extremely complex systems is necessary to allow humans to return to the Moon and proceed to Mars. Among these systems are launch vehicles, landers, and habitats, although many of the subsystems associated with these vehicles (such as power systems, propulsion systems, and life support systems) are sufficiently complex as to present serious design problems in their own right.

Much of the total lifecycle cost of a design is locked in during early phases of the design, and in order to decrease the total risk and lifecycle cost associated with the design and development of complex systems, several approaches may be considered. One such approach is the investigation of opportunities for commonality in the complex systems, to be carried out early in the design phase and implemented throughout the later stages. This topic is the subject of a PhD thesis effort by Hofstetter (2), and the methodology developed therein is implemented in this work.

An example of the potential for cost savings over the lifetime of a system is provided in (3), where the authors calculate reduction in spares mass required for system functionality as a result of increased commonality either within or between elements. The authors calculate that the reduction in mass of spares required due to complete commonality of components (due to two instances of the same element) may be as high as 33%, and that one-third commonality in components may result in a mass savings of up to 11%, if inter-element and intra-element commonality are both considered. Given the number and type of elements which make up portfolios of complex systems for crewed surface exploration, such a high degree of commonality may be unlikely; however, the total mass delivered to the surface by such a portfolio is also very high, and a reduction of just a few percent in this mass can equate to significant cost savings, especially when the masses are weighted according to their ultimate delivery point. For instance, it costs much more (due to propulsive requirements) to deliver 10 kilograms to the surface of the Moon than to low Earth orbit, and any cost savings on 10 kilograms delivered to the surface of the Moon will be proportionately leveraged as well.

1.2 Commonality

The investigation of commonality in complex systems focuses on the implementation of common manufacturing processes, parts, or operational procedures in order to reduce initial development costs or operational costs. Commonality may result in benefits due to a lessened need for dedicated design efforts or due to a reduced requirement for spares. Unfortunately, such commonality in either subsystems or in various systems within a portfolio of complex systems may result in penalties as well as benefits, in that some of the subsystems or complex systems within the portfolio will be non-optimal, due to increased requirements or interface mass. Methodology is currently under development to analyze, as part of the early phases of design, the potential for commonality among different complex systems in a portfolio, so that the potential benefits and penalties might be explored and qualitatively analyzed early in the design process (2). This work seeks to take one such methodology (2) and apply it to an existing engineering problem.

1.2.1 Complex Systems for Test Case

A portfolio of systems is a collection of systems that are interrelated in some way, insofar as they serve a shared purpose but many differ in the details of their functions and requirements, and may also stand individually but are typically used as a group. Thus a portfolio of complex systems may be a series of vehicles, as in the case of NASA's proposed vehicular architecture for planned crewed exploration missions of the Moon and Mars. This portfolio is a collection of systems which serve the function of protecting and providing for the transport of the human occupant, and yet includes such diverse complex systems in its membership as EVA (Extra-Vehicular Activity) suits and launch vehicles. In this work, only the Environmental Control and Life Support (ECLS) systems for a planetary surface exploration mission will be examined. This allows for the analysis to be applied to a portfolio of what are rather complex systems, and are also such that some reliable data are available.

1.3 Methodology

1.3.1 General Commonality Analysis Methodology

The broader Commonality Analysis Methodology (CAM) implemented in this thesis has three major steps.

CAM has three major steps, detailed as:

1. Identify interesting architectures for each of the complex systems in the portfolio.
2. Identify opportunities for commonality from among the interesting architectures.
3. Compare commonality-containing portfolios on the basis of metrics such as total lifecycle cost, development cost, and total equivalent campaign mass.

1.3.2 General Modeling

Modeling of this problem was carried out in OPN (Object-Process Network), a meta-language developed by Koo (4), based on work done by Dori (5). One application of OPN, illustrated by Simmons et al. (6), is the automated creation and evaluation of a series of system architectures. This method was used here to implement the creation of a set of architectures for ECLS systems.

In the architecture-creation mode, OPN functions with the objects serving as markers for decisions that must be made, and with the processes denoting options for each decision. In the model developed here, decisions are functions that must be fulfilled by the ECLS system architecture, such as elimination of carbon dioxide from the atmosphere, provision of potable water, and provision of oxygen. Options for each decision are technology options that can carry out the functions under which they are listed. Therefore an architecture is a series of technology options that can carry out all the necessary functions of an ECLS system.

The OPN software functions by sending data structures called tokens propagating through the network of objects and processes. In an architecture-generation model, such as is used here, each individual step along the chain of functions creates a new series of tokens, resulting in a list of architectures that combinatorially exhausts the complete possible design space. The tokens which result at the end of the model's execution are the architectures. Each architecture contains key data in the form of metrics, which are calculated as the token propagates through the decision tree. For the model designed here, the metrics tracked are consumables mass, consumables volume, equipment mass, equipment volume, equipment power required, and equipment heat generated. These metrics are incremented in each token as it passes through the network, building up a unique value for each separate architecture, based on the contributions to the metrics from each individual technology option chosen. From these metrics, an overall equivalent mass can be calculated, and on this basis the various architectures can be compared to select interesting architectures.

1.3.3 Implementation

The model was implemented by first splitting the design space. The original model of the problem included the entire design space, and was too large for successful computation. However, the design space was split into four subsections, referred to as instantiations. The instantiations selected were modeled in part on the natural splitting of the design space into four basic types (or basic instantiations) of vehicles which include an ECLS system. These four instantiations are EVA suits, pressurized rovers, long-term habitats, and transfer vehicles (such as the LSAM, a Mars surface transfer vehicle, and the CEV).

Justification for the division of the design space into the four partitions is also provided by noting that there are some distinguishing qualities between the various instantiations. Duration of use is one distinguishing factor, in that longer-use instantiations tend to imply high-closure systems, as the crossover points between the total mass of regenerable technology systems and the total mass of resupplied consumables for non-regenerable systems tend to have been passed.

Rechargeability is another distinguishing factor, in that some systems must run continually, but others can be used for a period of time and then put into a dormant phase for recharging. It may also be noted that the rechargeable instantiations tend to have more mobility requirements, in that they consist of the EVA suit and the pressurized rover, and that these place some restrictions on the mass and volume of technology options that can be selected, which may be stricter than the mass and volume restrictions on the less-mobile instantiations of the habitat and the transfer vehicle. Figure 1 illustrates the four instantiations.

Using these four instantiations, four OPN models were created. Appropriate restrictions for each instantiation were written into the models, such that the total number of technology options for each function to be fulfilled was decreased until the entire OPN model produced an output of manageable size (a few hundreds or thousands of architectures) in a reasonable time.

Duration of use / Rechargeability	**Short system use duration**	**Long system use duration**
System is rechargeable (non-continual use)	Extravehicular activity suit (EVA)	Pressurized rover (PR)
System is NOT rechargeable (continual use)	Transfer vehicle, such as lunar surface access module or Mars descent/ascent vehicle (LSAM)	Long-term habitat (Hab)

Figure 1. Instantiations for the OPN Model.

These four OPN models generate lists of architectures, each of which are a series of technology options with associated metrics of mass, volume, power, and heat. The architectures can be sorted by equivalent mass (or any of the other metrics tracked), and the top few architectures by these metrics can be selected as interesting.

The total number of combinatorial architectures for each instantiation can reach the tens of thousands, as seen in Table 1.

Architectures	Habitat	EVA suit	Press. Rover	Transfer Veh.
Combinatorial	36,864	45	504	3760
Generated	4914	16	222	440
Interesting	2	2	2	1

Table 1. Number of architectures.

Note, however that the various OPN models for each instantiation also contain connections between the technology options available for one function and those available for subsequent functions. The total number of combinatorial architectures is not generated; the design space is trimmed according to these connections. Thus the list of architectures generated is not exhaustive.

The connections may be of three types, as seen in Figure 2. The connections disallow some possible architectures and force others, resulting in a shrinking of the total design space. The architectures which are generated after the application of these rules are a subset of the combinatorial architectures but a superset of the interesting architectures.

An example of the sorts of rules which appear in the OPN models is that carbon dioxide removal via a non-regenerative method (such as lithium hydroxide canisters) cannot be coupled with reduction of carbon dioxide, via methods such as Sabatier reactors or Bosch reactors.

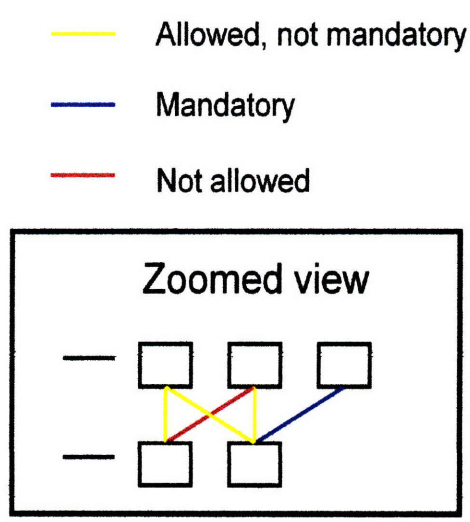

Figure 2. Types of connections in OPN models of instantiations.

In the final sorting of architectures only the top-performing architectures according to the tracked metrics are chosen. For this work, the number of interesting architectures is kept small, to make the design space more amenable to the implementation of the Commonality Analysis Methodology developed by Hofstetter (2).

1.4 Tool Development

In order to develop the OPN models, data was first collected from sources including published books (7), websites maintained by industry, and standard reference texts (8), (9). This information was placed into a database, most of the entries from which appear in Chapter 2 of this thesis. Data tracked in the database included existence data, which marked the presence of the various functions and the presence of technology options for these functions, but also sizing parameters, such as the mass and volume per person-day, and included notes and other information, such as the TRL (Technology Readiness Level).

This data was used to fill in the technology option slots in the OPN models for each instantiation. Details for each technology option (such as whether dry or wet air was output) determined some of the development of connection rules, which govern the selection of feasible architectures from all of the combinatorial architectures. Finally, the tool was run and the architectures were sorted to find a handful of interesting architectures. This process is seen in Chapter 3 of this thesis.

1.5 Benchmarking and Validation

The architectures generated were validated via comparison to existing ECLS systems. Although no high-closure ECLS systems have yet been built and flown, leaving an area of the design space that cannot be validated, the values for mass, volume, and power of existing ECLS systems associated with the Skylab, Apollo, and ISS programs were located, and the aggregated equivalent system masses from the appropriate generated architectures were compared to the aggregated equivalent system masses for the existing ECLS systems.

1.6 Implementation of Commonality Analysis

The handful of interesting architectures selected in Chapter 3 were assembled into portfolios for commonality analysis in Chapter 4. To implement the analysis, further tools developed by Hofstetter (2) were adapted and applied, and assessments were made of the development cost, transport cost, and total lifecycle cost of the various portfolios, as aggregated from the interesting architectures included in each portfolio.

The results of this analysis follow, and Chapter 5 develops conclusions and recommendations, while Chapter 6 suggests future work that may build upon the work in this thesis.

CHAPTER 2. ECLS Systems Database

The process of identifying interesting architectures for ECLS systems began with the development of a database of available ECLS technology. The database, the key elements of which are described in this chapter, captures two important types of information about ECLS systems and ECLS technology options.

2.1 Information in the Database

The first type of information captured is the list of functions for the ECLS system and the technology options which can fulfill each function. The database includes a name for each of the ten functions required to sustain human life, and associated with each function is a sublist of technology options which can fulfill that function. For example, carbon dioxide must be removed from the atmosphere by an ECLSS, and lithium hydroxide canisters, solid amine water desorption beds, molecular sieves, and metal oxides are all technology options which can provide this function.

The second type of information captured in the database is the scaling parameters for each technology option, along with associated notes. Each technology option has some equipment mass, equipment volume, consumables mass, consumables volume, equipment heat generated, and equipment power required associated with it. All of these can be normalized to a per-person-day basis. Some of these values may also be zero for some technology options. These parameters are taken from literature, including (7) and (8), and provide the basis for calculation of the main metric for system comparison, system equivalent mass. The notes associated with each technology option indicate the Technology Readiness Level (TRL) and other important features. Notes are often the basis for rules related to the feasibility of connecting one technology option to another in the set of feasible architectures for an ECLS system.

The software modeling language called Object-Process Network, or OPN (4), is used to develop a model for system architecture generation. An example appears below, in Figure 3.

The OPN architecture generation tool denotes functions by green boxes, and denotes technology options by blue ovals. A list of functions shows that each has one to several technology options associated with it.

The OPN language creates data structures, called tokens, which propagate through the architecture generation tree and collect information according to the path taken through the tree. Each token takes only one path, and then creates new tokens for every new possible path which branches away from its termination point in an object. Thus the final tokens are a set of architectures, each containing information such as mass, power, volume, and heat for the system architecture, as well as a list of technology options used in that system architecture. If every possible path in the architecture tree were to be taken, the resulting set of architectures would be the combinatorial set of all possible architectures, but as the architecture generation tree includes rules governing which possible paths can or cannot be taken from certain objects or by certain tokens (see Table 2), the final set of architectures generated is the feasible set of system architectures.

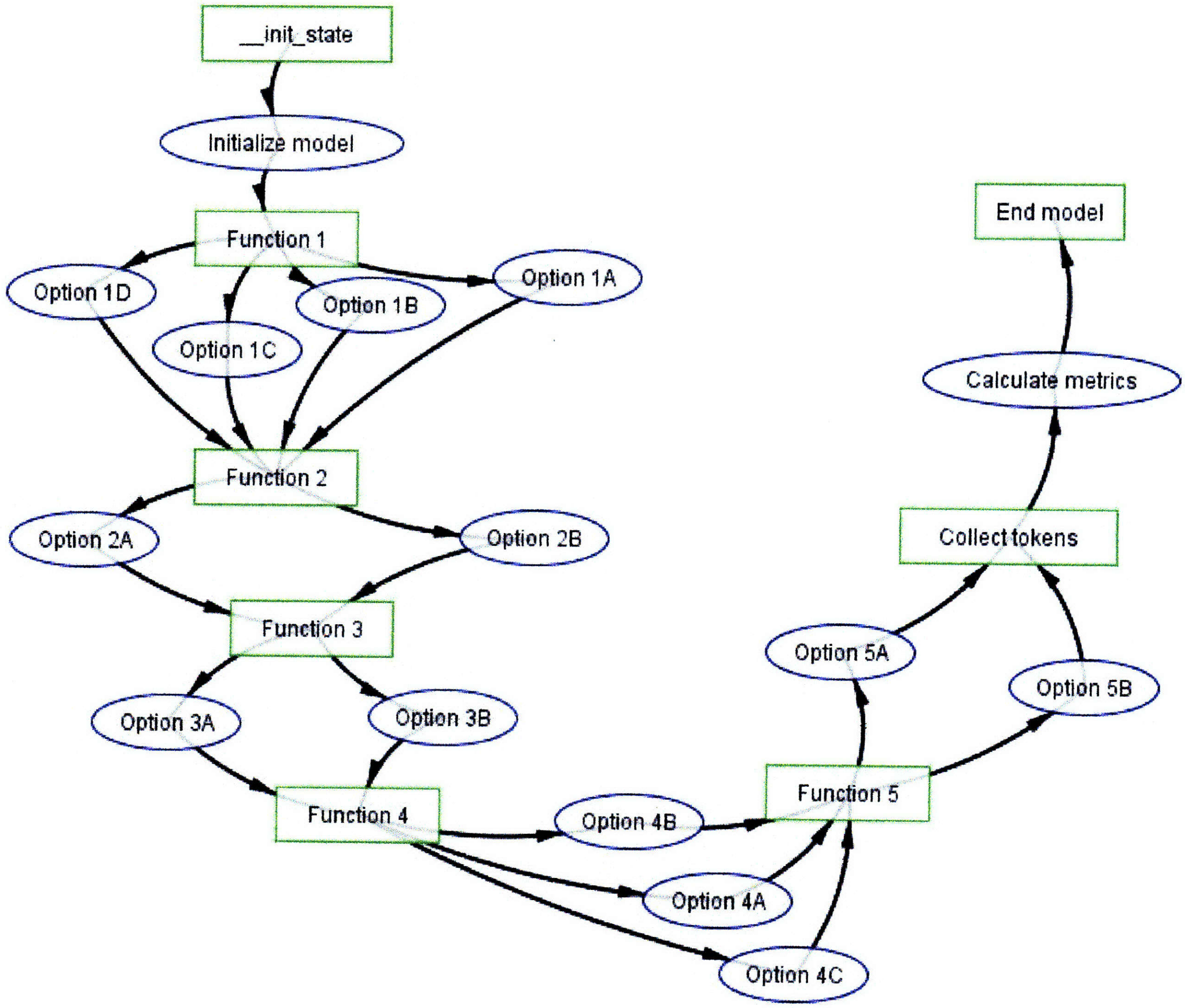

Figure 3. Example OPN architecture generation tool.

This set of feasible system architectures can be ranked according to the value of a metric, calculated from the weighted values of mass, volume, power, and heat which are tracked and accumulated by the tokens. Ranking the set of feasible architectures results in a few top architectures (either some few architectures, or a family of architectures) that dominate all others in terms of the metric, and these architectures or this family of architectures contains the interesting architectures. The list of ranked feasible architectures can be truncated at a reasonable point in order to make the total space of interesting architectures amenable to further calculation by hand or by the current generation of tools for the Commonality Analysis Methodology.

2.2 Instantiations

There are four instantiations for the generalized ECLS system model, developed as a means of splitting the design space and thus reducing complexity and decreasing computational effort required. These four instantiations map onto the actual elements likely to occur in a lunar or Martian surface exploration architecture. The instantiations are an Extravehicular Activity (EVA) suit, a pressurized rover, a transfer vehicle (meant to ferry the crew for a short period of time from orbit to surface or vice versa, or on short transfers), and a long-term habitat, meant for occupation by the entire crew during a long interplanetary coast phase or a long surface stay.

All instantiations consist of notional designs, rather than detailed technical descriptions, because the level of information at the design phase in which commonality analysis is applied is too low to allow for extremely developed designs for the instantiations. Therefore each instantiation is only matured to a partial degree, but some implications of the notional design affect later development of the analysis methodology.

The EVA suit is based on current pressurized suit designs, which rely on atmosphere-retaining bladders to provide the necessary counterpressure delivered by an EVA suit (9). This results in the EVA suit not being required to provide nitrogen. This function is eliminated in this instantiation because it is desirable to maintain the pressure inside the suit at the lowest level possible, while still keeping a normoxic environment and preventing decompression sickness, and so the suit's internal atmosphere consists entirely of oxygen at about 29.6 kPa (4.3 psi) (8). Another limitation on the EVA suit instantiation is the weight. Current suit designs mass upwards of 100 kg, but it was deemed prudent to limit the mass of the suit ECLS system to much less than this if possible, given that extended periods of time will be spent utilizing the EVA suit. Some sources even recommend limiting total suit mass as low as 30-50 kg to allow for potential deconditioning over the course of extended missions (8). More than this may result in mobility on planetary surfaces being compromised. Some technology options are instantly eliminated by this barrier, allowing for simplification of the design space.

Furthermore, EVA suits have rechargeable components, and allowances were made for the non-portable elements in the overall mass budget for the system. This way, although the astronaut may carry only a few kilograms of metal oxide for carbon dioxide absorption, the equipment in the suit and back at the habitat required to reduce the carbon dioxide produced (thus recapturing the oxygen consumed) is all accounted for in the model.

The pressurized rover notional design is based on the concept advanced by NASA for the lunar surface infrastructure (10). This rover is designed to carry two people on traverses of up to seven days, and is also designed to allow for fast access from the interior of the rover to the surface via EVA suit. One result of this requirement is the need to minimize prebreathing when transitioning from the rover to the EVA suit, which necessitates that the rover instantiation will, like the EVA suit instantiation, also not include the function of supplying nitrogen. In addition, the pressurized rover will include some rechargeable components, which will require modeling of the mobile and non-mobile equipment mass separately.

The transfer vehicle notional design is based on the current baseline for the Lunar Surface Access Module (LSAM), but includes notions of designs for Mars Descent/Ascent Vehicles. A transfer vehicle is any vehicle meant to ferry the crew from surface to orbit or vice versa, or both, or from surface to surface through long-range powered flight. The Crew Exploration Vehicle (CEV) provides a baseline validation design for this instantiation, even though it is not necessarily meant to touch down on a surface. The CEV is meant to support a crew for a few days, and to transfer from one gravity well to another or to orbit. Because the time frame of use for transfer vehicles is typically short, open-loop or high-closure ECLS systems are feasible for use in this instantiation, whereas they are less so in other instantiations.

The habitat notional design is meant to capture all systems wherein the entire crew remains inside the structure for large fractions of a long period of time. This provides for inclusion of both deep-space transit habitats and surface habitats in this instantiation of the general model. Due to the fact that the number of crew-days that habitats are likely to be used is sufficiently high that the mass requirement for a highly closed (i.e., utilizing massive equipment and power-generation systems, but with few consumables) crosses below most open-loop (using many consumables but little dedicated equipment and low power) system architectures, it makes sense to consider only highly-closed systems and their subsidiary technology options for inclusion in the habitat instantiation.

Duration of use / Rechargeability	**Short system use duration**	**Long system use duration**
System is rechargeable (non-continual use)	Extravehicular activity suit (EVA)	Pressurized rover (PR)
System is NOT rechargeable (continual use)	Transfer vehicle, such as lunar surface access module or Mars descent/ascent vehicle (LSAM)	Long-term habitat (Hab)

Figure 4. Instantiations for the OPN model.

2.3 Functions and Technology Options

The following sections comprise a listing of the functions of a typical ECLS system, together with a listing of, and some details on, the various technology options. Note that some functions do not appear in certain instantiations, and that, for modeling and scaling purposes, every technology option must have some associated parameters, such as mass and volume required per person per day. Different ways of delivering a function constitute essential technology options, although the physical hardware that delivers the function may differ from one realization to the next. For instance, water electrolysis is one way of providing oxygen (other ways include cryogenic gas storage or carbon dioxide electrolysis), but different items of physical hardware actually exist to perform water electrolysis. In most cases, different hardware items are not captured in the model, although they are present in the ECLS systems database, and one set of hardware is chosen as representative of the technology option in general. This is reflective of the difficulty in designing systems to include commonality when component parts have not yet been designed in any detail, or even selected. An individual example of a water electrolysis unit may be designed in several ways, and in the early stages of the design of a portfolio of complex systems that may include at least one water electrolysis unit, it is most likely that the design details can be adjusted to allow for commonality if it should be seen to be advantageous to the portfolio.

2.3.1 Provide Oxygen

An ECLS system must deliver breathable air to the crew, and a major component of this function is the provision of oxygen for uptake and metabolic use.

-Water electrolysis (exemplified by Proton Exchange Membrane Electrolysis)

Water electrolysis is the splitting of water to create hydrogen and oxygen. This technology is commonly used on naval submarines, and is already in use on the ISS. Therefore, it has a high TRL (8). Because the Bosch and Sabatier processes create water, water electrolysis can be coupled with these to regenerate carbon dioxide into breathable oxygen. This process also produces hydrogen, which can be fed back into a Sabatier or Bosch reactor to reduce the consumables requirement. The water electrolysis technology option is sized to deliver oxygen from a stoichiometrically accurate amount of water, as would be produced from a closed air loop (if, for instance, a Bosch or Sabatier reactor were being used). Some makeup oxygen is still required, and this amount is bookkept here as cryogenically-stored gaseous oxygen, with a tankage mass wrapping factor of 1.26 and a density of 1140 kg/m^3. The power required and heat rejected by the need to store cryogenic makeup oxygen is carried as an addition to the equipment power and equipment heat lines, indicated by an additive term in these lines.

The electrolysis process is assumed to operate at about 50% efficiency, so half of the energy consumed goes into electrolysis, while the other half is dissipated as heat. Therefore a differential exists between the quoted power requirement and the estimated heat rejection requirement. The power used for the cryogenic storage, however, is entirely converted to heat for later rejection, as no major chemical change takes place in this process.

All mass, volume, power, and heat requirements for equipment are quoted in kilograms per person (kg/p), cubic meters per person (m^3/p), or Watts per person (W/p). Consumables are quoted in kilograms per person per day (kg/p/d) and cubic meters per person per day (m^3/p/d).

Water electrolysis parameters (TRL 8)			Ref
Equipment mass	30.48	kg/p	(11)
Equipment volume	0.0172	m^3/p	
Equipment power	8.594 + 16.33	W/p	
Equipment heat	4.297 + 16.33	W/p	
Consumables mass	0.1424	kg/p/d	
Consumables volume	0.000125	$m^3/p/d$	

-Carbon dioxide electrolysis (exemplified by Zirconia Cell Electrolysis)

Carbon dioxide electrolysis splits carbon dioxide into carbon monoxide and oxygen. Because this process vents oxygen atoms (bound into carbon monoxide), more makeup oxygen will be required than for other regenerative systems. The same assumptions as to tankage mass wrapping factor and storage density apply to the makeup oxygen. Zirconia electrolysis requires a feed of dry carbon dioxide, and so cannot be fed wet carbon dioxide, such as is the output of a Solid Amine Water Desorption (SAWD) system, a 2-bed molecular sieve, or an Electrostatic Decomposition Concentration (EDC) system.

As with water electrolysis, an energy-utilization efficiency level of 50% is assumed.

Carbon dioxide electrolysis parameters (TRL 7)			Ref
Equipment mass	33.6	kg/p	(12)
Equipment volume	0.0084	m^3/p	
Equipment power	999.6 + 16.33	W/p	
Equipment heat	499.8 + 16.33	W/p	
Consumables mass	0.6023	kg/p/d	
Consumables volume	0.0005	$m^3/p/d$	

-Cryogenic gas storage

Some consumable gas storage will be required even in an otherwise-closed ECLSS, as the stated requirement for atmospheric oxygen per person per day (8) does not match the stoichiometric amount of oxygen that can be recovered from the average amount of carbon dioxide exhaled per person per day (8). There is a shortfall of 0.113 kg of oxygen per person per day. This will have to be made up some way, and the way in which gases are usually supplied in space is via cryogenic storage. All makeup gases are assumed to be stored cryogenically, but it is also possible to supply all required oxygen or other gases (not just makeup gases) through cryogenic methods, and this technology option reflects this. Note that cryogenic gas storage requires only some amount of tankage, and that this tankage mass is bookkept as additional consumable mass and volume. The mass is found using a wrapping factor 1.26 applied to the actual required mass of consumable gas, and the volume is then set based on the gas density, set to 1140 kg/m^3 for liquid cryogenic oxygen. The power required for cryogenic storage is defined by an equation from (13), and is a function of the heat leak rate, which is estimated from (14). Hastings et al. indicate that heat leak rate is a function of tank surface area; a baseline tank volume of 1 cubic meter was converted to surface area and then used to generate an approximate average heat leak rate (including a factor added in for heat penetration) of 4.8 W.

The estimated heat leak rate is used to calculate a required cooling power, which is then divided up between the number of crew members who would be expected to share a one cubic meter tank. The resulting number is presented as an estimate of the power required per person per day to keep cryogenic gases in storage for a reasonably long period of time. Note that some instantiations may keep cryogenic gas in storage for a long period of time, having been filled with consumables before the mission began; while others are periodically filled and refilled (like tanks in an EVA suit). Therefore this number is an estimate across a number of instantiations.

The parameters for heat generation rate (which is here taken as equivalent to the power requirement, rather than the heat leak rate, which depends on tank insulation and geometry properties) and power requirement are different for different gases, as reflected in the appropriate tables.

Although in most cases the mass wrapper for tankage is bookkept as consumables mass and volume, for the EVA suit instantiation, the tankage mass and volume is bookkept as equipment mass and volume, since the EVA suit must be so frequently recharged (once after every use, and with no use longer than about a third of a day) from larger reservoirs of consumables that it is likely it will rely on consumable resupply in containers suitable for larger amounts of consumables than would be required for one EVA.

Cryogenic gas storage parameters (TRL 9)			Ref
Equipment mass	0 (0.2184 for EVA suit)	kg/p	(15)
Equipment volume	0 (0.00019 for EVA suit)	m^3/p	
Equipment power	16.33	W/p	
Equipment heat	16.33	W/p	
Consumables mass	1.0584 (0.84 for EVA suit)	kg/p/d	
Consumables volume	0.00093 (0.000737 for EVA suit)	m^3/p/d	

-High pressure gas storage

Required gases, for makeup or for general consumption, can also be stored in high-pressure tanks instead of cryogenic tanks. High-pressure gaseous storage uses a mass wrapping factor (similarly applied directly to the mass of the consumable gas) of 1.9 and a density of 9130 kg/m^3. It is assumed that no cooling or power is required to maintain high-pressure gases in storage.

The same assumptions about resupply from larger tanks apply to this technology option when it is used in the EVA suit instantiation. Tankage mass and volume are calculated via a wrapping factor, but are bookkept as equipment rather than consumables.

High pressure gas storage parameters (TRL 9)			Ref
Equipment mass	0 (0.756 for EVA suit)	kg/p	(8)
Equipment volume	0 (0.00663 for EVA suit)	m^3/p	
Equipment power	0	W/p	
Equipment heat	0	W/p	
Consumables mass	1.596 (0.84 for EVA suit)	kg/p/d	
Consumables volume	0.000175 (0.000737 for EVA suit)	$m^3/p/d$	

-Chemical compounds (exemplified by potassium superoxides)

Chemical compounds can react with carbon dioxide and release oxygen. Similar types of items are already in use on the ISS, in the form of Russian oxygen candles. Although there are many varieties of chemical compounds, potassium superoxide offers a competitive amount of oxygen per kilogram of chemical compound, and so is used as the example. Potassium superoxide has a bulk density of 2140 kg/m^3, and this is used to calculate the volume required per person per day.

Chemical compounds parameters (TRL 8)			Ref
Equipment mass	0	kg/p	(16)
Equipment volume	0	m^3/p	
Equipment power	0	W/p	
Equipment heat	0	W/p	
Consumables mass	2.2105	kg/p/d	
Consumables volume	0.0010	$m^3/p/d$	

2.3.2 Remove Carbon Dioxide

The second major component of an ECLS system's function of delivering breathable air to the crew is the removal of carbon dioxide from the atmosphere.

-2 Bed Molecular Sieve

A 2-bed molecular sieve is a newer technology, which does not require a separate drying stage for the air it processes. It uses a carbon-based molecular sieve, which adsorbs carbon dioxide highly preferentially over water (17). If the 2BMS is used to desorb carbon dioxide to vacuum, some water will be lost, but not as much as with the 4BMS or SAWD, because the 2BMS is far less hydrophilic. (18) indicates that the 2BMS can lose up to 1.665 kg per person per day of water if operated on the PLSS of an EVA suit; for general purposes, it is assumed that improved desiccation of the air before passing it through the 2BMS can cut this loss to 10% of the stated level. This places the consumables loss for the 2BMS lower than that of the 4BMS, which is appropriate given that the 2BMS is more hydrophobic and this should vent less water. Furthermore, this loss only applies if the bed vents to vacuum.

2BMS parameters (TRL 6)			Ref
Equipment mass	7.4	kg/p	(18)
Equipment volume	0.0084	m^3/p	(7)
Equipment power	76.67	W/p	
Equipment heat	76.67	W/p	
Consumables mass	0.1699 (vacuum vent)	kg/p/d	
Consumables volume	0.00017 (vacuum vent)	m^3/p/d	

-4 Bed Molecular Sieve

The 4-bed molecular sieve is a mature technology, exemplified by the Carbon Dioxide Removal Assembly (CDRA) on the ISS and Space Shuttle. It dries air before removing carbon dioxide, and as such requires some amount of self-regenerating silica gel (19). Notably, if operated by venting to vacuum, the CDRA also loses approximately 0.005 kg of air per day (19). Because it is also assumed that the 4BMS cannot dry air completely before venting carbon dioxide (a 10% residue of the 2.28 kg per person per day is assumed to remain after the desiccating step), this consumable mass is also lost if the 4BMS is vented to vacuum.

4BMS parameters (TRL 8)			Ref
Equipment mass	29.3	kg/p	(7)
Equipment volume	0.11	m^3/p	
Equipment power	178.3	W/p	
Equipment heat	178.3	W/p	
Consumables mass	0.242 (vacuum vent)	kg/p/d	
Consumables volume	0.000238 (vacuum vent)	m^3/p/d	

-Electrostatic Depolarization Concentration

The EDC is a mid-TRL technology option. It requires hydrogen and oxygen sources to perform its function, and therefore must be coupled with a water-electrolysis unit when included in an ECLS system.

EDC parameters (TRL 6)			Ref
Equipment mass	11.1	kg/p	(7)
Equipment volume	0.0178	m^3/p	
Equipment power	37	W/p	
Equipment heat	84	W/p	
Consumables mass	0	kg/p/d	
Consumables volume	0	m^3/p/d	

-Lithium Hydroxide (LiOH) canisters

Lithium hydroxide canisters are a mature technology for carbon dioxide removal. They are not regenerable; carbon dioxide captured by LiOH canisters cannot be reduced to recover the oxygen it binds. Although some equipment is required to produce airflow through the canisters, such equipment would be required for the provision of proper air circulation anyway, and therefore no additional equipment is required to use LiOH canisters. According to (7), lithium hydroxide has a carbon dioxide absorption capacity superior to other chemical means (such as potassium superoxides), but is still counterindicated for long-duration missions due to the weight penalty such a large daily consumable requirement incurs. Because it can absorb more carbon dioxide on a per-kilogram of sorbent basis than can sodasorb, sodasorb is dominated as a technology option by lithium hydroxide, and because neither can be regenerated or provides oxygen, sodasorb is not listed as a separate technology option here. The number provided for mass includes the canister mass, and the volume is based on an approximate density of 500 kg/m^3 estimated from (18).

LiOH parameters (TRL 9)			Ref
Equipment mass	0	kg/p	(7)
Equipment volume	0	m^3/p	(18)
Equipment power	0	W/p	
Equipment heat	0	W/p	
Consumables mass	2	kg/p/d	
Consumables volume	0.004	$m^3/p/d$	

-Solid Amine Water Desorption (SAWD)

The SAWD system absorbs water and carbon dioxide together, and as such can desorb at higher pressures than can the 4BMS (7), but slowly loses water to venting, if opened to vacuum rather than to a carbon dioxide reduction system. Therefore it has some consumable requirement not indicated in the case of the 4BMS and other systems. This consumable amount is set to 35% of the mass of water perspired or respired into the atmosphere per person per day – 2.28 kg (7), which means that the loss is 0.798 kg of water per person per day. This water is assumed to be lost only when the bed desorbs to vacuum; a closed carbon dioxide loop will recover the water as well as the carbon dioxide. This amount is assumed to be lost based on the fact that 35% of the mass of water in the bed allows for optimum absorption of carbon dioxide (20).

SAWD parameters (TRL 6)			Ref
Equipment mass	17.1	kg/p	(7)
Equipment volume	0.07	m^3/p	
Equipment power	151.33	W/p	
Equipment heat	151.33	W/p	
Consumables mass	0.798 (vacuum vent)	kg/p/d	
Consumables volume	0.000798 (vacuum vent)	m^3/p/d	

<u>-Solid Amine Vacuum Desorption (SAVac)</u>

The solid amine system is currently being developed into improved versions. Sources (21) describe new models of solid amine systems. These systems are sufficiently hydrophilic that they can perform humidity control, at a nominal rate of 0.14 kg/hr water removal (22), as well as carbon dioxide control. This water is, however, lost to venting, as the system is not used in conjunction with a carbon dioxide reduction unit.

The new solid amine system is carried forward as a separate technology option from the SAWD, as it is a pressure-swing system rather than a temperature-swing (as is the case with SAWD) system. It may be used as part of a pressurized rover or on an EVA suit (23).

SAVac parameters (TRL 6)			Ref
Equipment mass	3.917	kg/p	(21)
Equipment volume	0.0046	m^3/p	(22)
Equipment power	0.7	W/p	
Equipment heat	0.7	W/p	
Consumables mass	3.43 (vacuum vent)	kg/p/d	
Consumables volume	0.000343 (vacuum vent)	m^3/p/d	

-<u>Chemical compounds (exemplified by potassium superoxides)</u>

Chemical compounds can serve to remove carbon dioxide from the atmosphere much as they supply oxygen. They can also, however, provide oxygen in the process of adsorbing carbon dioxide, and as such represent a potentially attractive technology option, even though they are dominated in terms of mass required for simple carbon dioxide absorption by lithium hydroxide.

Chemical compounds parameters (TRL 8)			Ref
Equipment mass	0	kg/p	(16)
Equipment volume	0	m^3/p	
Equipment power	0	W/p	
Equipment heat	0	W/p	
Consumables mass	3.236	kg/p/d	
Consumables volume	0.0015	$m^3/p/d$	

-<u>Metal Oxide</u>

Metal oxide canisters are currently used on the Extravehicular Mobility Units (EMUs) on-orbit with the International Space Station. They are designed for use with an EVA suit, and include both a mobile mass (the canister itself, which requires no power or cooling) and the regenerator, which requires a power level (here amortized from peak during the ten-hour regeneration cycle over a full 24-hour day period) and consequent cooling. The model also includes some immobile separated equipment mass and volume, which is nonetheless included in the total system mass and volume. This immobile mass is required as part of the regeneration cycle for the metal oxide canisters themselves. Note also that the metal oxide regenerator is assumed to be able to feed to a carbon dioxide regeneration system, and expels dry carbon dioxide.

The mobile equipment masses are assigned by distributing one canister per person, with replacement canisters to be assessed under sparing requirements, not considered directly here. Given that each canister will operate for at least 55 cycles (11), and crew members will not go on EVA every day, but rather once every two to three days, this seems a reasonable assumption. It is assumed that one regenerator can provide sufficient capacity for up to two canisters at one time. This provides a scale for sizing up the mass and volume of immobile equipment that will be required, assuming that the regenerator will need to provide regeneration for up to the entire crew simultaneously in one twenty-four hour period in a worst-case scenario.

Metal oxide parameters (TRL 9)			Ref
Equipment mass	21.77 + 23.82 immob.	kg/p	(11)
Equipment volume	0.012 + 0.0828 imm.	m^3/p	
Equipment power	208.33 immob.	W/p	
Equipment heat	208.33 immob.	W/p	
Consumables mass	0	kg/p/d	
Consumables volume	0	m^3/p/d	

2.3.3 Reduce Carbon Dioxide

Once carbon dioxide has been removed from the atmosphere, it is desirable to recover and process it, as this can release oxygen, via a reduction process, or water, either of which can be consumed later and thus used to reduce daily consumable requirements for the crew.

One component of a carbon dioxide regeneration unit which will be required on any technology option is a compressor. Most of the carbon dioxide removal technology options described in the preceding section can deliver carbon dioxide to a regeneration system, but do so at near-vacuum (2BMS, 4BMS) or cabin pressure (SAWD, MetOx). The Sabatier, Bosch, and zirconia electrolysis processes operate at higher reactant pressures, and therefore for proper system functioning, it will be necessary to include in the ECLS system a compressor for the concentrated carbon dioxide.

The compressor technology option included in the carbon dioxide regeneration processes below is based on a solid-state temperature-swing absorption compressor first described by (24). The original design compared favorably to a mechanical compressor used as a comparison baseline, but further design developments by (25) and (26) resulted in a prototype compressor, the TRL of which is estimated at 6. This prototype adds approximately 2.875 kg per person, 0.0014 m^3, and 33.33 W of heat and power to the equipment parameters listed for the various carbon dioxide regeneration options which require it. The parameter tables reflect this.

-Sabatier Reactor

The Sabatier reactor operates according to a well-understood chemical equation, and generates water for electrolysis and methane from carbon dioxide, if given a source of hydrogen as feedstock. This hydrogen is accounted for as consumables mass and volume, and is given cryogenic tankage mass and volume wrappers. The Sabatier reactor can accept carbon dioxide with or without water mixed in; this is confirmed by (27), who imply that, even in previous work done with other equipment, the reaction rate depends somewhat (but not strongly or solely) on the pressure of the water vapor in the reactant mixture. Therefore, the Sabatier reactor can accept carbon dioxide collected by either a drying source (like metal oxide or the 4-bed molecular sieve) or a wet source (like solid amine water desorption). The hydrogen storage requirement and oxygen makeup requirement also lead to an additional power requirement for cooling the cryogenic storage tanks.

The increased TRL of the Sabatier unit is based in part on the recent awarding of a contract by NASA to the Hamilton Sundstrand company, which indicates that an on-orbit unit is scheduled to be launched in late 2009 (28).

Sabatier parameters (TRL 7)			Ref
Equipment mass	17.9 + 2.875 comp	kg/p	(7)
Equipment volume	0.03 + 0.0014 comp	m^3/p	
Equipment power	50 + 26.04 + 33.33 comp	W/p	
Equipment heat	268 + 26.04 + 33.33 comp	W/p	
Consumables mass	0.309	kg/p/d	
Consumables volume	0.0045	m^3/p/d	

-Zirconia Electrolysis

Zirconia electrolysis is based on a technology which was scheduled to be flown on the Mars 2001 Lander (29). If this technology is used for carbon dioxide regeneration, it automatically supplies oxygen directly, rather than requiring water electrolysis as well. Zirconia electrolysis requires a carbon dioxide compressor.

Zr electrolysis parameters (TRL 7)			Ref
Equipment mass	33.6 + 2.875 comp	kg/p	(7)
Equipment volume	0.0084 + 0.0014 comp	m^3/p	
Equipment power	999.6 + 33.33 comp	W/p	
Equipment heat	999.6 + 33.33 comp	W/p	
Consumables mass	0	kg/p/d	
Consumables volume	0	m^3/p/d	

-Bosch Reactor

The Bosch reaction creates water from carbon dioxide and hydrogen, much as the Sabatier reactor does, but it generates packed carbon rather than methane, and the splitting of the water created for oxygen generation also provides enough hydrogen to sustain the cycle stoichiometrically. The Bosch reactor is, however, much more massive and more power-intensive than the Sabatier reactor, and has a slightly lower TRL.

Bosch parameters (TRL 6)			Ref
Equipment mass	102.1 + 2.875 comp	kg/p	(7)
Equipment volume	0.57 + 0.0014 comp	m^3/p	
Equipment power	239 + 33.33 comp	W/p	
Equipment heat	313 + 33.33 comp	W/p	
Consumables mass	0	kg/p/d	
Consumables volume	0	m^3/p/d	

-<u>None</u>

An ECLS system, while it allows for the regeneration of carbon dioxide, does not require it. Some systems may not include this option, and will instead pay a penalty in terms of required supply of daily consumable mass. This is reflected by noting that the selection of this technology option requires the system to provide oxygen from either cryogenic or high-pressure storage (or from the electrolysis of consumable water), although such a system may still include a regenerable mechanism (such as SAWD) for the removal of carbon dioxide from the atmosphere.

No regeneration parameters			Ref
Equipment mass	0	kg/p	
Equipment volume	0	m^3/p	
Equipment power	0	W/p	
Equipment heat	0	W/p	
Consumables mass	0	kg/p/d	
Consumables volume	0	m^3/p/d	

Methane Catalysis (Advanced Carbon-Forming Reactor System, ACRS)

The Sabatier process creates methane and water as products. Methane catalysis, or "cracking," releases the carbon from the methane. Ordinarily, the Sabatier process requires a net input of hydrogen to operate, but regeneration of the hydrogen from methane via catalysis eliminates this requirement for daily consumables. A technology option which combines this feature with the standard Sabatier process is called the Advanced Carbon-Forming Reactor, or ACRS. Eckart (7) notes that it packs carbon better than does the Bosch reactor, but has a much lower TRL.

ACRS parameters (TRL 3)			Ref
Equipment mass	60 + 2.875 comp	kg/p	(7)
Equipment volume	0.1 + 0.0014 comp	m^3/p	
Equipment power	133 + 33.33 comp	W/p	
Equipment heat	-50 + 33.33 comp	W/p	
Consumables mass	0	kg/p/d	
Consumables volume	0	$m^3/p/d$	

Other technologies for regenerating carbon dioxide exist. Among these is the Reverse Water-Gas Shift, or RWGS. However, the RWGS reaction creates carbon monoxide and oxygen from carbon dioxide, similarly to zirconia electrolysis, which means that it will require more makeup oxygen to complete closure than would other regeneration technologies. But operating the RWGS requires either recycling the flow to drive the reaction to completion or the use of a mid-process desiccant or electrolysis unit (30). It is unlikely that the RWGS reaction will be as efficient as the zirconia electrolysis reaction, and the process has not been as well-developed, but the end chemical products are the same. Therefore this process is not considered in detail here.

2.3.4 Provide Nitrogen

Although nitrogen is not consumed directly by the crew, instantiations such as a Habitat and a Transfer Vehicle may include this function, as nitrogen can serve to make up for leaks and allow pressurization of large internal volumes without using a potentially dangerous 100% oxygen atmosphere. Nitrogen is counterindicated in EVA suits, which function best at minimum pressures (and thus require high percentages of oxygen to maintain a normoxic interior (8)), as well as in pressurized rovers, which are required to allow for rapid access from the interior to the EVA suit without prebreathing (10), and thus this function does not appear in all instantiations.

-Cryostorage

Much as oxygen can be stored cryogenically, so can nitrogen. The air leakage rate for the Habitat and Transfer Vehicle instantiations is estimated conservatively at 1.25 kg/day, which translates to 0.313 kg/person/day of nitrogen. Cryogenic storage of nitrogen is assumed in general to have parameters similar to the cryogenic storage of oxygen, although the cooling and power requirements are calculated separately, based on information from the same sources used to calculate cooling and power requirements for other cryogenic gas storage. Here again, the parameters for oxygen (mass wrapping factor of 1.26 and density of 9130) are used.

Cryostorage parameters (nitrogen) (TRL 9)			Ref
Equipment mass	0	kg/p	(7)
Equipment volume	0	m^3/p	
Equipment power	20.83	W/p	
Equipment heat	20.83	W/p	
Consumables mass	0.3944	kg/p/d	
Consumables volume	0.000346	m^3/p/d	

-High Pressure storage

Much as oxygen can be stored at high pressures, so can nitrogen. According to (7), storage of nitrogen has a wrapping factor of 1.5, rather than the 1.9 factor that applies to oxygen. It is assumed to have the same density as oxygen.

High-pressure storage parameters (nitrogen) (TRL 9)			Ref
Equipment mass	0	kg/p	(7)
Equipment volume	0	m^3/p	
Equipment power	0	W/p	
Equipment heat	0	W/p	
Consumables mass	0.4695	kg/p/d	
Consumables volume	0.000051	m^3/p/d	

2.3.5 Control Temperature

The temperature inside a habitable volume must be maintained within certain comfortable limits. Although gross thermal control is left as a separate problem, to be handled by the thermal control systems of the exploration systems rather than the ECLS systems, the temperature of the crew-inhabited volume must be regulated. This task falls to methods which either use reservoirs to store heat (such as ice or chilled water) or to heat exchangers which pass the heat on to the thermal-control system loops.

-Condensing Heat Exchanger

A condensing heat exchanger (CHX) removes both water and heat from the air stream, and has been used for many years in spacecraft. Heat exchangers require no consumables, and it is assumed for modeling purposes that they generate no excess heat. Their power requirements are derived from the average heat loads per person as listed in (8): 165 W/p, with the coefficient of performance being assumed as 3.0.

When a CHX may potentially be used in a zero-gravity environment for an extended period of time, such as is the case with the EVA suit and transfer vehicle instantiations, it must also include a water-gas separator. This adds to the usual parameters for a CHX in the table below the additional terms denoted by WS. Note that these terms do not affect instantiations expected to operate primarily in gravity fields, such as the surface habitat and the pressurized rover.

Condensing heat exchanger parameters (TRL 9)			Refs
Equipment mass	1.47 + 1.7257 WS	kg/p	(7)
Equipment volume	0.00661 + 0.0053 WS	m^3/p	(11)
Equipment power	55 + 14.33 WS	W/p	
Equipment heat	0	W/p	
Consumables mass	0	kg/p/d	
Consumables volume	0	m^3/p/d	

-Chilled water or ice (heat sink)

Chilled water or a block of ice can serve as a heat sink for EVA suits or in a pressurized rover (10). The water can be heated from a low temperature to a high temperature, but remains in the liquid state. Ice transitions from solid to liquid. Both of these methods require some regeneration of the heat sink periodically, and so the heat sink itself serves as a mass of "mobile equipment" which is carried around on EVA or in the pressurized rover, while a separate regeneration equipment mass is also required. The mobile equipment mass and volume are sized by the mass and volume of the required amount of water or ice times a wrapping factor of 1.02, and the immobile regeneration equipment is sized according to the parameters of a condensing heat exchanger, assuming that the heat exchanger would have to regenerate the water or ice in a period of twelve hours or less.

Water is assumed to have a temperature range of 35 degrees, this being approximately the range from freezing temperature to body temperature (at which point it can no longer accept waste heat from an astronaut). Given a specific heat capacity of 4.186 kJ/kg-K, the mass of water needed to allow for a day's worth of activity at rates of between 250 and 300 W, a figure derived from descriptions of Apollo EVAs in (31), can be found. The power needed is taken from the CHX parameters, and the heat to be rejected is the sum of that power and the cooling required.

The immobile equipment mass, volume, power and heat are the estimates for the regeneration equipment, which will not be located on the EVA suit or pressurized rover. They are sized based on the parameters for a condensing heat exchanger, which assumes that the regeneration system will be able to bleed heat into a dedicated thermal control loop which includes radiators or other heavy heat-rejection systems. The parameters are scaled based on the assumption that the amount of heat absorbed during an 8-hour EVA will then need to be dumped in the remainder of the day. Allowing for preparation and donning and doffing time, about 12.5 hours are estimated to remain for cooling and heat sink regeneration, so the scale factor used is about 1.58.

Chilled water parameters (TRL 5)			Ref
Equipment mass	157. 27 + 2.33 imm.	kg/p	
Equipment volume	0.157 + 0.0105 imm.	m^3/p	
Equipment power	87.15 immob.	W/p	
Equipment heat	348.6 immob.	W/p	
Consumables mass	0	kg/p/d	
Consumables volume	0	m^3/p/d	

The parameters for ice are slightly different from those for water, in that the temperature range is higher (it is assumed that ice is first melted by being brought from 223 K to 273 K, and then heated as water. The specific heat capacity for ice is set to 2 kJ/kg-K, and the same parameters (derived from a CHX) are used to estimate the required mass, volume, and power of the necessary regeneration equipment. Note that the heat of melting for water (334 kJ/kg) is also included, and this allows for a further reduction in the total mass of heat sink material needed. The same mass wrapper is used, but volume is set by using a density of 920 kg/m^3, to reflect the volume and density changes ice undergoes when it melts or refreezes.

Ice parameters (TRL 5)			Ref
Equipment mass	39.62 + 2.33 imm.	kg/p	(32)
Equipment volume	0.0431 + 0.0105 imm.	m^3/p	
Equipment power	87.15 imm.	W/p	
Equipment heat	348.6 imm.	W/p	
Consumables mass	0	kg/p/d	
Consumables volume	0	m^3/p/d	

-Sublimator

A sublimator can serve as a cooling mechanism by allowing water to sublimate, thus releasing energy from the immediate environment of the crew. This technology option is already is use for EVA suits, and is included as a possible choice for EVA suits and pressurized rovers.

Parameters for the sublimator are taken from the X-38 sublimator described by Hamilton Sundstrand. The sublimator consumes water, and thus there is some consumable requirement. The X-38 sublimator is scaled down to the level of heat rejection needed for one person (estimated at 261 W per person), and the resulting parameters are used to scale the equipment mass and volume. The power requirement is set to one-third of the heat rejected (based on a Coefficient of Performance of 3.0), and the heat requirement is set to zero. The consumable water is calculated based on the amount of energy needed to sublimate ice to cool a human for a ten-hour EVA. The usual mass wrapping factor for water (1.02) and density (1000 kg/m^3) are used to allow for the mass and volume of consumables.

Sublimator parameters (TRL 9)			Ref
Equipment mass	0.2367	kg/p	(11)
Equipment volume	0.000267	m^3/p	
Equipment power	87	W/p	
Equipment heat	0	W/p	
Consumables mass	10.132	kg/p/d	
Consumables volume	0.01013	m^3/p/d	

2.3.6 Control Humidity

The immediate environment of the crew must be kept within a specified range of humidity levels as well as temperature levels in order for the crew to function at maximum efficiency, and water must be removed from the atmosphere to provide this function. Crew members continually generate water via metabolic exhalation and perspiration, which creates a need for removal of water from the air.

-Silica gel

Silica gel is a common desiccant which can absorb up to 40% of its dry mass in water. It can be used and regenerated with heat and dry air (as is the case for the small amounts of silica gel used in the 4-bed molecular sieve technology option described earlier in this chapter, where it is included in the equipment mass), but is here bookkept as a consumable resource. Here, silica gel is assumed to absorb water only up to 25% of its mass, to allow for maintaining a lower level of humidity in the habitable volume than is necessary to saturate the silica gel. This is applied to the 2.28 kg of water generated through perspiration and respiration per person per day to size the amount of silica gel required.

Silica gel parameters (TRL 9)			Ref
Equipment mass	0	kg/p	(33)
Equipment volume	0	m^3/p	
Equipment power	0	W/p	
Equipment heat	0	W/p	
Consumables mass	9.12	kg/p/d	
Consumables volume	0.0136	$m^3/p/d$	

-Condensing heat exchanger

The condensing heat exchanger's ability to remove water and heat from an air stream qualifies it to be used for humidity control as well as temperature control. If a heat exchanger is already being used for temperature control, it is assumed to be able to provide humidity control without any additional mass, volume, heat, or power penalties.

Condensing heat exchanger parameters (TRL 9)			Ref
Equipment mass	1.47	kg/p	(7)
Equipment volume	0.00661	m^3/p	(11)
Equipment power	55	W/p	
Equipment heat	0	W/p	
Consumables mass	0	kg/p/d	
Consumables volume	0	$m^3/p/d$	

2.3.7 Trace Contaminant Control

Various contaminants besides carbon dioxide accumulate in inhabited volumes, including small organic particles, gases from cabin equipment, and metabolic byproducts (7), and these must be removed or maintained at tolerable levels.

-Activated carbon

Activated carbon filters are a common means of removing trace particles from atmosphere. They are a consumable resource. The amount of carbon required per person per day is taken from (19), which indicates the sizing data for the International Space Station.

Activated carbon parameters (TRL 9)			Ref
Equipment mass	0	kg/p	(19)
Equipment volume	0	m^3/p	
Equipment power	0	W/p	
Equipment heat	0	W/p	
Consumables mass	0.084	kg/p/d	
Consumables volume	0.000225	$m^3/p/d$	

-Active TCC system

An active TCC system relies on catalysis as well as filtering to remove trace gases and contaminant particles. Although it has a lower TRL, it has potential advantages over other methods given that it requires little resupply. Some amount of consumable activated carbon is still required, but this amount is less than what would be needed for the use of activated carbon filters only. The amount of consumable activated carbon needed here is set to 10% of the amount required for the technology option of carbon filters only.

Active TCC system parameters (TRL 5)			Ref
Equipment mass	20	kg/p	(8)
Equipment volume	0.15	m^3/p	
Equipment power	50	W/p	
Equipment heat	50	W/p	
Consumables mass	0.008	kg/p/d	
Consumables volume	0.000023	$m^3/p/d$	

-Super-Critical Wet Oxidation (SCWO)

The Super-Critical Wet Oxidation system, although at a very low TRL, can potentially oxidize all contaminants in water or air processed through it, and thus presents an attractive multi-use technology option.

SCWO parameters (TRL 3)			Ref
Equipment mass	173.5	kg/p	(7)
Equipment volume	0.53	m^3/p	
Equipment power	90	W/p	
Equipment heat	360	W/p	
Consumables mass	0	kg/p/d	
Consumables volume	0	m^3/p/d	

2.3.8 Potable Water Regeneration

Much of the water used by the crew will be for cleaning, hygiene, and cooking. Much of this water, as well as water recovered from other sources, can be re-used after processing, reducing greatly the need for daily consumable supplies.

A baseline amount of 15 kg of water per person per day is allotted to cooking, cleaning, and general hygiene. This water is assumed to cycle through the main water regeneration system, and the efficiency of the technology option used in that system determines what percentage of the water must be made up from stores.

As illustrated in (34), typical water recycling systems such as the Water Reclamation System on the International Space Station distinguish to some extent between normal potable water and human liquid waste, meaning that the two can be separated when building a system architecture. This section addresses the hygiene, handwash, cooking, and other water (graywater), while the next sections address human liquid waste (blackwater) and solid waste.

-Hamilton-Sundstrand Water Processing Assembly (HSWPA)

The Hamilton-Sundstrand Water Processing Assembly takes water from various sources and repurifies it. The HSWPA is assumed to operate at 95% efficiency, meaning that 5% of the crew's daily water needs (estimated at 15 kg per person per day) must be made up from consumable stores. Makeup water has standard mass wrapping factors of 1.02 and an assumed density of 1000 kg/m^3.

HSWPA parameters (TRL 7)			Ref
Equipment mass	73.08	kg/p	(11)
Equipment volume	0.236	m^3/p	
Equipment power	101.67	W/p	
Equipment heat	101.67	W/p	
Consumables mass	0.765	kg/p/d	
Consumables volume	0.00765	m^3/p/d	

-Multifiltration

Multifiltration processes water through a series of filters to eliminate organics, acids, and particles before recycling it through the water system (7). Multifiltration has a sufficiently high efficiency (99.9%) that no makeup water is assumed to be required. However, some non-regenerable masss of activated carbon is required (here set to a nominal 0.01 kg per person per day).

Multifiltration parameters (TRL 5)			Ref
Equipment mass	0.975	kg/p	(7)
Equipment volume	0.00031	m^3/p	
Equipment power	0.095	W/p	
Equipment heat	0.095	W/p	
Consumables mass	0.01	kg/p/d	
Consumables volume	0.0000268	m^3/p/d	

-Electrodialysis

Electrodialysis breaks down water, oxidizes contaminants, and reconstitutes it for consumption. It is listed as 98% efficient; so therefore the equivalent of 2% of daily water needs must be supplied from daily consumables. Water supplied from consumable stores is assumed to be stored with a tankage mass wrapper of 1.02 and a density of 1000 kg/m^3. The system mass is minimal, as the major components are membranes to be inserted into existing water ducts; however, a notional system mass of 0.1 kg per person is assumed.

Electrodialysis parameters (TRL 4)			Ref
Equipment mass	0.1	kg/p	(7)
Equipment volume	0.00109	m^3/p	
Equipment power	1.92	W/p	
Equipment heat	1.92	W/p	
Consumables mass	0.306	kg/p/d	
Consumables volume	0.000306	m^3/p/d	

-Reverse Osmosis

Reverse osmosis is a technique similar to filtering in which a membrane strains contaminants from water while allowing the water molecules themselves to pass. Because this system is listed as only 80% efficient, it requires more consumables than do other alternatives.

Reverse osmosis parameters (TRL 5)			Ref
Equipment mass	2.125	kg/p	(7)
Equipment volume	0.014	m^3/p	
Equipment power	5	W/p	
Equipment heat	3.75	W/p	
Consumables mass	3.06	kg/p/d	
Consumables volume	0.00306	m^3/p/d	

-Stored supplies

Water can also be supplied exclusively from stores, although a penalty is incurred from the daily consumable requirement thus created. Water tankage is a small mass penalty, and power and heating requirements for stored water are minimal. A baseline usage rate of 15 kg of water per person per day is used.

Stored liquid water parameters			Ref
Equipment mass	0	kg/p	
Equipment volume	0	m^3/p	
Equipment power	0	W/p	
Equipment heat	0	W/p	
Consumables mass	15.3	kg/p/d	
Consumables volume	0.0153	$m^3/p/d$	

-Condensate recovery

Another option for water processing is condensate recovery, in which the perspiration and metabolic respiration products of crew work can be removed from the atmosphere and added to the water system (7). This technology option can also potentially be used in conjunction with other water systems. Because some part of the water thus recovered is originally brought as food mass, and is released by normal metabolic processes, this water is essentially free, because food requirements are not part of the ECLS system functions examined here. According to (7), this technology option can recover up to 45% of all condensate, which amounts to up to 1.7 kg of water per person per day. The mass of this system is provided; the volume is estimated by analogy with the bulk density of a condensing heat exchanger.

Condensate recovery parameters (TRL 8)			Ref
Equipment mass	0.34	kg/p	(7)
Equipment volume	0.00153	m^3/p	
Equipment power	0.000283	W/p	
Equipment heat	0.000283	W/p	
Consumables mass	13.566	kg/p/d	
Consumables volume	0.013566	m^3/p/d	

-Super-Critical Wet Oxidation (SCWO)

The Super-Critical Wet Oxidation system, whatever its input, produces potable water, which makes it suitable for recycling general water, as well as trace contaminant control or reclamation of water from human waste effluents.

SCWO parameters (TRL 3)			Ref
Equipment mass	173.5	kg/p	(7)
Equipment volume	0.53	m^3/p	
Equipment power	90	W/p	
Equipment heat	360	W/p	
Consumables mass	0	kg/p/d	
Consumables volume	0	m^3/p/d	

-HSWPA and condensate recovery hybrid

One option for regenerating water is the deployment of a system which includes condensate recovery and the Hamilton Sundstrand Water Processing Assembly. This option actually recovers more than 100% of the daily water requirement, as the HSWPA can provide 95% closure, while the condensate recovery unit provides another 11.3% closure at best performance. The net effect is that the environment becomes water-rich.

The source of this additional water from condensate is the food consumed by the crew. Some water is included in hydrated food, and other water is chemically bound in food and then released in the natural course of metabolism. This apparent over-closure of the water loop opens the way for much more detailed trades, such as reducing the closure of the primary water processing system in order to reduce equipment requirements, sending up partially-hydrated food in order to reduce mass requirements on that element of resupply, or even using the excess water for other purposes. To retain simplicity in the model used here, this option was simply assumed to afford full 100% closure, although the option of a water-rich environment is addressed via a sensitivity analysis on the Habitat instantiation in Chapter 3 of this thesis.

HSWPA and condensate recovery hybrid parameters (TRL 7)			Ref
Equipment mass	73.08 + 0.34	kg/p	(7)
Equipment volume	0.236 + 0.00153	m^3/p	
Equipment power	101.67 + 0.000283	W/p	
Equipment heat	101.67 + 0.000283	W/p	
Consumables mass	-0.969 (water-rich)	kg/p/d	
Consumables volume	-0.00097 (water-rich)	m^3/p/d	

2.3.9 Liquid Waste Processing

Human liquid waste can be processed to yield some amount of water, which can then be recycled, and to prepare the waste itself for storage or dumping. This water feed is assumed to be 1.5 kg per person per day (7), and derives from drinking water and food water (either hydrated or bound). Therefore, calculations of necessary makeup water for this function use a baseline of 1.5 kg per person per day.

-Thermoelectric Integrated Membrane Evporation System (TIMES)

The Thermoelectric Integrated Membrane Evaporation System has a designed efficiency of 91%, but a low TRL of 4-5. The TIMES model presented in (7) is for a flow rate of 20 kg per day, which corresponds to roughly 13 persons. This factor is used to scale the parameters given by

Eckart. Because this system recovers water from liquid human waste, rather than from general and hygiene water, it has a feedstock mass of 1.5 kg per person per day, rather than 15 kg per person per day.

TIMES parameters (TRL 4)			Ref
Equipment mass	5.101	kg/p	(7)
Equipment volume	0.0173	m^3/p	
Equipment power	12.75	W/p	
Equipment heat	12.75	W/p	
Consumables mass	0.135	kg/p/d	
Consumables volume	0.00014	$m^3/p/d$	

-Vapor Compression Distillation (VCD)

Vapor Compression Distillation allows for recovery of up to 70% of the water in liquid waste, and is estimated to have a TRL of 7, given that it performed well on flight tests in 2003, although complete results of the tests were not available (35).

VCD parameters (TRL 7)			Ref
Equipment mass	33.73	kg/p	(7)
Equipment volume	0.169	m^3/p	(35)
Equipment power	38.33	W/p	
Equipment heat	38.33	W/p	
Consumables mass	0.459	kg/p/d	
Consumables volume	0.000459	$m^3/p/d$	

-VAPCAR

The Vapor Phase Catalytic Ammonia Removal has a TRL of only 3, but has a listed efficiency of 95%.

VAPCAR parameters (TRL 3)			Ref
Equipment mass	22.67	kg/p	(7)
Equipment volume	0.08	m^3/p	
Equipment power	33.3	W/p	
Equipment heat	33.3	W/p	
Consumables mass	0.0765	kg/p/d	
Consumables volume	0.000765	$m^3/p/d$	

-Super Critical Wet Oxidation (SCWO)

The SCWO can be used for other purposes as well as trace contaminant control. If a SCWO is already present in one capacity, it is assumed that it can provide other functions without additional mass, volume, power, or heat penalties. The SCWO takes a feed of all spacecraft waste and used water sources and relies on water in its super-critical state to oxidize all contaminants, thus producing entirely potable water at an efficiency of 100%.

SCWO parameters (TRL 3)			Ref
Equipment mass	173.5	kg/p	(7)
Equipment volume	0.53	m^3/p	
Equipment power	90	W/p	
Equipment heat	360	W/p	
Consumables mass	0	kg/p/d	
Consumables volume	0	$m^3/p/d$	

-Air evaporation

The air evaporation system allows for nearly complete water recovery, while using felt wicks to retain solids. Although the efficiency is extremely high, some consumables requirement is created by the need to resupply wicks. Equipment mass is effectively zero, but using cabin air flow or a side stream thereof for evaporation will also result in a need for careful segregation of the drying air stream, to prevent the potential odor from discomforting the crew. The required mass and volume of felt pads needed was estimated based on the properties of felt. The numbers used reflect a mode of constant usage rather than batches, and thus only about 10% of the nominal daily mass of felt needed is used per day, as water is continually cycling out of the felt via evaporation and making room for more liquid waste to be absorbed and recovered.

Air evaporation parameters (TRL 7)			Ref
Equipment mass	0	kg/p	(7)
Equipment volume	0	m^3/p	(36)
Equipment power	39.375	W/p	
Equipment heat	39.375	W/p	
Consumables mass	0.0857	kg/p/d	
Consumables volume	0.0025	m^3/p/d	

2.3.10 Solid Waste Processing

Solid waste must also be processed for storage or disposal. Some recovery of water from solid waste is also possible. However, without use of a biological ECLS system, no recovery of carbon compounds or other organic resources is possible. The function of solid waste processing as described here focuses on the sterilization and/or storage of waste, rather than on recovery processes.

-Super Critical Wet Oxidation (SCWO)

The SCWO can be used for other purposes as well as trace contaminant control. If a SCWO is already present in one capacity, it is assumed that it can provide other functions without additional mass, volume, power, or heat penalties.

SCWO parameters (TRL 3)			Ref
Equipment mass	173.5	kg/p	(7)
Equipment volume	0.53	m^3/p	
Equipment power	90	W/p	
Equipment heat	360	W/p	
Consumables mass	0	kg/p/d	
Consumables volume	0	$m^3/p/d$	

-Incineration

Solid waste can be incinerated, essentially a burning of all organic material contained in it, in order to sterilize it. The load of solid waste per day (including water here, as well as human solid waste and hygiene solids) is estimated conservatively at 0.15 kg per person per day, based on information in (7). Scaling factors for an incinerator are taken from the commercial Pyrotechnix HL3000 model, described at (37). It is assumed that the incineration process requires the rejection of heat from burning the wastes, but also takes no net power input. The amount of heat rejection required is estimated from an average heating value given by (37). Because the waste product can be assumed to be dumped overboard, the only consumable requirement is a container of some kind, which is assumed to have a mass wrapper of 0.01 times the mass of the waste (which does not include water in solid wastes, and thus equates to 0.06 kg per person per day). Because this mass must be made up by food supplies, and because food supplies are considered separately from other major ECLS systems in this thesis, no additional consumable resupply penalty is assessed here for the mass of the waste, and the only consumable mass and volume is that of the plastic containers (with an assumed density of 1200 kg/m^3).

This technology option uses parameters scaled down from an existing system, and thus is not a conservative estimate. Furthermore, although incineration may be a mature technology on Earth, the degree of relationship between commercial incinerators and shipboard units may not be very significant, and so this technology option (when considered for the purposes of use in an ECLS system) is given a TRL of 3.

Incineration parameters (TRL 3)			Ref
Equipment mass	0.4182	kg/p	(37)
Equipment volume	0.000894	m^3/p	
Equipment power	0	W/p	
Equipment heat	26.1675	W/p	
Consumables mass	0.0006	kg/p/d	
Consumables volume	0.000005	m^3/p/d	

-Compaction and storage

The compaction and storage of solid waste is analogous to the waste-management system currently in use on the Space Shuttle and the International Space Station. Parameters for this technology option were taken from Hamilton-Sundstrand's website. Although this technology option is sized for events rather than persons, the listed parameters were divided by an assumed crew size (six) to estimate approximate parameters on a per-person basis. Consumables requirements are again limited to waste containers, and it is assumed that a single container can contain about five crew-days (30 person-days) worth of material. The plastic mass wrapping factor of 0.01 is used again, with the density set to 1200 kg/m^3. The mass of the waste itself is not counted as a consumable; only waste containers are.

Compaction and storage of solid waste is treated differently in the EVA and pressurized rover instantiations. There, only mass and volume wrapping factors for consumable waste-storage bags are used, and no heat or power is required. This is meant to reflect the way that waste is often collected and stored on EVA in current practice, which involves no compaction and only simple collection procedures.

Compaction and storage parameters (TRL 9)			Ref
Equipment mass	18.6	kg/p	(11)
Equipment volume	0.0916	m^3/p	
Equipment power	62.5	W/p	
Equipment heat	62.5	W/p	
Consumables mass	0.0015	kg/p/d	
Consumables volume	0.00000125	$m^3/p/d$	

The technology options described above are used in the construction of Object-Process Network (OPN) models which generate architectures for down-selection to a handful of interesting architectures, as described in the next chapter.

CHAPTER 3. Architectural Analysis

The first step of the Commonality Analysis Methodology is an architectural analysis, whereby a large set of system architectures is generated and then down-selected to a few interesting architectures. This chapter describes the architectural analysis process and concludes by presenting the small number of interesting architectures.

The descriptions of technology options from the previous chapter will be arranged into models, one for each of the four instantiations (Habitat, EVA suit, Pressurized rover, and Transfer vehicle). These models will generate ECLS system architectures, based on the parameters associated with the technology options. These system architectures can then be down-selected to a few interesting architectures, upon which the commonality process can be further applied.

The down-selection process applies metrics to compare architectures, and eliminates those which are uninteresting because they do not provide an advantage over other architectures or because they are less feasible than other architectures. The goal is to come to a handful of architectures which are known to be interesting and feasible.

3.1 Assignation of Technology Options to Instantiations

The four instantiations each encompass some subset of the total set of possible technology options. Certain technology options can be easily excluded from certain instantiations based on mobility considerations (for instance, it would be impossible for a human crewperson to carry around the necessary mass for a fully-closed regenerative ECLS system in an EVA suit), and other instantiations have other constraints. It is desirable to limit the mass of an ECLSS in a transfer vehicle instantiation, as many of these (such as LSAMs or MDAVs) are essentially parasitic masses until the final stages of their missions. Furthermore, it is also desirable to use high-closure systems whenever possible in instantiations which will be used for long periods of time (such as the Habitat).

Accordingly, a listing of the four instantiations, along with the technology options which are permitted for each instantiation, appears in this section.

3.1.1 Habitat Instantiation

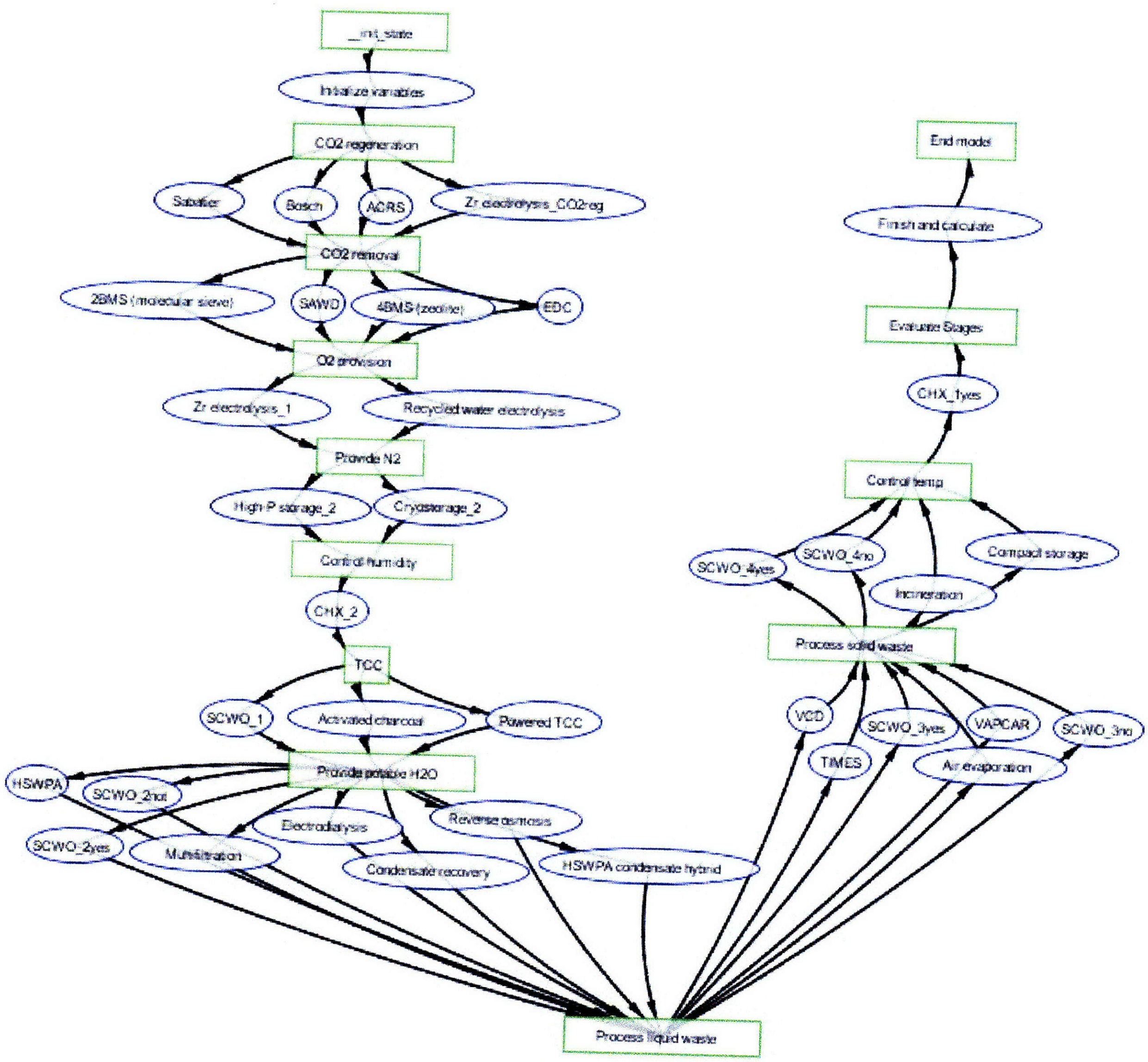

Figure 5. Habitat OPN Model.

The Habitat is a large surface infrastructure element, meant to hold the entire crew through long periods of the surface exploration mission, and is accordingly sized. Because it is immobile, there are no limits on the mass of the ECLS system that it can contain, and no strict volume limits are in effect either. However, high-closure technology options are preferred, because the Habitat is expected to operate continuously for the full duration of each of the eight six-month missions over the course of a campaign, and thus will easily pass the breakeven point where regenerable technology options become preferable to any non-regenerable option. Therefore, most technology options used in this instantiation model are regenerable.

Provide oxygen

Water electrolysis and carbon dioxide electrolysis are the regenerable options allowed for this instantiation. Non-regenerable methods of providing this function would require too much mass. Provision of oxygen via cryogenic tanks would alone require nearly one and a half metric tons of mass, before considering equivalent factors for volume, heat, and power, so this option is not likely to be feasible.

Remove carbon dioxide

Any regenerable technology option is feasible here, with only the high total campaign mass requirement of chemical compounds and LiOH canisters resulting in their disqualification. Metal oxide is also disqualified, as, although it can remove carbon dioxide from the atmosphere and then undergo regeneration, it cannot permanently sequester it. Regenerating metal oxide canisters would still require a second technology option to remove the released carbon dioxide from the atmosphere inside the regeneration locale, and using metal oxide non-regeneratively is mass-prohibitive.

Therefore, 2-bed molecular sieves, 4-bed molecular sieves, Electrostatic Decomposition Concentrators, and Solid Amine Water Desorption systems are permitted for this instantiation.

Reduce carbon dioxide

Regeneration of oxygen from carbon dioxide is highly desirable for a high-closure ECLS system, and therefore the Sabatier reactor, zirconia electrolysis, Bosch reactor, and ACRS are all feasible for this instantiation.

Provide nitrogen

Nitrogen can be provided by any means, including cryogenic storage or high-pressure storage.

Control temperature

The sublimator technology option requires far too much water to be feasible, and the heat sink option, whether water or ice, requires regeneration time, so the only remaining feasible option is the Condensing Heat Exchanger. Note that the control of temperature inside the Habitat is simply a problem of moving heat from within the crew compartment to an external loop, as it is assumed that the Habitat will have radiators operating. These radiators will represent a black box heat transfer system for the entire Habitat, and from the perspective of the ECLS system, it is only necessary to transfer heat to the external thermal control system. However, such systems often use working fluids (such as ammonia or toxic refrigerants) that can cause major problems if a leak occurs within a small pressurized volume, and so a transfer mechanism from the ECLS system to the thermal control system is needed.

Control humidity

Because a Condensing Heat Exchanger is already required, and silica gel would require over a ton of consumables in itself, the CHX is the only feasible option here.

Trace Contaminant Control

Any technology option is considered feasible, as the low daily consumable requirements for an activated carbon system may make it competitive with an active system or against a SCWO.

Potable water regeneration

Due to the high daily water requirement for the crew, stored supplies are infeasible, but any of the regenerable options, including the Hamilton-Sundstrand Water Processing Assembly (HSWPA), multifiltration, SCWO, electrodialysis, reverse osmosis, and condensate recovery, are viable. A special hybrid option that includes a HSWPA and a condensate recovery system, for making up inefficiencies in one system by using metabolic water harvested by the other, is included in this instantiation.

Liquid waste processing

To deliver this function, any technology option, including TIMES, VCD, VAPCAR, SCWO, or air evaporation, may be competitive.

Solid waste processing

Again, any technology option, whether SCWO, incineration, or compaction and storage, is potentially feasible for this instantiation.

3.1.2 EVA Suit Instantiation

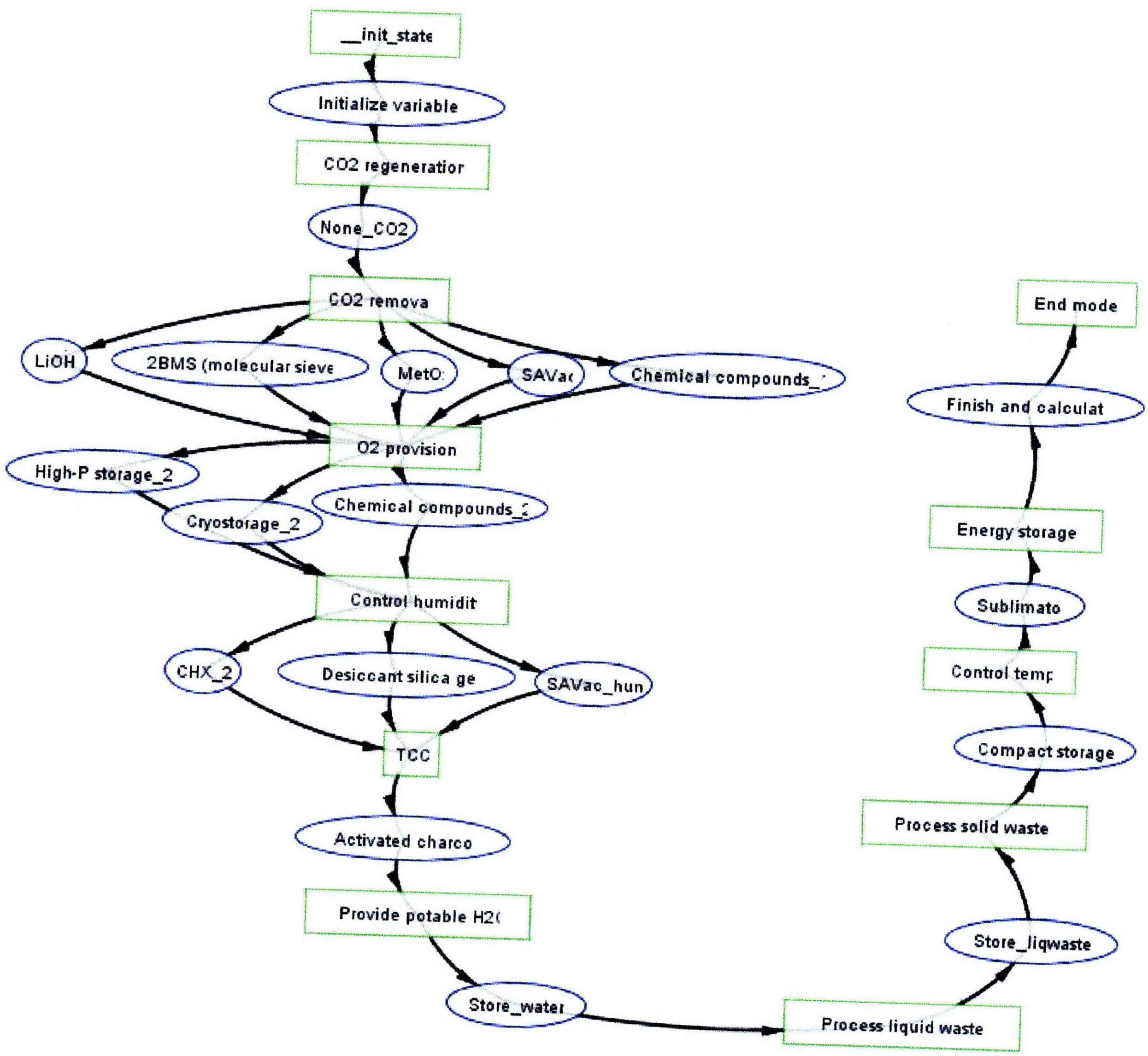

Figure 6. EVA Suit OPN Model.

The primary limitation on this instantiation is the amount of mobile mass afforded. The entire Personal Life Support System (PLSS) used for EVA suits should not mass more than absolutely necessary (some sources (8) cite maximum allowable masses of 30 kg or less), so any individual technology option which exceeds 20 kg per person will be impossible to use. Note also that regenerable options are not permitted, as no EVA is expected to last more than about ten hours, and a baseline duration of eight hours is expected. Therefore the EVA instantiation is modeled with a use duration of one-third of a person-day.

Provide oxygen

Water electrolysis and carbon dioxide electrolysis are too massive for inclusion, so oxygen must be supplied through either cryogenic storage, high-pressure storage, or chemical compounds. Although these are the technology options used on the EVA suit itself, when high-pressure or cryogenic storage of oxygen is selected, the ultimate source of oxygen is assumed to be the Habitat or some other stationary system, as shipping small EVA tanks of cryogenic or high-pressure oxygen is inefficient, and a regenerable system will be available on nearby instantiations at nearly all times. Therefore these two technology options use an immobile mass for the water electrolysis, cooling, and pumping equipment that would be required to supply oxygen in the proper state, and include a daily consumable requirement in the form of water to be electrolyzed by the Habitat's ECLS system rather than oxygen shipped alone.

Remove carbon dioxide

Only the 2-bed molecular sieve, LiOH canisters, SAWD, chemical compounds, and metal oxide canisters are feasible here. The EDC is ostensibly light enough to be included, but the EDC requires the inclusion of an oxygen generation system in the PLSS, and that is not feasible.

Reduce carbon dioxide

Reduction of carbon dioxide is not a feature of EVA suits, as it is both mass- and power-intensive. Reduction can be carried out at a fixed location using emplaced equipment, but the only technology options which permit the capture of carbon dioxide for this reduction (molecular sieves and pumps or steam-desorbed solid amines) are too massive to be carried by one person. Therefore the only technology option which permits carbon dioxide reduction is metal oxide, and the parameters for conducting this operation at the Habitat after EVAs end are carried under the Metal Oxide technology option for the function of removing carbon dioxide.

Provide nitrogen

Because EVA suits are typically pressurized to minimum possible levels in order to facilitate mobility, they are generally operated using a 100% oxygen atmosphere. Accordingly, the EVA suit instantiation will not provide nitrogen.

Control temperature

The amount of water or ice required by an EVA suit would be prohibitive, and it is necessary to include some kind of final heat transfer mechanism, so a simple Condensing Heat Exchanger will not suffice, as there is no external cooling loop where the heat can be dumped. For these reasons, and to allow for design heritage, the EVA suit instantiation will use a sublimator for cooling.

Control humidity

Because a Condensing Heat Exchanger is not used for temperature control, and because the silica gel requirement would be small for an EVA, the silica gel technology option is permitted here. However, the CHX has the advantage of serving as a water-saving option, wherein it removes humidity from the atmosphere before it is processed through the carbon-dioxide removal system. This has the advantage of allowing only dry carbon dioxide to be vented, which reduces the lifecycle consumable water requirement for the EVA suit. Notably, any system architecture which uses metal oxide to remove carbon dioxide is not open to vacuum, and so can avoid venting water with either a water-saving CHX or silica gel.

Trace Contaminant Control

Active TCC systems are far too massive, as is the SCWO technology option. Therefore this function must be delivered by activated carbon.

Potable water regeneration

The only viable technology option to deliver potable water is stored water, as the inclusion of a closed water loop inside the EVA suit system is needless complication, given that the amount of water used is small compared to the amounts used in the Habitat or Transfer Vehicle instantiations.

Liquid waste processing

To minimize the EVA suit's total mass, the only feasible technology option here is simple storage of the liquid waste. Unfortunately, the standard methods of regenerating water from liquid waste will not be applicable to the stored waste, as the high-absorbency garments which are typically used do not allow for easy recovery of the water.

Solid waste processing

For similar reasons, solid waste is assumed to be stored during EVA operations.

3.1.3 Pressurized Rover Instantiation

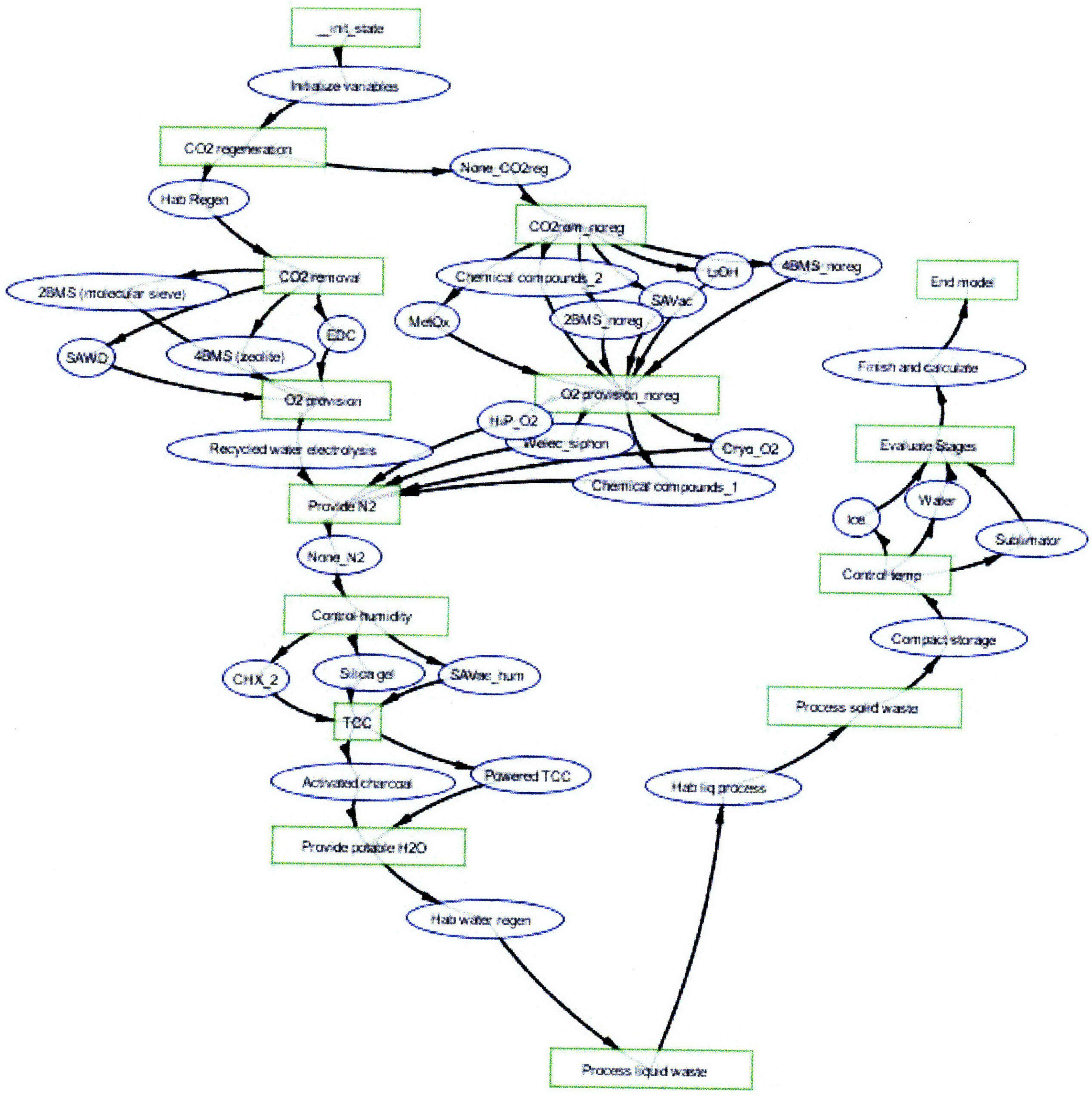

Figure 7. Pressurized Rover OPN Model.

The Pressurized Rover is intended to include rovers for short-distance moves as well as long-distance exploration traverses, and should be able to interface closely with the EVA suit ECLS system. Pressurized Rovers can include regenerable or non-regenerable technology options, as they may operate on their own for extended periods or be stopped and replenished on a regular basis. To allow for the long-distance traverse, the Pressurized Rover instantiation is given a use duration (not including regeneration periods) of 14 crew-days, which allows two crew to use it for up to seven consecutive days. The preferred technology options for a pressurized rover are those which permit recharging, that is, allow for the ultimate source of generated consumables to be emplaced separately from the pressurized rover itself. Ideally these rechargers will take the form of extra capacity in the Habitat's ECLS system, from which the pressurized rover can draw consumables. Unlike the EVA suit, the pressurized rover may actually have the capacity to sequester carbon dioxide for later reduction without the use of metal oxide (although metal oxide remains an option), and so these technology options appear in the OPN model.

Provide oxygen

The Pressurized Rover's ECLS system architecture can be either an open-loop or closed-loop configuration for the air cycle. In the open-loop configuration, it does not regenerate oxygen from carbon dioxide. In this case, oxygen can be provided in several ways, either shipped in tanks (cryogenic or high-pressure), shipped as chemical compounds, or taken aboard in tanks filled from a water electrolysis system that will be available on the Habitat, with consumables shipped as simple water. If the Pressurized Rover uses a closed-loop architecture, it must capture and sequester carbon dioxide, and oxygen can then be provided from the regeneration systems on the Habitat.

Remove carbon dioxide

Any technology option for carbon dioxide removal may also be regarded as feasible, including the 2-bed molecular sieve, 4-bed molecular sieve, Electrostatic Depolarization Concentrator, lithium hydroxide (LiOH) canisters, the Solid Amine Water Desorption (SAWD) system, chemical compounds, and metal oxide canisters. Note that some technology options, including the 2-bed and 4-bed molecular sieves, can operate either venting to vacuum or to an internal carbon dioxide storage system. The solid amine vacuum desorption system must vent to vacuum. Its counterpart solid amine system, the SAWD, is included as a separate technology option which requires steam desorption but can operate at cabin pressure.

Reduce carbon dioxide

Carbon dioxide regeneration is too power-intensive to be included on the pressurized rover. However, regeneration of oxygen via carbon dioxide reduction is possible at the Habitat, as the Pressurized Rover will be replenished there after every traverse anyway. The regenerable technology options that remove carbon dioxide from the atmosphere (such as the 4-bed molecular sieve, the EDC, the 2-bed molecular sieve, and the SAWD) use the Habitat to regenerate, as does metal oxide (although metal oxide is not a technology option which is regenerated during its active phase, and thus must be used in large amounts to capture all the carbon dioxide before it can all be regenerated).

Provide nitrogen

In order to allow for easy interface with and rapid access to the EVA suit from the pressurized rover, the pressurized rover will not provide nitrogen, thus reducing or eliminating pre-breathe time required before an EVA operation.

Control temperature

The pressurized rover, like the EVA suit, does not have an external cooling loop, so the Condensing Heat Exchanger is not a viable option. Heat sinks and sublimators, however, are.

Control humidity

Following logic similar to that applicable in the case of the EVA suit, a condensing heat exchanger is a viable option in a water-saving role, and so it is permitted here, as is consumable silica gel.

Trace Contaminant Control

Activated carbon or an active TCC system are feasible here. The SCWO system is expected to be very massive and power-intensive, and thus is disqualified.

Potable water regeneration

Because the Habitat instantiation will include significant water regeneration equipment, the Pressurized Rover can simply store its water and then carry it back to the Habitat for regeneration after the traverse ends.

Liquid waste processing

Much as potable water is ultimately regenerated at the Habitat, so will liquid waste be stored on the Pressurized Rover until it can be regenerated using other nearby equipment.

Solid waste processing

Solid waste can be simply stored, much as it is for the EVA suit instantiation.

3.1.4 Transfer Vehicle Instantiation

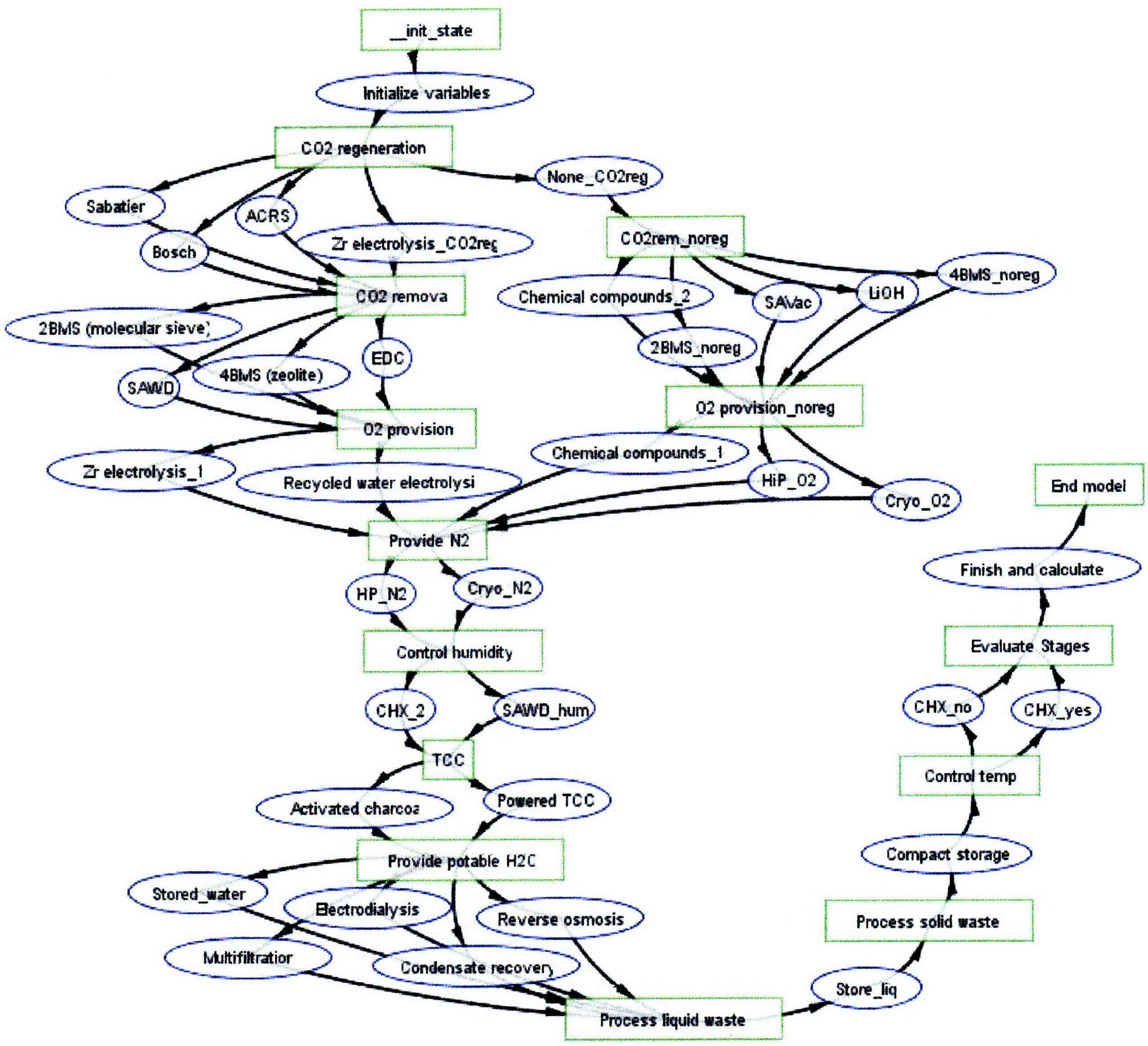

Figure 8. Transfer Vehicle OPN Model.

The transfer vehicle is the instantiation which covers vehicles that carry the crew for a short period of time, usually either from surface to orbit or vice-versa, or from the Earth to the Moon. The Crew Exploration Vehicle is a transfer vehicle. Many transfer vehicles will have ECLS system architectures which tend towards open systems, because for short periods of time they are less massive than highly closed systems. Because waste and water are typically not recycled on transfer vehicle flights, technology options which recycle these are not included. Furthermore, because the transfer vehicle is intended to be used for a short fraction of the total mission time, water requirements for crew members are considered to be decreased. Finally, because the transfer vehicle will not be used repeatedly (it will be used twice only), it does not include technology options which require regular downtime and regeneration.

Low-mass configurations of the ECLSS will be especially preferred for transfer vehicles, given that transfer vehicles such as the LSAM ascent stage will have to go through multiple burns during the course of the mission, and minimization of the mass of upper stages is preferable, as they are essentially parasitic masses (with consequent cascading effects on total launch mass) for most of the mission.

The set of architectures which is feasible depends to some extent on the use duration; here this is set to six crew-days, which is the equivalent of 24 person-days.

Provide oxygen

The transfer vehicle can provide oxygen using any of the technology options available, including water electrolysis, carbon dioxide electrolysis, cryogenic gas storage, high pressure gas storage, or chemical compounds.

Remove carbon dioxide

Carbon dioxide removal can include any technology option except metal oxide, which requires periodic regeneration cycles. Therefore, allowable technology options are 2-bed molecular sieves, 4-bed molecular sieves, EDCs, LiOH canisters, solid amine vacuum desorbed systems, and SAWD systems, as well as chemical compounds.

Reduce carbon dioxide

Because the transfer vehicle must support the entire crew for some time, technology options including the Sabatier reactor, zirconia electrolysis, the Bosch reactor, and the ACRS are possible choices for carbon dioxide regeneration, as is no regeneration at all. Note that two branches appear in the OPN model in Figure 8: one branch includes regeneration of oxygen via carbon dioxide reduction, the other is an open-loop system.

Provide nitrogen

Nitrogen can be provided via cryogenic gas storage or high-pressure gas storage.

Control temperature

A heat sink would be too massive to function without periodic regeneration, and a transfer vehicle does have an external cooling loop, so an evaporator is not needed. Therefore, a CHX is the best choice for temperature control. As with the Habitat instantiation, an external thermal control loop is assumed, which will use radiators and heavy-duty heat exchangers with noxious working fluids. The CHX used by the ECLS system will simply serve to transfer heat loads to the external thermal control system.

Control humidity

Given that a CHX is already present for temperature control, it can be used for humidity control as well. The SAWD or SAVac systems can also be used to control humidity, although the SAVac system vents water, while the SAWD system does not.

Trace Contaminant Control

Trace contaminant control is best accomplished on a transfer vehicle by lightweight means, but either activated carbon filters or active TCC systems are feasible.

Potable water regeneration

Any technology option for water regeneration is feasible, but it is desirable to keep the mass of the transfer vehicle (especially the ascent stage) down to the lowest possible level, so very heavy equipment like the SCWO and HSWPA will not be feasible. Multifiltration, electrodialysis, reverse osmosis, condensate recovery, and even purely stored supplies, however, are feasible.

Liquid waste processing

No major recycling of liquid waste is envisioned, so all waste will be simply stored.

Solid waste processing

Solid waste will likewise be stored rather than recycled, as not much will accumulate over the days during which the crew will use the transfer vehicle.

3.2 Generating ECLS System Architectures

A system architecture is an assignation of elements to functions, within defined system boundaries. An ECLS system architecture is the assignation of technology options to the ten functions that an ECLS system must deliver (some of which, like nitrogen provision, may be optional under certain circumstances) within the boundaries of one of the four instantiations developed. Therefore, an ECLS system architecture is a list of which technology option performs each function for one of the instantiations. Each instantiation will have a set of possible architectures, according to the various subsystems permitted for each function. The total number of possible architectures is simply a combinatorial result of the number of technology options permitted for each function, and may vary from instantiation to instantiation.

System architectures are developed by the use of the OPN modeling language, set up as a system architecture generation tool (4), (38), (6). The models developed create lists of system architectures, some subset of which may be defined as interesting.

OPN models also include internal rules, which govern whether some combinations between technology options can or cannot be made. These rules serve to shrink the set of possible system architectures down somewhat, given that certain chains of combinations now become disallowed. The set of system architectures in which the application of these rules results is no longer fully combinatorial. This set of system architectures is called here the set of feasible system architectures. The table below details some of the rules, and the locations where they are applied in the OPN models used in this thesis. Note that these rules are internal to the model, but do not constitute the only structure applied to the models – the layout of technology options assigned to different functions also carries implicit rules, in that every token that passes out of a function splits and then clones itself to pass into each one of the technology options following that function – unless one of the rules below disallows this action. The structure of the models, as illustrated particularly in Figure 7 and Figure 8, includes choices between separate types of systems. The models in Figure 7 and Figure 8 show split branches near the top of the trees, indicating an implicit choice between open-loop and high-closure systems.

Note that most of the listed rules indicate mandatory connections that must be made, as described in Figure 2. For any step in an OPN model where a mandatory rule applies, connections between one technology option and another which is mandated to follow it are marked with an internal code whereby a token is only permitted to pass through the model following the prescribed path. Other potential paths are marked with an internal code indicating that these paths are not allowed. An example of this is seen in the first rule in Table 2. In the Habitat instantiation OPN model (see Figure 5), potential token pathways leading from the zirconia electrolysis technology option under the carbon dioxide regeneration function are marked either mandatory (the pathway leading to the 4-bed molecular sieve) or not allowed (the pathways leading to the 2-bed molecular sieve, the EDC, and the SAWD unit).

In many cases, rules are not required, and all potential pathways are marked with a default internal code that signifies that the pathway is allowed but not mandatory. In the Habitat instantiation OPN model, this is the case for the nitrogen provision function: pathways to either cryogenic storage or high pressure storage are permitted.

Rule	Justification	Applied locations
Zirconia electrolysis requires a 4-bed molecular sieve	The zirconia electrolysis reaction requires dry carbon dioxide	Habitat, Pressurized Rover, Transfer Vehicle
Zirconia electrolysis for carbon dioxide reduction is also used for oxygen generation	Coupling zirconia electrolysis with water electrolysis or stored oxygen (except for makeup oxygen) is redundant	Habitat, Pressurized Rover, Transfer Vehicle
If a SCWO is used for TCC, it is used for water provision, liquid waste processing, and solid waste processing	The SCWO is multifunctional, and multi-use of it may be attractive	Habitat, Pressurized Rover
If a SCWO is used for water provision, it is also used for liquid waste processing, and solid waste processing	The SCWO is multifunctional, and multi-use of it may be attractive	Habitat, Pressurized Rover
If a SCWO is used for liquid waste processing, it is also used for solid waste processing	The SCWO is multifunctional, and multi-use of it may be attractive	Habitat, Pressurized Rover
If chemical compounds are used for carbon dioxide removal, they are also used for oxygen provision	Chemical compounds generate oxygen and take up carbon dioxide – multi-use may be attractive	Pressurized Rover, Transfer Vehicle
If SAWD supplies carbon dioxide removal, it also supplies humidity control	SAWD is inherently a dual-function technology option	Habitat, EVA Suit, Pressurized Rover, Transfer Vehicle
SAWD for humidity control permits a CHX for temperature control	SAWD functions are primarily carbon dioxide and humidity removal	Habitat, Transfer Vehicle

Table 2. Rules applied to OPN models.

Running each of the four OPN models results in four sets of ECLS system architectures, which consist of lists of technology options (representing the technology options assembled to complete the ECLSS in the physical sense, and the path taken by one data token in the model's computational sense) and associated metrics, including the mass, volume, power required, and heat required by all the equipment in an architecture and the mass and volume of consumables required as well.

3.3 Benchmarking and Validating Models

To validate the OPN models, ECLS system architectures generated by the models were compared to existing ECLS system architectures. Although high-closure ECLS system architectures are included in the set of system architectures generated for this thesis, most ECLS systems that have actually flown are much more open-loop than not.

Some degree of benchmarking is still possible. System architectures generated by the OPN models that match existing systems can be compared to the mass figures for those systems. Architectures can also be examined to see if they are ranked feasibly. Finally, the ECLS system architectures generated here can be compared to other concepts to see if the estimated masses for the systems are feasible.

According to (9), the mass of an Apollo-era Personal Life Support Systems (PLSS) was 61.2 kg. The Apollo EVA suit PLSS used lithium hydroxide canisters and high-pressure oxygen supplies, as described in (39). A similar ECLS system architecture, generated by the EVA suit instantiation OPN model, shows a total one-mission mass (including equipment and consumables) of 30.2 kg. This is not unrealistic, considering that the OPN model does not use sufficient detail to describe redundant systems, emergency systems, and subsystems like circulation and tubing. This system architecture is detailed in Figure 9.

Architecture	Apollo EVA	
Campaign mass	19452	
Equip mass	19.89	*TRL*
O2 prov	HP	9
CO2 Rem	LiOH	9
CO2 Redux	None	
N2 prov	X	
Temp	Sublimator	9
Hum	CHX	9
TCC	Charcoal	9
H2O prov	Stored	9
Liq waste	Store	9
Sol waste	Store	9
Spares mass per yr	1.989	
Dev cost, $M	153.97	
Unit/Spare cost, $M	57.28	
Transport cost, $M	778.08	

Figure 9. Modeled Apollo EVA suit ECLS system architecture.

Furthermore, the ECLS system architecture generated for the ISS-era PLSS, which uses metal oxide for carbon dioxide control, is 52.84 kg, which is significantly more than for the Apollo system. This remains realistic, as suits designed for free fall have fewer constraints related to total mass than those designed for use in a gravity well, and thus are often significantly more massive. This EVA suit architecture, which is one of the interesting architectures selected at the end of Chapter 3, is detailed in Figure 59.

Mass estimates for portions of the Skylab ECLS system available from (40), (41), and (42) can be summed to give an estimate for the ECLSS system, including at least oxygen provision, nitrogen provision, humidity control, trace contaminant control, water provision, and waste management. This sum is approximately 7418 kg. An adapted version of the OPN model provides an equivalent mass estimate of 4102 kg for a similar ECLS system architecture. This estimate is again on the low side, but is reasonably close to the value that should be expected for a long-duration space station habitat. The details of this ECLs system architecture appear in Figure 10.

Architecture	Skylab	
Campaign mass	4102	
Equip mass	165.54	*TRL*
O2 prov	HP	9
CO2 Rem	4BMS	9
CO2 Redux	None	
N2 prov	X	
Temp	CHX	9
Hum	CHX	9
TCC	Charcoal	9
H2O prov	Stored	9
Liq waste	Store	9
Sol waste	Store	9
Spares mass per yr	16.554	
Dev cost, $M	164.46	
Unit/Spare cost, $M	61.79	
Transport cost, $M	164.08	

Figure 10. Modeled Skylab ECLS system architecture.

Other published concepts can also be compared to ECLS system architectures developed by the OPN models. According to (43), a modular rover called the MORPHLAB (Modular Roving Planetary Habitat, Laboratory, and Base) has a total ECLSS mass of 1072.2 kg. This system uses water electrolysis, an EDC, a Sabatier reactor, gaseous nitrogen makeup, an active TCC system, multifiltration for water, a VAPCAR, and a SCWO. A similar ECLS system architecture created by the pressurized rover OPN model shows an equivalent ECLS system mass of 1221.5 kg. This is also reasonably close to the expected value, and therefore the OPN models appear to be reasonably accurate. The details of this architecture appear in Figure 11.

Architecture	MORPHLAB	
Campaign mass	2155	
Equip mass	1197.58	*TRL*
O2 prov	Welec	8
CO2 Rem	EDC	6
CO2 Redux	Sabat	7
N2 prov	HP	9
Temp	CHX	9
Hum	CHX	9
TCC	Active	5
H2O prov	MF	7
Liq waste	VAPCAR	3
Sol waste	SCWO	3
Spares mass per yr	119.758	
Dev cost, $M	238.77	
Unit/Spare cost, $M	93.79	
Transport cost, $M	86.2	

Figure 11. Modeled MORPHLAB ECLS system architecture.

3.4 Down-Selecting to Interesting ECLS System Architectures

After an OPN model generates the list of feasible system architectures for its particular instantiation, these system architectures can be ranked. The OPN models track and assess the mass, volume, power requirement, and heat rejection requirement of the ECLS system, and these parameters can be used as metrics in ranking the system architectures.

3.4.1 Metrics

Conversion of the four parameters to a single metric, total equivalent mass, is carried out according to the method described in (8): the total equipment mass is summed up, as are the total equipment volume, power requirement, and heat rejection requirement. Added to these are the consumables mass and consumables volume, found by multiplying the mass and volume per person per day times the number of crew-days an instantiation is operated. Volumes are converted to mass via a standard conversion factor, taken directly from (8), as are the power requirement and heat requirement. The masses and converted masses are summed to give a total equivalent campaign mass, which is the amount of mass associated with that instantiation's ECLSS that must be landed on the surface of a planetary body in order to explore it.

Given the total equivalent campaign mass now associated with each system architecture, the system architectures can be sorted and ranked according to this metric. Other metrics used include estimates of the system build cost, which is the sum of the design cost and the unit acquisition cost, the transport cost, and the technology/cost risk.

The system design cost and unit cost are based on (44), and the transport cost is simply a linear function of the campaign mass, based on an estimate of the cost per kilogram to the lunar surface.

The technology/cost risk is calculated by adding up the number of technology options per architecture with a TRL of 5 or lower. According to (45), including system components with a TRL less than 6 increases the risk of cost and schedule slip in the development of the system. Cost slip of up to 100% was observed, and schedule slip of up to 120%.

The following sections describe in detail the process of down-selecting to a few interesting ECLS system architectures per instantiation.

3.5 Habitat Architecture Downselection

The Habitat OPN model generated 4914 architectures. A plot of the campaign masses of these architectures appears in Figure 12.

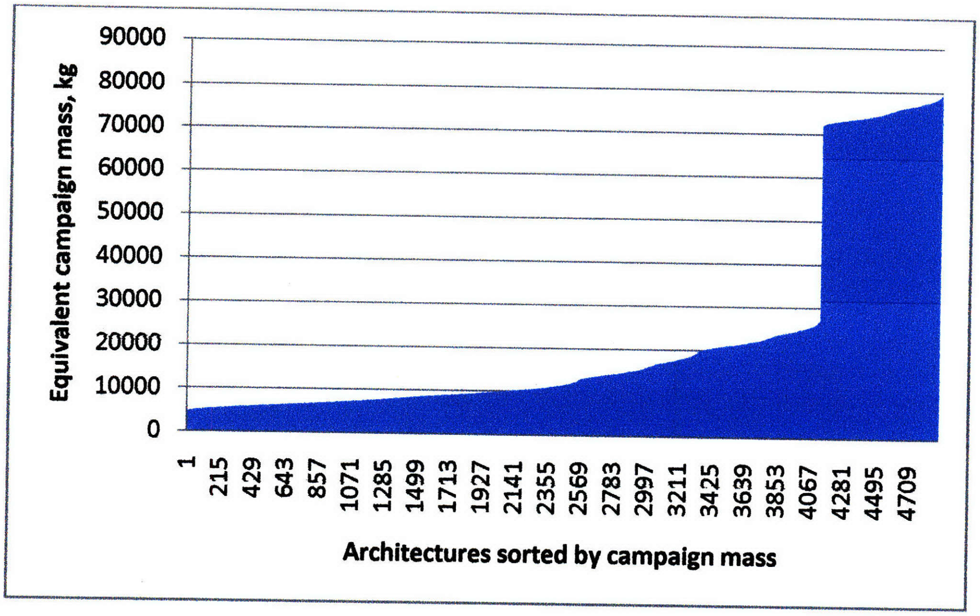

Figure 12. Habitat campaign masses.

Note that significant variance exists in the campaign masses. A plot of the campaign mass after sorting the architectures by the build cost (the sum of the development cost and the unit cost) appears in Figure 13.

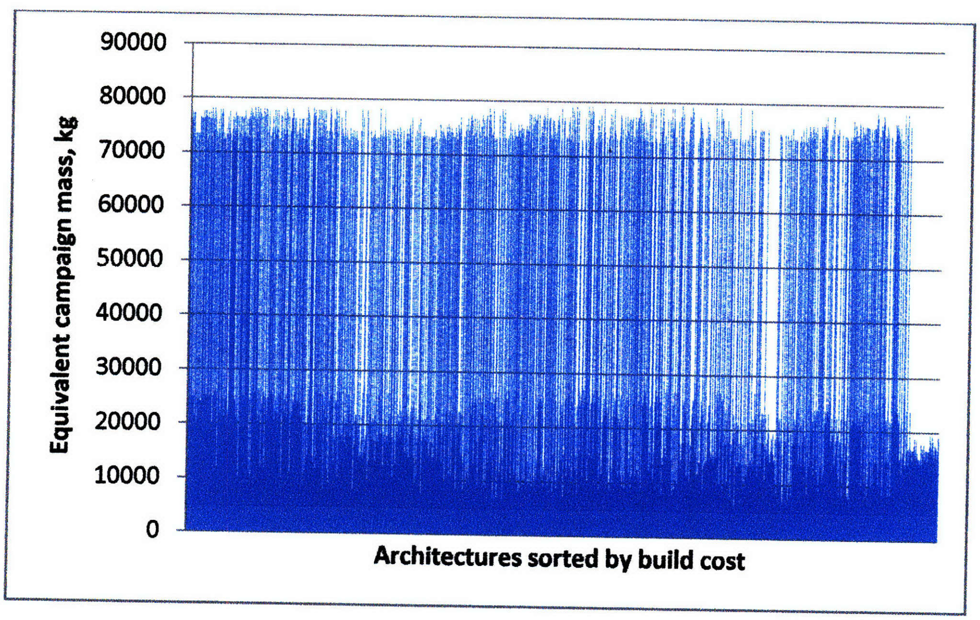

Figure 13. Habitat campaign masses sorted by increasing build cost.

This plot indicates that many high-mass architectures are distributed among all levels of build cost, and that many of the very lowest campaign mass architectures require very high development investment. A large cluster of the lowest-mass architectures is at the high end of the build cost curve.

This indicates that some significant investment of time and money may be required in order to reduce campaign mass to desired levels. This being the case, a TRL filter (which will minimize cost risk) becomes highly desirable. Application of this TRL filter, which quantifies the number of technology options in an architecture which are at TRL 5 or less (this list includes the SCWO, active TCC systems, TIMES, VAPCAR, reverse osmosis, waste incineration, EDC, electrodialysis, ACRS, and Bosch reactors) gives the results which appear in Figure 14.

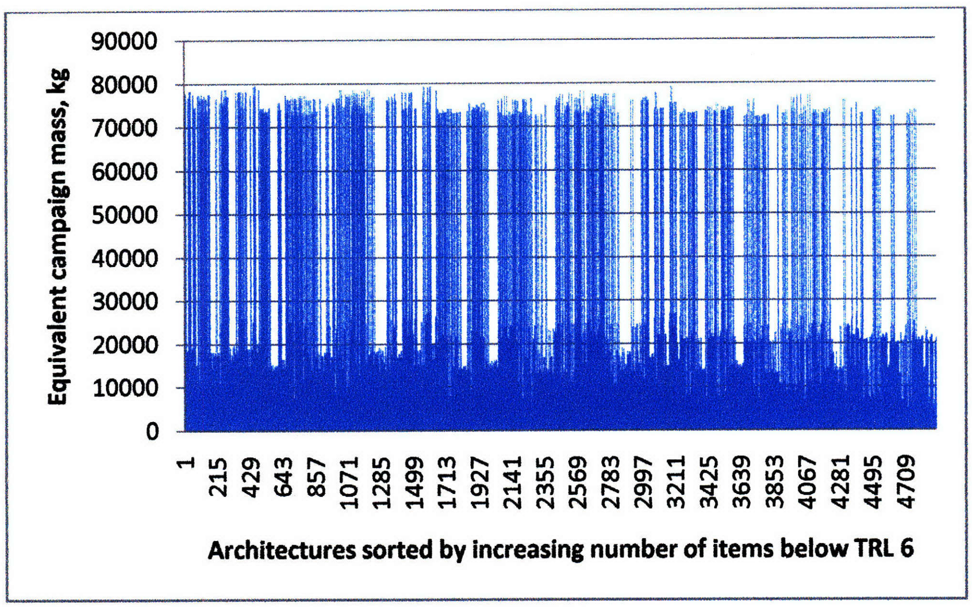

Figure 14. Habitat campaign masses sorted by TRL risk.

Of the architectures shown, 64 have no items below TRL 6; 496 have one or fewer; 1656 have two or fewer; 3242 have three or fewer; 4410 have four or fewer; 4850 have five or fewer; and all 4914 have six or fewer.

The best way to minimize risk is to hold the number of risky items to develop to one or fewer; this ensures that a program can have at most one technology development bottleneck. The first 496 architectures by this metric are in Figure 15.

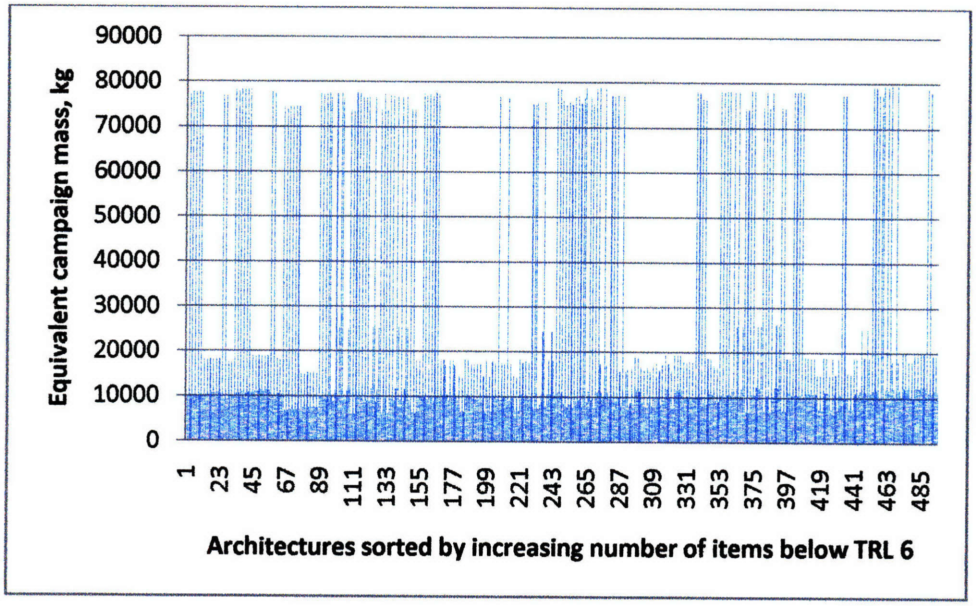

Figure 15. Habitat architectures with TRL risk level 1 or 0.

This plot indicates that many potentially interesting architectures are distributed within the smaller design space. Furthermore, the higher TRL risk is not apparent from the plot – that is, a higher risk in the development cost is not apparently correlated with the presence of interesting architectures. So these riskier architectures can be eliminated. To eliminate TRL risk completely, we now specify that the number of items at a TRL less than 6 to be developed should be held to zero. This results in the plot of architecture campaign masses (sorted by campaign mass) seen in Figure 16.

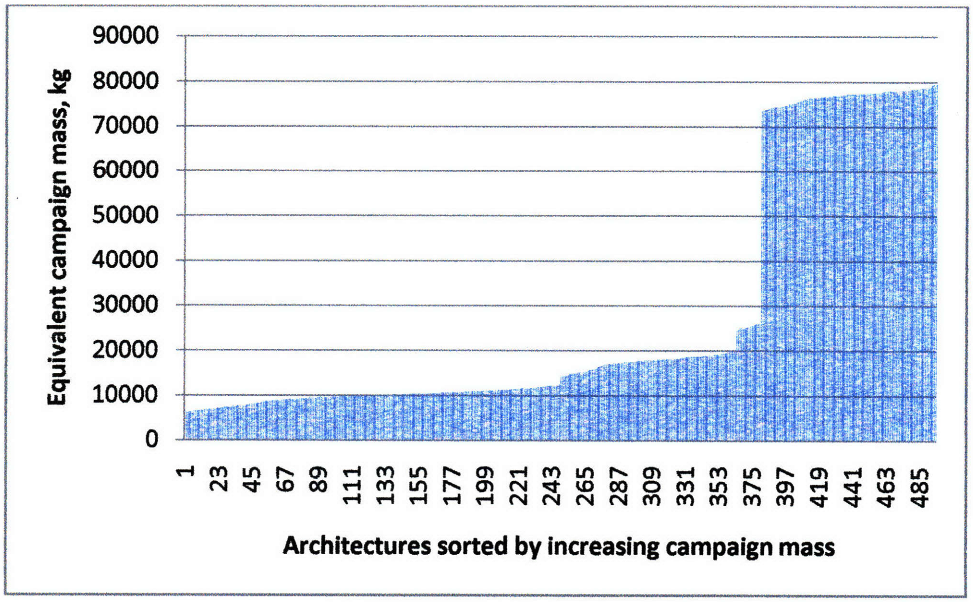

Figure 16. Habitat campaign masses.

Examination of the architectures shows that those which rely on 4-bed molecular sieves, 2-bed molecular sieves, and solid amine water desorption (SAWD) systems are very evenly distributed throughout the architectures, indicating that none of these technology options dominates the others. However, the SAWD and 4BMS are more mature than the 2BMS, and the 4BMS has already seen use on Skylab and the ISS. Therefore the 2BMS architectures are eliminated from consideration.

Other technology options which do not clearly dominate occur in the provision of nitrogen. High-pressure storage is preferred over cryogenic storage, as this technology option has been used on the Shuttle and ISS for some time, and furthermore does not require cooling power, as cryogenic storage does. Therefore, all architectures which include cryogenic storage of nitrogen are eliminated.

Notably, all the remaining highest campaign masses are associated with architectures that include a condensate recovery unit, but no other means of recycling water. This reflects the importance of water recycling in a high-closure ECLS system, as crew members use far more mass of water per day than any other resource. All of these architectures, which cluster at the far right of the plot in Figure 16, are eliminated. The second-highest cluster at the right end of

Figure 16 is composed of architectures that use reverse osmosis. Since these architectures are also clearly inferior in terms of campaign mass to other architectures with different technology options, they are also eliminated. Further examination reveals that the HSWPA architectures also cluster at the high end of a plot of campaign masses, indicating that they are equally inferior in terms of campaign mass, and thus less preferable. They are also eliminated.

Note that some architectures which include the HSWPA technology option, in a hybrid state with a condensate recovery unit, still remain under consideration.

The resulting architectures, plotted and sorted by campaign mass, appear in Figure 17.

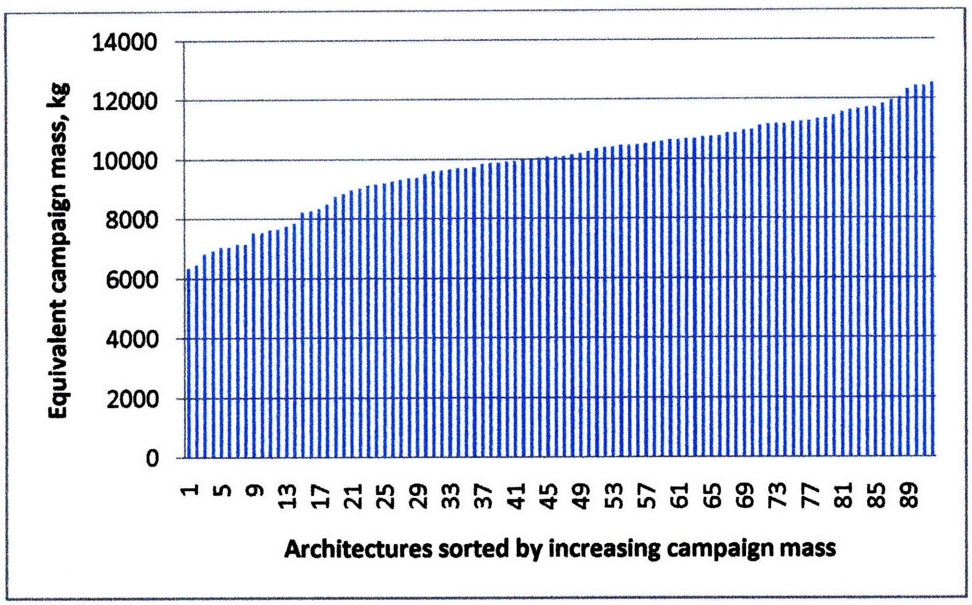

Figure 17. Pruned Habitat architectures.

Re-sorting these fewer architectures by build cost and then plotting the equivalent campaign mass gives the results seen in Figure 18.

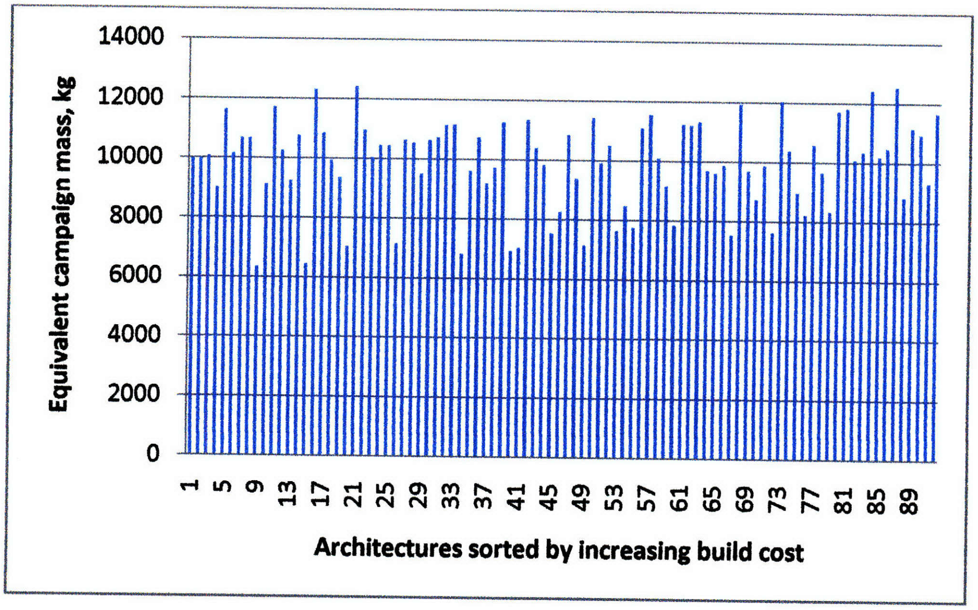

Figure 18. Pruned Habitat campaign masses sorted by build cost.

The build costs themselves stretch across the range of approximately a factor of two, as seen in Figure 19, where the build costs are plotted.

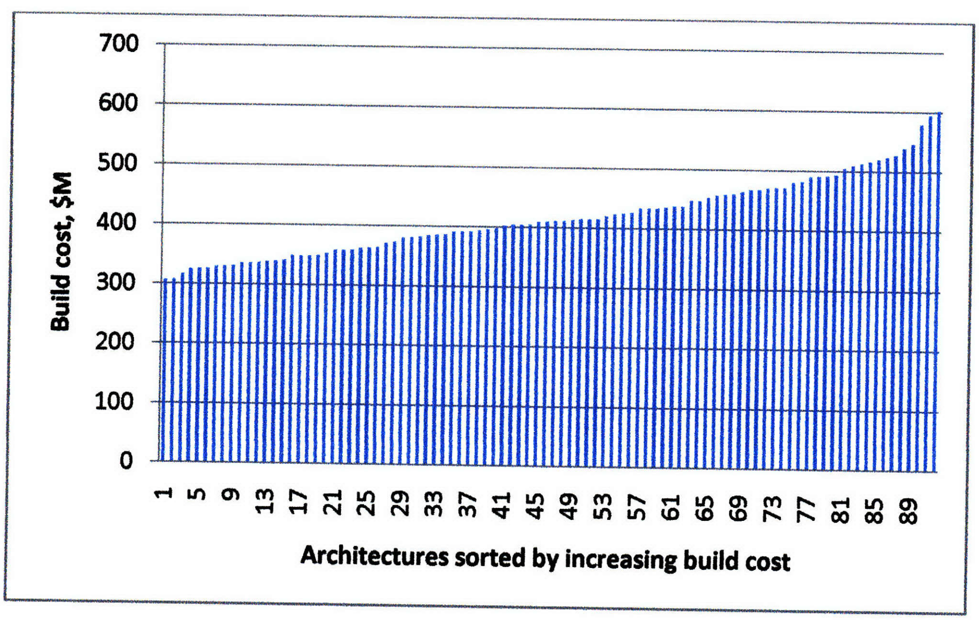

Figure 19. Build costs for pruned Habitat architectures.

Many of the low campaign masses which periodically occur in Figure 18 are seen to be those architectures which include an ACRS or Bosch unit. All but the first (lowest build cost) of these are eliminated. The ACRS units almost uniformly dominate the Bosch units in terms of lower build cost and lower campaign mass. Because of this, and because the ACRS can be developed based on a Sabatier-only platform, while the Bosch is an entirely separate system (this allows an existing functionality, based on a far more mature technology option, to be extensible), no Bosch architectures are retained.

Final pruning of the architectures is now conducted. Architectures which include a SCWO are distributed throughout the architectures when sorted by campaign mass (as in Figure 20), indicating that this technology option does not dominate the other choices, and as it is only TRL 3, all architectures which include a SCWO are eliminated. Note that any architecture which includes a SCWO includes no other technology options below TRL 5, as these architectures were eliminated previously via the TRL filter. The pruning step of eliminating any architectures which include a SCWO culls only those architectures which have a SCWO as a potential technology bottleneck. Although these architectures have only one potential technology development bottleneck, it is seen that the potential benefits of these architectures do not definitively outweight even this risk.

The same is true of the EDC – it does not dominate other architectures, and is not as mature as the other choices, and so it is also eliminated from consideration.

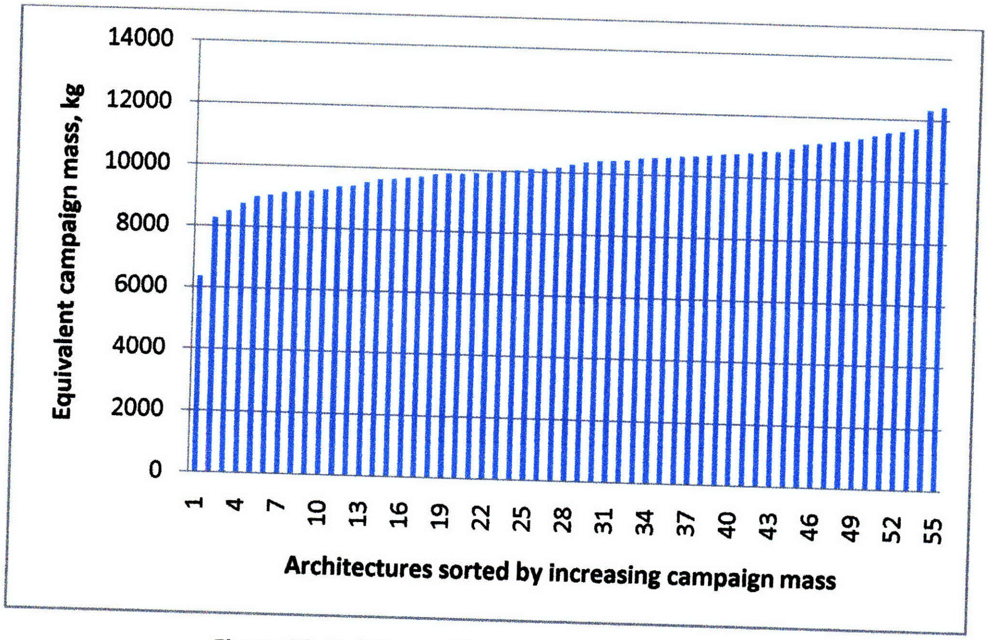

Figure 20. Habitat architectures for final pruning.

Finally, because there is still significant range in the campaign masses of the Habitat ECLS system architectures, a cap is set. All those system architectures with an equivalent campaign mass above 10 tonnes are eliminated. Thus, all those architectures which have extremely high equivalent campaign mass are now eliminated.

The build costs still retain a significant range as well, as seen in Figure 21. When sorted by build costs, the campaign masses do not display any clear trends with build cost, as in Figure 22. Retaining only the half of the architectures which rank lowest in build cost still allows the capturing of the lowest campaign masses, while minimizing the range (and absolute value) of build costs.

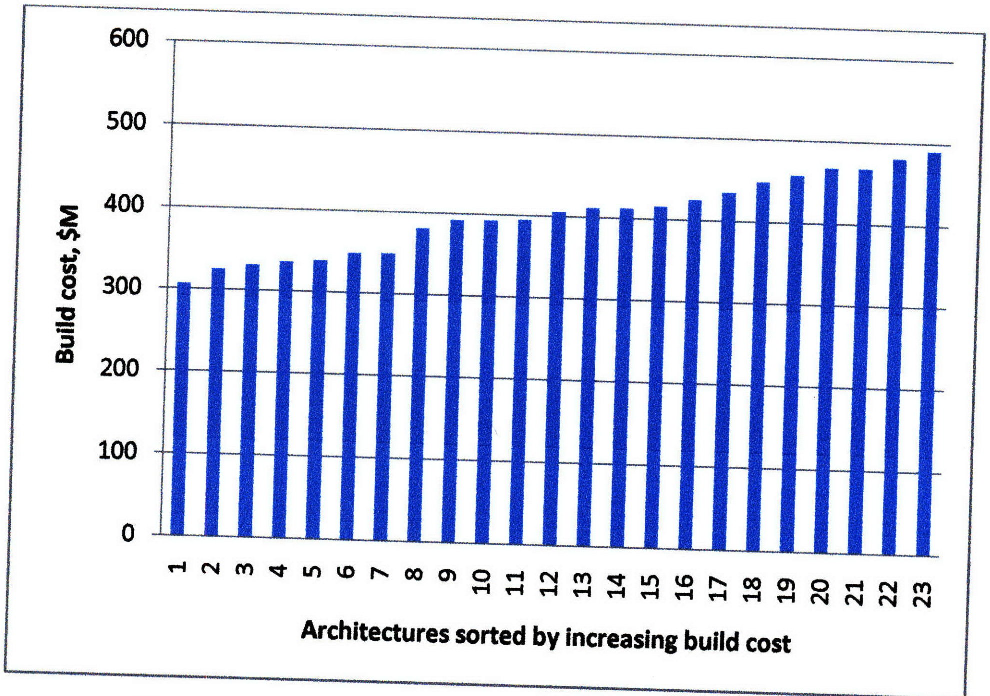

Figure 21. Build costs for final pruning of Habitat architectures.

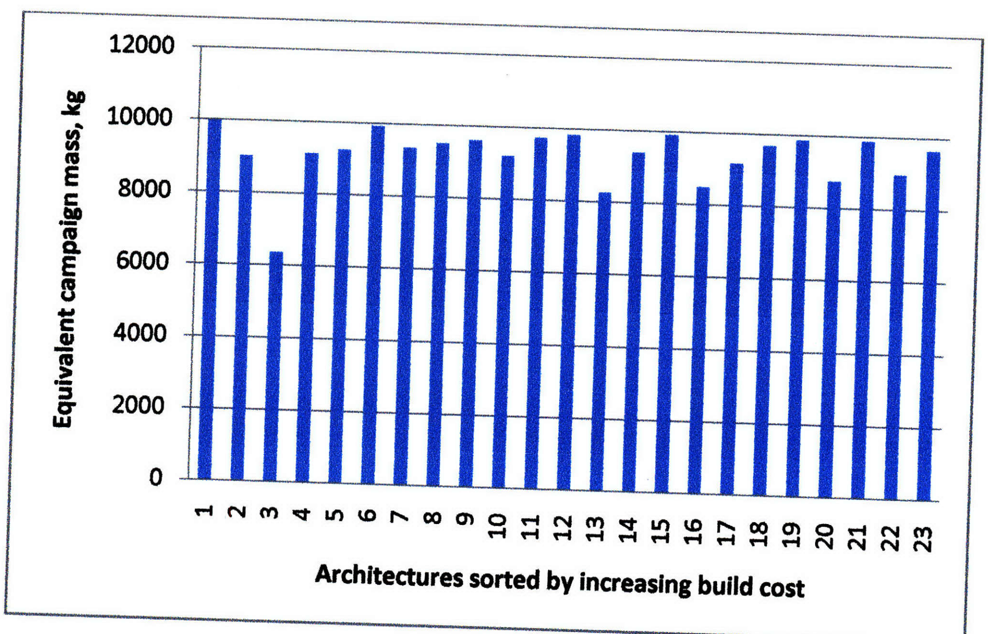

Figure 22. Habitat architectures for final pruning, sorted by build costs.

The remaining architectures are plotted in Figure 23. Notably, all the architectures at the right of the plot use zirconia electrolysis. Although zirconia electrolysis is potentially an interesting technology option, and may present architectures of even greater interest for use on a Mars surface exploration mission, as it can be applied to Mars ISRU (12) as well as internal ECLSS, here all these architectures are eliminated. Water electrolysis is a far more mature technology, and the zirconia electrolysis architectures do not dominate it sufficiently to justify its use.

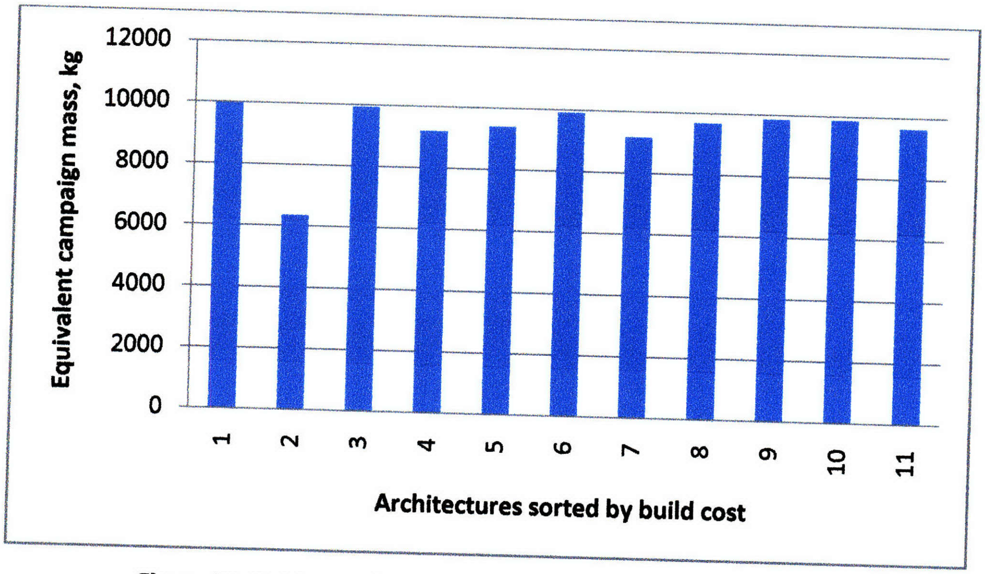

Figure 23. Habitat architectures only including air evaporation.

Of the remaining architectures, three technology options for liquid waste reclamation occur in regular cycles in the ranking, indicating that none are strongly dominant. These are TIMES, VAPCAR, and air evaporation. Of these, the VAPCAR (at TRL 3) is the least mature, (air evaporation is TRL 6, in fact, and TIMES is TRL 5), and so the VAPCAR architectures are eliminated.

One architecture includes an active TCC system, and another architecture uses solid waste incineration. Although these architectures are competitive, their competitors (activated carbon and compaction and storage) have far more in-space heritage, and as such are preferred.

The resulting five architectures include one ACRS, and one each of the four possible combinations between the HSWPA/condensate hybrid or MF technology options and the SAWD or 4BMS technology options.

In order to retain at least one architecture with nearly uniformly high TRL, a sixth architecture, exactly like one of the five already selected but including an air evaporation unit instead of a TIMES unit, was also added.

Architecture	Hab 1	TRL	Hab 2	TRL	Hab 3	TRL
Campaign mass	9142		9037		6356	
Equip mass	1233.51		1128.79		1185.26	
O_2 prov	Welec	9	Welec	9	Welec	9
CO_2 Rem	4BMS	9	SAWD	6	4BMS	9
CO_2 Redux	Sabat	7	Sabat	7	ACRS	3
N_2 prov	HP	9	HP	9	HP	9
Temp	CHX	9	CHX	9	CHX	9
Hum	CHX	9	CHX	9	CHX	9
TCC	Charcoal	9	Charcoal	9	Charcoal	9
H_2O prov	MF	6	MF	6	MF	6
Liq waste	TIMES	5	TIMES	5	Airevap	6
Sol waste	Compress	9	Compress	9	Compress	9
Spares mass per yr	123.351		112.879		118.526	
Dev cost, $M	241.35		233.81		237.88	
Unit/Spare cost, $M	94.90		91.65		93.40	
Transport cost, $M	365.68		361.48		254.24	

Figure 24. First three Habitat architectures.

Architecture	Hab 4	TRL	Hab 5	TRL	Hab 6	TRL
Campaign mass	9522		9627		10759	
Equip mass	1673.13		1777.85		1783.35	
O_2 prov	Welec	9	Welec	9	Welec	9
CO_2 Rem	SAWD	6	4BMS	6	4BMS	9
CO_2 Redux	Sabat	7	Sabat	7	Sabat	7
N_2 prov	HP	9	HP	9	HP	9
Temp	CHX	9	CHX	9	CHX	9
Hum	CHX	9	CHX	9	CHX	9
TCC	Charcoal	9	Charcoal	9	Charcoal	9
H_2O prov	HS/cond	7	HS/cond	7	HS/cond	7
Liq waste	TIMES	5	TIMES	5	Airevap	6
Sol waste	Compress	9	Compress	9	Compress	9
Spares mass per yr	167.313		177.785		178.335	
Dev cost, $M	273.01		280.55		280.94	
Unit/Spare cost, $M	108.53		111.77		111.94	
Transport cost, $M	380.88		385.08		430.36	

Figure 25. Last three Habitat architectures.

Sensitivity analysis: No hydrogen shipping for Sabatier

Shipping hydrogen to the Sabatier unit (to make up for losses incurred when venting CH_4) is used for the model that generated the architectures above. Note that many include a Sabatier system. However, this shipping requires a mass of 0.305 kg of hydrogen plus tankage to be delivered per person per day. Stoichiometrically, it is possible to ship up water (which is far more storable than hydrogen) and electrolyze it, which produces oxygen for breathing and hydrogen for the Sabatier unit. The breakeven amount of water to be shipped is 0.536 kg/p/d. An analysis of the Sabatier systems with this adjusted shipping requirement gives:

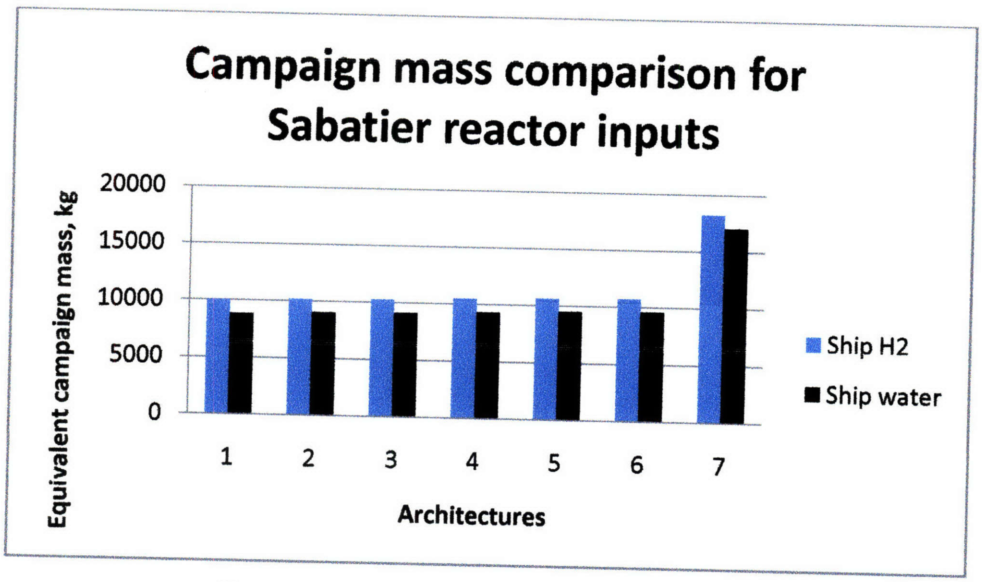

Figure 26. Pressurized Rover OPN model results.

The effect of shipping water instead of hydrogen, while visible, is not distinctive.

Sensitivity analysis: Water-rich environment

The HSWPA system is rated at 95% efficiency, and is modeled as such. However, the hybrid HSWPA-condensate system is modeled as 100% efficient. This is because the condensate unit pulls water from the air, some of which was originally shipped either as hydration in the food (not part of the model, and so the water in food is an external source of consumables) or as metabolic water in the food. Water shipped in food may account for up to 1.1 kg of water per person per day, and metabolic water may be up to 0.409 kg of water per person per day. In total, nearly 1.5 kg of water per person per day are available from fully-hydrated food. Most of this water is excreted as perspiration or via respiration (as is some further amount of water which is first consumed as a liquid). Some of it is also excreted as liquid waste.

Assuming that the selected liquid waste reclamation technology option permits the maximum degree of water recovery, and that a condensate unit is present, up to about 0.4 kg of excess water can be produced per person per day from metabolic water. Assuming that about 75% of the 1.1 kg of water used to hydrate food is also recoverable via the condensate unit (with some other amount being recoverable through the liquid waste processing system), this creates an excess of water, and the environment will become water-rich. Several benefits can be derived from this event.

The amount of water shipped up in food could be reduced. This would reduce the mass requirement for shipping food. Or the closure level of the water system can be reduced. The standard OPN model assumes that one of these events is the case. Either less water is shipped in food, or water deficits caused by imperfect closure estimates on the water recovery system are eliminated by the use of this margin. There is a third case, however. The water requirement could be reduced, resulting in a greatly-decreased consumable requirement. If it is assumed that the condensate unit recovers all of the available metabolic water, plus three-quarters of the hydrated food water, and the HSWPA is 95% efficient, then 1.23 kg of water per person per day are now produced on site, and a net gain of about 0.45 kg of water per person per day is available.

The results of introducing this change appear in Figure 27 and Figure 28. Three architectures which were labeled as interesting and included HSWPA/condensate units operating at 100% net water closure are compared to the same three architectures operating at metabolic water recovery levels (effectively over 100% water closure).

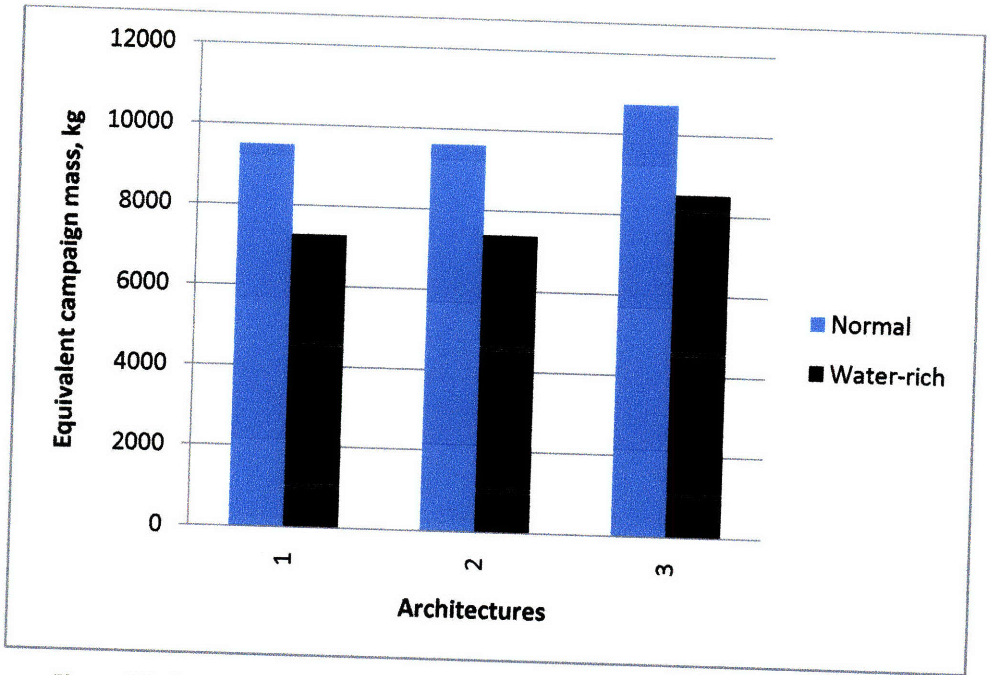

Figure 27. Campaign mass comparison for metabolic and food water recovery.

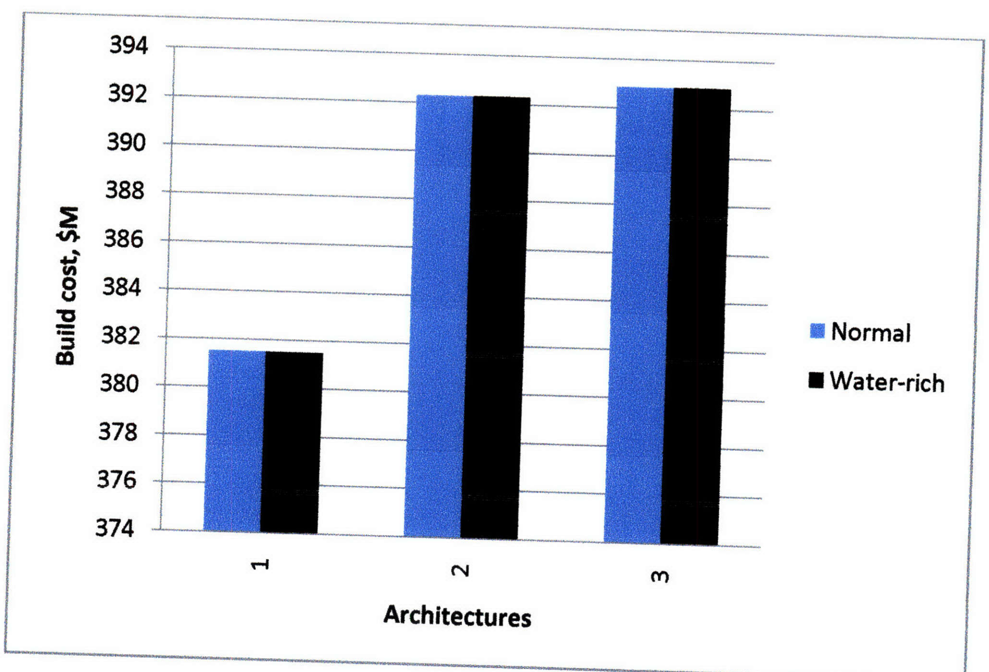

Figure 28. Build costs for metabolic and food water recovery.

Thus it can be seen that a negligible increase in build cost can create up to a 25% difference in total equivalent campaign mass. Therefore, the three system architectures which include the

HSWPA/condensate hybrid option are held over, and the new campaign masses are used, to reflect more clearly the potential benefits of a condensate unit.

Based on this analysis, the hybrid option dominates the multilfiltration technology option in terms of total equivalent campaign mass, as seen in Figure 29. Therefore, the final three interesting architectures are the one which includes the ACRS, and two with HSWPA/condensate hybrid water recovery units.

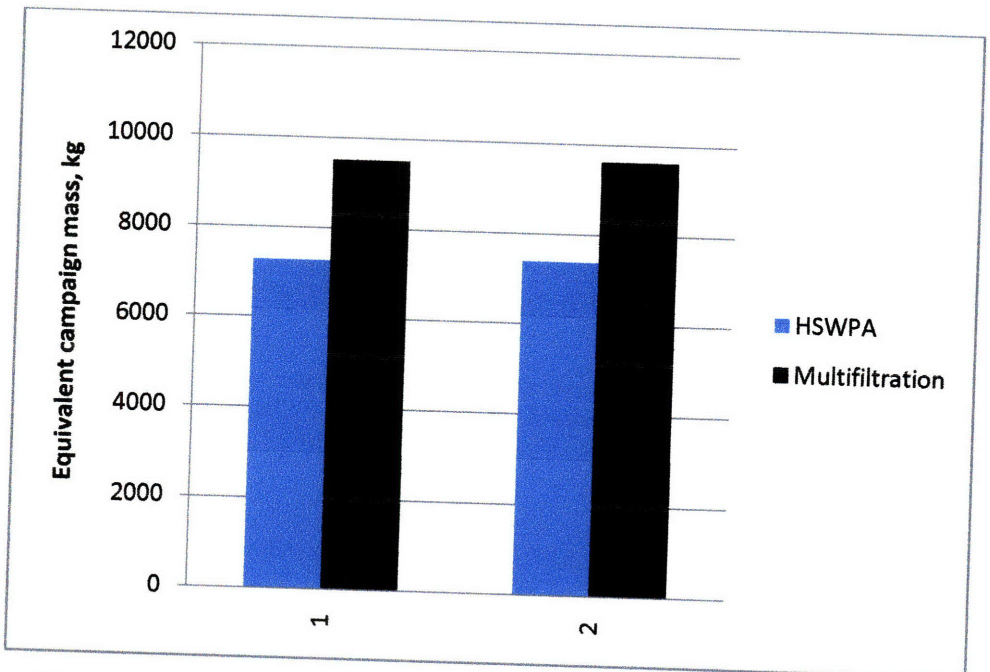

Figure 29. Campaign masses for HSWPA/condensate and MF technology options.

In order to cut down the number of architectures from which interesting portfolios will be generated in the next chapter, one final assessment of the available technologies is made. The use of a HSWPA/condensate hybrid system demonstrated that architecture campaign mass can be brought down to a level competitive with the use of an ACRS unit (7278 kg and 6356 kg, respectively), and as both of these involve some investment in technological development, but the HSWPA/condensate hybrid involves far less, and is much more likely to be a successful design, as both of its components have space heritage, it is preferred over the ACRS as a technology investment choice.

The final two interesting Habitat ECLS system architectures, which appear in Figure 30, are then one with a reasonable level of technological investment (a HSWPA/condensate hybrid unit, a SAWD system, and a TIMES unit) and one with very little technological investment (only a HSWPA/condensate hybrid and an air evaporation system) and extensive space heritage.

Architecture	Hab 1	TRL
Campaign mass	7278	
Equip mass	1673.13	
O2 prov	Welec	9
CO2 Rem	SAWD	6
CO2 Redux	Sabat	7
N2 prov	HP	9
Temp	CHX	9
Hum	CHX	9
TCC	Charcoal	9
H2O prov	HS/cond	7
Liq waste	TIMES	5
Sol waste	Compress	9
Spares mass per yr	167.313	
Dev cost, $M	273.01	
Unit/Spare cost, $M	108.53	
Transport cost, $M	291.12	

Architecture	Hab 2	TRL
Campaign mass	10759	
Equip mass	1783.35	
O2 prov	Welec	9
CO2 Rem	4BMS	9
CO2 Redux	Sabat	7
N2 prov	HP	9
Temp	CHX	9
Hum	CHX	9
TCC	Charcoal	9
H2O prov	HS/cond	7
Liq waste	Airevap	6
Sol waste	Compress	9
Spares mass per yr	178.335	
Dev cost, $M	280.94	
Unit/Spare cost, $M	111.94	
Transport cost, $M	430.36	

Figure 30. Top two habitat ECLS system architectures.

3.6 EVA Suit Architecture Downselection

The EVA suit OPN model generated 16 architectures. All technology options were over TRL 6, so no TRL filter was applicable.

A plot of equivalent campaign mass versus build cost (development cost plus unit cost) appears in Figure 31.

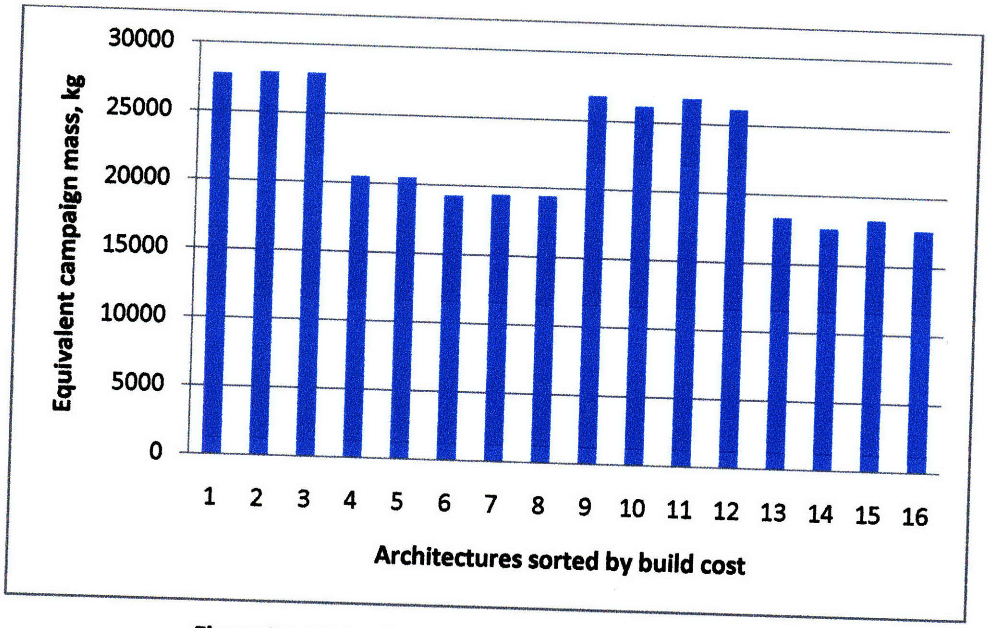

Figure 31. EVA suit campaign mass versus build cost.

There are five major groupings in the chart. The first three architectures are consumables-heavy (note that development cost correlates directly with equipment mass, and consumables do not contribute to equipment mass). The next two, just above 20 mT each, use solid amine vacuum (pressure-swing) beds, and the next three, just below the 20 mT line, are consumable except for humidity control, which is done with a CHX instead of silica gel. The next four use metal oxide or a 2-bed molecular sieve with silica gel, and the last four use metal oxide or a 2-bed molecular sieve with a condensing heat exchanger.

A plot displaying only the build cost for each architecture appears in Figure 32.

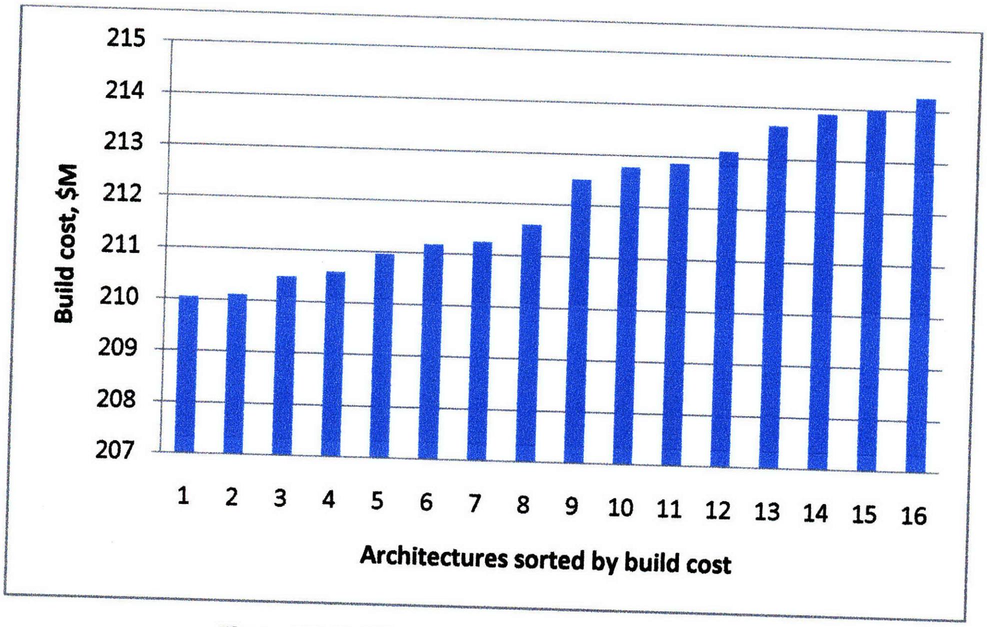

Figure 32. Build costs for EVA suit architectures.

Note that total build costs differ only by 1.9% at most. From this, it is apparent that equivalent campaign mass will be a metric of more importance than will build cost, as build costs do not differ much across architectures, while campaign mass does.

Finally, a plot of the build cost and transportation cost (based on transporting the campaign mass to the Moon at $40,000 per kilogram) appears in Figure 33.

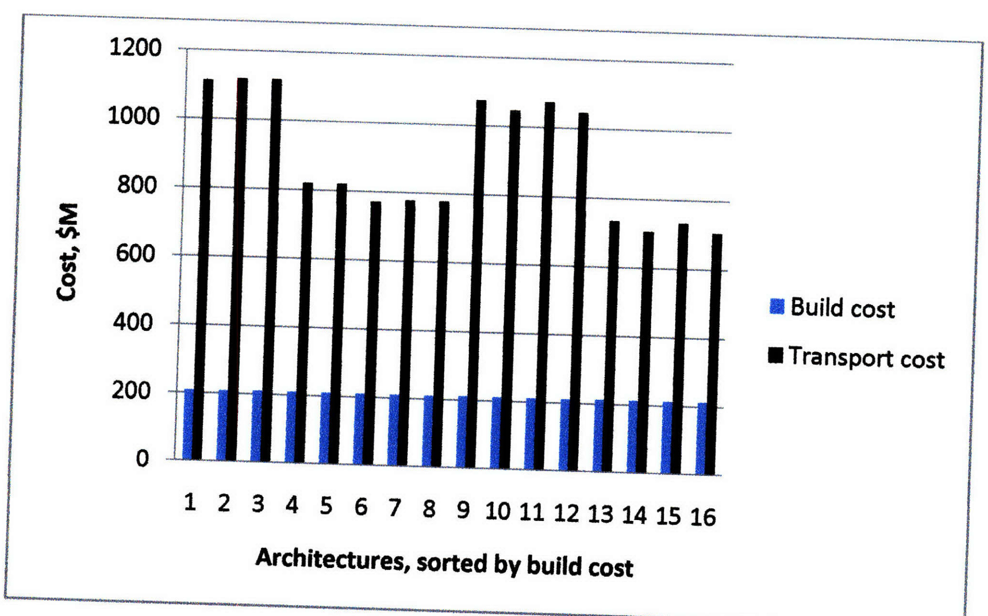

Figure 33. Build and transport costs for EVA suit architectures.

Note that transport costs dominate build costs by a factor of four or five. From this, it can be seen that differences in build cost are not nearly as important as differences in transport costs (which is directly related to campaign mass).

Therefore, the two groupings with higher campaign mass can be eliminated. Furthermore, the differences in campaign mass between the metal oxide and the 2-bed molecular sieve are not very significant (the ordering is dominated more by the presence or absence of a condensing heat exchanger than by the technology option used for carbon dioxide removal), so the more mature technology (metal oxide) is selected as more interesting. Finally, the solid amine vacuum (pressure-swing bed) architecture group and the consumables with a condensing heat exchanger architecture group are both pruned to one, whichever is slightly more dominant, and these two architectures are also carried forward as interesting.

So, a set of interesting architectures would include one architecture from each of the three lowest groups in Figure 31. Highly consumable architectures (from either of the two groups which include silica gel) will have transportation costs far beyond what is merited by their slightly-lower development costs.

Of the highly-consumable group that includes a condensing heat exchanger, the slightly dominant architecture uses chemical compounds (potassium superoxide) for both oxygen provision and carbon dioxide removal. While this technology option may be attractive due to its dual-use capability, it is not as mature in space applications as other consumable technology options, and so the architecture chosen from this group includes lithium hydroxide and stored gaseous oxygen, both of which are very mature technology options.

The three architectures chosen as interesting appear in Figure 34.

Architecture	EVA 1		EVA 2		EVA 3	
Campaign mass	20509		19452		18356	
Equip mass	13.58	*TRL*	19.89		43.2	*TRL*
O2 prov	HP	9	HP	9	HP	9
CO2 Rem	SAVac	6	LiOH	9	MetOx	8
CO2 Redux	None		None		Hab regen	6
N2 prov	X		X		X	
Temp	Sublimator	9	Sublimator	9	Sublimator	9
Hum	SAVac		CHX	9	CHX	9
TCC	Charcoal	9	Charcoal	9	Charcoal	9
H2O prov	Stored	9	Stored	9	Stored	9
Liq waste	Store	9	Store	9	Store	9
Sol waste	Compress	9	Compress	9	Compress	9
Spares mass per yr	1.358		1.989		4.32	
Dev cost, $M	153.52		153.97		155.65	
Unit/Spare cost, $M	57.08		57.28		58.00	
Transport cost, $M	820.36		778.08		734.24	

Figure 34. Interesting EVA suit architectures.

The abbreviation SAVac is for Solid Amine Vacuum desorption, meaning the pressure-swing bed that requires little power and has low mass, but loses water. Essentially, an open-loop, a solid amine, and a metal oxide system architecture may be of interest.

Sensitivity analysis: Water-save for Solid Amine Vacuum desorption

The SAVac system and the 2-bed molecular sieve may be able to lose less water if a condensing heat exchanger can be installed to remove humidity from the air before it reaches the amine or carbon sieve bed. A CHX designed for the Columbus module on ISS has displayed a measured 0% water carryover during operation; that is, all water is removed from the airstream (46). This indicates that full water recovery can probably be obtained, meaning that only dry air need be sent to the amine or carbon sieve bed, which will prevent loss of water due to venting.

Two new architectures, one using a 2BMS and one using SAVac, both with a water-saving CHX, are constructed and compared to the old 2BMS and SAVac architectures. A chart comparing the four architectures appears in Figure 35.

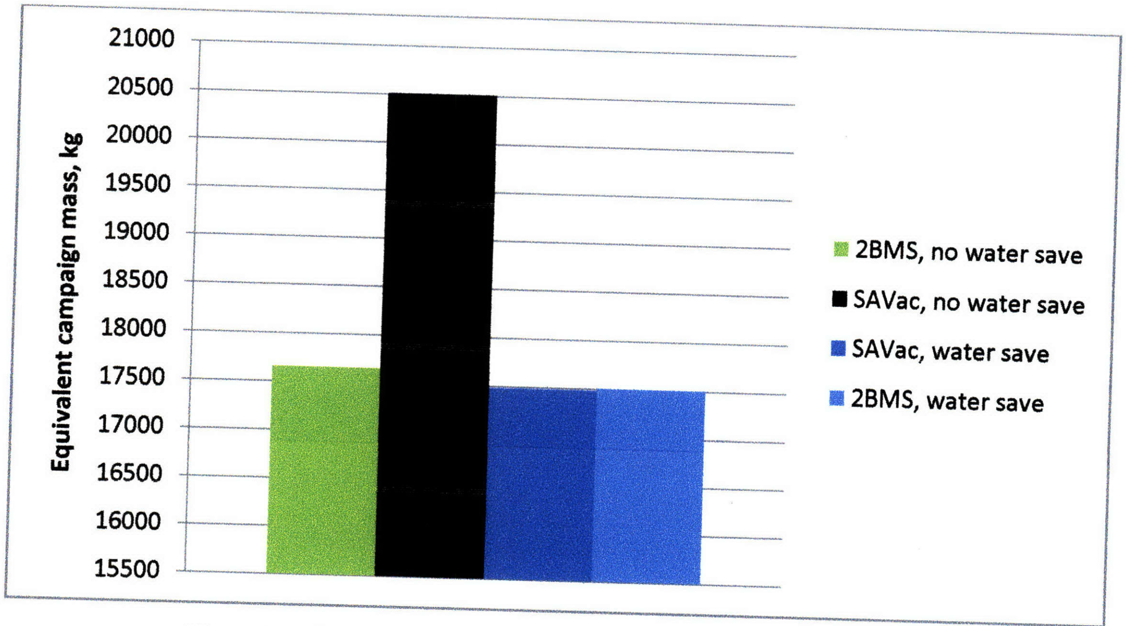

Figure 35. Effects of water save on 2BMS and SAVac architectures.

Note that the water save has a significant effect on the SAVac architecture, making it much more competitive. The 2BMS, however, does not see significant change in its equivalent campaign mass, and is therefore not picked back up. The SAVac architecture marked as interesting is, however, replaced with its water-saving counterpart.

Architecture	EVA 1	
Campaign mass	17484	
Equip mass	24.61	*TRL*
O2 prov	HP	9
CO2 Rem	SAVac	6
CO2 Redux	None	
N2 prov	X	
Temp	Sublimator	9
Hum	SAVac	
TCC	Charcoal	9
H2O prov	Stored	9
Liq waste	Store	9
Sol waste	Compress	9
Spares mass per yr	2.461	
Dev cost, $M	154.31	
Unit/Spare cost, $M	57.43	
Transport cost, $M	699.36	

Figure 36. Replacement water-saving SAVac ECLS system architecture.

Furthermore, the SAVac architecture with a water save edges out the highly-consumable architecture which relies on lithium hydroxide to remove carbon dioxide from the atmosphere, and as such this architecture is eliminated.

In summary, the top two interesting architectures for EVA suits include one using metal oxide and one using a solid amine vacuum desorption bed. A water-saving system should be used with the solid amine, and the use of consumable silica gel should be avoided.

3.7 Transfer Vehicle Architecture Downselection

The Transfer Vehicle model generated 440 architectures. A plot of these, sorted by equivalent campaign mass, appears in Figure 37.

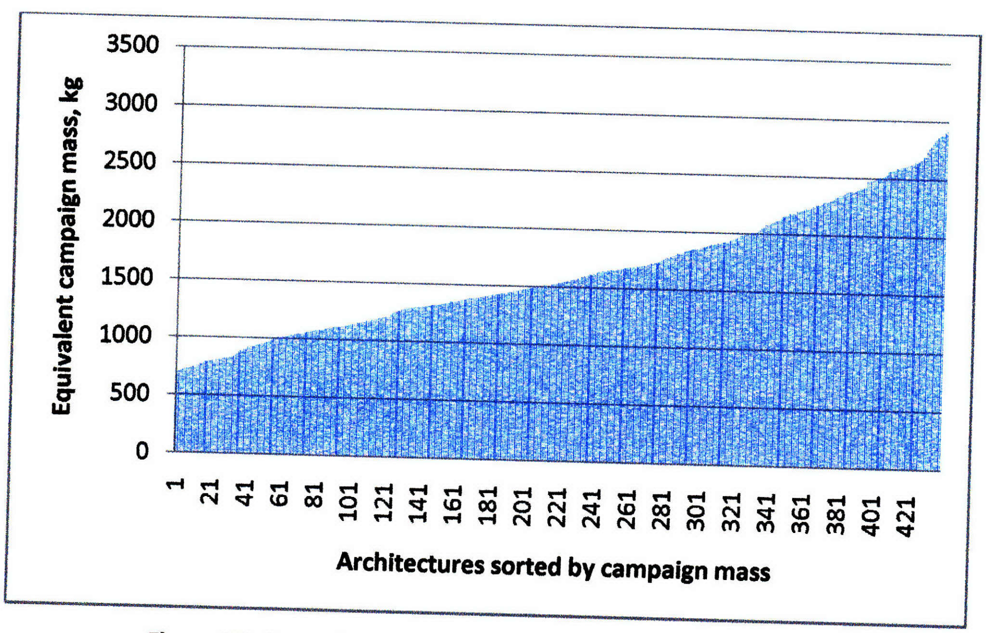

Figure 37. Campaign masses for Transfer Vehicle OPN model.

Note that significant variance exists in the campaign masses.

Sorting the architectures by build cost (development cost plus unit cost) cost gives the plot seen in Figure 38.

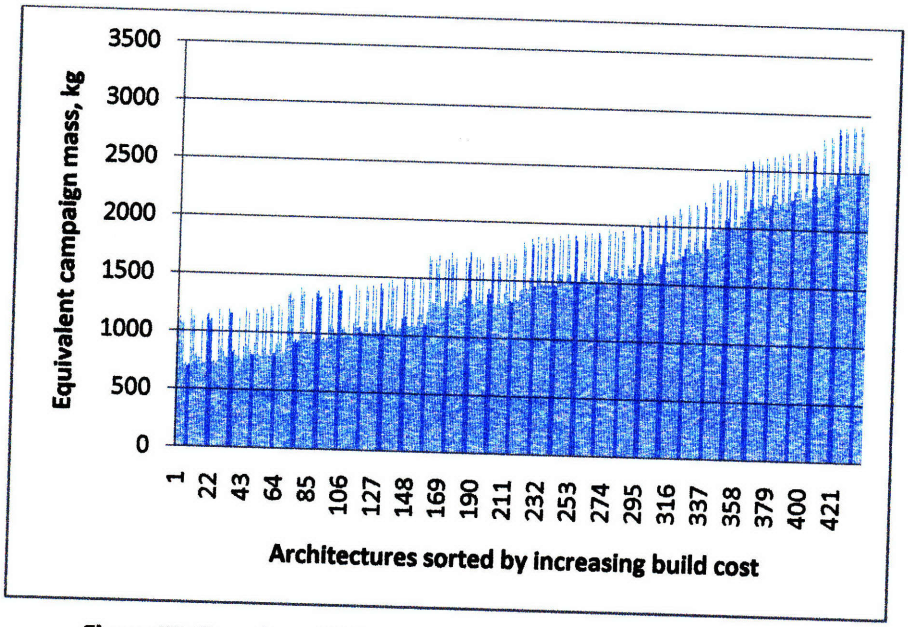

Figure 38. Transfer vehicle campaign masses sorted by build cost.

Figure 38 shows campaign masses going up and down as a function of development cost, but with an aggregate upward trend. The build cost by itself appears in Figure 39.

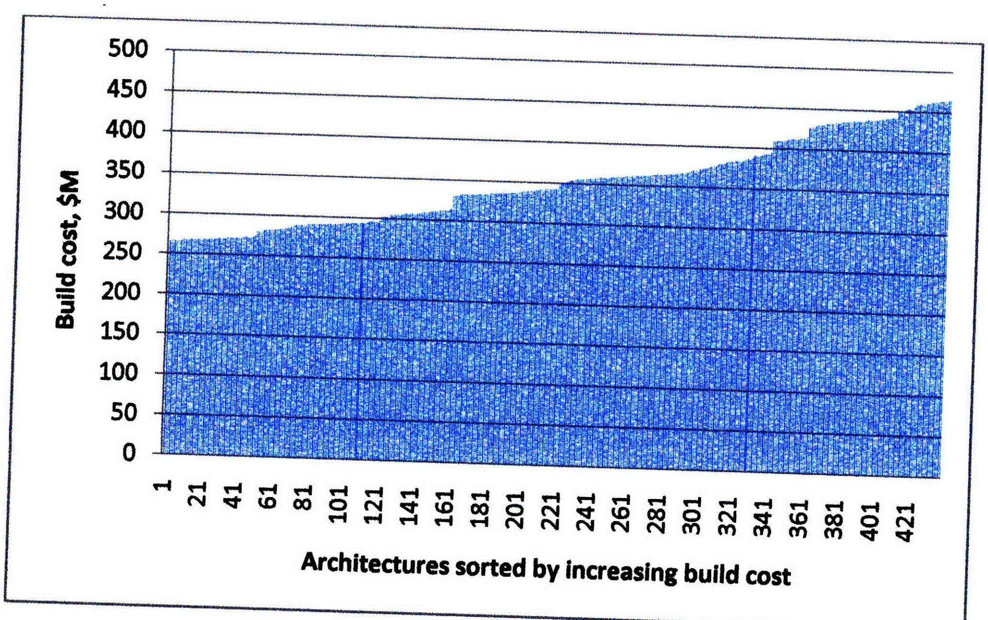

Figure 39. Build costs for transfer vehicle architectures.

This indicates that build cost is worth investigating, as it varies by nearly a factor of two over the design space.

Build cost and transport costs together appear in Figure 40.

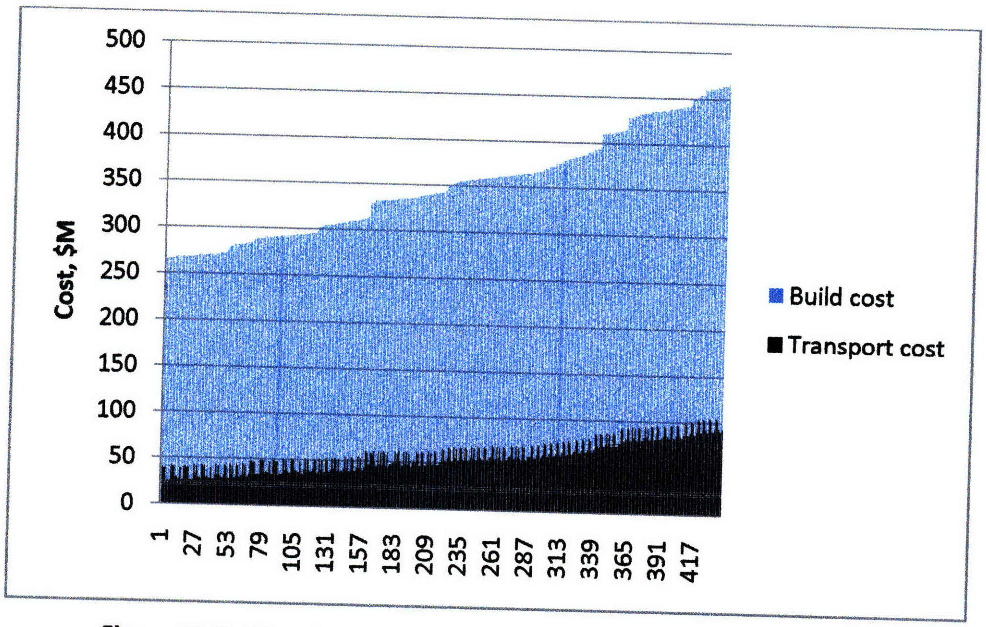

Figure 40. Build and transport costs for transfer vehicle architectures.

This indicates that build costs are the dominant factor in costs for a transfer vehicle. In this case, limiting the build costs will help greatly in limiting the total lifecycle costs.

The next step is to apply a TRL filter. A TRL filter is applied by summing the number of technology options below 6 in an architecture. Possible contributing technology options to a low TRL are the ACRS, Bosch, EDC, electrodialysis, Reverse Osmosis, and an active TCC system. A lower sum for these items is a more-mature system architecture (it is also less risky in terms of the potential for development costs to inflate or schedule to stretch).

After applying the filter and sorting the architectures by the number of items below TRL 6 that they contain, the plot in Figure 41 results.

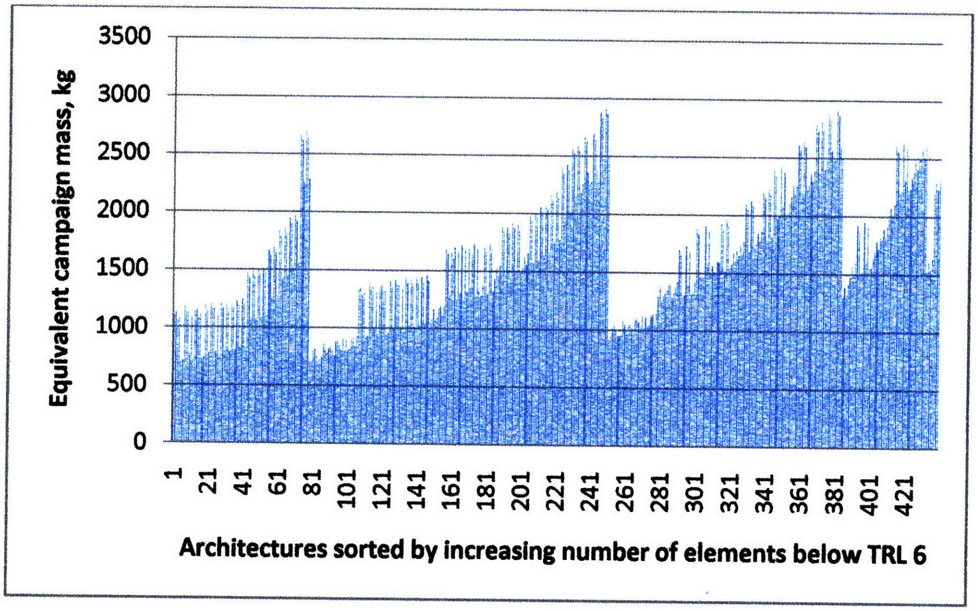

Figure 41. Results of TRL risk level ranking for Transfer Vehicle architectures.

Notably, as TRL risk level rises (to the right on the plot above), several cycles appear. Clearly the most interesting architectures will be those on the low end of the first cycle in the TRL filter plot.

All the architectures above the first cycle were pruned, and then the remainder were sorted by build cost. The equivalent campaign masses of these are seen in Figure 42.

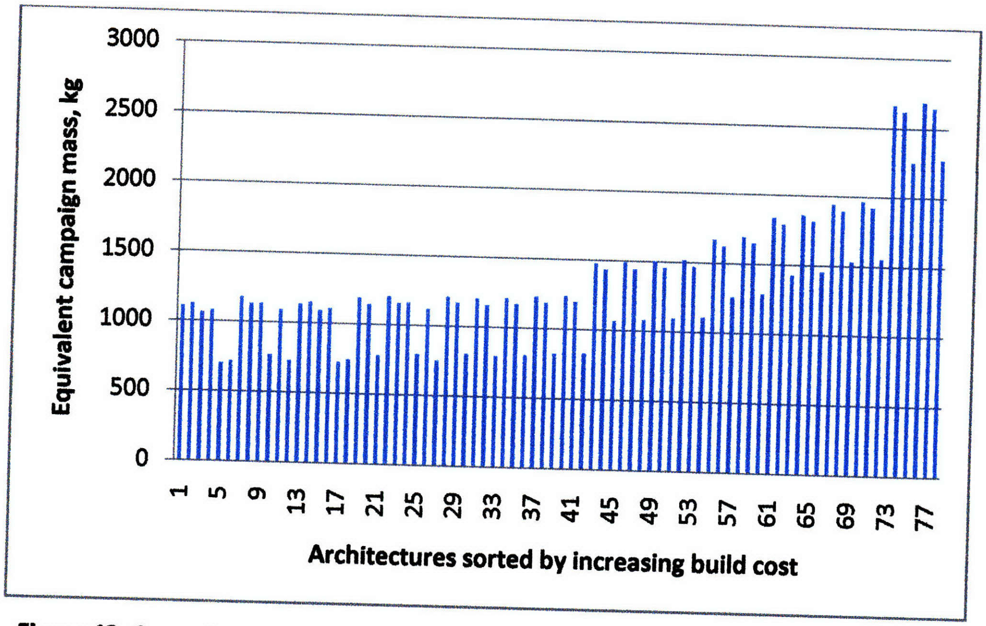

Figure 42. Campaign masses, sorted by build costs, for transfer vehicle architectures.

There is a knee in the curve after about 40 architectures, confirmed below by the plot of just build costs, which shows in Figure 43 that build costs have a brief rise near 45 architectures, which echoes Figure 42.

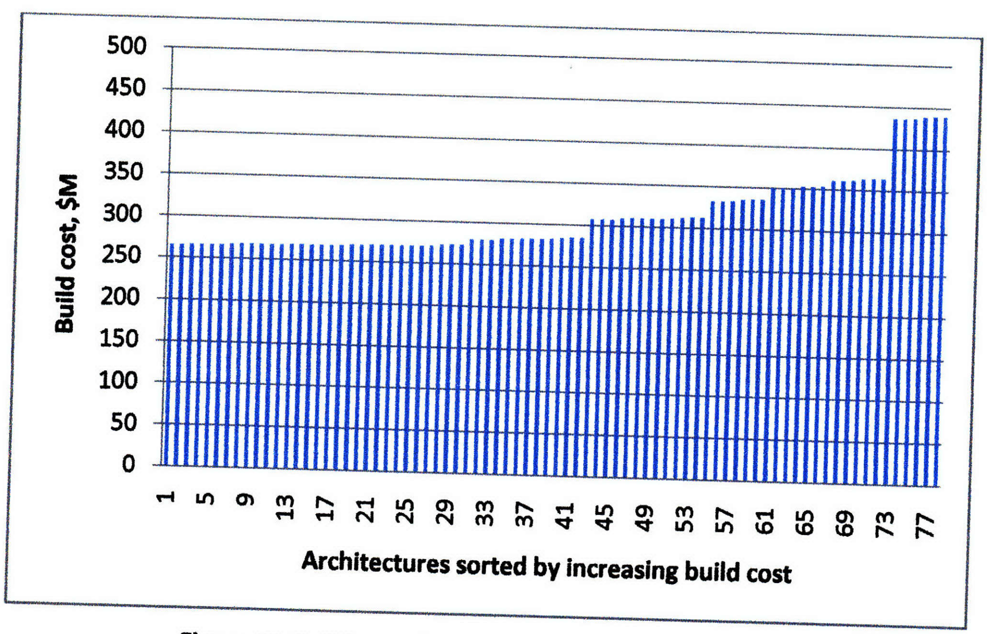

Figure 43. Build costs for transfer vehicle architectures.

Thus the most interesting architectures fall below about Architecture #45, as numbered in Figure 43. Limiting the design space to just these, it can be seen in Figure 44 that campaign mass continues to occur in cycles when plotted against rising build costs.

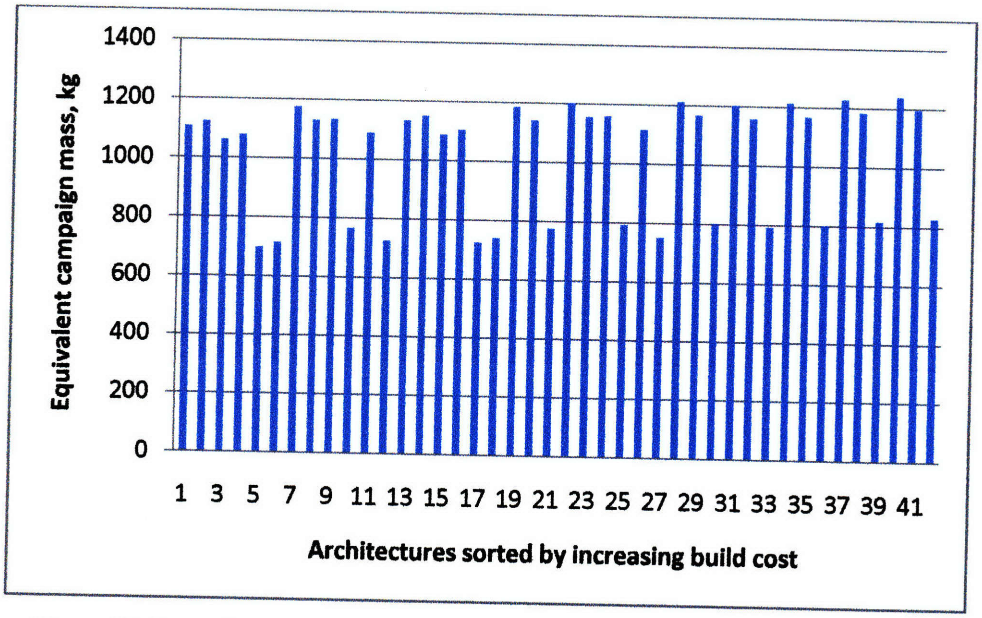

Figure 44. Campaign mass, sorted by build cost, for transfer vehicle architectures.

The build costs, sorted by build cost, are plotted in Figure 45.

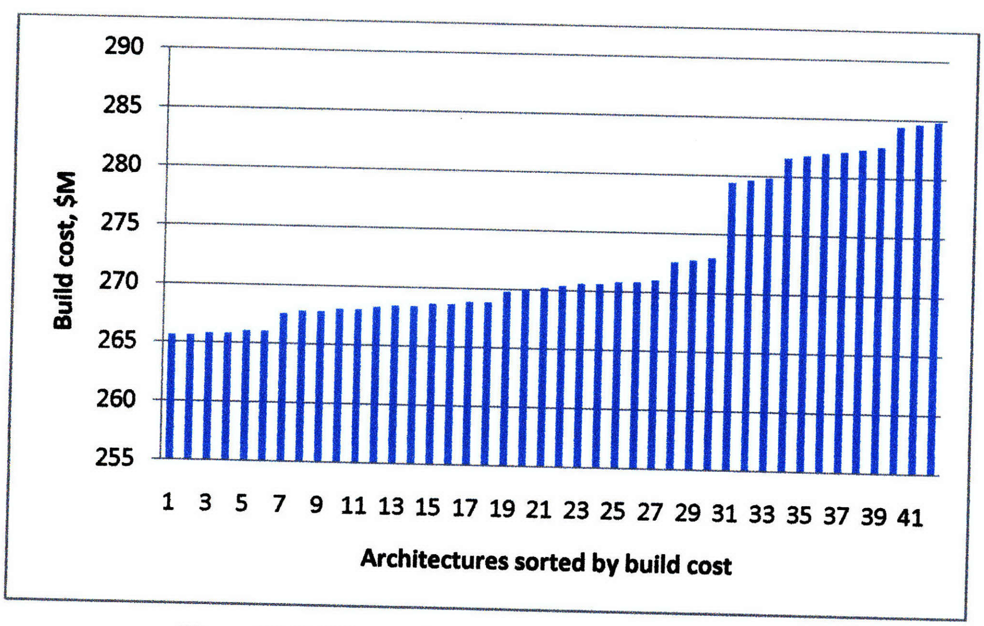

Figure 45. Build costs for transfer vehicle architectures.

There is about a 10% variation in build cost, while as build costs increase, the architectures occur in families of alternating high and low campaign mass architectures. After removing the high-campaign-mass architectures (those which break a cap of 1000 kg) from each family, the remaining architectures are plotted in Figure 46.

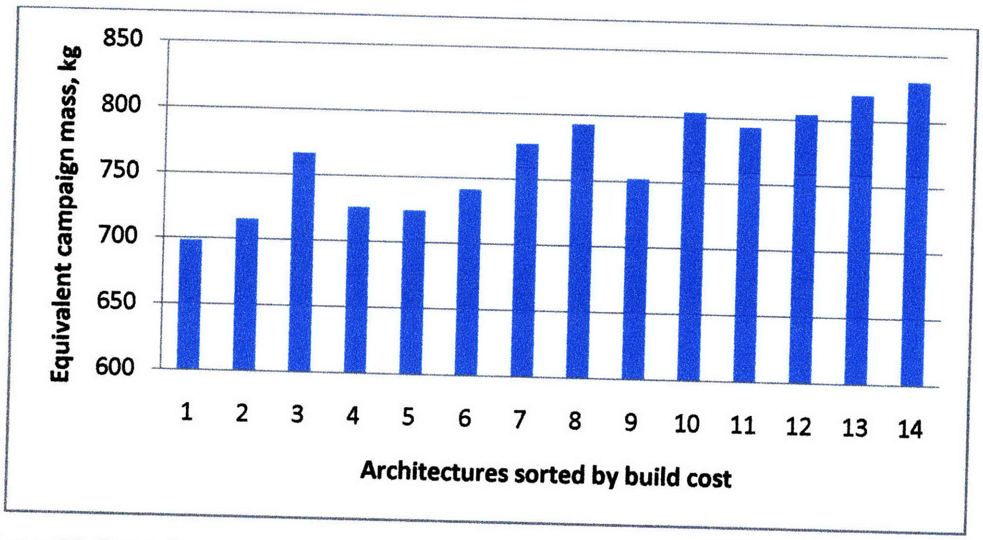

Figure 46. Campaign masses, sorted by build cost, for pruned transfer vehicle architectures.

The family effect is still evident, but the difference between families is much smaller. Examination shows that the architectures which stick out from their familial predecessors (#'s 3, 7, 8, and 10) are those which include the pressure-swing solid amine bed. The lowest of these is carried forward as an interesting architecture.

The four architectures with the highest total campaign masses (#'s 11-14) include 2-bed (carbon) molecular sieves. The lowest of these is carried forward as well.

Two of the remaining architectures (#'s 1 and 5) include superoxides for carbon dioxide removal and oxygen generation. Although this technology has dual-use capabilities that make it potentially attractive, especially for short-duration use cases, it is not as commonly used in space environments as other consumable options (such as tanks of oxygen and LiOH canisters), and so these two architectures are eliminated.

The remaining four architectures are extremely similar, their differences consisting only of whether they include cryogenic or high-pressure storage for oxygen and nitrogen. The dominant option (slightly, but still dominant) is high-pressure storage in both cases. This architecture becomes the third and last interesting architecture.

The interesting architectures appear in Figure 47.

Architecture	Xfer 1	TRL	Xfer 2	TRL	Xfer 3	TRL
Campaign mass	715.12		766.84		793.56	
Equip mass	552.04		571.22		686.27	
O2 prov	HP	9	HP	9	HP	9
CO2 Rem	LiOH	9	SAVac	6	2BMS	6
CO2 Redux	None		None		None	
N2 prov	HP	9	HP	9	HP	9
Temp	CHX	9	CHX	9	CHX	9
Hum	CHX	9	SAVac	6	CHX	9
TCC	Charcoal	9	Charcoal	9	Charcoal	9
H2O prov	MF	6	MF	6	MF	6
Liq waste	Store	9	Store	9	Store	9
Sol waste	Compress	9	Compress	9	Compress	9
Spares mass per yr	55.204		57.122		68.627	
Dev cost, $M	192.29		193.67		201.95	
Unit/Spare cost, $M	73.78		74.37		77.94	
Transport cost, $M	28.6048		30.6736		31.7424	

Figure 47. Interesting ECLS system architectures for Transfer Vehicle.

Of these three interesting architectures, however, the difference in campaign mass is barely 10% between any two architectures, and the difference in development cost between any two architectures is approximately half of that. Therefore there is little to recommend one of these architectures over any other for use in the development of interesting portfolios (to be carried out in the next chapter), but one point can yet be noted. Because these three architectures are nearly equivalent, the best option to carry forward for commonality analysis is the architecture which includes the SAVac unit.

The reasoning for this is based on the design of the CEV. Although the CEV is not yet completely designed, parts of its system architecture are known, and it will also use the SAVac system for carbon dioxide removal and humidity control. Because the two instantiations which will operate most closely in concert are the CEV and the Transfer Vehicle, in the sense that the two will remain docked during the entire trip to the Moon and then from the Moon back to Earth, commonality makes a great deal of sense in this case. The use of the same system on the Transfer Vehicle as on the CEV may permit on-orbit repairs in the case of minor failures, which would be sensible from the logistics point of view, as it is expected that crew (which travels in the CEV and Transfer Vehicle) will not be co-located with the great majority of supplies and spares (which travel on cargo landers) until they reach the surface of the Moon. Having near-duplicate systems for carbon dioxide removal on the CEV and Transfer Vehicle may allow for a ready source of backup parts, as well as consolidate on-orbit sparing requirements. Finally, such a design choice would allow for the SAVac unit already in use on the CEV to be simply emplaced in the Transfer Vehicle with minimal need for extra design effort, as the CEV and Transfer Vehicle both serve four crew, undergo similar time scales for activity and dormancy, and have closely related operational profile. High levels of commonality can be enabled here by selecting a common technology choice, and there is nothing to argue against such a selection. Therefore, the final interesting architecture to be carried forward for use in constructing interesting portfolios in the next chapter is the SAVac architecture.

Sensitivity analysis: water save for solid amine bed

Because the vacuum desorbed (pressure-swing) solid amine bed is again an interesting architecture, a sensitivity analysis, wherein the solid amine system is augmented with a water-saving CHX to reduce the amount of water lost, is again carried out.

The results appear in Figure 48.

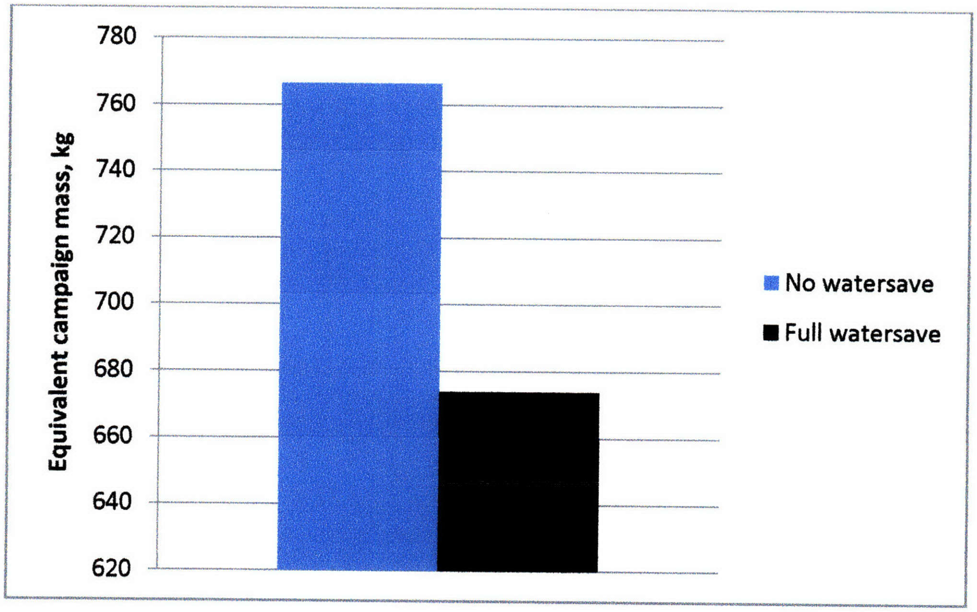

Figure 48. Campaign mass comparison for Transfer Vehicle water save.

Note that, although the water save reduces consumable requirements, it very slightly increases power requirements and sparing mass requirements, and in the end affects the total campaign mass for the transfer vehicle by only approximately 10%. When viewed in the context of the overall campaign, for which the total campaign mass is on the order of several tens or hundreds of metric tons, this is not a significant savings. Furthermore, integrating the water-saving system requires a slight increase in the complexity of the system, as well as slight increases in development cost and spares mass. Therefore, this enhanced technology option is actually no more an attractive option than is the solid amine bed by itself. Therefore the solid amine bed is left to operate without a water saving device.

3.8 Pressurized Rover Architecture Downselection

The Pressurized Rover OPN model generated 222 architectures. A plot of the campaign masses appears in Figure 49.

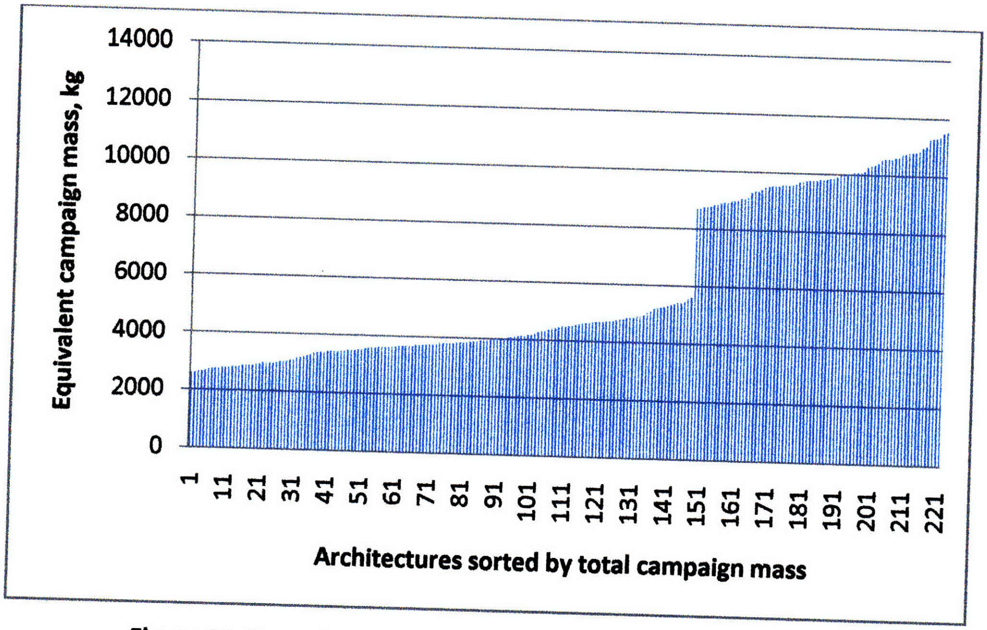

Figure 49. Campaign masses for Pressurized Rover instantiation.

A plot of the architectures' campaign masses arranged in order of ascending build cost is seen in Figure 50.

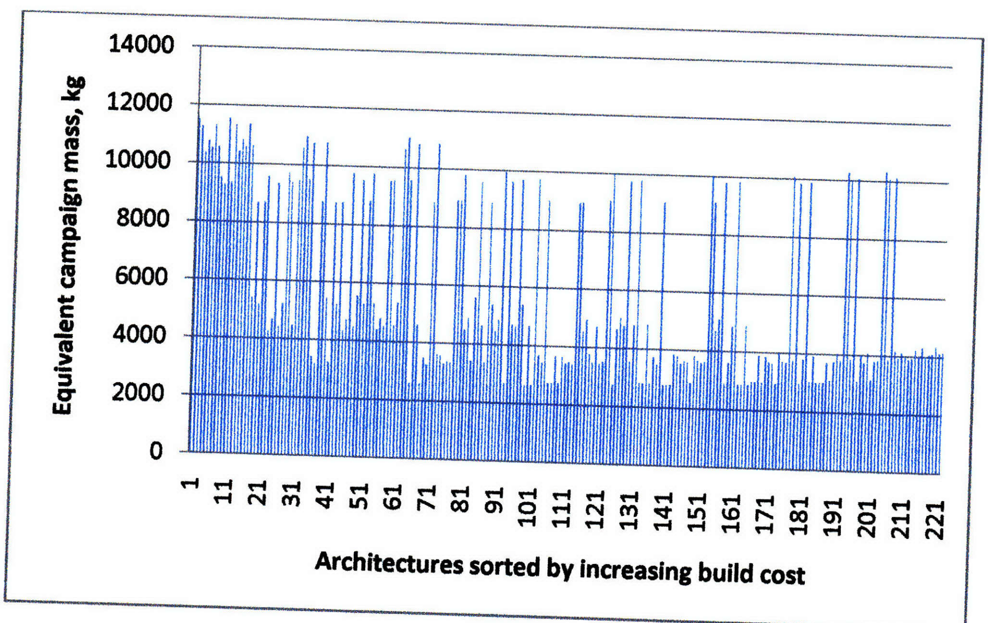

Figure 50. Campaign masses for Pressurized Rover instantiation, sorted by build cost.

Obviously, some low-mass architectures are mixed in with high-mass architectures. To minimize the development risk, the architectures are plotted against a TRL risk, which measures the number of the following items (all below TRL 6) which an architecture contains: ACRS, Bosch, EDC, Electrodialysis, Ice heat sink, Water heat sink, Active TCC system, Incinerator, TIMES, VAPCAR. The result appears in Figure 51.

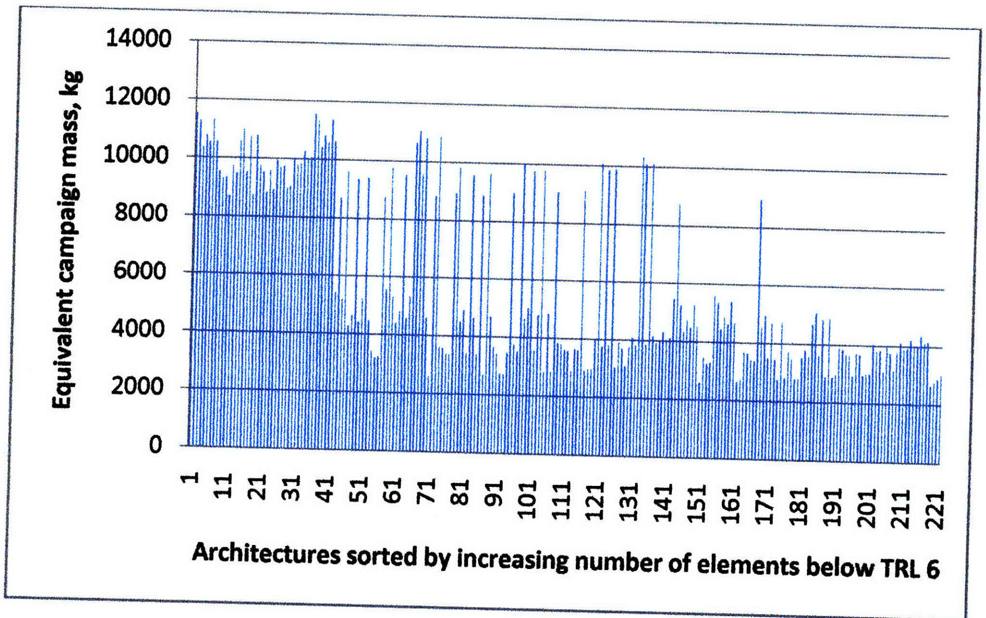

Figure 51. Campaign masses for Pressurized Rover instantiation, sorted by TRL risk level.

The risk levels and the number of architectures which fall at or below them include 35 architectures with zero risky technology options, 142 architectures with one or fewer ricky technology options, 218 architectures with two or fewer risky technology options, and 222 architectures with three or fewer risky technology options.

Limiting the number of risky items permitted to one in order to minimize the number of potential development bottlenecks and plotting the campaign masses (sorted by campaign masses) results in the plot seen in Figure 52.

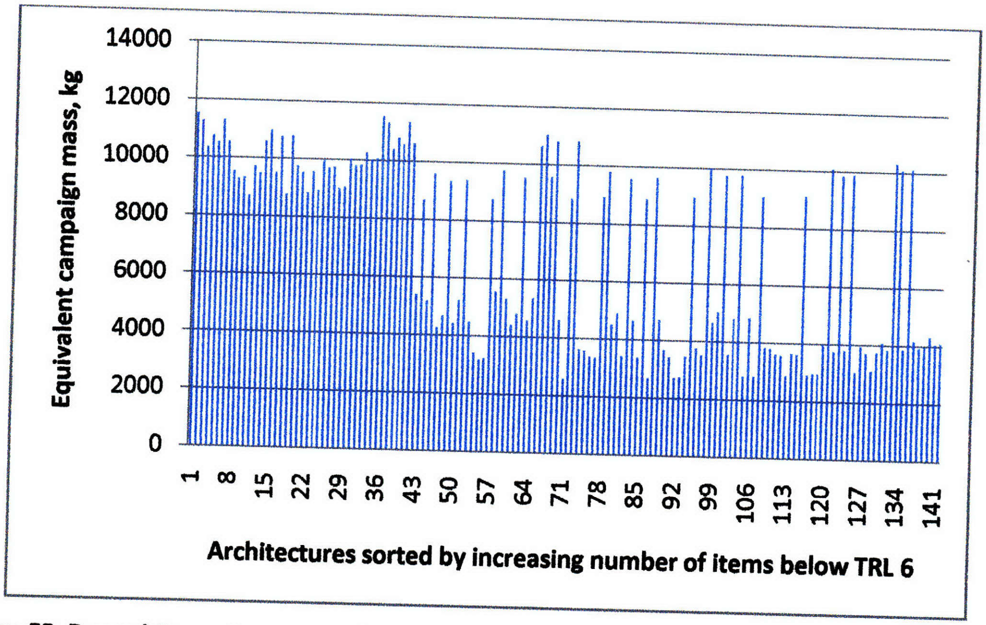

Figure 52. Pruned Campaign masses for Pressurized Rover instantiation, sorted by TRL risk level.

For a small pressurized rover, which will likely run on batteries, power is likely to be a critical issue. Rover traverses will last 168 hours, and if it is assumed that very good batteries have a capacity of 200 W-h/kg, then about 1.2 W are generated for every kilogram of batteries carried. Assuming that the mass of batteries that can be dedicated to the ECLS system is limited to 150 kg at most, we must then limit power to 180 W. Note that this is a conservative estimate of the amount of power that will be available to the ECLSS if only batteries can be used.

Figure 53 shows the campaign masses, sorted by power requirement, which fall below the 180 W cap.

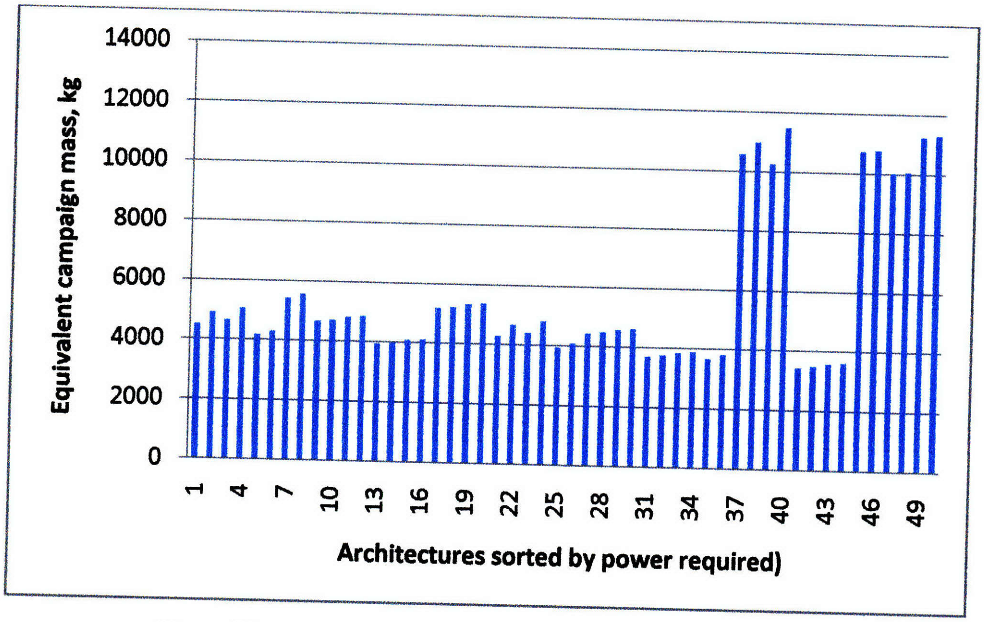

Figure 53. Campaign masses sorted by power requirement.

Examination of the design space reveals that all of the architectures which use metal oxide cluster toward higher design costs, but this may still be an attractive option, because metal oxide allows for the reduction of all carbon dioxide expelled over the course of a traverse, so the architecture which uses metal oxide and has the lowest campaign mass is carried forward, while the others are eliminated.

The two spikes in campaign mass seen in Figure 53 are determined upon inspection to result from architectures which use sublimators. Although these campaign masses are dominated by other technology options, the sublimator is a reliable and mature technology option, and as such the architecture which includes a sublimator and has the lowest campaign mass is carried forward, while the others are eliminated.

Some of the remaining architectures rely on chemicals (potassium superoxides) for carbon dioxide removal and oxygen provision. These can be especially problematic over long durations, and are not as space-tested a technology as other consumables (bottled oxygen and LiOH, for instance), and so they are also eliminated.

Architectures which rely on cryogenic storage of oxygen are interspersed with those that rely on high-pressure storage. As high-pressure storage is a more commonly-used technology option in the ECLS systems of crewed vehicles, and as neither conclusively dominates the other, the more mature option (high-pressure storage) is carried over and the other is eliminated.

Approximately half of the remaining architectures include the use of silica gel. Notably, all of these architectures have higher mobile (on-rover) masses than their counterpart architectures which rely on a CHX. Figure 54 shows this, comparing the mobile masses of each architecture which includes a CHX to its counterpart which uses silica gel. Accordingly, all architectures which use silica gel are eliminated, to maintain the mobile mass on the rover at a reasonable level.

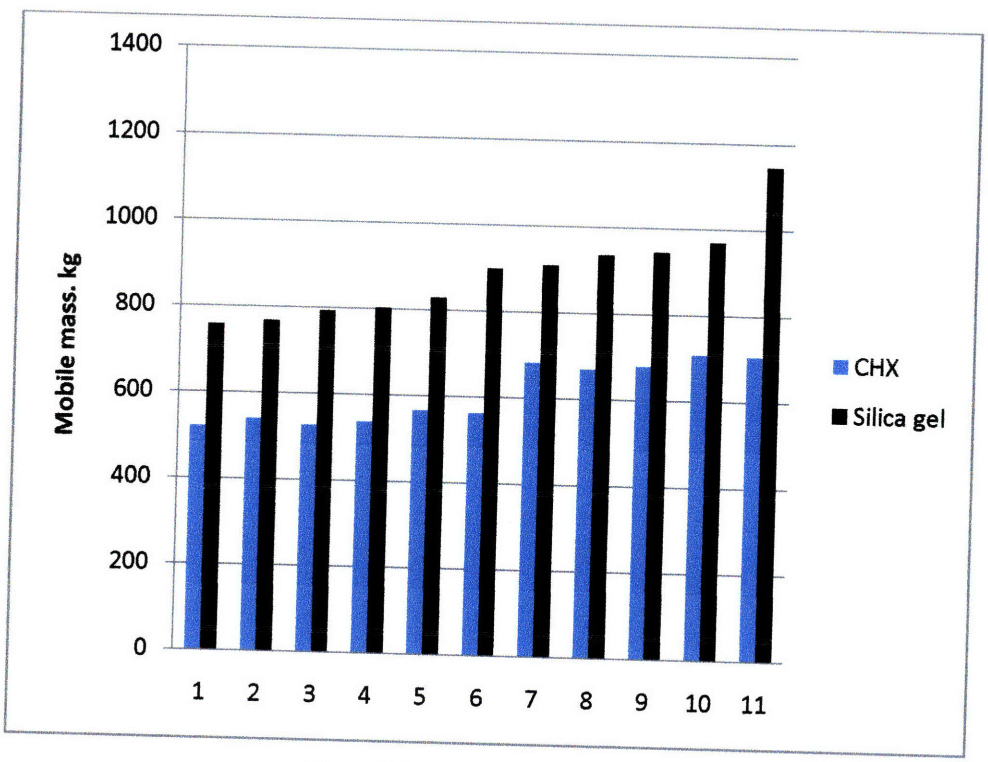

Figure 54. Mobile rover masses.

Of the remaining eleven architectures, about half use vacuum desorbed solid amine and the other half use lithium hydroxide canisters (one remaining architecture uses metal oxide). Of the architecture families using these three separate technology options, one each is retained and the others are eliminated.

The top three architectures appear in Figure 55.

Architecture	PR 1	TRL
Campaign mass	11517	
Equip mass	250.04	
O2 prov	HP	9
CO2 Rem	SAVac	6
CO2 Redux	None	
N2 prov	X	
Temp	Sublimator	9
Hum	SAVac	6
TCC	Charcoal	9
H2O prov	Stored	9
Liq waste	Store	9
Sol waste	Store	9
Spares mass per yr	25.004	
Dev cost, $M	170.54	
Unit/Spare cost, $M	64.41	
Transport cost, $M	414.612	

Architecture	PR 2	TRL
Campaign mass	4682	
Equip mass	445.42	
O2 prov	HP	9
CO2 Rem	LiOH	9
CO2 Redux	None	
N2 prov	X	
Temp	Ice	5
Hum	CHX	9
TCC	Charcoal	9
H2O prov	Stored	9
Liq waste	Store	9
Sol waste	Store	9
Spares mass per yr	44.542	
Dev cost, $M	184.61	
Unit/Spare cost, $M	70.47	
Transport cost, $M	168.552	

Architecture	PR 3	TRL
Campaign mass	3950	
Equip mass	1944.19	
O2 prov	HP	9
CO2 Rem	MetOx	9
CO2 Redux	Hab	7
N2 prov	X	
Temp	Ice	5
Hum	CHX	9
TCC	Charcoal	9
H2O prov	Stored	9
Liq waste	Store	9
Sol waste	Store	9
Spares mass per yr	194.419	
Dev cost, $M	292.52	
Unit/Spare cost, $M	116.93	
Transport cost, $M	142.2	

Figure 55. Interesting architectures for Pressurized Rover.

However, examination of the three interesting architectures shows that the equipment mass for the Metal Oxide architecture is nearly two tons, a factor of four higher than the other two. This is due to the necessity of carrying around large amounts of metal oxide canisters, and this amount of equipment mass is infeasible for a two-person rover, as a two-ton ECLS system is too large to fit on a small pressurized rover design. Thus, this architecture is eliminated, leaving only the first two Pressurized Rover architectures from Figure 55.

3.9 Final ECLS System Architectures

The ECLS system architectures described in the previous sections can be described more exactly. The following figures list the parameters for each of the seven most interesting architectures again.

Architecture	Hab 1	
Campaign mass	7278	
Equip mass	1673.13	*TRL*
O2 prov	Welec	9
CO2 Rem	SAWD	6
CO2 Redux	Sabat	7
N2 prov	HP	9
Temp	CHX	9
Hum	CHX	9
TCC	Charcoal	9
H2O prov	HS/cond	7
Liq waste	TIMES	5
Sol waste	Compress	9
Spares mass per yr	167.313	
Dev cost, $M	273.01	
Unit/Spare cost, $M	108.53	
Transport cost, $M	291.12	

Figure 56. Hab 1 architecture.

Architecture	Hab 2	
Campaign mass	10759	
Equip mass	1783.35	*TRL*
O2 prov	Welec	9
CO2 Rem	4BMS	9
CO2 Redux	Sabat	7
N2 prov	HP	9
Temp	CHX	9
Hum	CHX	9
TCC	Charcoal	9
H2O prov	HS/cond	7
Liq waste	Airevap	6
Sol waste	Compress	9
Spares mass per yr	178.335	
Dev cost, $M	280.94	
Unit/Spare cost, $M	111.94	
Transport cost, $M	430.36	

Figure 57. Hab 2 architecture.

Architecture	EVA 1	
Campaign mass	17484	
Equip mass	24.61	*TRL*
O2 prov	HP	9
CO2 Rem	SAVac	6
CO2 Redux	None	
N2 prov	X	
Temp	Sublimator	9
Hum	SAVac	
TCC	Charcoal	9
H2O prov	Stored	9
Liq waste	Store	9
Sol waste	Compress	9
Spares mass per yr	2.461	
Dev cost, $M	154.31	
Unit/Spare cost, $M	57.43	
Transport cost, $M	699.36	

Figure 58. EVA 1 architecture.

Architecture	EVA 2	
Campaign mass	18356	
Equip mass	43.2	*TRL*
O2 prov	HP	9
CO2 Rem	MetOx	8
CO2 Redux	Hab regen	6
N2 prov	X	
Temp	Sublimator	9
Hum	CHX	9
TCC	Charcoal	9
H2O prov	Stored	9
Liq waste	Store	9
Sol waste	Compress	9
Spares mass per yr	4.32	
Dev cost, $M	155.65	
Unit/Spare cost, $M	58.00	
Transport cost, $M	734.24	

Figure 59. EVA 2 architecture.

Architecture	Xfer 1	
Campaign mass	766.84	
Equip mass	571.22	
O2 prov	HP	9
CO2 Rem	SAVac	6
CO2 Redux	None	
N2 prov	HP	9
Temp	CHX	9
Hum	SAVac	6
TCC	Charcoal	9
H2O prov	MF	6
Liq waste	Store	9
Sol waste	Compress	9
Spares mass per yr	57.122	
Dev cost, $M	193.67	
Unit/Spare cost, $M	74.37	
Transport cost, $M	30.6736	

Figure 60. Transfer Vehicle 2 architecture.

Architecture	PR 1	
Campaign mass	11517	
Equip mass	250.04	*TRL*
O2 prov	HP	9
CO2 Rem	SAVac	6
CO2 Redux	None	
N2 prov	X	
Temp	Sublimator	9
Hum	SAVac	6
TCC	Charcoal	9
H2O prov	Stored	9
Liq waste	Store	9
Sol waste	Store	9
Spares mass per yr	25.004	
Dev cost, $M	170.54	
Unit/Spare cost, $M	64.41	
Transport cost, $M	414.612	

Figure 61. Pressurized Rover 1 architecture.

Architecture	PR 2	
Campaign mass	4682	
Equip mass	445.42	*TRL*
O2 prov	HP	9
CO2 Rem	LiOH	9
CO2 Redux	None	
N2 prov	X	
Temp	Ice	5
Hum	CHX	9
TCC	Charcoal	9
H2O prov	Stored	9
Liq waste	Store	9
Sol waste	Store	9
Spares mass per yr	44.542	
Dev cost, $M	184.61	
Unit/Spare cost, $M	70.47	
Transport cost, $M	168.552	

Figure 62. Pressurized Rover 2 architecture.

To increase the size of the design space which is investigated for commonality opportunities, and to provide a reference point to actual exploration architectures, the Crew Exploration Vehicle (CEV) is included as an ECLS system architecture. See (47) for details on the ECLS system architecture as currently envisioned for the CEV.

The equivalent campaign mass for the CEV is estimated by looking up the CEV's ECLS system architecture in the results generated by the Transfer Vehicle instantiation OPN model. The campaign mass is adjusted to account for a use duration of 18 days, as described in (48), rather than the duration of six days used for other transfer vehicles.

Architecture	CEV	
Campaign mass	1177	
Equip mass	567.03	
O2 prov	Welec	9
CO2 Rem	SAVac	6
CO2 Redux	None	
N2 prov	HP	9
Temp	CHX	9
Hum	SAVac	6
TCC	Charcoal	9
H2O prov	Stored	6
Liq waste	Store	9
Sol waste	Compact	9
Spares mass per yr	56.703	
Dev cost, $M	193.37	
Unit/Spare cost, $M	74.24	
Transport cost, $M	47.08	

Figure 63. CEV architecture.

CHAPTER 4. Commonality Analysis

4.1 Identification of Commonality Opportunities

4.1.1 Defining Commonality

Now that a series of architectures have been enumerated for ECLS systems, and that a small handful of interesting architectures for these ECLS systems, sorted into four types of instantiations, have been selected, we must determine how to assess commonality between these architectures. The first concept to define is that of a portfolio of complex systems.

A portfolio of complex systems is a group of complex systems which often works together to serve a purpose or complete a mission, but may or may not always include the same subsets of complex systems. An example of a portfolio of complex systems is a military mounted unit. The unit's main mission is to engage enemy units, and to this end it may include infantry fighting vehicles, main battle tanks, and repair or resupply trucks. An infantry fighting vehicle is a complex system in itself, as is a main battle tank, and as is a supply truck. The portfolio may include various combinations of these complex systems, and may under some circumstances not include some (as when a short raid precludes bringing along supply trucks, or when urban terrain makes the use of large main battle tanks counterindicated).

The portfolio of complex systems with which this thesis is concerned is that which includes all the complex systems needed to conduct exploration activities on the surface of a planetary body, such as the Moon or Mars. The primary subset of complex systems (referred to as instantiations to avoid confusion) included in such a portfolio covers four items: habitats, both for transit and on the surface; extra-vehicular activity suits; pressurized rovers; and transfer vehicles, which carry the crew from the surface to orbit (or vice-versa) or on short interplanetary trips, such as from the Earth to the Moon. Some surface-exploration portfolios may include two separate habitats, some may include only one. Some portfolios may even include no pressurized rovers, but the basic subset of instantiations from which a portfolio is built is the same.

Although the complex systems that are used as instantiations here include a number of smaller complex systems in themselves, these systems are here simplified down to the level of an ECLSS and blackboxes. This allows for analysis of the commonality between the ECLS systems – such systems are always grouped together in a portfolio, as are assorted other complex systems, including communications systems, structural systems, and even propulsion and power systems, but the elements of commonality between ECLS systems and other systems are not considered in detail here. At some level, many types of commonality may be expected – a standardized method of electrical wiring and gross manufacturing means that a pressurized rover and a habitat will have some level of part commonality, simply because both include an amount of wiring and structural members. However, suppression of the non-ECLS systems in the instantiations allows the commonality between elements of the ECLS systems to be examined more clearly. This is of interest because ECLS systems for surface exploration will require the detailed design and development of certain technologies (such as Sabatier reactors and active trace contaminant control systems) which involve significant investment of time and money, and early identification of the potential benefits and penalties of commonality among these expensive-to-develop systems may improve the lifecycle costs for the entire portfolio of complex surface exploration systems.

A report by the RAND corporation on commonality vocabulary (49) provides a useful background. The systems of interest for this thesis are ECLS systems, which occur in instantiations. These instantiations include more systems than just the ECLS system, but the other systems are suppressed for clarity. So each instantiation has one ECLS system, which has a certain architecture. The ECLS system on the instantiation is meant to be functional by itself, that is, it serves to support life without external interfaces (except perhaps to other suppressed systems on the instantiation, such as power and thermal control), and it has a series of functions which it delivers. Each function delivered by the ECLS system is accomplished via a particular technology option, which in the physical sense is a component of the system, and in the commonality sense is a design choice which may or may not be similar to other design choices made for ECLS systems on other instantiations. An instantiation has all major systems except the ECLS system suppressed, and the various technology options (e.g., the metal oxide canisters which remove carbon dioxide from the atmosphere, or the condensing heat exchangers that regulate cabin temperature and humidity) which deliver the key functions of the ECLS system are the components of this ECLS system. A portfolio of systems is a collection of instantiations that are all used together in the completion of some mission. Note that this maps closely onto the definition for "system" at a high hierarchical level provided in (49).

The definition of commonality is drawn in part from the commonality vocabulary report, specifically from the terminology recommended for application as "common" in (49). "Common" items are those which occur in one or more systems, and commonality as applied to ECLS systems for planetary surface exploration in this thesis means that technology options of the same type (e.g., LiOH canisters) are used to perform the same function (remove carbon dioxide from the atmosphere) for different instantiations (the LSAM transfer vehicle and the pressurized rover, for example). This circumstance indicates a condition of commonality between the two instantiations, which means that potentially fewer point design solutions must be produced, and that sparing requirements are potentially lowered, but also that consumable resupply requirements and overall portfolio mass are potentially increased. The trades between these costs define the benefits and penalties of commonality. It is best to think of the commonality approach here as defining ways in which the standardization of key elements of the ECLS systems may decrease overall lifetime costs of designing, manufacturing, and operating the system.

It is also worth noting that commonality at the level applied in this thesis is not the only level. Commonality at the design choice level enables reduction in design costs, but also helps to enable reductions in manufacturing costs, as well as commonality at lower levels. These lower levels may include lower levels of functionality, such as the standardization of components of ECLS systems, down to the level of common bolt sizes, common control elements, or common physical and structural interfaces. Commonality of design choices at the technology option level helps to enable these, in the sense that technology options which are common may be designed as common (or perhaps scalable or modular) ORUs, and this detailed design is made easier if the underlying technologies are similar.

An example of technology option commonality may be found in the carbon dioxide removal systems of the Apollo Command Module and Lunar Module. Both used lithium hydroxide systems (a technology option commonality), although the two systems were not standardized or interchangeable. The lack of detailed commonality meant that effort had to be expended and in-situ engineering applied to utilize the Command Module lithium hydroxide canisters in the Lunar Module's ECLS system, but the commonality at the level of technology option design choice enabled the effort in the first place. In a similar vein, common technology options for a portfolio of surface exploration instantiations will help to enable potential standardization of system elements, although the decision to fully standardize the elements or not must be made much later in the design process.

Many of the detailed decisions about commonality cannot be made until the design of the surface exploration portfolio has been matured further, but the early identification of such opportunities via the Commonality Analysis Methodology applied here will enable such decisions at later stages of the design process.

4.1.2 Applying Adapted Commonality Identification Tools

Once a set of interesting ECLS system architectures have been identified, it is necessary to examine them for commonality opportunities. Tools to this end have been developed in (2), and adapted versions of these tools are deployed here. The tools are designed to identify opportunities for commonality within a set of ECLS system architectures, which may or may not already display some commonality.

The first tool to be adapted and applied is the Commonality Sorter Matrix, a notional example of which is seen in Figure 64.

Function	Technology	Operational building blocks					
		Environment I		Environment II		Environment III	
		Active	Dormant	Active	Dormant	Active	Dormant
Function 1	Technology Option 1A						
	Technology Option 1B	1			1	1	1
	Technology Option 1C						
Function 2	Technology Option 2A						
	Technology Option 2B			1	1	1	1
	Technology Option 2C						
Function 3	Technology Option 3A						
	Technology Option 3B	1	1	1	1		1
	Technology Option 3C						

Figure 64. Notional Commonality Sorter Matrix.

This matrix lists the functions of an ECLS system, along with all possible technology options as subcategories under each function, in the left-most columns. To indicate the presence of a technology option in an ECLS system architecture, a "1" is placed in a box in the appropriate row of the matrix, beside the technology option which is used to deliver that function. A full ECLS system architecture will have at least ten technology options selected. The top-most rows of the matrix indicate another dimension of interest: operational environment. While the vertical dimension of the matrix captures the presence of a technology option, the horizontal dimension captures its operational profile. To indicate a certain technology option delivering a certain function, "1s" are placed in the appropriate row of the matrix, in columns defined by the appropriate environments and operational states. In this way, the matrix describes the working definition of commonality used in this thesis: the same technology option delivering the same function in the same operational environment is a point of commonality if it occurs on two or more different instantiations. More detailed examination of this working definition can be found in (2).

The operational environment axis is meant to capture three aspects: gravity, pressure, and activity/dormancy. To this end, five major states are listed, and each has a subcategory for active and a subcategory for dormant. The five states are launch/entry (which is assumed always to be pressurized), partial or full gravity while pressurized, partial or full gravity while unpressurized, microgravity while pressurized, and microgravity while unpressurized. The active substate indicates that the technology option must be operating at or near full capacity in that environment, while the dormant substate indicates that it must simply maintain minimal or no functionality in that state, but will be required to operate again later. The intent is to capture all the states which may affect design requirements on the various technology options. A Sabatier unit intended to operate in orbit may have different design requirements than a Sabatier unit intended to function on a planetary surface, but that does not mean some commonality cannot exist between the two units. Furthermore, dividing the operational environment up in this fashion assures that some technology options in some architectures may be contained completely within others. That is, a Sabatier unit intended to operate both on orbit and on a planetary surface will have design requirements at least as strict as either an orbit-only or surface-only unit. Therefore, the Commonality Sorter Matrix tool will show that an orbit-only design is contained within an orbit-and-surface design, and some commonality is possible between these two units. In practical terms, this commonality could take the form of a platform design, where a common basic ground Sabatier reactor system can be adapted for orbital use by the addition of a micro-gravity functionality module. The detailed method of implementation of commonality in the identified opportunity must wait until the detailed design phase to be described fully, but early identification of the opportunity can guide later design phases to paths that will allow for potential reduction of total lifecycle costs for the system and its associated portfolio of other exploration systems.

An example of the Commonality Sorter Matrix tool appears in Figure 65.

Functions	Technology options	Operational Environments									
		Launch/entry		Gravity, pressurized		Gravity, vacuum		Micro g, pressurized		Micro g, vacuum	
		Active	Dormant	Active	Dormant	Active	Dormant	Active	Dormant	Active	Dormant
Oxygen provision	Zr electrolysis										
	Water electrolysis										
	Cryostorage										
	High-P storage										
	Chemical compounds										
Carbom dioxide removal	2BMS										
	4BMS										
	SAWD										
	SAVac										
	EDC										
	Chemical compounds										
	LiOH										
	MetOx										
Carbon dioxide reduction	Sabatier										
	None										
	ACRS										
	Bosch										
	Zr electrolysis										
Nitrogen provision	Cryostorage										
	High-P storage										
	None										
Trace contaminant control	Activated charcoal										
	Active TCC system										
	SCWO										
Humidity control	CHX										
	SAVac										
	Silica gel										
Temperature control	CHX										
	Ice heat sink										
	Water heat sink										
	Sublimator										
Potable water provision	Stored water										
	HSWPA										
	Condensate										
	SCWO										
	Electrodialysis										
	RO										
	HSWPA and condensate										
	MF										
Liquid waste management	VCD										
	TIMES										
	Air evaporation										
	Store										
	VAPCAR										
	SCWO										
Solid waste management	Compact storage										
	Store										
	Incinerator										
	SCWO										

Figure 65. Commonality Sorter Matrix input.

Note that the dimensions of technology options' presence and operational environments are captured. The matrix pictured in Figure 65 is actually only one element of the Commonality Sorter Matrix tool. Each individual ECLS system architecture out of a portfolio to be examined for commonality opportunities is described in one of the input matrices shown in Figure 65. These input matrices are then overlaid to create a set of similar matrices which describe points where commonality may occur.

4.1.3 Environmental States for Different Instantiations

The Habitat instantiation operates primarily on the surface for lunar exploration missions; it need only survive launch and coast in a dormant state. It will remain dormant until touchdown on the lunar surface, at which point it will pressurize (probably using nitrogen tanks to build up pressure and then adding oxygen). Upon arrival of a crew, it will function throughout the duration of their mission (up to six months), after which it will sit dormant until another crew arrives, nominally six months later.

EVA suits will be stowed and inactive during launch phases, but will be activated, filled with consumables, checked, and donned for the first time from within a pressurized volume. They may also return to pressurized volumes from time to time for repairs, but for the most part will remain outside (crew members will likely enter and exit suits through suitlocks), and thus will be both dormant and active in unpressurized gravity-well environments. EVA suits may also be used for brief or contingency EVAs on orbit, and as such will need to be operable in micro-gravity environments as well.

The pressurized rover will be dormant through launch and coast, and will be activated and operated on the lunar surface, where it will both sit during traverse while crews perform EVA (thus running dormant in a pressurized environment) and in between traverses (running dormant in an unpressurized state).

The transfer vehicle, here understood to mean the LSAM, sits dormant during launch, and then operates after it is docked with the CEV and checked out. It continues to run while the crew travels in microgravity, and then lands on the lunar surface. It is closed down, causing it to sit dormant in vacuum conditions, until the crew returns and reactivates it either when the six-month mission ends or when a contingency arises, at which point it returns to active life and a pressurized state.

The Crew Exploration Vehicle (CEV), which is inserted into portfolios as a baseline and to allow investigation of commonality opportunities with legacy systems, operates actively during the launch and entry phases, during which it carries the crew, and must also run actively in a pressurized gravity well during checkout and launch preparation, when it sits on the launch pad. It operates both actively and dormantly during its long wait in lunar orbit while the crew conducts their mission on the lunar surface, before ascending in the LSAM (a transfer vehicle instantiation) and making rendezvous before returning to Earth.

The International Space Station (ISS), also present in portfolios as a legacy and baseline system, operates exclusively in a microgravity environment, as it is permanently on orbit above the Earth. It is also continually pressurized, as the only EVA excursions are via the main airlock or via the airlocks of visiting Shuttles. However, ISS components are tested on the ground, and generally can be assumed to operate successfully in full gravity as well as in partial gravity. Therefore the list of operational environments for the technology options that are a part of the ISS ECLS system includes gravity wells.

4.1.4 Output of Commonality Analysis Tools

The points for commonality are determined by comparing the percentage of operational environment similarity for any given technology option in one architecture to that in another architecture. If the percentage of similarity exceeds a predetermined threshold (set to 50% here), then an opportunity for commonality is determined to exist for that technology option delivering that function between those two architectures. In more physical terms, if one ECLS system architecture uses the same technology option to deliver a certain function in roughly half the same operational environments as another ECLS system architecture, then a potential point of commonality has been identified. An architecture which uses lithium hydroxide to remove carbon dioxide from the atmosphere while in orbit and on the surface will be a good candidate for commonality with an architecture that uses lithium hydroxide to remove carbon dioxide from the atmosphere while in orbit and during launch.

This scheme makes the commonality analysis instantiation-neutral – that is, overlap matrices are generated for nearly every pair of architectures, and in this way options for commonality between different instantiations can be identified.

The end product of the application of the adapted Commonality Sorter Matrix tool is a full overlap matrix, which shows all the potential points of commonality. For this application of the methodology, the adapted Commonality Sorter Matrix tool was operated on a set of six ECLS system architectures – four of the architectures described above (one from each instantiation) in Figure 56 to Figure 62 and two baseline architectures, the Crew Exploration Vehicle (CEV) and the International Space Station (ISS). Figure 66 shows an example of the full overlap matrix. Note that the matrix is symmetric, and information in the lower diagonal has been suppressed for clarity. Points where commonality opportunities have been identified are also highlighted in the upper diagonal, to aid in visibility.

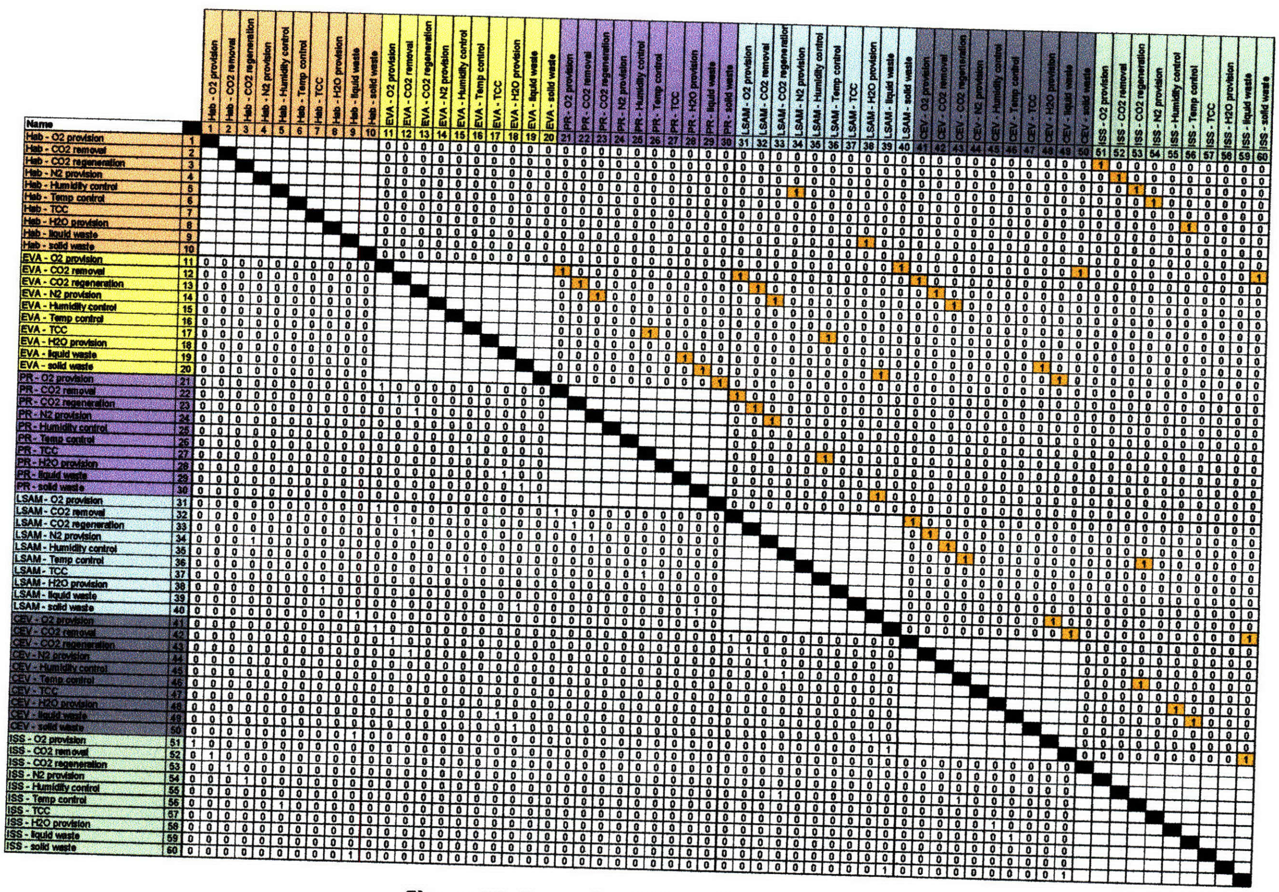

Figure 66. Exemplar full overlap matrix.

Once the full overlap matrix has been generated, a second tool can be applied to aid in the development of commonality-containing portfolios of surface exploration systems. This tool is a Design Structure Matrix (DSM), originally developed by Tyson Browning, Qi Dong, Carlos I. G.

Fernandez, and Ali Yassine of MIT, which takes the full overlap matrix in Figure 66 and runs a partitioning algorithm on it. The end result is as seen in Figure 67, with clustering indicating the technology options amenable to commonality.

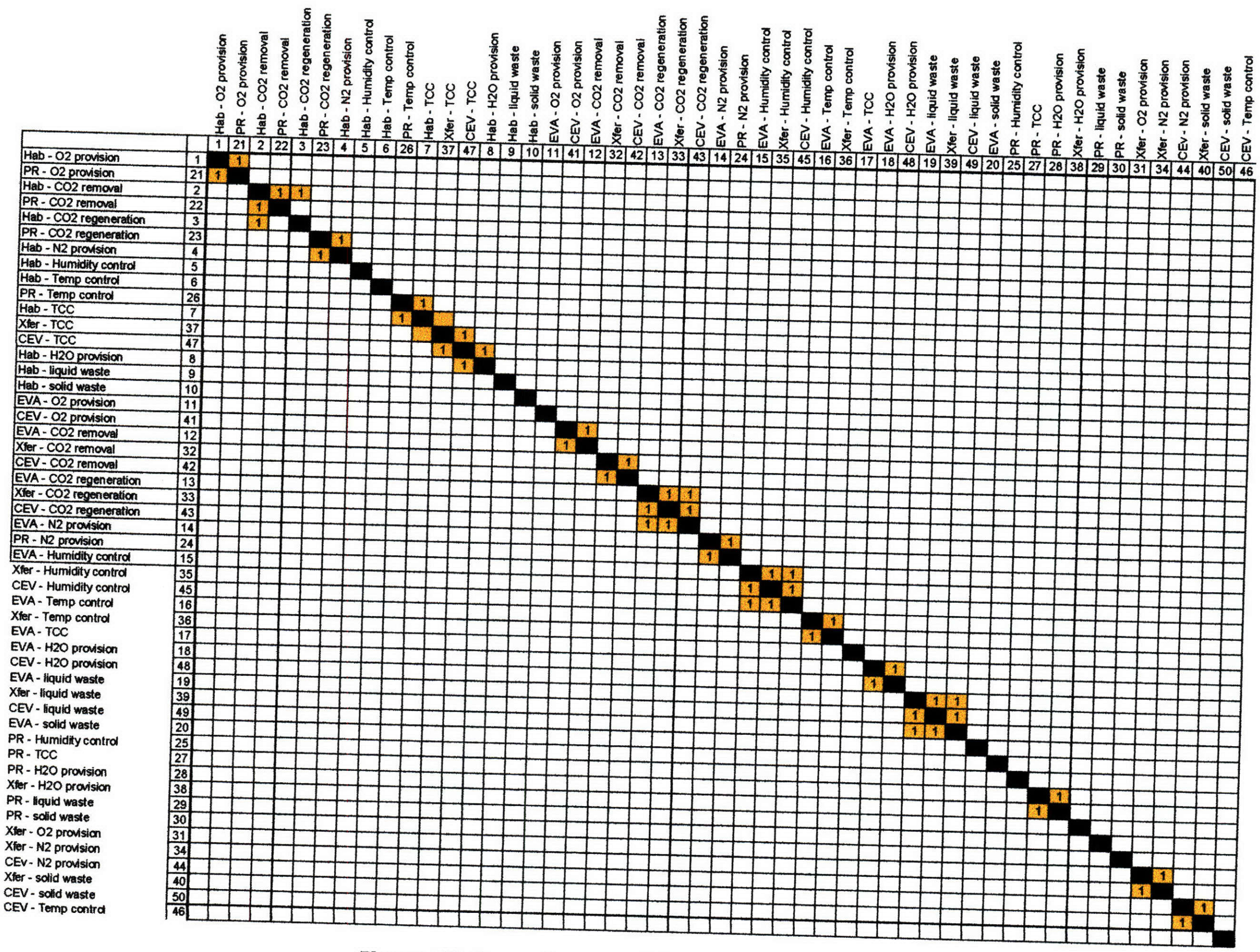

Figure 67. Exemplar sorted full overlap matrix.

The matrix in Figure 67 is the result of a clustering algorithm applied to the matrix seen in Figure 66. Points of overlap are again highlighted in orange to call attention to commonality opportunities. Note that the ISS is not included in Figure 67. This reflects the fact that, while the CEV has a set ECLS system architecture, it has not been designed in detail yet, and may be amenable to detailed commonality with the other instantiations in the portfolio, the ECLS system on the ISS has been designed and will be built before the design of the lunar surface exploration portfolio is complete. Although commonality with ISS is possible, as shown by Figure 66, careful development of portfolio commonality with ISS at the detailed design level may not be, athough it is still possible with the CEV. Therefore it is excluded from the sorted full overlap matrix, which is intended to be a guide for designers in selecting the instantiations from which to draw requirements when designing for commonality.

4.2 Development of Interesting Portfolios

Once a series of interesting architectures have been selected, and opportunities for commonality have been identified from among these architectures, portfolios for surface exploration can be constructed. Instantiations for these exploration portfolios are again described via the suppression of all systems other than ECLS systems, for simplicity. A portfolio is a set of complex systems that work together to perform some mission, so a surface exploration portfolio will naturally consist of some number of instantiations working together to explore the surface of a planetary body. The seven interesting system architectures selected in the previous chapter are used to develop eight portfolios with varying degrees of commonality.

Given that the portfolios are intended to serve a planetary surface exploration mission purpose, it is reasonable to base them on a predicted future planetary surface exploration mission. For this thesis, that mission will be a lunar outpost mission, consisting of a crew of four and lasting a total of six months on the lunar surface. A portfolio for this mission will consist of four examples of one EVA suit instantiation (backup EVA suit components will be covered under a spares model), one Habitat instantiation, two examples of a Pressurized Rover instantiation for enhanced surface mobility, one transfer vehicle for landing and ascent from the Moon's surface (for the case of a lunar surface exploration, this will specialize to the LSAM), and one transfer vehicle for traveling from the Earth to low lunar orbit and back (for lunar surface exploration, this will specialize to the CEV). Note that each example of an instantiation is a duplicate of any other examples (as in the case of the EVA suit and Pressurized Rover), and that each instantiation will have only one system architecture – that is, only one design for each instantiation will be developed to completion, although several examples of that design may be included in any portfolio.

However, the lifecycle of the portfolio includes more than one repetition of this exact mission. The portfolio includes a series of six-month missions on the lunar surface over a period of eight years. The cumulative time on the surface (which applies to the Habitat) is 1440 days for a crew of four. There are two pressurized rovers included, and they are scheduled to be used once every four weeks, for a total of seven days, by two crewmembers. Allowances are made for EVA to occur three times per week, as well as on rover traverses. The total time used by a pressurized rover is assessed as 560 person-days, while EVA suits must last for 784 person-days. The transfer vehicle need only last for a total of 24 person-days (six days maximum for four crew), and the CEV lasts for 18 days of crew support, as specified in (48).

A total of eight LSAMs are required to carry out the mission, as they remain either on the lunar surface (for the descent stage) or in low lunar orbit (for the ascent stage) while only one CEV is needed (it need not actually be the same CEV, but returning to Earth allows for a chance to refurbish and reuse the same vehicle essentially for free).

Although the ISS is included in the portfolio as a legacy system, it is present primarily to show any commonality opportunities, and does not contribute to the portfolio's campaign mass, spares mass, cost, or cost risk.

Figure 68 shows the notional systems associated with one mission, and Table 3 lists the total number of each instantiation required for a full campaign.

Instantiation	**Number of examples required for full campaign**
Habitat	1
EVA suit	4
Pressurized Rover	2
Transfer Vehicle (LSAM)	8
CEV	1
ISS	1 (comparison only)

Table 3. Instantiations required for full campaign.

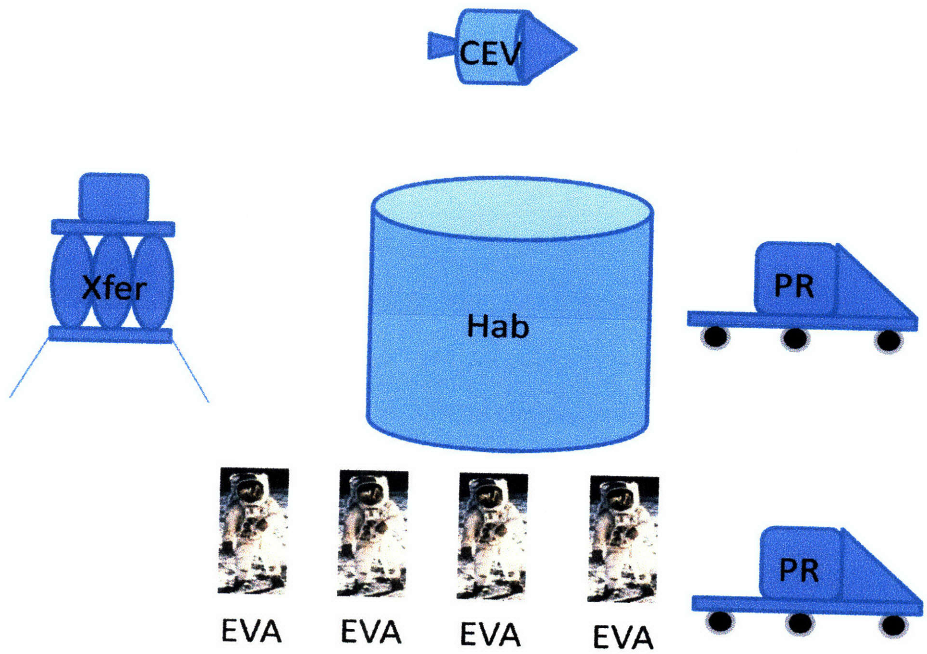

Figure 68. Lunar surface exploration portfolio for one mission.

4.3 Calculation of Benefits and Penalties of Commonality

The bases upon which to calculate the benefits and penalties of commonality include the mass that must be landed on the surface and the development costs of the systems in the surface exploration portfolio. Four things are tracked to calculate the potential benefits and penalties of commonality: the total equivalent portfolio mass over the campaign, the required spares mass, the development cost as discounted with the proxy metric of the number of unique items to be developed, and the development cost risk as measured by the TRLs of technology options included in the portfolio.

4.3.1 Spares model

The total equivalent campaign mass is calculated by the OPN models for each instantiation, and a different total equivalent campaign mass is associated with each ECLS system architecture generated by the OPN models. Each ECLS system architecture also has associated with it a certain equipment mass, and the mass of spares for each system is set to 10% per year as a baseline. By this measure, one-tenth of the mass of the system's equipment will need to be made available as spares, meaning that it also must be shipped to the surface.

Commonality has the potential to reduce sparing requirements, both because common spares (spares which can be used in more than one location if needed) can be kept, and because some cannibalization and temporary use of alternate system components as spares can be done.

Siddiqi and de Weck (50) develop a model for spares requirements on space missions if commonality of element components or reconfigurability of components (essentially temporary cannibalization of underutilized common components) is available. They suggest that sparing requirements can be reduced from 3 to 2 or 1 for components which are common between one or more elements, which equates to a reduction in spares mass of 33% or even 50% for appropriate levels of availability.

This assessment will be applied to the sparing model by calculating the percent drop in spares mass requirements for the case of common components between elements, which for the purposes of this thesis means common technology options between different instantiations. The total amount of spares is calculated as 10% of the equipment mass, where equipment mass is taken from the total number of elements in the portfolio. Any portfolio includes six instantiations (Habitat, EVA suit, Pressurized rover, Transfer vehicle, CEV, and ISS), but also includes more than one of each instantiation. Four EVA suits, two pressurized rovers, and one transfer vehicle per mission, for a total of eight, are required. Ten percent of the total equivalent equipment mass of all these elements is used as the spares mass requirement. As the lifetime of the portfolio is eight years, the sparing requirement of ten percent per year for each instantiation is multiplied by eight, with the exceptions of the CEV (which operates anew effectively once per year) and the ISS (the spares for which are not considered).

The equation $R = (m_u - m_c)/m_u$ is applied, where R is the reduction fraction in total spares mass, m_u is the spares mass for the case where all systems are unique (no commonality occurs), and m_c is the spares mass for the case where commonality does occur. If the baseline spares mass (which is ten percent of the equipment mass) is known and R is known, the spares mass of the commonality-containing portfolio can be calculated.

If the equation $R = (m_u - m_c)/m_u$ is manipulated, an expression for R in terms of the level of sparing (the quantity which (50) suggests is reduced by commonality or reconfigurability) and the number of common elements. This equation, derived in Appendix A, is $R = (1-x)n_c/N$, where N is the total number of elements, and $x = s_c/s_u$ is the reduction fraction in sparing level permitted by the adoption of commonality. For the case examined in (50), x = 0.67 or 0.50. For the purposes of this thesis, x will be set to the more conservative value of 0.67.

The highest possible number of unique elements to be designed in any portfolio is 56, as each of the six instantiations in a portfolio has ten functions to deliver, thus requiring the selection of up to sixty different technology options and the design of sixty component elements. The exceptions to this are the pressurized rover and the EVA suit, neither of which provide nitrogen or themselves reduce carbon dioxide in order to regenerate oxygen. This reduces the number of unique elements to 56, and further commonality due to design choices (made either as a side effect of architecture downselection or as a deliberate choice) further reduces the number of unique elements to be designed.

4.3.2 Cost model

Another factor in calculating the benefits and penalties of commonality is the development cost of the portfolio. This is roughly related to the number of components to be developed, so a commonality-containing portfolio will have lower development costs due to the need to develop fewer unique components.

A model for cost, in terms of FY2010 dollars, was developed from (44). The cost model includes separate segments for component development cost and unit cost, and as such the total cost is the sum of development costs plus unit costs. Worth noting is that the model in (44) is designed to apply to systems rather than components, but that it takes into account the system mass, which means that the substitution of one component for another in a system affects the system's cost. This provides a position from which to adjust the development cost to account for commonality.

As noted, the total cost is the sum of development and unit acquisition costs. The unit acquisition costs are primarily a function of ECLS system mass, and as the exploration portfolios are set up with one ECLS system per instantiation, the total mass of ECLS systems to be acquired is simply the sum of the masses of each instantiation's ECLS system times the number of examples of that instantiation included in a portfolio. This cost is a constant, and is not affected by commonality. Some benefits in manufacturing or materials acquisition costs may exist due to the effects of the learning curve or economies of scale, but these effects are not assessed in detail in this thesis. The development cost can be affected by commonality, however. Given that the modeling of ECLS systems for this thesis is such that commonality exists on a level between components of the ECLS systems, the commonality discount to cost is applied by taking the ratio of unique elements in all the ECLS systems to the total number of elements in all the ECLS systems. This means that the cost is reduced by a factor equal to $(N - n_C)/N$, where N is the total number of elements and n_C is the number of common elements.

4.3.3 Development cost risk

Development cost risk is the risk that development cost will expand. As noted in (45), any technology with a TRL below 6 is at risk of growth in development cost. It is very difficult to quantify such risk exactly, especially for immature technologies, and as such this element of portfolio costs is left qualitative. Portfolios which do not include any technology options below TRL 6 may be considered much less risky to develop than those that do include such technology options, and as such are more attractive to develop.

4.4 Results from Interesting Portfolios

The details of and results from applying the Commonality Analysis Methodology to the eighteen portfolios are now presented, along with the portfolios themselves. The benefits and penalties of commonality for each portfolio are calculated, and the full overlap matrices and sorted full overlap matrices are presented.

4.4.1 Portfolio I

The first portfolio includes the architectures designated Habitat 1, EVA Suit 1, Pressurized Rover 1, and Transfer Vehicle 1. The architectures are listed in detail again in Figure 69. Note that the CEV is understood to be included in the portfolio, but it is not listed, as it is the same from portfolio to portfolio, and is also very similar in architecture to the transfer vehicle.

Architecture	Hab 1	TRL	EVA 1	TRL	PR 1	TRL	Xfer 1	TRL
Campaign mass	7278		17484		11517		766.84	
Equip mass	1673.13		24.61		250.04		571.22	
O2 prov	Welec	9	HP	9	HP	9	HP	9
CO2 Rem	SAWD	6	SAVac	6	SAVac	6	SAVac	6
CO2 Redux	Sabat	7	None		None		None	
N2 prov	HP	9	X		X		HP	9
Temp	CHX	9	Sublimator	9	Sublimator	9	CHX	9
Hum	CHX	9	SAVac		SAVac	6	SAVac	6
TCC	Charcoal	9	Charcoal	9	Charcoal	9	Charcoal	9
H2O prov	HS/cond	7	Stored	9	Stored	9	MF	6
Liq waste	TIMES	5	Store	9	Store	9	Store	9
Sol waste	Compact	9	Store	9	Store	9	Compact	9
Spares mass per yr	167.313		2.461		25.004		57.122	
Dev cost, $M	273.01		154.31		170.54		193.67	
Unit/Spare cost, $M	108.53		57.43		64.41		74.37	
Transport cost, $M	291.12		699.36		414.612		30.6736	

Figure 69. Portfolio I architectures.

The full overlap matrix and sorted full overlap matrix appear as Figure 70 and Figure 71, and the portfolio's characteristics appear in Table 4.

The full overlap matrix in Figure 70 presents the points of commonality between the five instantiations in the portfolio (Habitat, EVA suit, Pressurized Rover, Transfer Vehicle, and CEV) and the ISS. The matrix displays the ten functions for each instantiation along the axes, ordered by instantiation, and then marks points of commonality with a highlighted numeral 1. The visual display shows where points of commonality occur, and the inclusion of the ISS allows for immediate evaluation of the commonality between instantiations in the portfolio and an operational design.

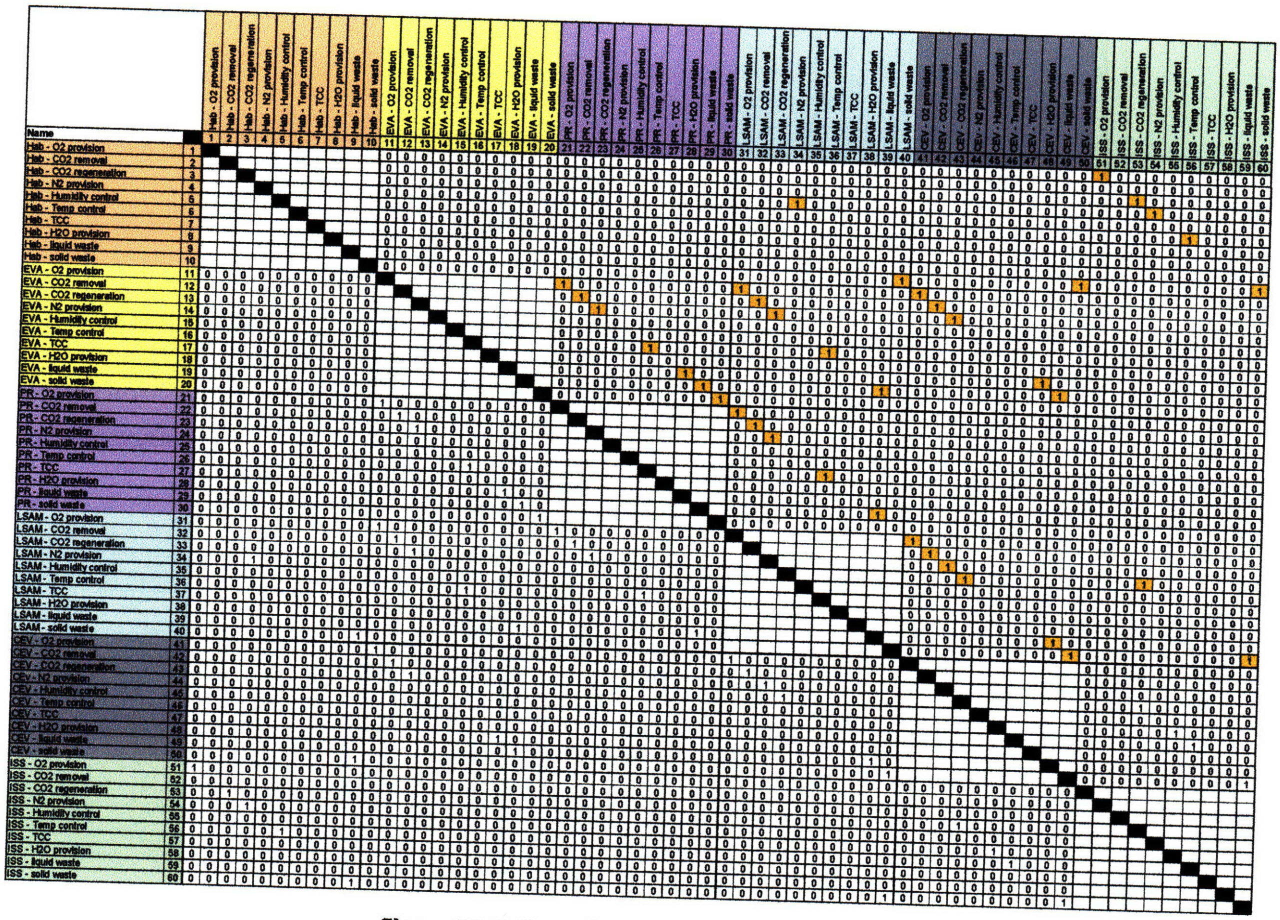

Figure 70. Full overlap matrix for Portfolio I.

The sorted full overlap matrix, seen in Figure 71, displays results from the full overlap matrix, but first sorts the points of commonality via a clustering DSM algorithm. The points of commonality between the ISS and the other instantiations in the portfolio are also not displayed in this figure. This permits clearer visual display of the same information.

The full overlap matrix visually indicates all points of commonality, while the sorted full overlap matrix provides insight for the design of new ECLS systems (which is another reason to exclude the ISS from this matrix – its ECLS system is already built, and does not require further major design effort) by clustering common items together. Note that the CEV is still included in the sorted full overlap matrix – although its ECLS system architecture is already set, it has yet to be designed in detail and built, and therefore retains the option to include common components. Reading the sorted full overlap matrix shows which technology options should be made common, and from which instantiations requirements for the design of these technology options should be drawn.

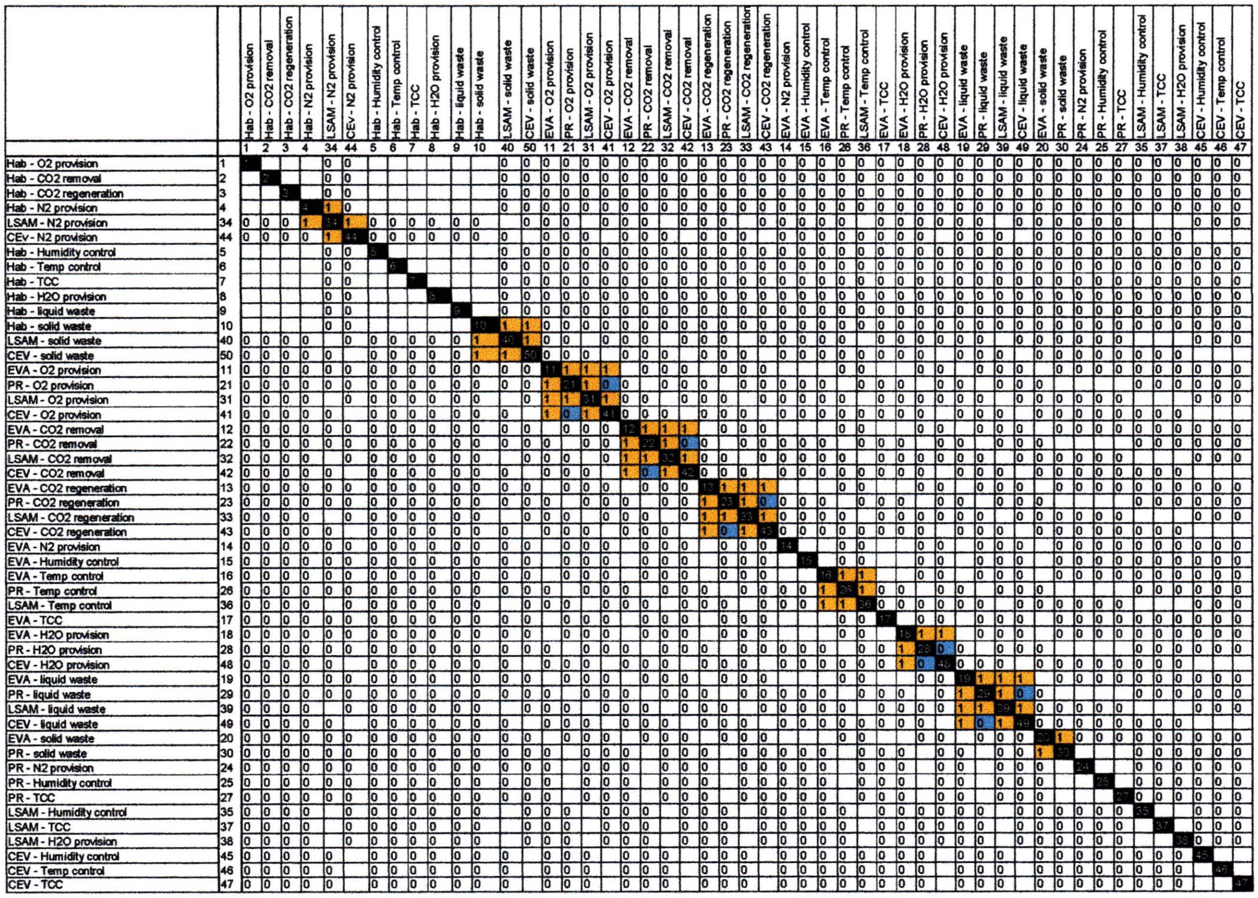

Figure 71. Sorted full overlap matrix for Portfolio I.

Once the points of commonality have been marked, the characteristics of the portfolio can be calculated, as a means of displaying the benefits and penalties of commonality. Each portfolio's total equivalent campaign mass, total spares mass, total development cost, total cost (which includes development cost, acquisition cost, and transport cost), and number of items at various TRL levels are displayed.

Given this information, it is possible to assess the penalties and benefits of commonality.

Portfolio (Architectures)	I (Hab 1, EVA 1, PR 1, Xfer 1)
Total Equivalent Campaign Mass (mT)	107.6
Total Spares Mass (kg)	1704
Total Development Cost ($M, FY2010)	454.57
Total Cost ($M, FY 2010)	3073.68
TRL levels	TRL 6+: 17 TRL 5: 1 TRL 4: 0 TRL 3: 0

Table 4. Characteristics of Portfolio I.

4.4.2 Portfolio II

The second portfolio includes the architectures designated Habitat 1, EVA Suit 1, Pressurized Rover 2, and Transfer Vehicle 1. The detailed architectures are repeated in Figure 72.

Architecture	Hab 1	TRL	EVA 1	TRL	PR 2	TRL	Xfer 1	TRL
Campaign mass	7278		17484		4682		766.84	
Equip mass	1673.13		24.61		445.42		571.22	
O2 prov	Welec	9	HP	9	HP	9	HP	9
CO2 Rem	SAWD	6	SAVac	6	LiOH	9	SAVac	6
CO2 Redux	Sabat	7	None		None		None	
N2 prov	HP	9	X		X		HP	9
Temp	CHX	9	Sublimator	9	Ice	5	CHX	9
Hum	CHX	9	SAVac		CHX	9	SAVac	6
TCC	Charcoal	9	Charcoal	9	Charcoal	9	Charcoal	9
H2O prov	HS/cond	7	Stored	9	Stored	9	MF	6
Liq waste	TIMES	5	Store	9	Store	9	Store	9
Sol waste	Compact	9	Compact	9	Store	9	Compact	9
Spares mass per yr	167.313		2.461		44.542		57.122	
Dev cost, $M	273.01		154.31		184.61		193.67	
Unit/Spare cost, $M	108.53		57.43		70.47		74.37	
Transport cost, $M	291.12		699.36		168.552		30.6736	

Figure 72. Portfolio II architectures.

The full overlap matrix and sorted full overlap matrix appear as Figure 73 and Figure 74, and the portfolio's characteristics appear in Table 5.

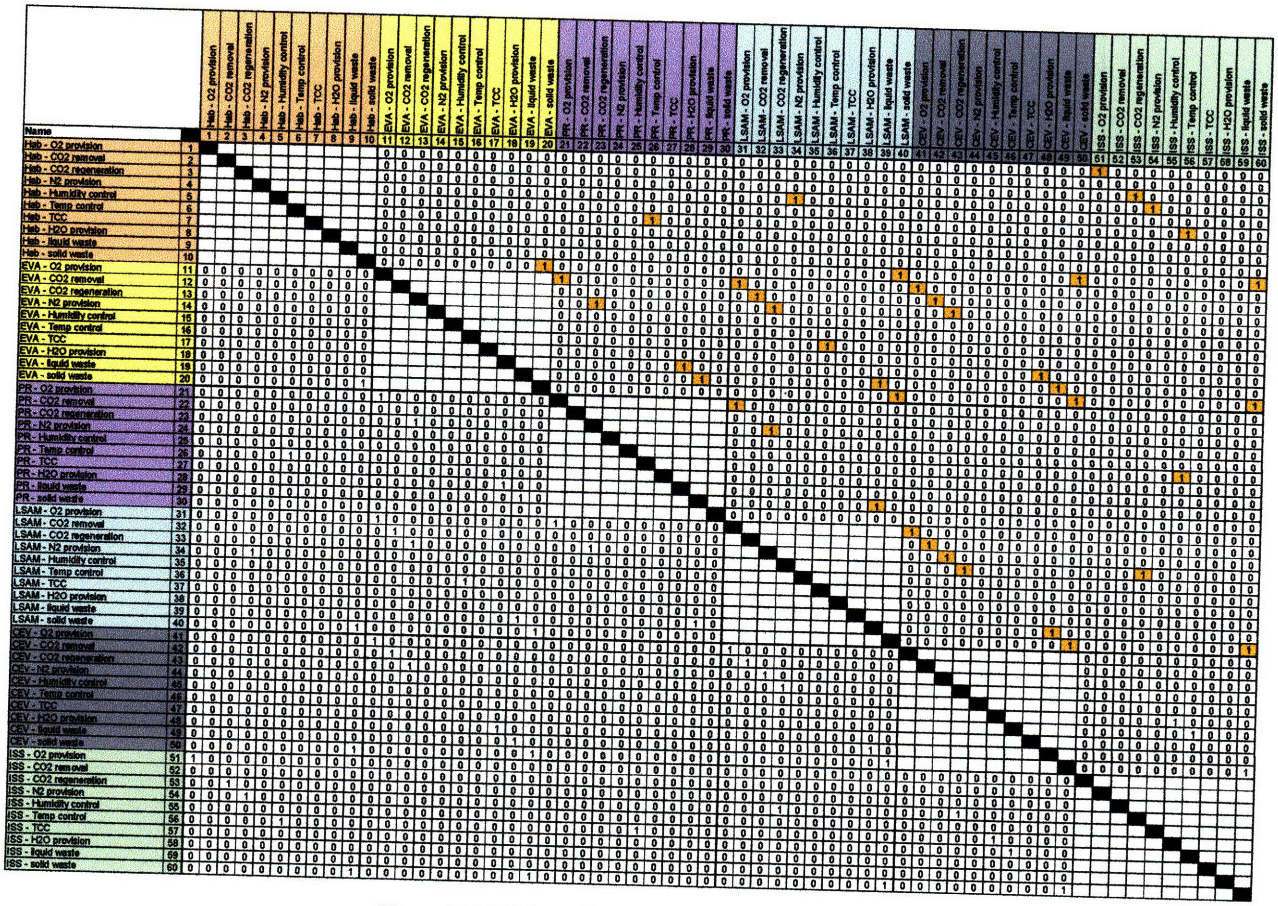

Figure 73. Full overlap matrix for Portfolio II.

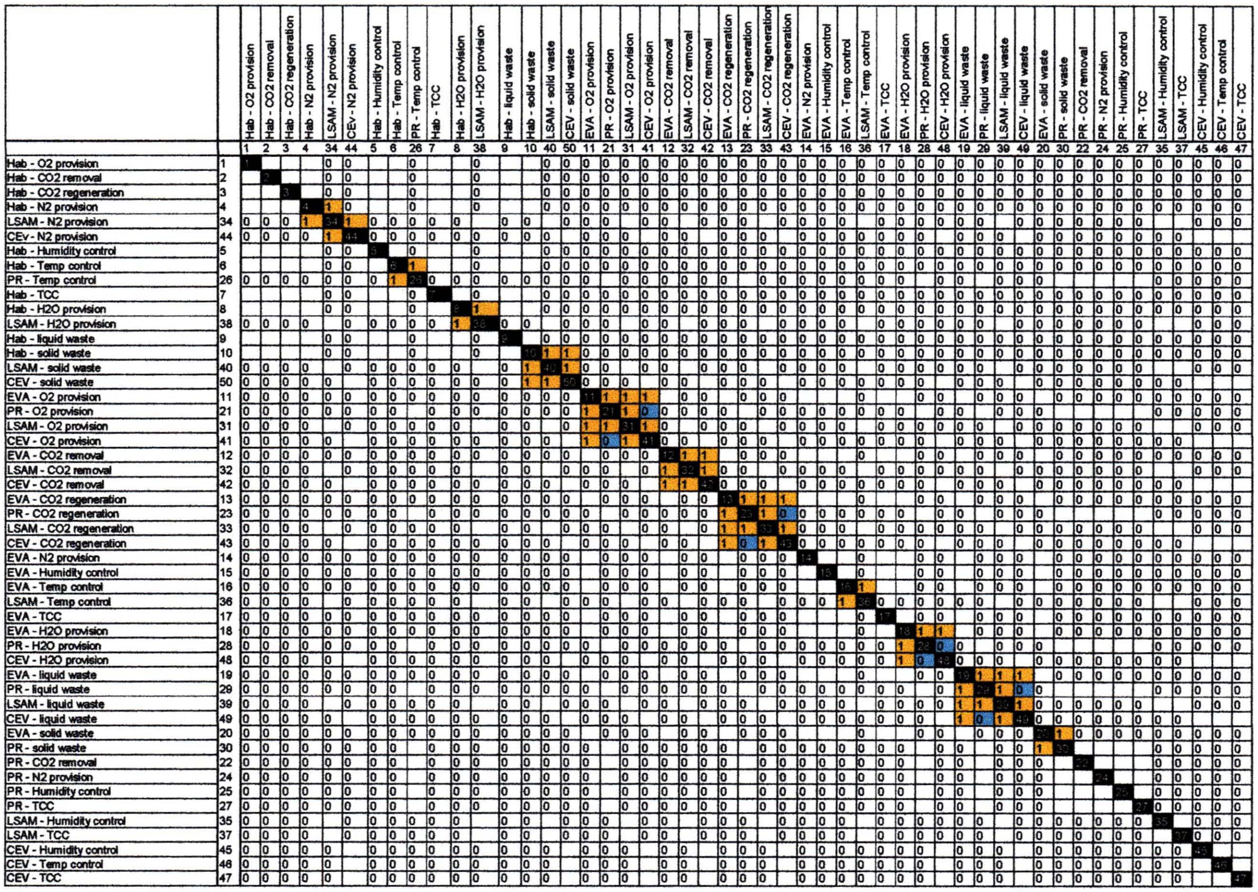

Figure 74. Sorted full overlap matrix for Portfolio II.

Portfolio (Architectures)	II (Hab 1, EVA 1, PR 2, Xfer 1)
Total Equivalent Campaign Mass (mT)	93.9
Total Spares Mass (kg)	1861
Total Development Cost ($M, FY2010)	499.48
Total Cost ($M, FY 2010)	2884.64
TRL levels	TRL 6+: 18 TRL 5: 2 TRL 4: 0 TRL 3: 0

Table 5. Characteristics of Portfolio II.

4.4.3 Portfolio III

The third portfolio includes the architectures designated Habitat 1, EVA Suit 2, Pressurized Rover 1, and Transfer Vehicle 1. The detailed architectures appear again in Figure 75.

Architecture	Hab 1	TRL	EVA 2	TRL	PR 1	TRL	Xfer 1	TRL
Campaign mass	7278		18356		11517		766.84	
Equip mass	1673.13		43.2		250.04		571.22	
O2 prov	Welec	9	HP	9	HP	9	HP	9
CO2 Rem	SAWD	6	MetOx	8	SAVac	6	SAVac	6
CO2 Redux	Sabat	7	Hab regen	6	None		None	
N2 prov	HP	9	X		X		HP	9
Temp	CHX	9	Sublimator	9	Sublimator	9	CHX	9
Hum	CHX	9	CHX	9	SAVac	6	SAVac	6
TCC	Charcoal	9	Charcoal	9	Charcoal	9	Charcoal	9
H2O prov	HS/cond	7	Stored	9	Stored	9	MF	6
Liq waste	TIMES	5	Store	9	Store	9	Store	9
Sol waste	Compact	9	Store	9	Store	9	Compact	9
Spares mass per yr	167.313		4.32		25.004		57.122	
Dev cost, $M	273.01		155.65		170.54		193.67	
Unit/Spare cost, $M	108.53		58.00		64.41		74.37	
Transport cost, $M	291.12		734.24		414.612		30.6736	

Figure 75. Portfolio III architectures.

The full overlap matrix and sorted full overlap matrix appear as Figure 76 and Figure 77 and the portfolio's characteristics appear in Table 6.

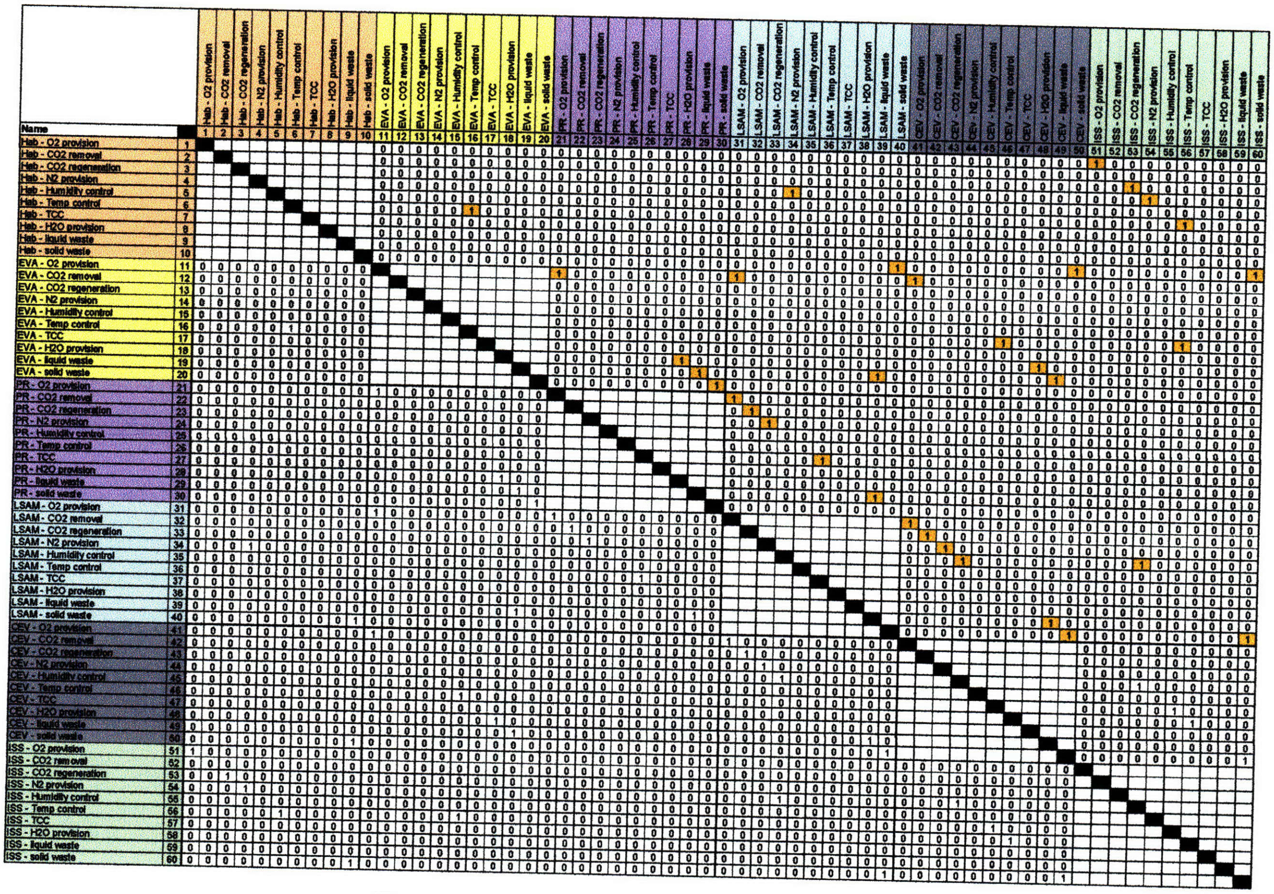

Figure 76. Full overlap matrix for Portfolio III.

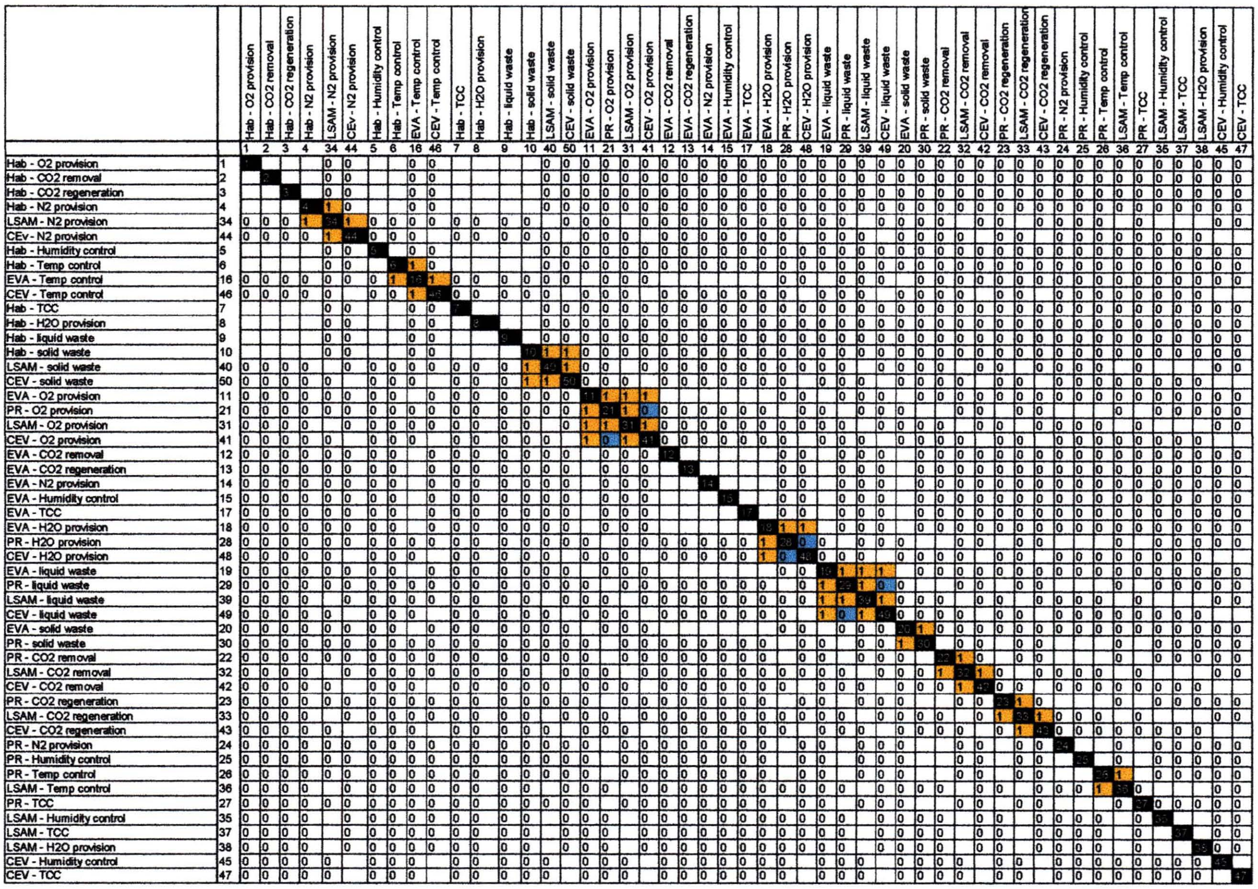

Figure 77. Sorted full overlap matrix for Portfolio III.

Portfolio (Architectures)	III (Hab 1, EVA 2, PR 1, Xfer 1)
Total Equivalent Campaign Mass (tonnes)	111.0
Total Spares Mass (kg)	1725
Total Development Cost ($M, FY2010)	468.46
Total Cost ($M, FY 2010)	3124.75
TRL levels	TRL 6+: 18 TRL 5: 1 TRL 4: 0 TRL 3: 0

Table 6. Characteristics of Portfolio III.

4.4.4 Portfolio IV

The fourth portfolio includes the architectures designated Habitat 1, EVA Suit 2, Pressurized Rover 2, and Transfer Vehicle 1. The detailed architectures appear again in Figure 78.

Architecture	Hab 1	
Campaign mass	7278	
Equip mass	1673.13	*TRL*
O2 prov	Welec	9
CO2 Rem	SAWD	6
CO2 Redux	Sabat	7
N2 prov	HP	9
Temp	CHX	9
Hum	CHX	9
TCC	Charcoal	9
H2O prov	HS/cond	7
Liq waste	TIMES	5
Sol waste	Compact	9
Spares mass per yr	167.313	
Dev cost, $M	273.01	
Unit/Spare cost, $M	108.53	
Transport cost, $M	291.12	

Architecture	EVA 2	
Campaign mass	18356	
Equip mass	43.2	*TRL*
O2 prov	HP	9
CO2 Rem	MetOx	8
CO2 Redux	Hab regen	6
N2 prov	X	
Temp	Sublimator	9
Hum	CHX	9
TCC	Charcoal	9
H2O prov	Stored	9
Liq waste	Store	9
Sol waste	Store	9
Spares mass per yr	4.32	
Dev cost, $M	155.65	
Unit/Spare cost, $M	58.00	
Transport cost, $M	734.24	

Architecture	PR 2	
Campaign mass	4682	
Equip mass	445.42	*TRL*
O2 prov	HP	9
CO2 Rem	LiOH	9
CO2 Redux	None	
N2 prov	X	
Temp	Ice	5
Hum	CHX	9
TCC	Charcoal	9
H2O prov	Stored	9
Liq waste	Store	9
Sol waste	Store	9
Spares mass per yr	44.542	
Dev cost, $M	184.61	
Unit/Spare cost, $M	70.47	
Transport cost, $M	168.552	

Architecture	Xfer 1	
Campaign mass	766.84	
Equip mass	571.22	*TRL*
O2 prov	HP	9
CO2 Rem	SAVac	6
CO2 Redux	None	
N2 prov	HP	9
Temp	CHX	9
Hum	SAVac	6
TCC	Charcoal	9
H2O prov	MF	6
Liq waste	Store	9
Sol waste	Compact	9
Spares mass per yr	57.122	
Dev cost, $M	193.67	
Unit/Spare cost, $M	74.37	
Transport cost, $M	30.6736	

Figure 78. Portfolio IV architectures.

The full overlap matrix and sorted full overlap matrix appear as Figure 79 and Figure 80, and the portfolio's characteristics appear in Table 7.

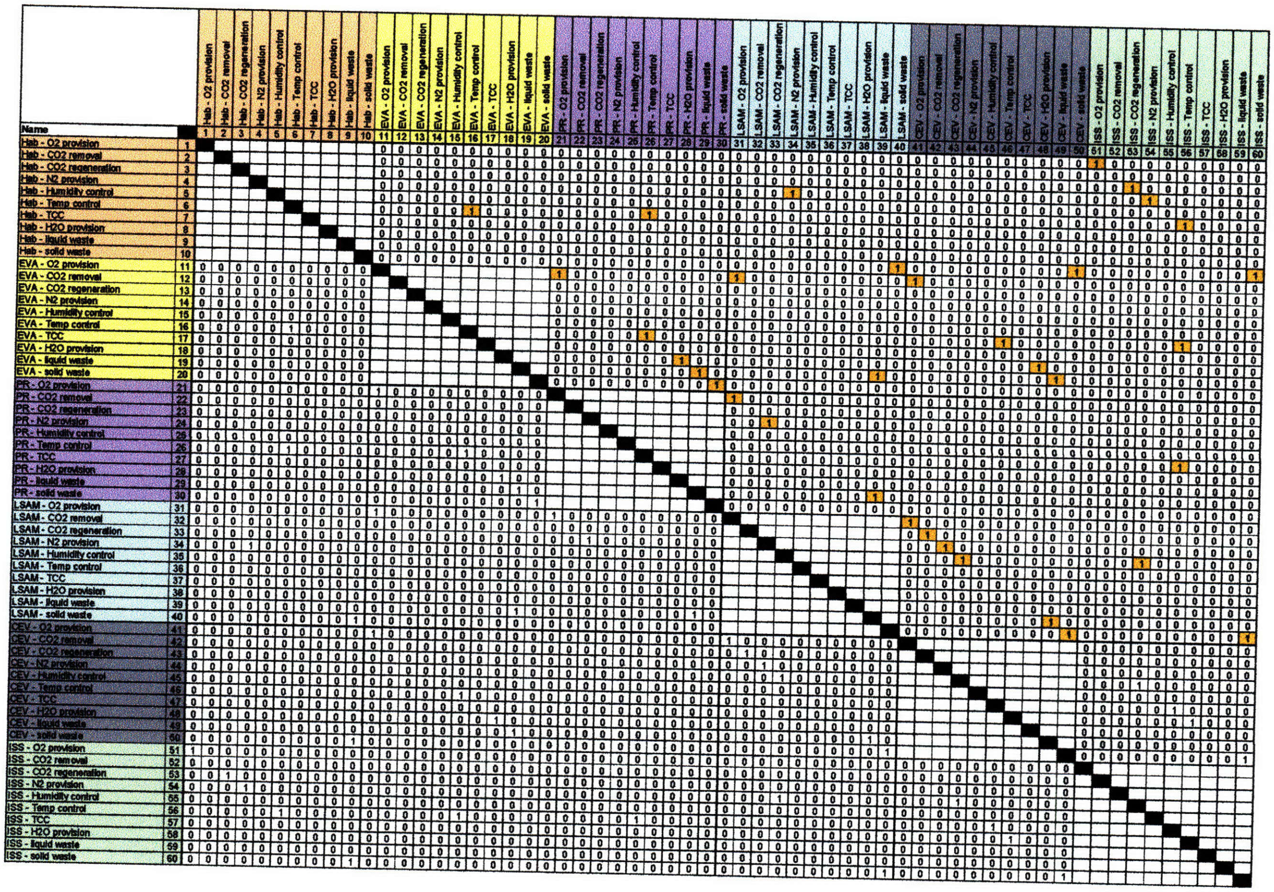

Figure 79. Full overlap matrix for Portfolio IV.

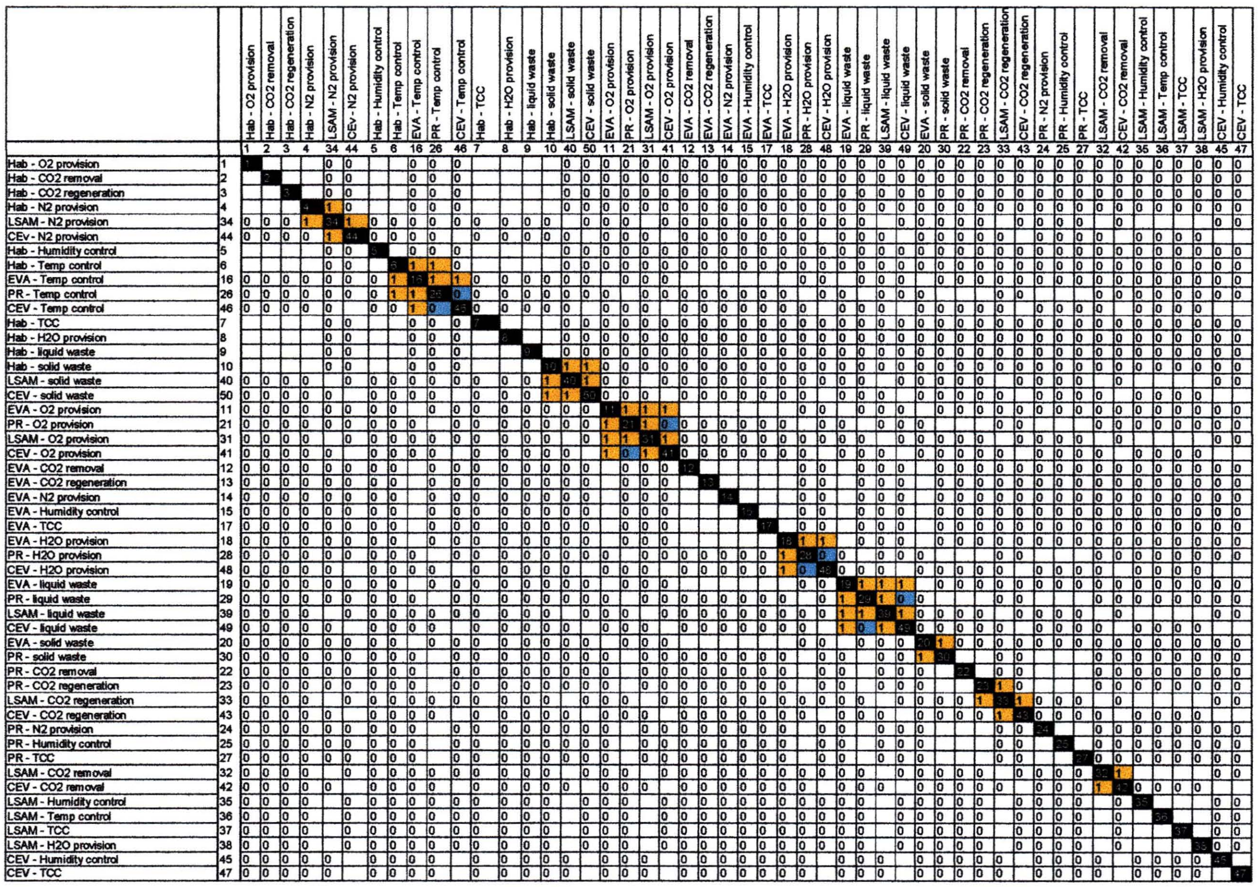

Figure 80. Sorted full overlap matrix for Portfolio IV.

Portfolio (Architectures)	IV (Hab 1, EVA 2, PR 2, Xfer 1)
Total Equivalent Campaign Mass (tonnes)	97.4
Total Spares Mass (kg)	1882
Total Development Cost ($M, FY2010)	512.35
Total Cost ($M, FY 2010)	2934.70
TRL levels	TRL 6+: 19 TRL 5: 2 TRL 4: 0 TRL 3: 0

Table 7. Characteristics of Portfolio IV.

4.4.5 Portfolio V

The fifth portfolio includes the architectures designated Habitat 2, EVA Suit 1, Pressurized Rover 1, and Transfer Vehicle 1. The detailed architectures appear again in Figure 81.

Architecture	Hab 2	TRL	EVA 1	TRL	PR 1	TRL	Xfer 1	TRL
Campaign mass	10759		17484		11517		766.84	
Equip mass	1783.35		24.61		250.04		571.22	
O2 prov	Welec	9	HP	9	HP	9	HP	9
CO2 Rem	4BMS	9	SAVac	6	SAVac	6	SAVac	6
CO2 Redux	Sabat	7	None		None		None	
N2 prov	HP	9	X		X		HP	9
Temp	CHX	9	Sublimator	9	Sublimator	9	CHX	9
Hum	CHX	9	SAVac		SAVac	6	SAVac	6
TCC	Charcoal	9	Charcoal	9	Charcoal	9	Charcoal	9
H2O prov	HS/cond	7	Stored	9	Stored	9	MF	6
Liq waste	Airevap	6	Store	9	Store	9	Store	9
Sol waste	Compact	9	Store	9	Store	9	Compact	9
Spares mass per yr	178.335		2.461		25.004		57.122	
Dev cost, $M	280.94		154.31		170.54		193.67	
Unit/Spare cost, $M	111.94		57.43		64.41		74.37	
Transport cost, $M	430.36		699.36		414.612		30.6736	

Figure 81. Portfolio V architectures.

The full overlap matrix and sorted full overlap matrix appear as Figure 82 and Figure 83, and the portfolio's characteristics appear in Table 8.

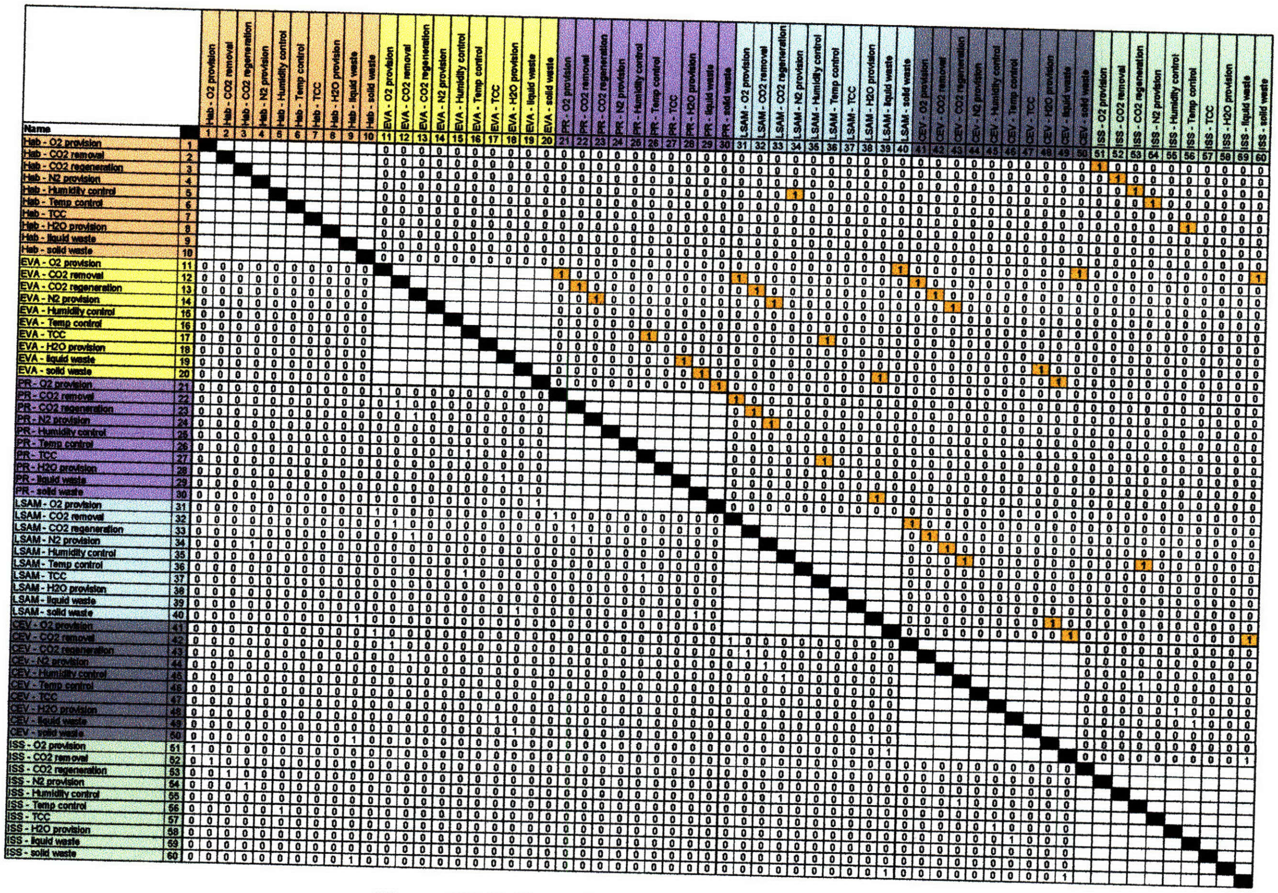

Figure 82. Full overlap matrix for Portfolio V.

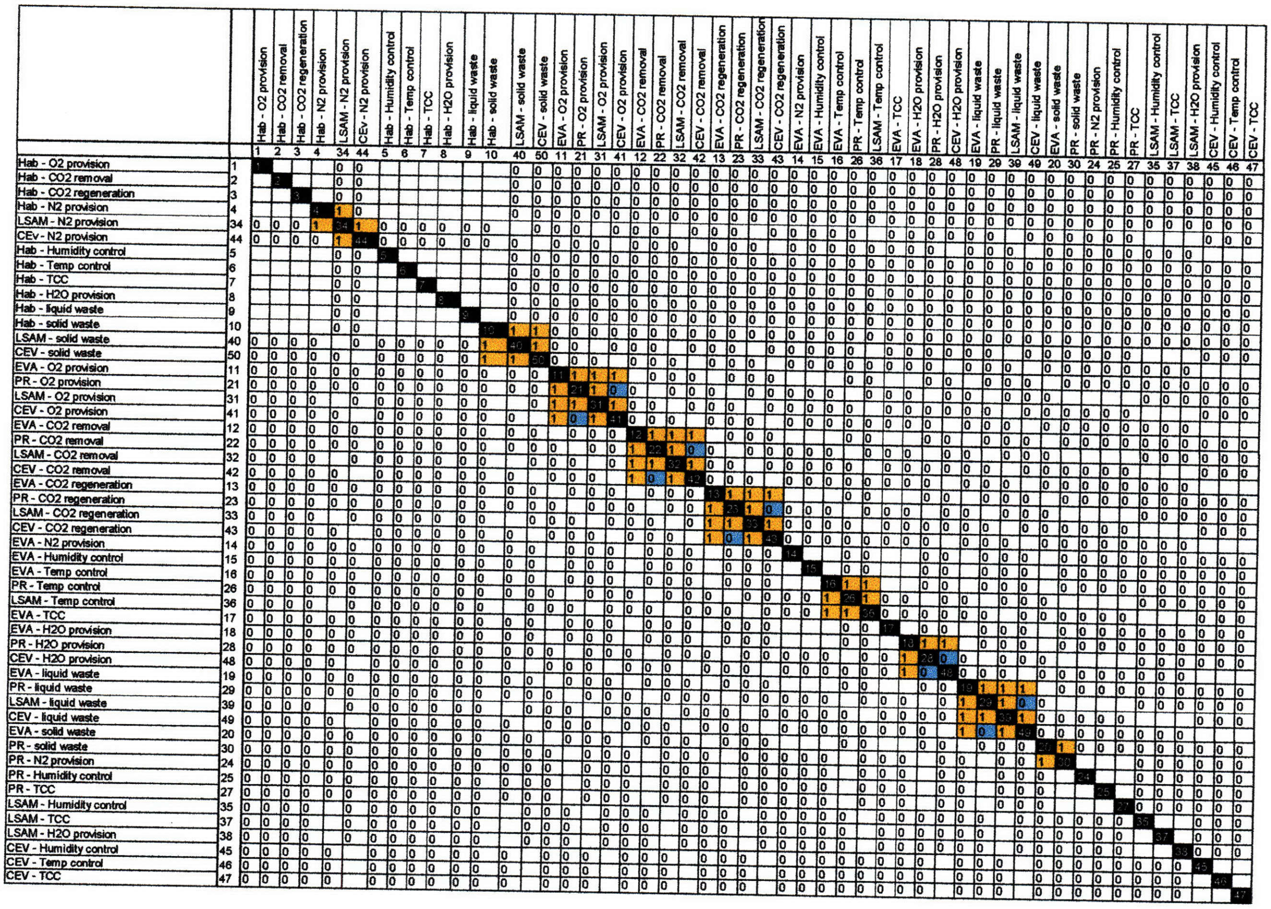

Figure 83. Sorted full overlap matrix for Portfolio V.

Portfolio (Architectures)	V (Hab 2, EVA 1, PR 1, Xfer 1)
Total Equivalent Campaign Mass (tonnes)	111.0
Total Spares Mass (kg)	1776
Total Development Cost ($M, FY2010)	458.23
Total Cost ($M, FY 2010)	3219.99
TRL levels	TRL 6+: 18 TRL 5: 0 TRL 4: 0 TRL 3: 0

Table 8. Characteristics of Portfolio V.

4.4.6 Portfolio VI

The sixth portfolio includes the architectures designated Habitat 2, EVA Suit 1, Pressurized Rover 2, and Transfer Vehicle 1. The detailed architectures appear again in Figure 84.

Architecture	Hab 2	*TRL*	EVA 1	*TRL*	PR 2	*TRL*	Xfer 1	*TRL*
Campaign mass	10759		17484		4682		766.84	
Equip mass	1783.35		24.61		445.42		571.22	
O2 prov	Welec	9	HP	9	HP	9	HP	9
CO2 Rem	4BMS	9	SAVac	6	LiOH	9	SAVac	6
CO2 Redux	Sabat	7	None		None		None	
N2 prov	HP	9	X		X		HP	9
Temp	CHX	9	Sublimator	9	Ice	5	CHX	9
Hum	CHX	9	SAVac		CHX	9	SAVac	6
TCC	Charcoal	9	Charcoal	9	Charcoal	9	Charcoal	9
H2O prov	HS/cond	7	Stored	9	Stored	9	MF	6
Liq waste	Airevap	6	Store	9	Store	9	Store	9
Sol waste	Compact	9	Store	9	Store	9	Compact	9
Spares mass per yr	178.335		2.461		44.542		57.122	
Dev cost, $M	280.94		154.31		184.61		193.67	
Unit/Spare cost, $M	111.94		57.43		70.47		74.37	
Transport cost, $M	430.36		699.36		168.552		30.6736	

Figure 84. Portfolio VI architectures.

The full overlap matrix and sorted full overlap matrix appear as Figure 85 and Figure 86, and the portfolio's characteristics appear in Table 9.

		Hab - O_2 provision	Hab - CO_2 removal	Hab - CO_2 regeneration	Hab - N_2 provision	Hab - Humidity control	Hab - Temp control	Hab - TCC	Hab - H_2O provision	Hab - liquid waste	Hab - solid waste	EVA - O_2 provision	EVA - CO_2 removal	EVA - CO_2 regeneration	EVA - N_2 provision	EVA - Humidity control	EVA - Temp control	EVA - TCC	EVA - H_2O provision	EVA - liquid waste	EVA - solid waste	PR - O_2 provision	PR - CO_2 removal	PR - CO_2 regeneration	PR - N_2 provision	PR - Humidity control	PR - Temp control	PR - TCC	PR - H_2O provision	PR - liquid waste	PR - solid waste	LSAM - O_2 provision	LSAM - CO_2 removal	LSAM - CO_2 regeneration	LSAM - N_2 provision	LSAM - Humidity control	LSAM - Temp control	LSAM - TCC	LSAM - H_2O provision	LSAM - liquid waste	LSAM - solid waste	CEV - O_2 provision	CEV - CO_2 removal	CEV - CO_2 regeneration	CEV - N_2 provision	CEV - Humidity control	CEV - Temp control	CEV - TCC	CEV - H_2O provision	CEV - liquid waste	CEV - solid waste	ISS - O_2 provision	ISS - CO_2 removal	ISS - CO_2 regeneration	ISS - N_2 provision	ISS - Humidity control	ISS - Temp control	ISS - TCC	ISS - H_2O provision	ISS - liquid waste	ISS - solid waste
Name		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
Hab - O_2 provision	1											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Hab - CO_2 removal	2											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Hab - CO_2 regeneration	3											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Hab - N_2 provision	4											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Hab - Humidity control	5											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hab - Temp control	6											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Hab - TCC	7											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hab - H_2O provision	8											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hab - liquid waste	9											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hab - solid waste	10											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
EVA - O_2 provision	11	0	0	0	0	0	0	0	0	0	0											1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EVA - CO_2 removal	12	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EVA - CO_2 regeneration	13	0	0	0	0	0	0	0	0	0	0											0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EVA - N_2 provision	14	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EVA - Humidity control	15	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EVA - Temp control	16	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EVA - TCC	17	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EVA - H_2O provision	18	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
EVA - liquid waste	19	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
EVA - solid waste	20	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PR - O_2 provision	21	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0											1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PR - CO_2 removal	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PR - CO_2 regeneration	23	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0											0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PR - N_2 provision	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PR - Humidity control	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PR - Temp control	26	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
PR - TCC	27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PR - H_2O provision	28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PR - liquid waste	29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0											0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PR - solid waste	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - O_2 provision	31	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0											1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - CO_2 removal	32	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - CO_2 regeneration	33	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0											0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - N_2 provision	34	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
LSAM - Humidity control	35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - Temp control	36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - TCC	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - H_2O provision	38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - liquid waste	39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0											0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
LSAM - solid waste	40	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
CEV - O_2 provision	41	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0
CEV - CO_2 removal	42	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0
CEV - CO_2 regeneration	43	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0
CEV - N_2 provision	44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0											0	0	0	1	0	0	0	0	0	0
CEV - Humidity control	45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0
CEV - Temp control	46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	1	0	0	0	0
CEV - TCC	47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	1	0	0	0
CEV - H_2O provision	48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0
CEV - liquid waste	49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0											0	0	0	0	0	0	0	0	0	0
CEV - solid waste	50	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1											0	0	0	0	0	0	0	0	0	1
ISS - O_2 provision	51	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
ISS - CO_2 removal	52	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
ISS - CO_2 regeneration	53	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
ISS - N_2 provision	54	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0										
ISS - Humidity control	55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
ISS - Temp control	56	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0										
ISS - TCC	57	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0										
ISS - H_2O provision	58	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
ISS - liquid waste	59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
ISS - solid waste	60	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1										

Figure 85. Full overlap matrix for Portfolio VI.

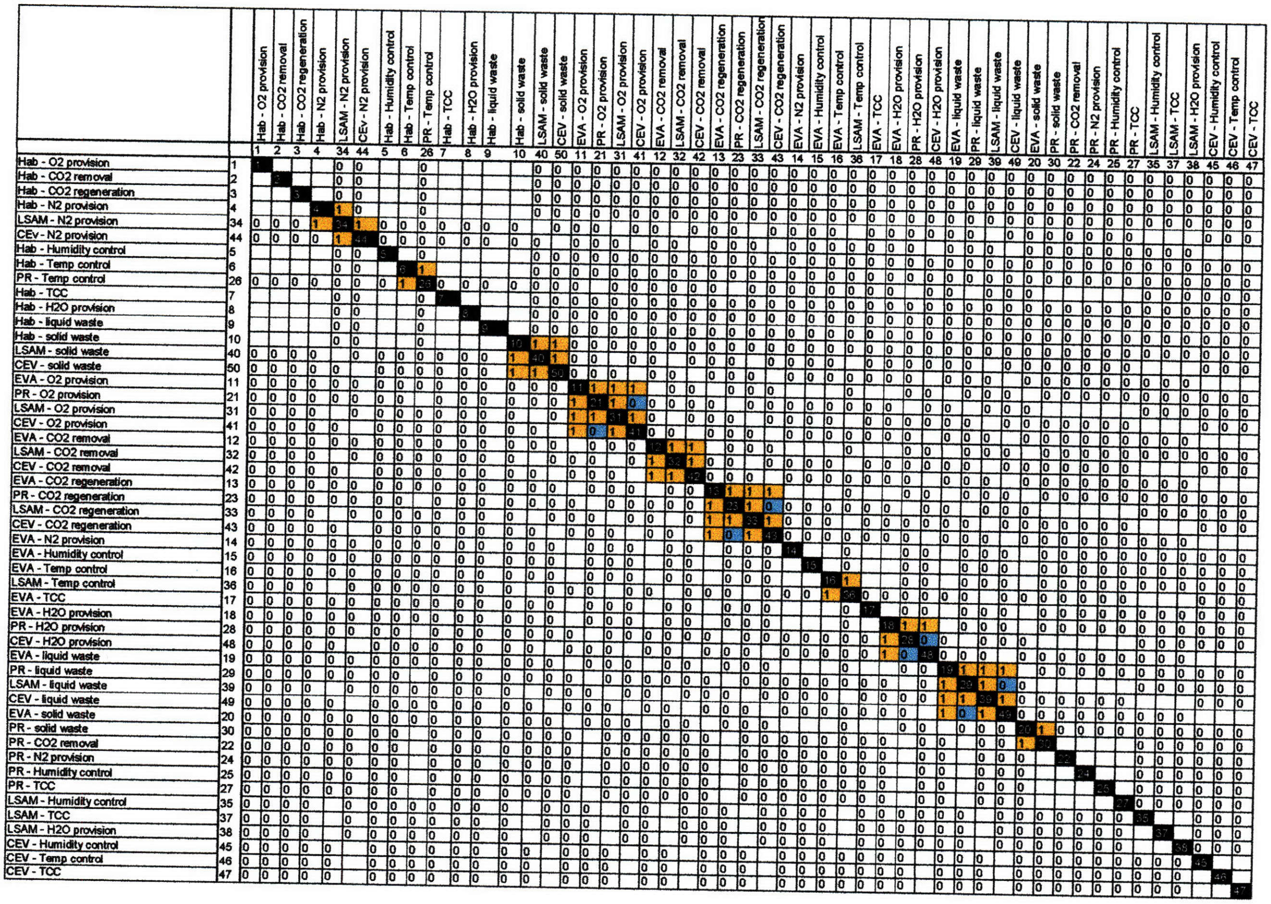

Figure 86. Sorted full overlap matrix for Portfolio VI.

Portfolio (Architectures)	VI (Hab 2, EVA 1, PR 2, Xfer 1)
Total Equivalent Campaign Mass (tonnes)	97.4
Total Spares Mass (kg)	1934
Total Development Cost ($M, FY2010)	503.45
Total Cost ($M, FY 2010)	3031.27
TRL levels	TRL 6+: 19 TRL 5: 1 TRL 4: 0 TRL 3: 0

Table 9. Characteristics of Portfolio VI.

4.4.7 Portfolio VII

The seventh portfolio includes the architectures designated Habitat 2, EVA Suit 2, Pressurized Rover 1, and Transfer Vehicle 1. The detailed architectures appear again in Figure 87.

Architecture	Hab 2	TRL	EVA 2	TRL	PR 1	TRL	Xfer 1	TRL
Campaign mass	10759		18356		11517		766.84	
Equip mass	1783.35		43.2		250.04		571.22	
O2 prov	Welec	9	HP	9	HP	9	HP	9
CO2 Rem	4BMS	9	MetOx	8	SAVac	6	SAVac	6
CO2 Redux	Sabat	7	Hab regen	6	None		None	
N2 prov	HP	9	X		X		HP	9
Temp	CHX	9	Sublimator	9	Sublimator	9	CHX	9
Hum	CHX	9	CHX	9	SAVac	6	SAVac	6
TCC	Charcoal	9	Charcoal	9	Charcoal	9	Charcoal	9
H2O prov	HS/cond	7	Stored	9	Stored	9	MF	6
Liq waste	Airevap	6	Store	9	Store	9	Store	9
Sol waste	Compact	9	Store	9	Store	9	Compact	9
Spares mass per yr	178.335		4.32		25.004		57.122	
Dev cost, $M	280.94		155.65		170.54		193.67	
Unit/Spare cost, $M	111.94		58.00		64.41		74.37	
Transport cost, $M	430.36		734.24		414.612		30.6736	

Figure 87. Portfolio VII architectures.

The full overlap matrix and sorted full overlap matrix appear as Figure 88 and Figure 89, and the portfolio's characteristics appear in Table 10.

Name		Hab - O2 provision 1	Hab - CO2 removal 2	Hab - CO2 regeneration 3	Hab - N2 provision 4	Hab - Humidity control 5	Hab - Temp control 6	Hab - TCC 7	Hab - H2O provision 8	Hab - liquid waste 9	Hab - solid waste 10	EVA - O2 provision 11	EVA - CO2 removal 12	EVA - CO2 regeneration 13	EVA - N2 provision 14	EVA - Humidity control 15	EVA - Temp control 16	EVA - TCC 17	EVA - H2O provision 18	EVA - liquid waste 19	EVA - solid waste 20	PR - O2 provision 21	PR - CO2 removal 22	PR - CO2 regeneration 23	PR - N2 provision 24	PR - Humidity control 25	PR - Temp control 26	PR - TCC 27	PR - H2O provision 28	PR - liquid waste 29	PR - solid waste 30	LSAM - O2 provision 31	LSAM - CO2 removal 32	LSAM - CO2 regeneration 33	LSAM - N2 provision 34	LSAM - Humidity control 35	LSAM - Temp control 36	LSAM - TCC 37	LSAM - H2O provision 38	LSAM - liquid waste 39	LSAM - solid waste 40	CEV - O2 provision 41	CEV - CO2 removal 42	CEV - CO2 regeneration 43	CEV - N2 provision 44	CEV - Humidity control 45	CEV - Temp control 46	CEV - TCC 47	CEV - H2O provision 48	CEV - liquid waste 49	CEV - solid waste 50	ISS - O2 provision 51	ISS - CO2 removal 52	ISS - CO2 regeneration 53	ISS - N2 provision 54	ISS - Humidity control 55	ISS - Temp control 56	ISS - TCC 57	ISS - H2O provision 58	ISS - liquid waste 59	ISS - solid waste 60
Hab - O2 provision	1											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Hab - CO2 removal	2											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Hab - CO2 regeneration	3											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Hab - N2 provision	4											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Hab - Humidity control	5											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hab - Temp control	6											0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Hab - TCC	7											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hab - H2O provision	8											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hab - liquid waste	9											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hab - solid waste	10											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
EVA - O2 provision	11	0	0	0	0	0	0	0	0	0	0											1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EVA - CO2 removal	12	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EVA - CO2 regeneration	13	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EVA - N2 provision	14	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EVA - Humidity control	15	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EVA - Temp control	16	0	0	0	0	0	1	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
EVA - TCC	17	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EVA - H2O provision	18	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
EVA - liquid waste	19	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
EVA - solid waste	20	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PR - O2 provision	21	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0											1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PR - CO2 removal	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PR - CO2 regeneration	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PR - N2 provision	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PR - Humidity control	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PR - Temp control	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PR - TCC	27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PR - H2O provision	28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PR - liquid waste	29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0											0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PR - solid waste	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - O2 provision	31	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0											1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - CO2 removal	32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0											0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - CO2 regeneration	33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0											0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - N2 provision	34	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
LSAM - Humidity control	35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - Temp control	36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - TCC	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - H2O provision	38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - liquid waste	39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0											0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
LSAM - solid waste	40	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
CEV - O2 provision	41	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0
CEV - CO2 removal	42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0
CEV - CO2 regeneration	43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0
CEV - N2 provision	44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0											0	0	0	1	0	0	0	0	0	0
CEV - Humidity control	45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0
CEV - Temp control	46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	1	0	0	0	0
CEV - TCC	47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	1	0	0	0
CEV - H2O provision	48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0
CEV - liquid waste	49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0											0	0	0	0	0	0	0	0	0	0
CEV - solid waste	50	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1											0	0	0	0	0	0	0	0	0	1
ISS - O2 provision	51	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
ISS - CO2 removal	52	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
ISS - CO2 regeneration	53	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
ISS - N2 provision	54	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0										
ISS - Humidity control	55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
ISS - Temp control	56	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0										
ISS - TCC	57	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0										
ISS - H2O provision	58	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
ISS - liquid waste	59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
ISS - solid waste	60	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1										

Figure 88. Full overlap matrix for Portfolio VII.

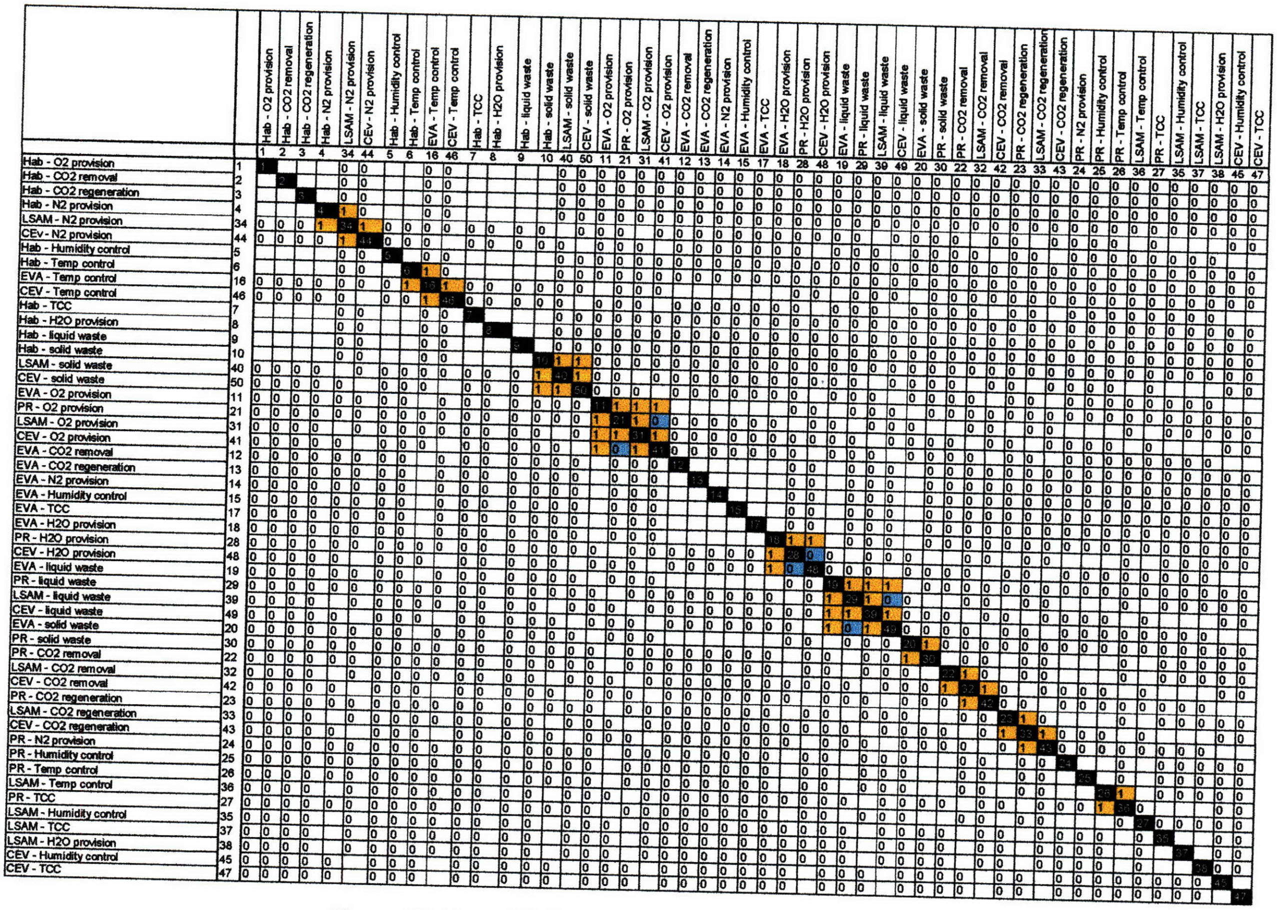

Figure 89. Sorted full overlap matrix for Portfolio VII.

Portfolio (Architectures)	VII (Hab 2, EVA 2, PR 1, Xfer 1)
Total Equivalent Campaign Mass (tonnes)	114.6
Total Spares Mass (kg)	1798
Total Development Cost ($M, FY2010)	472.23
Total Cost ($M, FY 2010)	3271.18
TRL levels	TRL 6+: 19 TRL 5: 0 TRL 4: 0 TRL 3: 0

Table 10. Characteristics of Portfolio VII.

4.4.8 Portfolio VIII

The eighth portfolio includes the architectures designated Habitat 2, EVA Suit 2, Pressurized Rover 2, and Transfer Vehicle 1. The detailed architectures appear again in Figure 90.

Architecture	Hab 2	TRL	EVA 2	TRL	PR 2	TRL	Xfer 1	TRL
Campaign mass	10759		18356		4682		766.84	
Equip mass	1783.35		43.2		445.42		571.22	
O2 prov	Welec	9	HP	9	HP	9	HP	9
CO2 Rem	4BMS	9	MetOx	8	LiOH	9	SAVac	6
CO2 Redux	Sabat	7	Hab regen	6	None		None	
N2 prov	HP	9	X		X		HP	9
Temp	CHX	9	Sublimator	9	Ice	5	CHX	9
Hum	CHX	9	CHX	9	CHX	9	SAVac	6
TCC	Charcoal	9	Charcoal	9	Charcoal	9	Charcoal	9
H2O prov	HS/cond	7	Stored	9	Stored	9	MF	6
Liq waste	Airevap	6	Store	9	Store	9	Store	9
Sol waste	Compact	9	Store	9	Store	9	Compact	9
Spares mass per yr	178.335		4.32		44.542		57.122	
Dev cost, $M	280.94		155.65		184.61		193.67	
Unit/Spare cost, $M	111.94		58.00		70.47		74.37	
Transport cost, $M	430.36		734.24		168.552		30.6736	

Figure 90. Portfolio VIII architectures.

The full overlap matrix and sorted full overlap matrix appear as Figure 91 and Figure 92, and the portfolio's characteristics appear in Table 11.

		Hab - O_2 provision	Hab - CO_2 removal	Hab - CO_2 regeneration	Hab - N_2 provision	Hab - Humidity control	Hab - Temp control	Hab - TCC	Hab - H_2O provision	Hab - liquid waste	Hab - solid waste	EVA - O_2 provision	EVA - CO_2 removal	EVA - CO_2 regeneration	EVA - N_2 provision	EVA - Humidity control	EVA - Temp control	EVA - TCC	EVA - H_2O provision	EVA - liquid waste	EVA - solid waste	PR - O_2 provision	PR - CO_2 removal	PR - CO_2 regeneration	PR - N_2 provision	PR - Humidity control	PR - Temp control	PR - TCC	PR - H_2O provision	PR - liquid waste	PR - solid waste	LSAM - O_2 provision	LSAM - CO_2 removal	LSAM - CO_2 regeneration	LSAM - N_2 provision	LSAM - Humidity control	LSAM - Temp control	LSAM - TCC	LSAM - H_2O provision	LSAM - liquid waste	LSAM - solid waste	CEV - O_2 provision	CEV - CO_2 removal	CEV - CO_2 regeneration	CEV - N_2 provision	CEV - Humidity control	CEV - Temp control	CEV - TCC	CEV - H_2O provision	CEV - liquid waste	CEV - solid waste	ISS - O_2 provision	ISS - CO_2 removal	ISS - CO_2 regeneration	ISS - N_2 provision	ISS - Humidity control	ISS - Temp control	ISS - TCC	ISS - H_2O provision	ISS - liquid waste	ISS - solid waste
Name		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
Hab - O_2 provision	1											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Hab - CO_2 removal	2											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Hab - CO_2 regeneration	3											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Hab - N_2 provision	4											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Hab - Humidity control	5											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hab - Temp control	6											0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Hab - TCC	7											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hab - H_2O provision	8											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hab - liquid waste	9											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hab - solid waste	10											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
EVA - O_2 provision	11	0	0	0	0	0	0	0	0	0	0											1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EVA - CO_2 removal	12	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EVA - CO_2 regeneration	13	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EVA - N_2 provision	14	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EVA - Humidity control	15	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EVA - Temp control	16	0	0	0	0	0	1	0	0	0	0											0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
EVA - TCC	17	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EVA - H_2O provision	18	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
EVA - liquid waste	19	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
EVA - solid waste	20	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PR - O_2 provision	21	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0											1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PR - CO_2 removal	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PR - CO_2 regeneration	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PR - N_2 provision	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PR - Humidity control	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PR - Temp control	26	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
PR - TCC	27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PR - H_2O provision	28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PR - liquid waste	29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0											0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PR - solid waste	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - O_2 provision	31	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0											1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - CO_2 removal	32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - CO_2 regeneration	33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0											0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - N_2 provision	34	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
LSAM - Humidity control	35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - Temp control	36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - TCC	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - H_2O provision	38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - liquid waste	39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0											0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
LSAM - solid waste	40	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
CEV - O_2 provision	41	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0
CEV - CO_2 removal	42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0
CEV - CO_2 regeneration	43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0
CEV - N_2 provision	44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0											0	0	0	1	0	0	0	0	0	0
CEV - Humidity control	45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0
CEV - Temp control	46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	1	0	0	0	0
CEV - TCC	47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	1	0	0	0
CEV - H_2O provision	48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											0	0	0	0	0	0	0	0	0	0
CEV - liquid waste	49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0											0	0	0	0	0	0	0	0	0	0
CEV - solid waste	50	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1											0	0	0	0	0	0	0	0	0	1
ISS - O_2 provision	51	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
ISS - CO_2 removal	52	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
ISS - CO_2 regeneration	53	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
ISS - N_2 provision	54	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0										
ISS - Humidity control	55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
ISS - Temp control	56	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0										
ISS - TCC	57	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0										
ISS - H_2O provision	58	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
ISS - liquid waste	59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
ISS - solid waste	60	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1										

Figure 91. Full overlap matrix for Portfolio VIII.

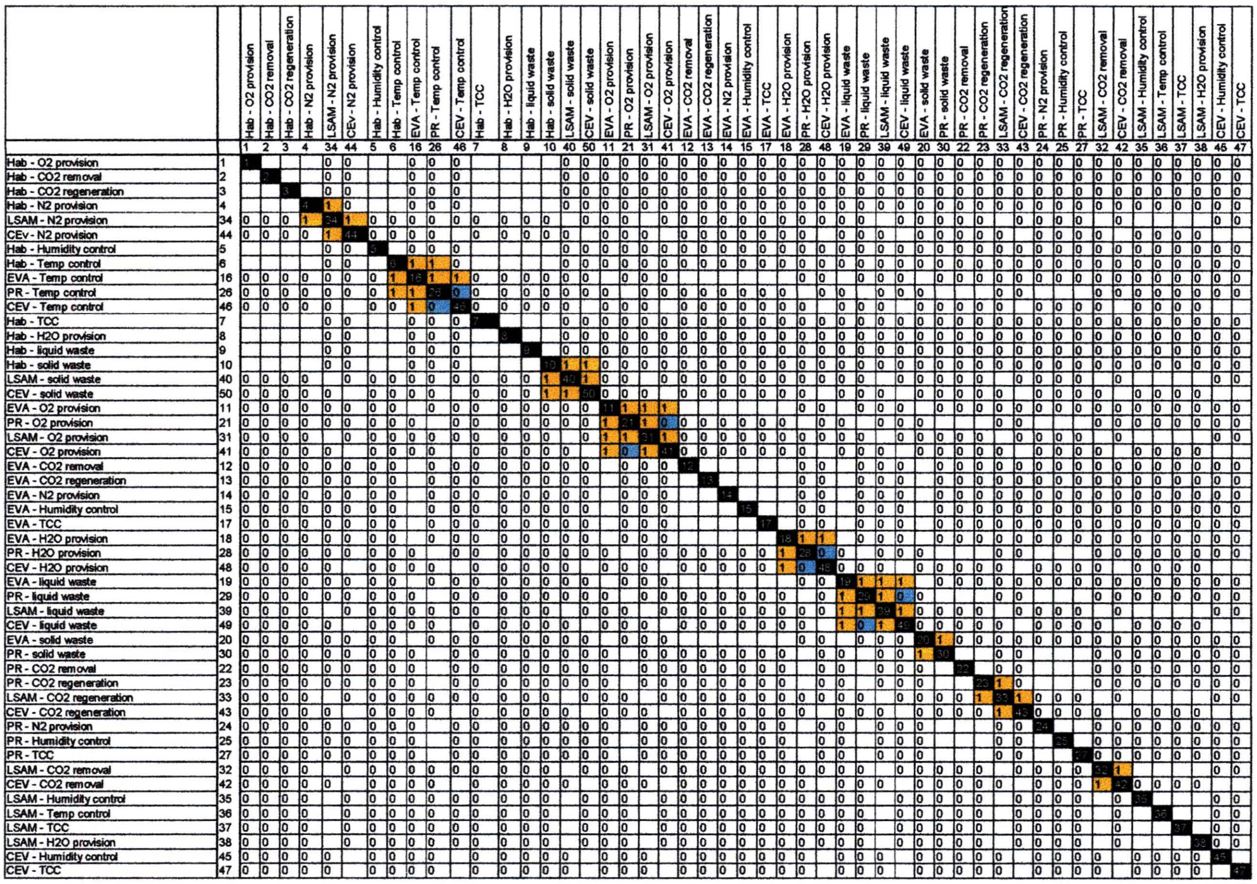

Figure 92. Sorted full overlap matrix for Portfolio VIII.

Portfolio (Architectures)	VIII (Hab 2, EVA 2, PR 2, Xfer 1)
Total Equivalent Campaign Mass (tonnes)	100.9
Total Spares Mass (kg)	1956
Total Development Cost ($M, FY2010)	516.42
Total Cost ($M, FY 2010)	3081.42
TRL levels	TRL 6+: 20 TRL 5: 1 TRL 4: 0 TRL 3: 0

Table 11. Characteristics of Portfolio VIII.

A summary table listing all the major features of each portfolio appears in Table 12.

Portfolio (Architectures)	I (Hab 1, EVA 1, PR 1, Xfer 1)	II (Hab 1, EVA 1, PR 2, Xfer 1)	III (Hab 1, EVA 2, PR 1, Xfer 1)	IV (Hab 1, EVA 2, PR 2, Xfer 1)	V (Hab 2, EVA 1, PR 1, Xfer 1)	VI (Hab 2, EVA 1, PR 2, Xfer 1)	VII (Hab 2, EVA 2, PR 1, Xfer 1)	VIII (Hab 2, EVA 2, PR 2, Xfer 1)
Total Equiv. Campaign Mass (mT)	107.6	93.9	111.0	97.4	111.0	97.4	114.6	100.9
Total Spares Mass (kg)	1704	1861	1725	1882	1776	1934	1798	1956
Total Dev Cost ($M, FY2010)	454.57	499.48	468.46	512.35	458.23	503.45	472.23	516.42
Total Cost ($M, FY 2010)	3073.68	2884.64	3124.75	2934.70	3219.99	3031.27	3271.18	3081.42
TRL levels	6+: 17 5: 1 4: 0 3: 0	6+: 18 5: 2 4: 0 3: 0	6+: 18 5: 1 4: 0 3: 0	6+: 19 5: 2 4: 0 3: 0	6+: 18 5: 0 4: 0 3: 0	6+: 19 5: 1 4: 0 3: 0	6+: 19 5: 0 4: 0 3: 0	6+: 20 5: 1 4: 0 3: 0

Table 12. Summary of portfolio properties.

These eight portfolios represent eight arrangements of the seven interesting ECLS system architectures for each of the four instantiations plus the CEV, each of which presents different types of opportunities for commonality. The level of overall commonality in any one portfolio is roughly apparent from inspection of the number of items at various TRL levels. The sum of the numbers of items at each TRL level is the total number of unique items to be developed. Fewer unique items represents a higher degree of commonality, although in some cases the number of items is smaller because some dual-use items are in the portfolio (such as a CHX).

Also of note is the fact that some items are common because no other design choices exist rather than by deliberate selection. An example of this is the fact that the Habitat, Transfer Vehicle, and CEV all use a CHX for temperature control, due to the fact that they all have bulk thermal control systems to which heat must be transferred in order to be rejected, and thus a CHX is the only reasonable choice. This tends to lead to a somewhat lower number of total unique items to develop than might be expected (as the four instantiations plus the CEV deliver the same ten functions five times, up to fifty unique choices could theoretically be made, although this is not realistic).

CHAPTER 5. Conclusions and Recommendations

Based on the results of commonality analysis presented in the previous chapter, some recommendations for technological development and commonality can be made. This chapter summarizes these recommendations.

5.1 Technological Development Recommendations

Technological development recommendations are drawn as much from the results of the architectural analysis conducted as from the commonality analysis.

5.1.1 Develop high-closure water systems

One result of the architectural analysis was the identification of a few dominant technologies for water reclamation. Technology options which offer at or near 100% recovery of water used (such as multifiltration) displayed a tendency to dominate architectures, and technology options which offer the best amount of water reclamation possible (such as the HSWPA/condensate hybrid unit, which can even recuperate metabolic water from carbohydrates in food) also show great potential for reducing the total amount of mass that must be shipped to the surface of the Moon over the course of an exploration campaign.

This is a logical result, as the amount of water budgeted for consumption per person per day (more than 15 kg in the Habitat, more than 5 kg on traverse or on EVA) dominates the amount of oxygen budgeted for consumption per person per day (0.84 kg) greatly. Even though the overhead for shipping water is much lower than for shipping oxygen, the difference in consumption is such that water dominates the amount of mass that must be shipped to the surface. Therefore, conserving this resource by limiting net consumption of it (as some technology options have the potential to allow) should be an early goal of further technology development efforts.

5.1.2 Continue to pursue full closure of the carbon loop

In the architectural analysis conducted, technology options which allow recovery of carbon dioxide and its reduction to regenerate oxygen are seen to be either competitive with or dominant over purely open-loop options. The dominance of carbon dioxide removal using regenerable systems in long-duration instantiations has been marked ever since the Skylab program, and it is seen here that even when short-duration instantiations, such as EVA suits, are used repeatedly over the course of a long campaign, the benefits of technology options such as the solid amine vacuum desorbed (pressure-swing) beds become apparent. Further development of such technology is an attractive area for the investment of research efforts.

5.1.3 Incorporate water saving systems into solid amine technology option

Although the amount of oxygen recoverable from carbon dioxide may not be large except when aggregated over long periods of time, further development need not focus exclusively on this aspect of the technology. The solid amine vacuum desorbed bed also controls humidity, but a consequence of this feature of the technology is that water, in the form of humidity created by perspiration and respiration from the human, is also lost. A key improvement in this technology, which is attractive in terms of its power and mass requirements, even to the point where it may be a feasible option for use on EVA suits, would be the incorporation of a water saving system into the ECLS system. Placing a water saving device before the carbon dioxide removing solid amine bed would allow for the reduction or even complete elimination of water losses via the solid amine bed.

5.1.4 Develop Sabatier systems with extensibility potential

As noted in Chapter 3, the ACRS technology option may be attractive strictly in terms of overall equivalent campaign mass, although its current low TRL makes it risky to develop. The Bosch reactor technology option suffers from many similar maturity and technological problems, although it has a somewhat higher TRL. The Sabatier system, however, is well understood and mature. It is preferred over the ACRS or Bosch units because of its far lower risk and greater maturity.

However, the Sabatier reactor vents gas in the form of methane, and this necessitates a net influx of hydrogen, resulting in a shipping requirement of a certain amount of either hydrogen or water for every day over the course of the campaign. While this penalty is not at all intolerable, it would be preferable to eliminate it completely. One possible solution for this is to design Sabatier units with extensibility.

The ACRS unit is simply a methane catalysis system attached to a Sabatier reactor. The ACRS captures the methane expelled from the Sabatier unit and produces carbon and hydrogen. The hydrogen is recycled into the Sabatier unit, eliminating the need for shipments of consumable hydrogen, and the carbon can be packed and dumped. Since a Sabatier unit can function very well in a highly-closed ECLS system by itself, but an ACRS has the potential to increase the closure level even higher, it may be advisable to develop and deploy Sabatier reactors with inherent capability to interface with a future ACRS system. Although ACRS technology is not now the best option itself for development, retaining the ability to take advantage of it should it become available in the future is one potential way to make maximum leverage of existing useful technology.

5.1.5 Enable low-mass pressurized rover architectures via heat sinks

One further recommendation is the further development of heat sink technology options for use on the Pressurized Rover instantiation. Large instantiations such as the Habitat, CEV, and Transfer Vehicle include dedicated thermal control systems, with radiators for final rejection of heat to the surrounding environment. The EVA suit and Pressurized Rover instantiations do not use radiators, and so must rely on either the proven technology of water sublimation or a separate technology, such as the use of a heat sink. The water heat sink is too massive to be useful on either the Pressurized Rover or the EVA suit, but the ice heat sink is not too massive to be carried around by the Pressurized Rover. Notably, ECLS system architectures which rely on this technology option do not display the large campaign masses characteristic of ECLS system architectures which must consume considerable amounts of water per person per day in order to provide cooling, and therefore this technology option should be pursued.

Further benefits from carrying an ice heat sink may also be realizable. Large amounts of water, whether in solid or liquid form, can provide some shielding from solar proton events should the crew of the Pressurized Rover find themselves caught in such an event while on traverse. Furthermore, the slow melting of the ice will provide a stock of emergency water, should it be needed.

This technology option is currently assessed as being at TRL 5, because while the basic principles of using ice as a heat sink are well understood and have been in wide use for some time, no prototype of a space-qualified ice heat sink is yet known to exist. It is not expected that the technological development required will be significant, due to the well-understood properties of the basic physical mechanism, and so further development of this technology option is likely to benefit future exploration efforts greatly.

5.2 Commonality Recommendations

The benefits and penalties of commonality, although detailed in the previous chapter, can also be understood through comparison of the aggregated results.

A plot of the trend in development cost, plotted against the portfolios arranged roughly in order of increasing commonality (arranged in descending order by number of unique items to develop) appears in Figure 93. Note that the development cost drops as commonality increases.

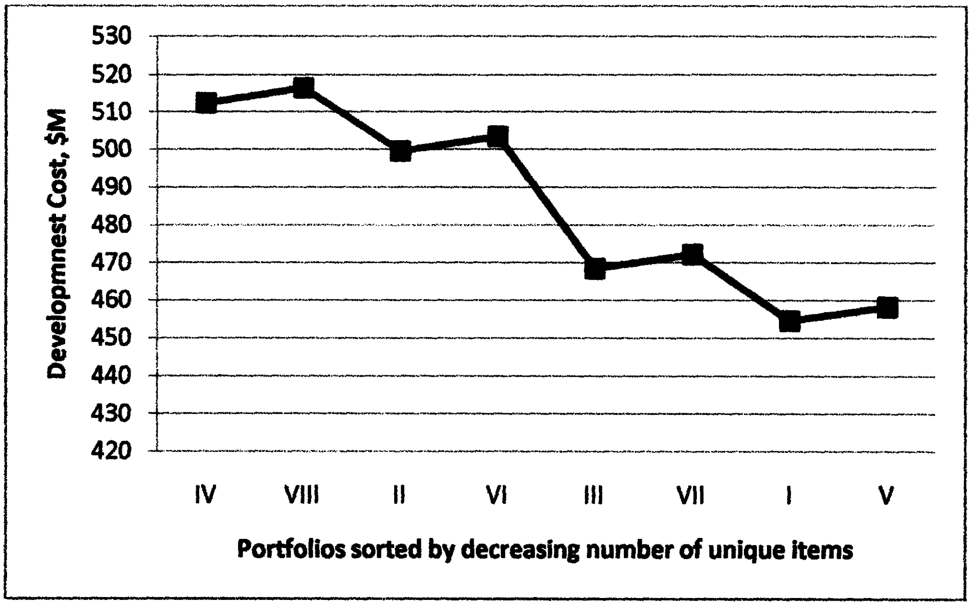

Figure 93. Development costs for portfolios, arranged by increasing commonality.

Notably, risk and total cost remain interrelated. A plot of all the portfolios, arranged by the number of unique items to be developed for each portfolio (which correlates to the degree of commonality in the portfolio), appears in Figure 94.

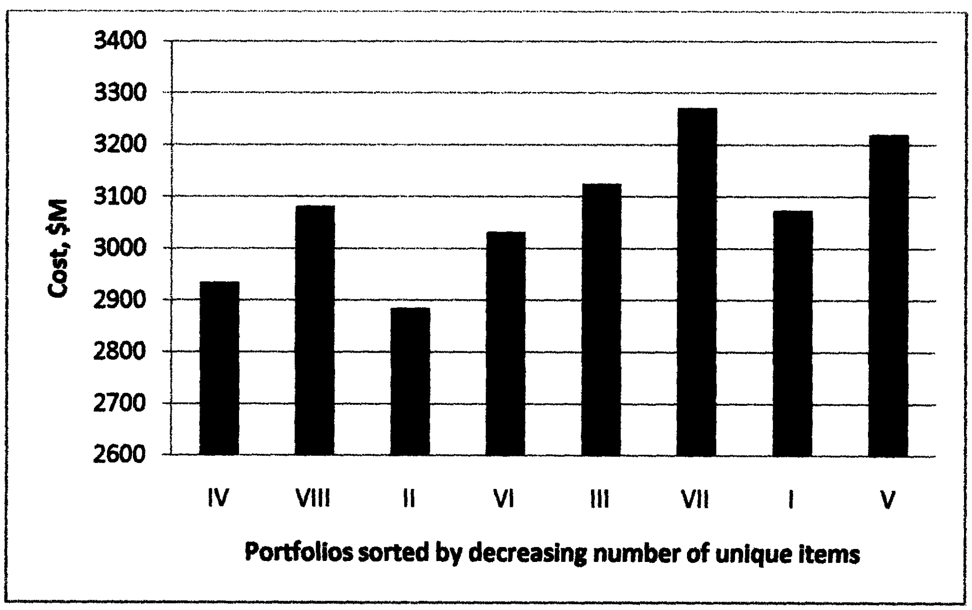

Figure 94. Total portfolio costs, sorted by commonality.

Note that the two lowest overall costs are enabled by risk, in that Portfolios II and IV both have two items at TRL 5, rather than one or none. Of the portfolios with one item at TRL 5, the lowest total cost is that of Portfolio VI, closely followed by Portfolio I. Of these, Portfolio I notably includes commonality for carbon dioxide removal (using the solid amine vacuum desorption technology option) across the EVA suit, Pressurized Rover, Transfer Vehicle, and CEV instantiations. Portfolio VI, however, does not, yet Portfolio VI displays slightly lower lifecycle costs than does Portfolio I.

The key lesson is that, while commonality opportunities may abound, they do not all result in decreased lifecycle costs. However, comparison of estimated costs should be made on a one-to-one basis between portfolios, as this analysis reveals that, while some portfolios with commonality may dominate others without it, this is not always the case. As seen here, the most dominant portfolio is in fact Portfolio II (with a common solid amine vacuum desorption technology option for the EVA suit, Transfer Vehicle and CEV instantiations, but a point design for the Pressurized Rover). The use of a solid amine vacuum desorption unit on the Pressurized Rover instantiation would be an increase in commonality, but it would not benefit the portfolio as a whole over its lifecycle.

This is seen in comparing Portfolios I and II. As the Pressurized Rover instantiation is moved from commonality (Portfolio I) to a point design (Portfolio II), total cost drops, rather than increases. On the other hand, as the EVA suit is also moved away from commonality (Portfolio II) to a point design (Portfolio IV), spares mass increases, development cost increases, and the total cost also increases. Thus the point of optimal commonality lies neither with all four of the Habitat, EVA suit, CEV, and Pressurized Rover as point designs, nor with all four as more common designs. The best point of commonality is somewhere in between.

5.3 Conclusions

This thesis has adapted a Commonality Analysis Methodology, proposed and developed by Hofstetter (2), and applied it to the analysis of ECLS systems for planetary surface exploration. A large set of ECLS system architectures was generated, and downselection to a few interesting architectures was conducted. The seven interesting architectures were used in combination with the baseline architecture of the CEV and the heritage design of the International Space Station to locate and visually display the points of potential commonality. Once these points were displayed, a sorting DSM algorithm presented the same points in a fashion intended to aid designers in setting requirements on common items. Once this was completed, the use of metrics, including overall equivalent campaign mass, spares mass, total cost, and technological development risk allowed assessment of the penalties and benefits of commonality. Notably, it was seen that higher degrees of commonality (meaning broader use of the same technology option to deliver the same function in more different instantiations) was not necessarily always an enabler of lower lifecycle costs. An optimal point for commonality exists, as some instantiations perform better as point designs, even in the context of the portfolio of exploration systems as a whole. Finally, technology risk is seen to correlate somewhat inversely to the benefits of commonality – there are trades that must be made between predicted cost and the risk of that cost increasing by up to 100%. Thus, it is concluded that the designer of such a portfolio of surface exploration systems must carefully assess all the benefits and penalties of commonality for all interesting portfolios before deciding what and how much commonality to pursue.

CHAPTER 6. Future Work

6.1 Inclusion of More Technology Options in Database

One step that can be taken to further the work presented here is the inclusion of more technology options in the database which is used to create the OPN models. The inclusion of a technology option requires that information be available on its sizing data (so that sizing parameters, such as its equipment mass per person and its consumables mass per person per day) can be derived for it, and that information on its general method of functioning be available, so that relationships between it and other technology options included in the ECLS system can be extrapolated.

Technology associated with life support systems is under continual development, and new applications for existing technology are continually being developed. New technology options for ECLS systems are likely to arise, and the inclusion of these technology options in the database will allow for a broader set of possible opportunities for commonality to be examined.

There are some technology options which were not included here but which would be included in future versions of the OPN models. Chief among these technology options are the following:

High Efficiency Particulate Air (HEPA) filters

Filters are already used in some ECLSS applications, and may be able to replace the use of activated charcoal partially or completely in some circumstances. Although filters are also generally more consumable than regenerable, they may be able to be engineered sufficiently lightweight and with sufficient affinity for contaminants of all molecular weights that they will dominate activated charcoal in consumable applications.

Aqueous Phase Catalytic Oxidation Post-Treatment System (APCOS)

The APCOS (7) is another technology option intended to be used in recycling human liquid wastes.

Reverse Water-Gas Shift (RWGS) reactor

The Reverse Water-Gas Shift (RWGS) reaction has been proposed for Mars In-Situ Resource Utilization activities, but it may be applicable for ECLSS as well, given that it operates on carbon dioxide with hydrogen to produce water and carbon monoxide. Research interest in the realm of reduction of carbon dioxide has typically focused on the Sabatier reaction, with less attention being paid to RWGS and Bosch units. However, the RWGS unit has some drawbacks of its own. It produces carbon monoxide, which inside a habitable volume may pose an increased risk if leaks were to occur, and furthermore loses some oxygen atoms this way, and is thus not able to provide complete closure of the air loop in an ECLS system. Finally, the zirconia electrolysis reaction creates similar products, without requiring hydrogen input, the use of a water-electrolysis unit, or even the same high levels of power that a RWGS system does. Although this technology option was not included here, a full and exhaustive exploration of the design space would add it to the database and OPN models.

Radio Isotope Thermal Energy (RITE)

The RITE process (7) is also another technology option intended to apply to the processing of human solid and liquid waste. It utilizes oxidation and a plutonium heat source.

Wet oxidation

The technology option for wet oxidation of solid wastes is a form of combustion (7). Some development work has been done, and a drawing-board prototype has been constructed (51).

Hydrazine decomposition

The use of hydrazine, chemical formula N_2H_4, which stores in liquid form with properties similar to those of water (7), is a possible choice for the generation of atmospheric nitrogen. Hydrazine can be electrolyzed into nitrogen and ammonia (7), and the resulting nitrogen can be used to pressurize habitable volumes.

Hydrazine is a liquid, and has better storage characteristics than gaseous nitrogen (7). Furthermore, it has a density near that of water (about 1240 kg/m^3), and is storable at room temperature (52).

Because hydrazine is a toxic chemical, it brings an increased element of risk when it is included inside a habitable volume. Primarily for this reason, this technology option was excluded from the database and from OPN models. However, other portfolios for other exploration missions may include circumstances where this technology option becomes more interesting, such as for long-term in-space habitats where hydrazine may be useful both as a source of nitrogen and as a propellant. In cases such as this, the inclusion of this technology option may be merited.

6.2 Continued Investigation of Existing Technology Options

The technology options which are included in the OPN models are themselves subject to change, especially in terms of the performance parameters associated with certain of the lower-TRL technology options. The development of the 2-bed molecular sieve illustrates this. It appears as TRL 2 or 3 in (7), but has improved performance parameters and a TRL of 5 or 6 when described in (18). As technological and research advances are made, new technology options will appear for ECLSS and existing technology options are likely to improve. The effects of improvement may change the results of this commonality analysis, especially in terms of improvements that reduce the need for consumables for any one technology option. If the amount of water vented to space along with carbon dioxide by a 4-bed molecular sieve or a Solid Amine Water Desorption unit can be reduced or eliminated completely, the consumables requirement for any ECLS system architecture which includes those technology options drops, and this may affect greatly the lifetime mass requirement (and thus life cycle cost) of these ECLS system architectures. The existing commonality analysis methodology is capable of dealing easily with such changes, but the database must be updated regularly.

Furthermore, the production of useful results from the commonality analysis is an important aspect of the process, and correct results require correct models. Although the database used here is well-researched, further investigation and verification of the parameters used may be appropriate. Especially as this methodology is applied to missions of longer duration (such as Mars surface exploration missions), small changes in the parameters of key technology options may affect the final results of the analysis.

6.3 Further Development of OPN Models

The OPN models used in this thesis suppress several aspects of an ECLS system. The function of fire detection and suppression, which is usually considered by NASA to be a part of ECLS, is not included in the models used here, nor is the provision of food, nor the provision of ventilation and air circulation. All these things require mass, volume, and some amount of power, but they are suppressed in the models used by this thesis.

Part of the reason for this involves complexity. The provision of food will likely be done in the same way no matter what air and water loops are used by an ECLSS system, as is likely also the case for fire detection and ventilation. The models are meant to be as simple as possible, but no simpler, and as such capture the differential mass of ECLS systems, rather than the entire mass. Some allowance is made for items like structural members, tubing, and wiring by the use of conversion factors taken from (8) that convert volume, power, and heat requirements into approximate equivalent mass, but nonetheless the OPN models do not capture the entire ECLS systems, only the parts of greatest interest for commonality analysis.

More complex and subtle models for ECLS systems could be developed, although care would need to be taken to ensure that the models, which will necessarily become more complex, do not also become so complicated that they cease to be easy to understand.

One specific adjustment to the OPN models might include a more detailed accounting of the usefulness of highly closed water loops. At the moment, this is accounted for by the hybrid HSWPA and condensate recovery technology option, which recovers some of the water that is included in fully-hydrated food and returns it to the water loop. As currently modeled, this has the effect of reducing daily consumable requirements, because less water needs to be supplied (either directly as drinking or wash water or indirectly as fully-hydrated food), but this advantage in daily consumables could also be translated into a reduced need for makeup oxygen, as the excess water could be electrolyzed for some incremental investment in power. The hydrogen released by this process could also aid in reducing the consumables requirement for a Sabatier reactor, if that technology option were also included in the ECLS system architecture.

Another improvement to modeling ECLS systems using OPN models might include the careful assessment of batch processes. Currently the model sizes everything for an approximated level of flow and functionality per day, but a model with options for batch-processing would include more details related to the temporary storage of effluents and reaction products, which would necessarily entail more detailed sizing of tanks and work rates. This would in turn allow the tailoring of ECLS systems to available power profiles.

6.4 Further Automation of Analysis Tools

The process of selecting and analyzing a set of ECLS system architectures for commonality opportunities requires as yet considerable investment of time and hand work. After assembling a database on the technology options available for each function of the ECLSS, these options must be assembled into a set of OPN models, which requires some effort, and the output of the models must be sifted for interesting architectures. Interesting architectures must then be entered by hand into a Commonality Sorter Matrix, which also requires some investment in its initial construction. After the Commonality Sorter Matrix has been run, a DSM partitioning tool identifies opportunities for commonality, and then system architectures must be extracted from the set of interesting architectures to create a set of exploration system portfolios.

The various steps of this process could be improved by being further automated. One key step on the way to full automation of the process would include the development of an interface tool that allows technology options to be selected from or entered into a database and then constructs an OPN model using the appropriate technology options arranged under the appropriate list of functions.

Another key automation effort would be the integration of the output of the down-selection process and the input steps for the Commonality Sorter Matrix. This would entail some amount of detailed coding, as the size of the Commonality Sorter Matrix depends on the original OPN model, and the results of the down-selection process are translated into the Commonality Sorter Matrix's blank spaces.

A third useful addition to the software tools used in the commonality analysis process would be an integrated operating environment. At the moment, the commonality analysis methodology relies on Excel tools and OPN tools, and while there do exist pathways for easy communication between the two programs, a unified operating interface would make comprehending the process and implementing it much simpler.

6.5 Investigate Limits of Design Space

When implemented according to the methods described in this thesis, the commonality analysis process compares only the portfolios that include interesting ECLS system architectures. More such interesting portfolios might exist, if more interesting ECLS system architectures are identified and carried forward into the commonality analysis phase after architecture generation and down-selection. Although it is likely that the most interesting are the first to be captured, this may not necessarily be the case. The repetition of the Commonality Analysis Methodology, to the extent of exhausting all possible interesting portfolios, may be an advisable future step. However, the number of interesting portfolios is a combinatorial result of the number of interesting architectures for each instantiation, and thus it is a very large design space that increases in size rapidly as the number of interesting architectures grows. If it cannot be explored fully, an investigation which locates and describes limits on the size of the space (or at least the interesting regimes therein) may also be a fruitful endeavor.

6.6 Expansion of Methodology to New Functions

Although work in this thesis is confined to examining the commonality between ECLS systems, it is possible to expand the general framework of commonality analysis to include any other system as well. However, systems on operating exploration vehicles do not stand completely alone, and commonality across systems as well as across instantiations may benefit life cycle costs.

Systems which are very good candidates for commonality with ECLS systems (and thus very good candidates for inclusion in future commonality analysis) include power systems, propulsion systems (both power and propulsion systems may include water as coolant, feed, or product), and of course In-Situ Resource Utilization systems. The inclusion of elements of these systems in the commonality analysis process would be simple in concept. It would only be necessary to add to the list of functions, where some would be ECLSS functions, and other would be power, ISRU, or propulsion systems functions. Then the inclusion of technology options, selection of interesting architectures, and identification of commonality opportunities could proceed as it otherwise would.

BIBLIOGRAPHY

1. **Bush, George W.** The President's Vision for Space Exploration. 2004.

2. **Hofstetter, Wilfried K.** Commonality Analysis. *PhD Thesis.* Cambridge, MA : MIT, To be published, 2008.

3. *Estimating Spare Parts Requirements with Commonality and Redundancy.* **Kline, Robert C. and Bachman, Tovey C.** 4, s.l. : AIAA Journal of Spacecraft and Rockets, 2007, Vol. 44.

4. **Koo, Ben.** *A Meta-Language for Systems Architecting.* Engineering Systems, MIT. Cambridge, MA : s.n., 2005. PhD Thesis.

5. **Dori, Dov.** *Object-Process Methodology.* s.l. : Springer, 2002.

6. *Architecture Generation for Moon-Mars Exploration Using an Executable Meta-Language.* **Simmons, Willard, Koo, Ben and Crawley, Edward.** CA : s.n., 2005. AIAA Space.

7. **Eckart, Peter.** *Spaceflight Life Support and Biospherics.* Torrance, CA : Microcosm, Inc., 1996.

8. **Larson, Wiley J. and Pranke, Linda K.** *Human Spaceflight Mission Analysis and Design.* New York : McGraw-Hill.

9. **Eckart, Peter (editor).** *The Lunar Base Handbook: An Introduction to Lunar Base Design, Development, and Operations.* New York : McGraw-Hill, 1999.

10. *Exploration Systems Mission Directorate Lunar Architecture Update.* **Stanley, Doug, et al.** Long Beach, CA : s.n., 2007. Presentation to Space 2007.

11. **Hamilton Sundstrand Space Systems International.** *Hamilton Sundstrand: Renewable Energy, Regenerative Fuel, and Space Suits.* [Online] 2003. http://www.snds.com/ssi/ssi/index.html.

12. **Hoffman, Stephen J., Kaplan, David L. and (eds).** *Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team.* Houston, TX : Lyndon B. Johnson Space Center, 1997.

13. **Plachta, David and Kittel, Peter.** *An Updated Zero Boil-Off Cryogenic Propellant Storage Analysis Applied Upper Stages or Depots in an LEO Environment.* Hanover, MD : NASA Center for Aerospace Information, 2003.

14. **Hastings, L. J., Hedayat, A. and Brown, T. M.** *Analytical Modeling and Test Correlation of Variable Density Multilayer Insulation for Cryogenic Storage.* s.l. : NASA, 2004.

15. **Dumoulin, Jim.** NSTS News Reference Manual. [Online] NASA, August 31, 2000. [Cited: May 2, 2008.] http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/stsref-toc.html.

16. **McGoff, M. J. and King, J. C.** *Superoxide Configurations for Atmosphere Control Systems.* Wright-Patterson AFB, Ohio : Aerospace Medical Research Laboratories, 1966.

17. **Chang, Craig and Rousseau, Jean.** *Space Station Molecular Sieve Development, NASA Contract NA58-36424.* Los Angeles : AiResearch Manufacturing Company, 1986.

18. **AlliedSignal Aerospace.** *Enhanced Molecular Sieve CO2 Removal Evaluation.* Torrance, CA : s.n., 1997.

19. **Josh Matthew, Book Manager.** International Space Station Environmental Control and Life Support System. *Mission Operations Directorate, Space Flight Training Division, Systems Training Branch.* Houston, TX : NASA, May 25, 2001.

20. **Wydeven, Theodore.** *A Survey of Some Regenerative Physico-Chemical Life Support Technology; NASA TM 101004.* Moffett Field, CA : NASA Ames Research Center, 1988.

21. *Development of a Prototype Pressure Swing CO2/H2O Removal System for an Advanced Spacesuit.* **Filburn, Thomas, Dean, W. Clark and Thomas, Gretchen.** Danvers, MA : SAE, 1998. 28th International Conference on Environmental Systems.

22. *Development of Pressure Swing Adsorption Technology for Spacesuit Carbon Dioxide and Humidity Removal.* **Papale, William, Paul, Heather and Thomas, Gretchen.** Norfolk, VA : SAE, 2006. 36th International Conference on Environmental Systems (ICES).

23. *Development Status of the Carbon Dioxide and Moisture Removal Amine Swing-bed (CAMRAS).* **Nalette, Tim, Papale, Wiliam and Smith, Fred.** Chicago : SAE, 2007. 37th International Conference on Environmental Systems (ICES).

24. *A Solid-State Compressor for Integration of CO2 Removal and Reduction Assemblies.* **Mulloth, Lila M. and Finn, John E.** Toulouse, France : SAE, 2000. 30th Internation Conference on Environmental Systems.

25. *Air-Cooled Design of a Temperature-Swing Adsorption Compressor for Closed-Loop Air Revitalization Systems.* **Mulloth, Lila M., et al.** Colorado Springs, CO : SAE, 2004. 34th International Conference on Environmental Systems (ICES).

26. *Development and Testing of a Temperature-Swing Adsorption Compressor for Carbon Dioxide in Closed-Loop Air Revitalization Systems.* **Rosen, Micha S., et al.** Rome : SAE, 2005. 35th International Conference on Environmental Systems (ICES).

27. *Kinetics of the Sabatier Reaction on a Nickel Catalyst in a Flow-Through System.* **Naumov, V. A., Krylov, O. V. and Gavrilov, L. I.** 1979, Kinetics and Catalysis, Vol. 20, pp. 740-744.

28. **Morring, Frank Jr.** NASA Aims for All-Commercial ISS Resupply. *Aviation Week online.* April 20, 2008, pp. URL: http://www.aviationweek.com/aw/generic/story_generic.jsp?channel=awst&id=news/aw042108p2.xml&headline=NASA%20Aims%20for%20All-Commercial%20ISS%20Resupply.

29. *The 2001 Mars In-Situ-Propellant-Production Precursor (MIP) Flight Demonstration: Project Objectives and Qualification Test Results.* **Kaplan, D. I., et al.** Long Beach, CA : AIAA, 2000. AIAA-2000-5145.

30. *A Survey of Alternative Oxygen Production Technologies.* **Lueck, Dale E., et al.** s.l. : American Institute of Physics, 2001. Space Technology and Applications International Forum - 2001. pp. 127-132.

31. **Waligora, J. M. and Horrigan, D. J.** Metabolism and Heat Dissipation during Apollo EVA Periods. *Biomedical Results of Apollo.* [Online] February 28, 2002. [Cited: April 21, 2008.] http://lsda.jsc.nasa.gov/books/apollo/s2ch4.htm.

32. **The Engineering Toolbox.** Ice - Thermal Properties. *The Engineering Toolbox.* [Online] 2005. http://www.engineeringtoolbox.com/ice-thermal-properties-d_576.html.

33. SilicaGel.net FAQ. *SilicaGel.net.* [Online] [Cited: May 20, 2008.] http://www.silicagel.net/faq.html.

34. *ISS Water Reclamation System Design.* **Parker, David S., O'Connor, Edward W. and Bagdigian, Robert.** Denver, CO : SAE, 1999. 29th International Conference on Environmental Systems.

35. *Results of the Vapor Compression Distillation Flight Experiment (VCD-FE).* **Hutchens, Cindy F. and Graves, Rex.** Colorado Springs, CO : SAE, 2004. 2004-01-2450.

36. Technical Felt Properties. [Online] Southeastern Felt and Supply Corp. http://www.sefelt.com/tfelt.htm.

37. **Tanner Management Corporation Incineration Systems.** Pyrotechnix Incinerator Systems. [Online] June 17, 1997. [Cited:] http://www.incineration.com.

38. *Space Systems Architecting Using Meta-Language.* **Simmons, Willard, Koo, Ben and Crawley, Edward.** 2005. 56th Internation Astronautical Congress.

39. **Carson, Maurice A., et al.** Extravehicular Mobility Unit. *Biomedical Results of Apollo.* [Online] February 28, 2002. [Cited: May 3, 2008.] http://lsda.jsc.nasa.gov/books/apollo/S6CH6.htm.

40. **Sakolosky, J. J.** *The Skylab Humidity Problem and Several Possible Solutions - Case 620.* Washington, D. C. : Bellcomm, Inc., 1970.

41. **George C. Marshall Space Flight Center.** *MSFC Skylab Orbital Workshop TM-64813 Vol. 5.* Washington D. C. : NASA, 1974.

42. —. *MSFC Skylab Structures and Mechanical Systems Mission Evaluation, TMX-64824.* Washington, D. C. : NASA, 1974.

43. **Albritton, John, et al.** MORPHLAB summary. *Dave Akin's Web Site at the University of Maryland Space Systems Laboratory.* [Online] [Cited: April 28, 2008.] http://spacecraft.ssl.umd.edu/academics/484S04/morphlab_summary.pdf.

44. **Charles Stark Draper Labs and MIT.** *Concept Exploration and Refinement Study.* Cambridge, MA : s.n., 2005.

45. **United States General Accounting Office.** *Best Practices: Better Management of Technology Development Can Improve Weapon System Outcomes.* 1999. GAO/NSIAD-99-162.

46. *Columbus Orbital Facility Condensing Heat Exchanger and Filter Assembly.* **Rose, Susan, et al.** Denver, CO : SAE, 1999. SAE 1999-01-2005.

47. *Boeing Crew Exploration Vehicle Environmental Control and Life Support System Architecture Overview.* **Saiidi, Mo and Lewis, John F.** Chicago : SAE, 2007. 37th International Conference on Environmental Systems (ICES).

48. *Crew Exploration Vehicle Environmental Control and Life Support Development Status.* **Lewis, John F.** Norfolk, VA : SAE, 2006. 36th International Conference on Environmental Systems (ICES).

49. **RAND Corporation.** *Speaking with a Commonality Language: A Lexicon for System and Component Development.* Santa Monica, CA : RAND Corporation, 2007.

50. *Spare Parts Requirements for Space Missions with Reconfigurability and Commonality.* **Siddiqi, Afreen and de Weck, Olivier L.** 2007, Journal of Spacecraft and Rockets, Vol. 44 No. 1, pp. 147-155.

51. **Eltron Research and Development Inc.** Spacecraft Water Regeneration by Catalytic Wet Air Oxidation. [Online] 2007. http://www.eltronresearch.com/sbir269.html.

52. **Pratt and Whitney Rocketdyne.** Theoretical Performance of Rocket Propellant Combinations (poster).

53. **Crawley, Edward and Simmons, Willard.** *Towards a Formalism for System Architecture -- From Value to Architecture.* MIT. October, 2006.

54. **Rozenblum, Ziv.** *Object-Process Networks & Object Process Diagrams -- Implimentation Issues of Oil Exploration Systems.* MIT. Cambridge, MA : s.n., 2007. Thesis.

55. **Crawley, Edward.** Course notes. *ESD.34 System Architecture.* [Course Notes]. s.l. : MIT, January 2006-December 2007.

56. **Leffler, William L., Pattarozzi, Richard and Sterling, Gordon.** *Deepwater -- Petroleum Exploration and Production -- A Nontechnical Guide.* s.l. : PennWell, 2003.

57. **Raymond, Martin S. and Leffler, William L.** *Oil and Gas Production in Nontechnical Language.* s.l. : PennWell, 2006.

58. *Exploration Rover Concepts and Development Challenges.* **Zakrajsek, James J., et al.** Orlando, FL : AIAA, 2005. 1st Space Exploration Conference.

59. **Wang, Tsen C. and Hendry, Charles R.** *Carbon Dioxide Removal With Mixture of Lithium Hydroxide and Sodasorb in Underwater Life Support Systems.* Ft. Pierce, FL : Harbor Branch Oceanographic Institution.

60. *Managing NASA's International Space Station Logistics and Maintenance Program.* **Butina, Anthony J.** s.l. : American Institute of Physics, 2001. Space Technology and Applications International Forum 2001.

61. *A Small Pressurized Rover Concept for Extended Lunar and Mars Exploration.* **Akin, David L. and Bowden, Mary L.** Long Beach, CA : AIAA, 2005. Space 2005.

62. **ILC Dover.** Questions and Answers About Space Suits. *Space Suit Evolution From Custom Tailored To Off-The-Rack.* s.l. : ILC Dover, Inc., 1994.

63. **George C. Marshall Space Flight Center.** *MSFC Skylab Orbital Workshop TM X-64813 Vol. 3* . Washington, D. C. : NASA, 1974.

64. International Space Station Familiarization and Training Manual. Houston, Texas : NASA, 1998. Revision A. ISS Fam C 21109.

65. **Yeh, H. Y.** *VPCAR and BWRS Trade Study.* Houston, TX : Lockheed Martin Space Operations, 1999. Contract NAS9-19100.

66. *ISS ECLSS Technology Evolution for Exploration.* **Carrasquillo, Robyn L.** Reno, NV : AIAA, 2005. AIAA-2005-337.

67. *Assessment of Technology Readiness Level of a Carbon Dioxide Reduction Assembly (CRA) for use on International Space Station.* **Murdoch, Karen, et al.** Colorado Springs, CO : SAE, 2004. SAE 2004-01-2446.

68. **Simmons, Willard Lennox.** A Framework for Decision Support in Systems Architecting. Cambridge, MA : MIT, 2008. Ph.D. Thesis.

Appendix A. Derivation of Sparing Model Equation

Mass of spares for unique items: m_U

Mass of spares for common items: m_C

Total number of spares: s_C (common items), s_U (unique items)

Reduction fraction in spares from commonality: $x = s_C/s_U = 0.67$; Siddiqi and de Weck, 2007.

The reduction fraction taken from Siddiqi and de Weck is meant to be conservative; not that they suggest reductions in spares mass from 33% to 50%. This corresponds to a reduction in backup ORUs on hand from 3 (for all unique items) to 2 (for common items). Although not all spares will be ORUs, this is used as an approximation of the total reduction in spares mass.

Reduction equation: R = reduction rate in spares mass = $(m_U - m_C)/m_U$. Thus, $m_C = (1 - R)m_U$.

This equation describes the mass of spares using commonality, if the mass of spares for all unique items and the reduction rate are known. The mass of spares for a baseline case with no specific commonality is set to 10% of the system's equipment mass per year.

The reduction rate can be calculated as follows.

Assume that the baseline case has spares mass described by the number of items as spares times the mass of each spare.

$$0.10m_{eq} = \sum_i s_i m_i$$

The total spares mass (estimated using the 10% rule) is the sum of the product of the number of spares for each item and the mass of each item across all items.

However, if some items are made common, then the previous equation should be expanded to include two summation terms: one for all common items and one for all unique items.

$$0.10m_{eq} = \sum_i s_i m_i + \sum_j s_j m_j$$

Here, the term *i* represents the number of unique items, while the term *j* represents the number of common items. Note that, for no common items, $j = 0$ and the equation reverts back to its previous form.

Further progress can be made after also making the simplifying assumption that the mass of spares is evenly distributed between components; that is, for any *i* or *j*, $m_i = m_j = m$. This allows summing of the terms according to

$$m_{spares} = m\left[\sum_i s_i + \sum_j s_j\right]$$

for the case where commonality exists. The terms can be further evaluated and the whole equation phrased as a percent reduction (according to $R = (m_U - m_C)/m_U$) as

$$R = \frac{m_{noncomm} - m_{comm}}{m_{noncomm}} = \frac{m[\sum_i s_i] - m[\sum_i s_i + \sum_j s_j]}{m[\sum_i s_i]}$$

Cancelling terms and multiplying through, where n_U is the number of unique items and n_C is the number of common items, it is seen that

$$R = \frac{s_U n_U - [s_U n_U + s_C n_C]}{s_U n_U}$$

Furhtermore, for the baseline case, the total number of items is N, and for the commonality-containing case, $N = n_U + n_C$. Therefore,

$$R = \frac{s_U N - [s_U(N - n_C) + s_C n_C]}{s_U N}$$

and if it is assumed that the number of spares in the case of common items is described by $s_C = xs_U$, where x is the reduction fraction in spares, here set to 0.67, then

$$R = \frac{s_U N - [s_U(N - n_C) + x s_U n_C]}{s_U N}$$

and so

$$R = \frac{N - [(N - n_C) + x n_C]}{N} = \frac{N - N + n_C - x n_C}{N} = \frac{n_C(1 - x)}{N}$$

resulting in the final equation for the reduction in spares mass, as $R = n_C(1-x)/N$. This results in a final spares mass for commonality of

$$m_C = \left(1 - (1 - x)\frac{n_C}{N}\right) m_U$$

and so the mass of spares for commonality can be described in terms of the mass of spares for a similar system with no commonality, the number of total items, the number of common items, and the reduction fraction, all of which are known or estimated.

Appendix B. Commonality Matrix Mathematics

The number of potential points of commonality in a set of system architectures can be described by the equation $C = F^*[(n^2 - n)/2 - y]$, where the factor $(n^2 - n)$ eliminates the points in the full overlap matrix where system architectures display potential commonality with themselves, the factor of ½ accounts for the symmetry of the full overlap matrix, and y is a term allowing for the non-main-diagonal bands in the matrix where architectures from one instantiation overlap with different architectures from the same instantiation. Assuming that only one architecture per instantiation will be developed, these intra-instantiation crossovers are less interesting. The term y is described by the equation $y = \sum_{j=1}^{j=k-1}(k - j)^*i$, where the term k = the number of architectures per instantiation in the design space, i = the number of instantiations, and the summation is from j = 1 to j = k -1. If we look at the overall equation describing the number of opportunities for commonality, we can set n = ki + c, where c is the number of fixed baseline architectures, and F is the number of functions for which any one architecture provides. Therefore, the total number of possible opportunities for commonality is described by the equation $C = F^*[((ki+c)^2 - (ki+c))/2 - \sum_{j=1}^{j=k-1}(j^*i)]$.

For the ECLS systems being analyzed in this thesis, F = 10, and c = 2 (for the CEV and ISS), just as i = 4. The number of potential points for commonality is then primarily a function of k, the number of architectures per instantiation. If k = 1, as in Chapter 3, then y = 0, and so C = 10*10 = 100. If k = 2, in the case where multiple portfolios are being compared, then y = i = 4, and C = 10*32 = 320, and as k climbs to 3, y becomes C = 10*66 = 660. At k = 4, y = 24 and C = 1120. As the number of potential opportunities for commonality rises with the number of portfolios being compared at once, so too does the calculation burden. The calculation burden consists of creating a number of input matrices equal to ki + c, adding data to them, and then creating a set of overlap matrices equal in size to C/F. Accordingly, a calculation burden of 15 in the case of k = 1 rises to 41 for k = 2, 79 for k = 3, and 129 for k = 4.