

Translating Life Support System Functions into Hardware Requirements and Operational Considerations for a Lunar Outpost Analogue

Bruce Davis, Jonathan Metts, and Dr. David Klaus
University of Colorado at Boulder, Aerospace Engineering Sciences Department

Abstract

Spacecraft analogues can provide valuable information in the early stages of the engineering design process, both in terms of optimizing the vehicle configuration and evaluating anticipated operational concepts for the mission. In order to do so in the most effective manner, attention must be paid to numerous details beyond the architectural layout and general field work to include simulation of the environmental control and life support subsystem (ECLSS) and related housekeeping tasks. Without this insight, significant components of analogue design and utilization can be overlooked, and the resultant flight vehicle design and mission operations may be compromised. These details can be defined and characterized through a series of related analyses.

Use of heuristic data can be employed to make first order mass estimates for ECLSS technologies, consumables, volume, and form factors. These can subsequently be derived from the mass data to incorporate their fit into the analogue habitat. *In Situ* Resource Utilization (ISRU) can also be factored in to the mass analysis. In addition, it has been shown that the maintenance time required for life support systems has been significantly underestimated in previous long term space habitats (Skylab and ISS), resulting in reduced crew time being available for the mission objectives. Therefore, in conjunction with specifying the volumetric inclusion of ECLSS hardware to be added to the analogue, we will work to define representative maintenance tasks to be conducted during the mission simulations to help ensure that proper operational expectations are established as well.

Another potential resource available for a Lunar Outpost infrastructure is the residual hardware left behind from the earlier Lunar Lander sortie flights. Identifying these capabilities and characterizing them using cost/benefit trade studies can influence the ultimate design of the outpost. The analogue is an ideal test bed for evaluating the potential inclusion of the various Lander components left on the lunar surface. This proposal, therefore, will extend the work we are currently doing in building an engineering prototype of the Lunar Lander habitat toward the longer term goals of the PISCES Lunar Outpost Analogue.

Finally, as it is likely that at some point the life support functions will be met in part by biological systems, the Lunar Outpost Analogue presents an excellent opportunity to evaluate the operational needs of actually maintaining living plants or other bioprocessing technologies in the analogue. Doing so will provide valuable insight to the designers of these various systems, an opportunity to examine automation solutions, and a realistic expectation of the crew time, skills, tools, and resupply deliveries needed to maintain the systems. We will help the PISCES team to determine if/when it becomes appropriate to add this feature to the analogue.

The ultimate success of establishing an Outpost on the moon is highly dependent on rigorously designing and testing the vehicle systems on Earth, and the use of a Lunar Outpost Analogue plays a critical role in this process. Ensuring the analogue design and utilization scenarios are as realistic as possible will make this role even more valuable. The Lunar-MARS team at CU is ready, willing and more than able to help bring this success about.

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1 Nomenclature

AES	= Aerospace Engineering Sciences (Major and Department)
AIAA	= American Institute of Aeronautics and Astronautics
ConOps	= Concept of Operations
CU	= University of Colorado at Boulder
EVA	= Extra-Vehicular Activity
ESAS	= Exploration Systems Architecture Study (Produced by NASA)
ECLSS	= Environmental Control and Life Support System
ISRU	= <i>In Situ</i> Resource Utilization
KSNN	= Kids’ Science News Network
Lunar-MARS	= Lunar Module & Analogue Research Station (at the University of Colorado)
NASA	= National Aeronautics and Space Administration
PISCES	= Pacific International Space Center for Exploration Systems
RFI	= Request for Information
VSE	= Vision for Space Exploration

2 Introduction

In the fall of 2006, a group of graduate students from the University of Colorado inspired by NASA's Vision for Space Exploration (VSE) began working on a full-scale Lunar Lander mockup with the goal to understand the constraints of the proposed vehicle and to supply feedback to the stakeholders. Over the course of the past fourteen months, the idea has developed into a system engineering process in which top level system requirements can be determined early within a program by iterating between the mockup use and mission requirement development. The research has matured into the University of Colorado Lunar Module & Analogue Research Station (Lunar-MARS) facility, consisting of three separate teams who are focusing on: 1) fabricating the Lunar Lander Mockup, 2) conducting a Subsystem Mass Analysis, and 3) developing a Concept of Operations. These teams have worked together to establish realistic top-level hardware and operational requirements. At the current time, the work is focused on developing Lunar Lander operational scenarios and hardware in conjunction with a detailed analysis of subsystems requirements pertaining to the docking mechanism, universal hatch, internal suit storage, and an innovative spacesuit-dustlock concept. It is our goal to use this knowledge to establish better requirements early within the VSE program to address human interfaces and vehicle maintenance.

The work being performed at the University of Colorado (CU) fuses well with the near and long term mission goals of PISCES. Figure 1 shows the proposed joint development plan in which the CU Lunar-MARS team can contribute to PISCES. On the left-hand side of Figure 1 is the current work being performed at the University of Colorado and incorporates the development of hardware requirements and technical studies being performed under the operational umbrella defined by NASA's "Lunar Exploration Objectives". (NASA, 2006) We are proposing several areas of research to be used in conjunction with the systems engineering "process" to help ensure that appropriate hardware and operational requirements are developed for the PISCES Outpost Analogue.

Our proposed effort (red/bold font in Figure 1) is to first conduct a mass/volume analysis to determine the impact that various internal subsystem components will have on the spacecraft habitat and to define environmental control and life support subsystem (ECLSS) maintenance tasks for the astronauts to ensure realistic operations are conducted in the Lunar Outpost simulations. The proposal also initiates a study to examine how the Lunar Lander hardware left behind after each sortie mission can be integrated into the Lunar Outpost infrastructure. Finally, the proposal leads to later examination of how biologically based processes (such as plants and microbes) can be studied at PISCES to supplement the ECLSS subsystem of future missions.

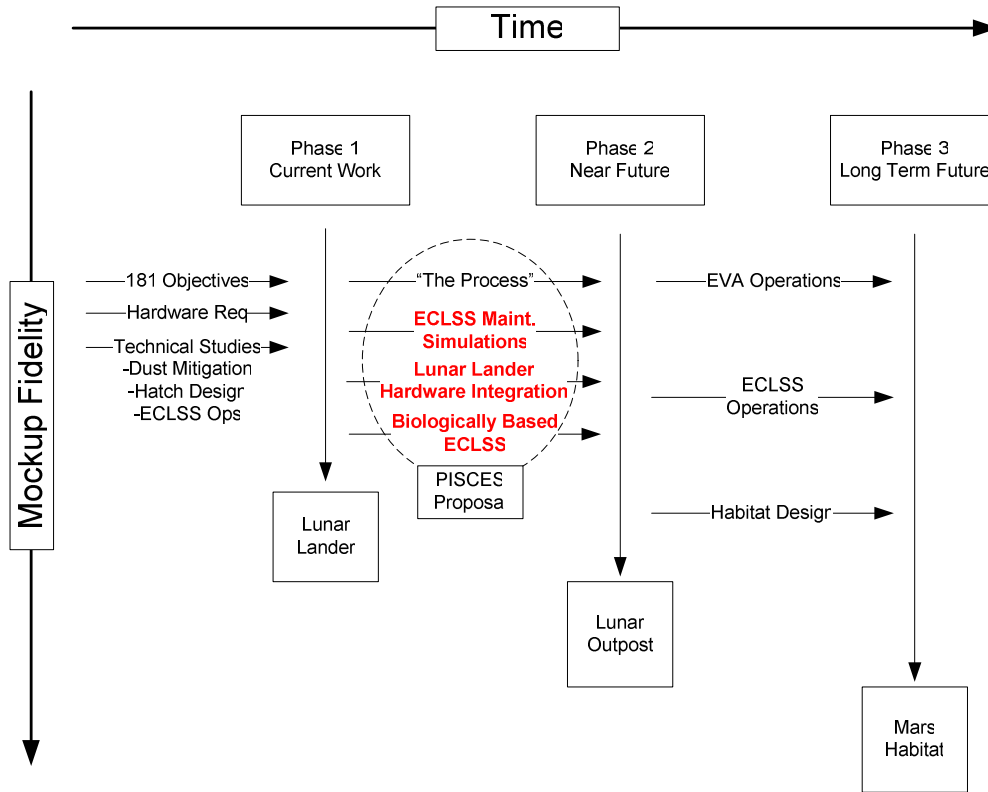


Figure 1: Lunar-MARS Information Development Plan

Together, these proposed efforts will enhance the PISCES Lunar Outpost design and operations, and they will be performed in conjunction with similar activities of Lunar-MARS at the University of Colorado. In Section 5 of this proposal, we discuss how, by using heuristic data, we can estimate the top level mass and volume allocations of the ECLSS and therefore establish a representative top-level module mass breakdown within the PISCES Lunar Analogue. This allows initial trade studies to be performed based on mass budgets to assess which systems are most efficient to incorporate. Once the mass budget has matured, the module volume for the PISCES application can be estimated that will allow realistic design of the analogue. This can also be coupled with the crew maintenance operations and expose the human factors associated with ECLSS operations. This knowledge will then play an iterative role in the design process, in which current NASA requirements will form the PISCES Lunar Outpost guidelines, while the experience gained using the PISCES facility will flow back to NASA and help assess which requirements are verifiable and applicable to the mission goal. We will conclude this proposal by discussing extensibility of the Lunar Lander to supplement the Lunar Outpost and how bioregenerative ECLSS functions can be incorporated into the PISCES facility. Finally, we will discuss the future plans for the Lunar-MARS facility at the University of Colorado and how they have potential to tie in with the PISCES Lunar Outpost analogue.

3 Work to Date

3.1 “The Process” Philosophy

The idea of applying a systems engineering approach at the analogue stage of the effort is that the sooner hardware and operational design requirements can be established early within a program and validated by understanding the vehicle function through use of a full-scale mockup, the more cost effective the ultimate vehicle design becomes. This aspect of systems engineering provides certainty to the top-level requirements and reduces the possibility that unknowns or problems might appear later within the program. When applied to the Lunar Lander vehicle, unknowns such as human factors, ECLSS operations, and maintenance needs can be established and will help to save on cost and time. It was determined by the CU Lunar-MARS team that the best way to implement this process is to first develop a Concept of Operations; from there, establish operationally-driven system design requirements. Next, hardware requirements and operational scenarios can be written in conjunction with the full

scale mockup. This iterative process can be created by taking a day-in-the-life scenario and identifying efficiencies in design. For the CU Lunar-MARS team, questions such as interior volume, top-level EVA procedures, and ECLSS maintenance can be determined. As the top level requirements solidify, the mockup will achieve an increasingly higher level of fidelity that translates into better defined subsystem-based requirements.

3.2 Lunar Lander Mockup Team

Our physical mockup activity started with the construction of a form-factor skeleton of the Lunar Lander as defined by NASA's Exploration Systems Architecture Study (ESAS) baseline configuration. The construction was iterated over the course of several months to ensure that the proper materials were used and that the skeleton remained re-configurable. At the beginning of the spring semester, a special topics graduate-level class continued to develop and refine the mockup facility, incorporating systems engineering processes for future project-related studies with direction from Johnson Space Center. By mid-summer of 2007, the initial construction phase of the mockup shell was completed, and more detailed work was initiated on hatch design and dust mitigation processes. The current configuration of the mockup is a 3 meter diameter shell composed of ½ inch EMT conduit with a re-configurable floor and an exterior covering of wire mesh and Mylar panels. All parts were constructed separately to enable rapid reconfiguration. The lunar mockup is currently divided into two separate sections, with one side representing the habitat / airlock and the other representing the ascent module. The ascent module has an end-cap and is fitted with tinted windows simulating those used by the astronauts during landing. The ascent module is currently being used as a basis for lateral undocking mechanism research. In addition to constructing a mockup of the Lunar Lander, a computer model was developed. One of the main advantages of the model is that it enables the students to arrange realistically sized objects inside for ease of evaluating location and geometry to optimize space. All objects can be shifted and sized prior to making actual changes in the mockup. The CAD model also enables students to assess different configurations in floor height or wall placement.



Figure 2: University of Colorado Lunar Lander Mockup (ca. April 2007)

3.3 Mass Analysis Team

In conjunction with the Lunar Lander mockup construction, another team was created to start analyzing the actual vehicle mass requirements. This effort began as a graduate course in the spring of 2006 that culminated in a mass analysis report submitted in response to NASA's Request for Information (RFI) for *Lunar Lander Concept Studies* (NNJ06LSAM05L) in June of 2006. The team initiated a follow on study in the spring of 2007 by first defining the different configurations of the Lunar Lander, identifying variables that would change the mass over time. The team then created a theoretical model that can be used to systematically manage the full vehicle mass analysis. The idea is that some elements depend heavily on other elements (such as propulsion mass) but others (such as module dry mass) are largely defined independently. Thus, the algorithm must calculate the independent pieces first and "build" up the vehicle mass in increasing levels of dependence. The team delivered a flow diagram as well as an input/output schematic explaining how the model works. Finally, the model was extrapolated to show that once complete, it would be ideal to determine the center of mass, thrust misalign vector, and radiation shielding, and it can be coupled with risk and cost factors as well.

3.4 Concept of Operations Team

NASA has been working with the global community in industry and academia to define the lunar exploration objectives. Over a year of workshops and editing led to the “Lunar Exploration Objectives” summary, which categorizes the different types of activities expected to be conducted on the Moon. (NASA,2004) From this list, the CU Lunar-MARS team formed a Concept of Operations (ConOps) to help establish top-level hardware and operational requirements for our mockup.

The ConOps team divided the lunar objectives into categories that addressed whether the objective fit into a sortie, outpost, or long duration mission, as well as internal or extravehicular activities. The lessons learned from this task were that common interfaces need to be maintained and that design modularity needs to be considered for changing mission architectures in terms of mission duration. Next the team divided the objectives into operational scenarios. This led to defining an operational handbook in which the team derived Level 2 requirements, or a set of “Shall Statements”, that could be used by future Lunar Lander engineers to ensure that the design is flexible enough to complete lunar objectives by future crews. A main focus of the ConOps team was to analyze top-level operational requirements of the Environmental Control & Life Support System (ECLSS) subsystem. These will be valuable when performing simulations and astronaut training in the full scale mockup, as they will highlight the complexities of the ECLSS system.

4 Current Lunar-MARS Tasks

4.1 Developing Requirements

Our current efforts are aimed at developing hardware requirements and operational scenarios in concert with the mockup hardware and the ConOps considerations defined thus far. There is significant value in developing hardware requirements, not only for engineering design considerations, but also for utilizing ConOps and prototype hardware concurrently. As a consequence, achievable and useful requirements can be examined using these specialized hardware studies, and this information can be fed back to NASA to help with the design of the flight hardware. This information also provides valuable knowledge for the people who will continue to work with both the analogue hardware and the flight units, as it shows some level of history and usage characterization during the development work.

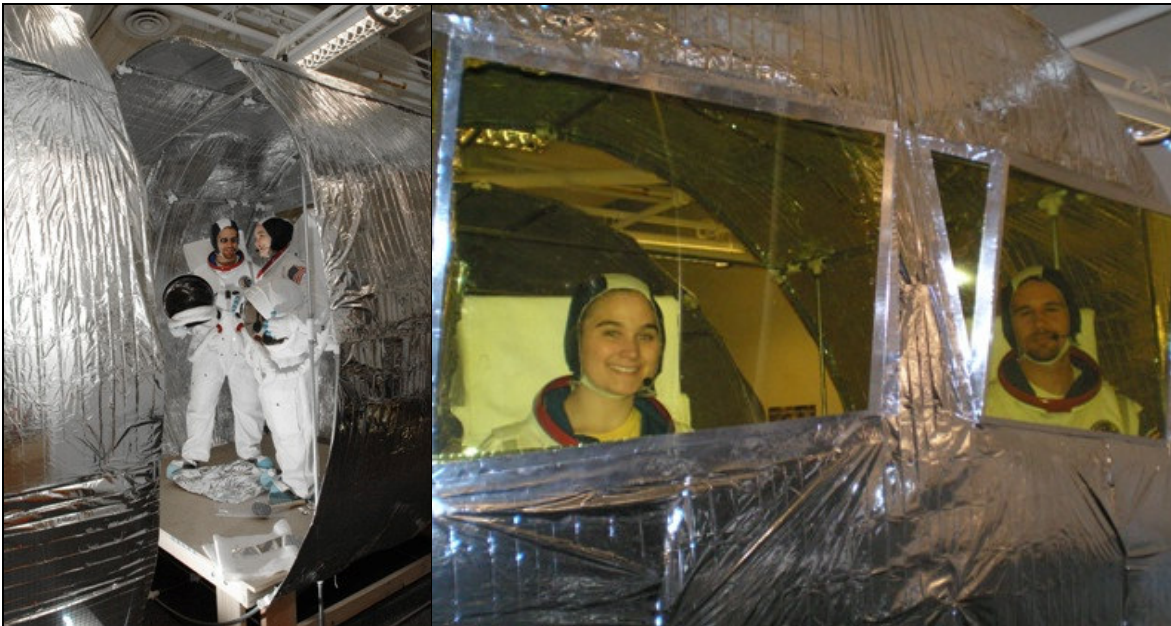


Figure 3: “Concept of Operations” Activities

The goal of the Lunar-MARS requirements development process is to define an optimal configuration for the flight hardware and to identify a subset of requirements to be validated using the Lunar-MARS mockup. In doing so, both hardware and operational requirements will be identified and documented. Each requirement in the Subsystem Requirements Documents is contained within a single Requirements Verification and Tracking Matrix (RVTM). The matrix identifies a method and level for verification of each requirement for each requirement as

applicable. Additionally, each subsystem requirement is evaluated against a set of pre-defined criteria to ensure the quality of each statement. All of this information is contained within a single spreadsheet for easy management and real-time update capabilities.

Through the summer and into fall of 2007, the CU Lunar-MARS team has been focused on implementing the process. With ConOps established, and with the first iteration of our full-scale mockup built, we are writing detailed and comprehensive hardware and operational requirements for the flight Lunar Lander. Those requirements which we are able to directly study via the mockup are being identified among the full set. Throughout this period, the mockup hardware is being revised to reflect the new requirements, and the requirements themselves are revised based on the “lessons learned” from each hardware iteration.

4.2 Focused Areas of Analysis

The primary subsystems of interest in our requirements development phase are the docking mechanism, universal hatch, internal suit storage, and an innovative dustlock concept. The Lunar Lander docking mechanism is unprecedented in that NASA plans for the Ascent module to lift off tangentially from the Habitat module, rather than with a normal axial separation. The hatch also allows passage among the Ascent module, Habitat / Airlock module, and the external environment. Internal suit storage is being studied due to the limited volume of the Lunar Lander. Finally, the dustlock is an original concept that includes a deployable, unpressurized vestibule in which crew members don and doff oversuits designed to prevent lunar dust from infiltrating the actual EVA suits (a major problem for the Apollo astronauts). The vestibule itself is designed to prevent lunar dust from entering the Lunar Lander, where it could harm the unprotected crew members as well as contaminate the ECLSS hardware and other sensitive machinery (Klaus et al., 2007).

5 Proposed CU Activities for PISCES

5.1 ECLSS Mass Analysis

The ECLSS mass estimate for PISCES facility was determined by a heuristic analysis and is primarily a function of crew size, duration of the mission, and equipment and tools applicable to the mission statement. This was calculated following the equation seen below where X_i represents the consumable variables, Y_j the dry mass variables, C_m the number of crew, and t the time in days. The equation was used to calculate the chart seen in Figure 4 below, which shows the mass requirements of a human for a 6 month duration mission. For PISCES, the analysis was modified to accommodate additional mission duration and crew size and can be seen in Figure 5. As expected, the required open-loop ECLSS mass representative plots are linearly dependent on crew size and mission duration. For the PISCES application, the analysis was further developed to specifically accommodate a crew of four over the course of a 180 day mission.

$$\text{Total ECLSS Mass} = \sum_{i=1}^n X_i(C_m, t) + \sum_{j=1}^n Y_j(C_m) \quad (1)$$

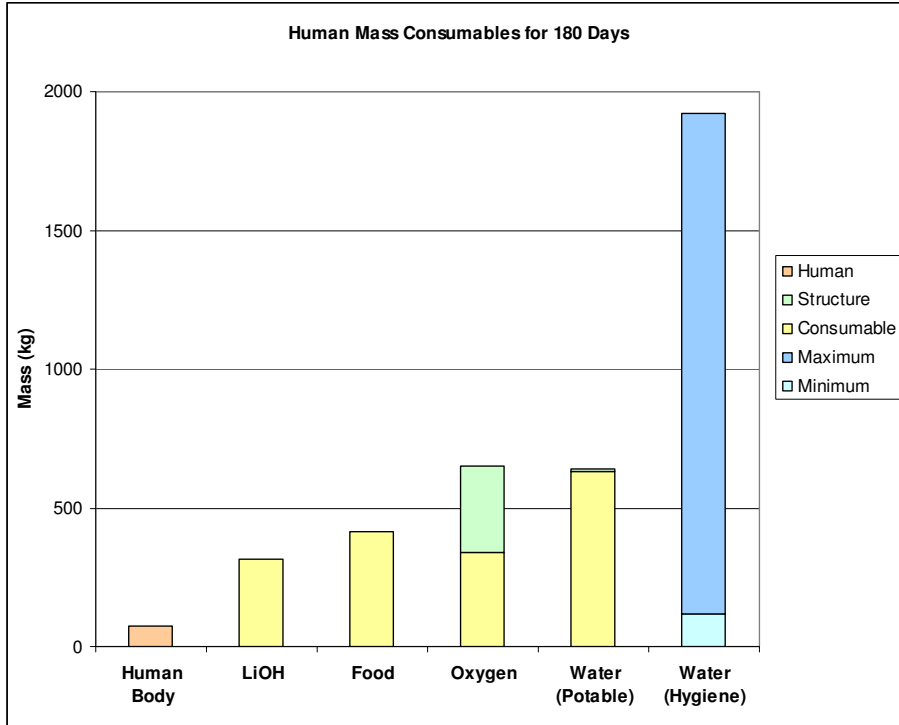


Figure 4: Comparison of human consumable-related variables, NASA (Aug, 2004)
 Note: the analysis in this paper does not include Hygiene water unless otherwise stated.

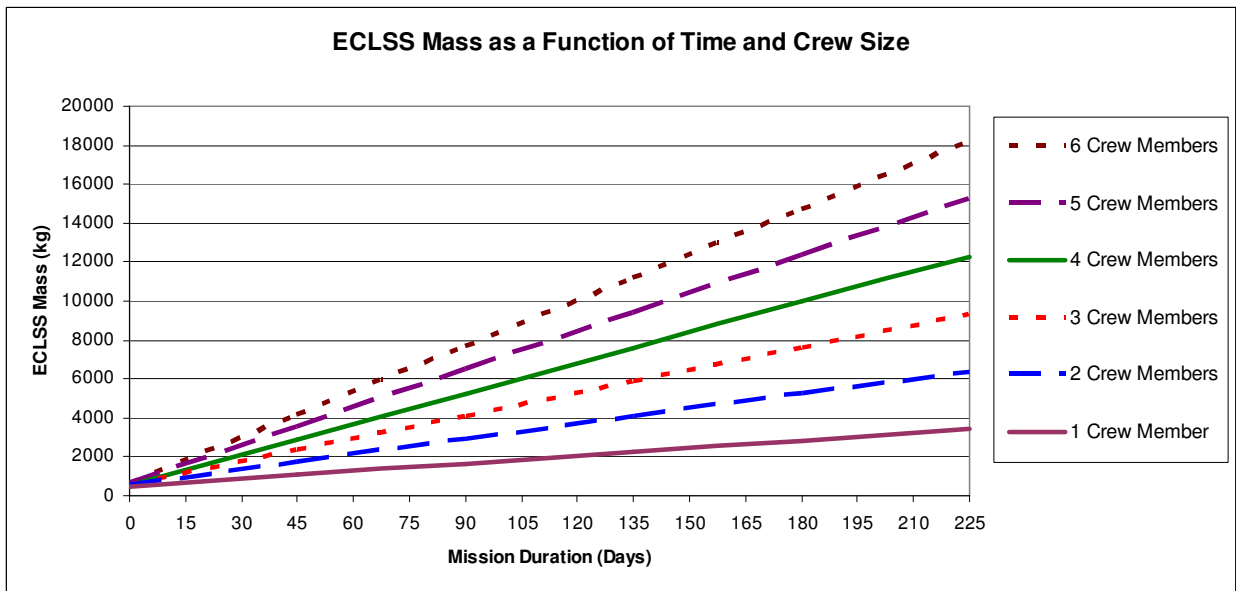


Figure 5: Open-loop ECLSS mass as a function of mission duration and crew size

The mass analysis can be split into five main categories:

Equipment/Tools- This category contains a wide range of items which remain fixed over the course of the mission, such as mobility tools, hand tools, mobility aids, operational supplies, cleaning hardware, and multimedia devices.

Human Factors- This category relates to accommodating human needs at both the operational and psychological level. This category has several fixed items such as a gallery for food preparation, waste

management facilities, medical items, and hygiene hardware. This category also has several items which are dependent on crew size, such as clothing, personal hygiene (not including water), and sleeping restraints.

ECLSS-Specific Structure- This category includes the supporting structure to accommodate the needs of the consumable materials such as oxygen and water.

Food / Potable Water- This category details all liquid and solid human consumables and is dependent on crew size and mission duration.

Atmospheric Consumables- This category is sized by crew size and mission duration and includes breathable oxygen and carbon dioxide scrubbers.

When the masses of these five categories are found as a function of time, a trend occurs that is displayed in Figure 6 below. Although the trends of each subcategory follow a linear trend, it can be seen that the initial mass does not start at zero due to baseline ECLSS structural mass and equipment. Figure 6 gives a top level representation for the required mass of the ECLSS subsystem, which rapidly grows as the mission duration increases. The open-loop mass for a mission of the Lunar Outpost duration quickly becomes very large relative to the structure mass, as a 180 day mission requires an ECLSS mass alone of ~10,000 kilograms. For the PISCES application, it may be more mass effective to include a water regeneration system. Figure 7 shows how the total ECLSS mass would be affected if a water regeneration system is included. It can be seen that this requires additional mass at the beginning of the mission; however, there exists a point where the length of the mission justifies this trade. Figure 8 shows a hypothetical “break even” point at which having a water regeneration system becomes preferable in terms of overall system mass.

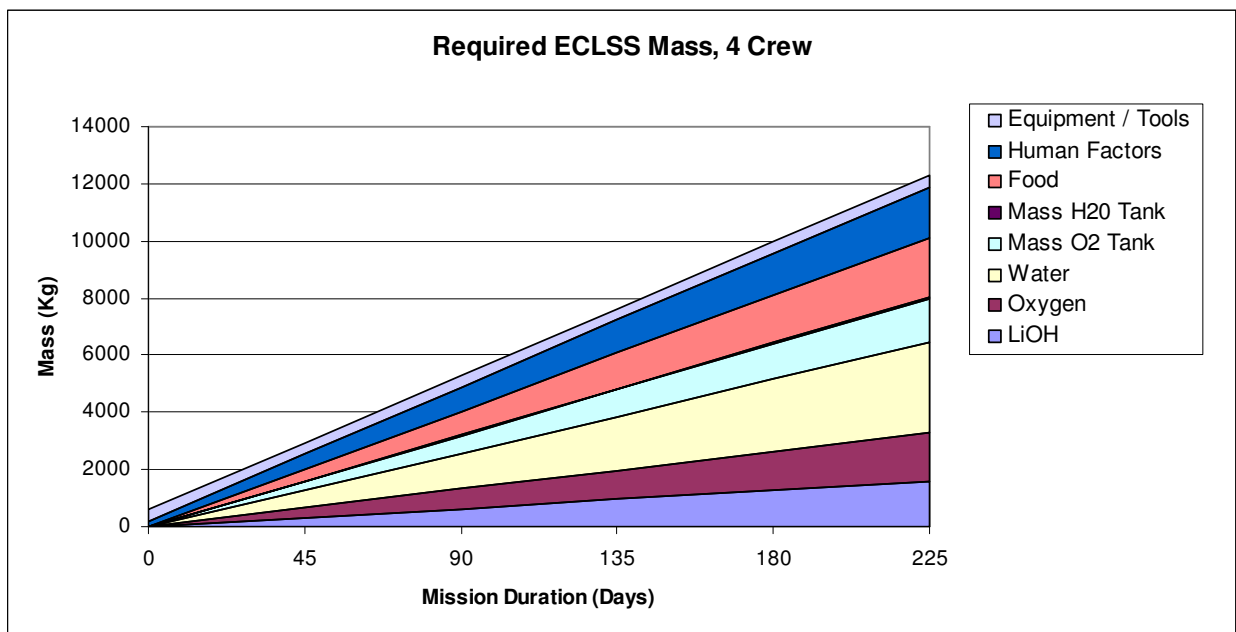


Figure 6: Total ECLSS mass as a function of mission duration, open loop [Larson]

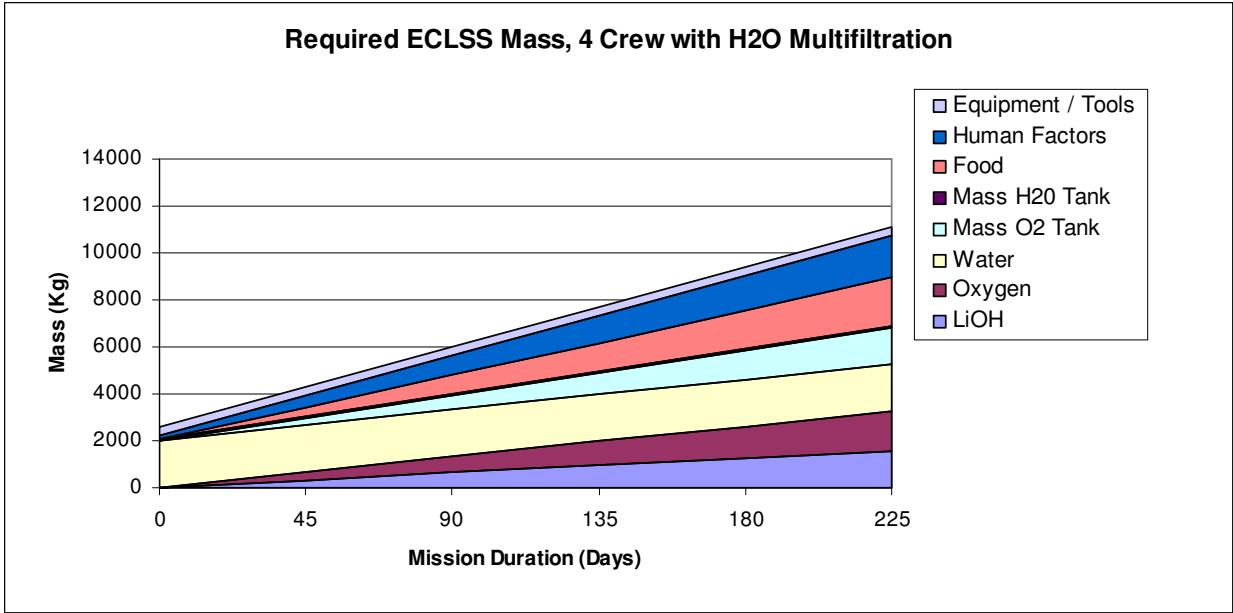


Figure 7: Total ECLSS mass as a function of mission duration, open loop

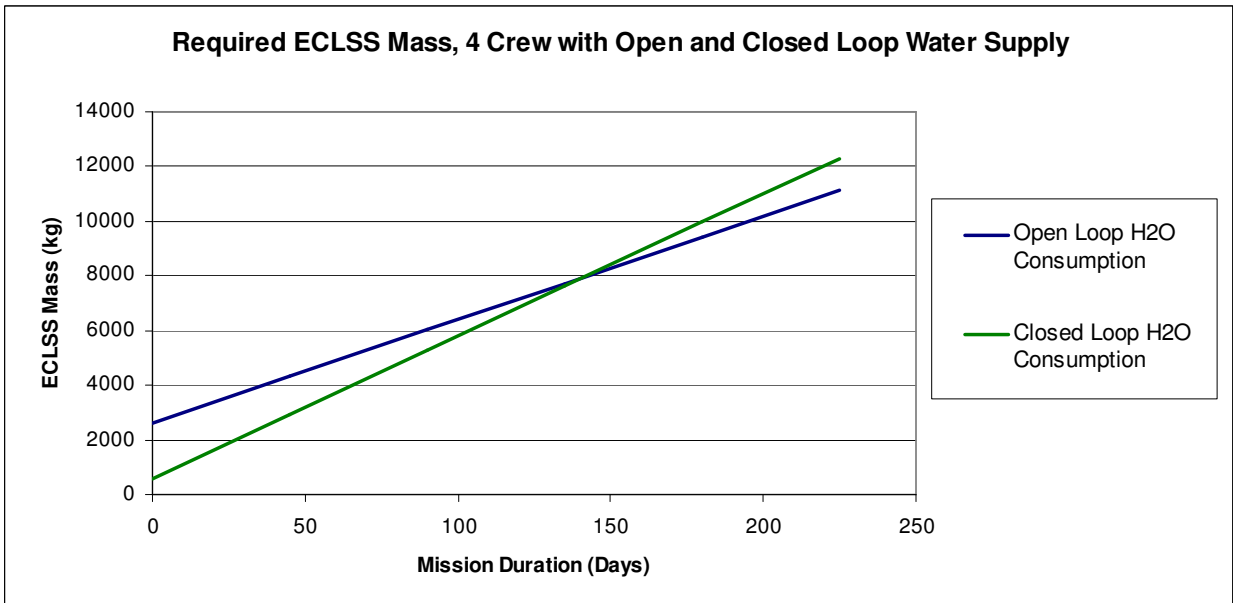


Figure 8: Comparison of ECLSS mass as a function of mission duration and open/closed loop water usage

In addition to regeneration technologies such as water reclamation, there are other possibilities for reducing lifetime consumable mass usage or leakage in a long-term mission such as the Lunar Outpost. *In Situ* Resource Utilization, or ISRU, is the concept of processing materials found on the lunar surface, in this case for consumable use in a crewed facility. On the Moon, the most readily available ECLSS resource may be oxygen, mined and processed from the abundant oxidized iron ores in lunar regolith. Metals such as iron and aluminum may also be utilized from lunar resources for construction purposes. In terms of mission planning, ISRU generally requires a higher initial mass but can reduce the consumption rate of ECLSS consumables over time. Because mass is being added to the system, ISRU is by definition an open system whether or not the processed resources are regenerated after initial use.

Another method of reducing the initial mass of ECLSS consumables is to send resupply vehicles to the Lunar Outpost, much like the Progress vehicles currently sent to replenish supplies and remove wastes from the International Space Station. A resupply logistics chain would allow the initial launch to carry less consumable mass, since additional vehicles would be periodically launched to the Moon with additional consumables. This method also results in an open loop system, because mass is being periodically added to the system (and waste mass may be removed from the system, as with Progress). Incorporating a resupply scheme requires an overall mission trade study, but from an engineering perspective, it is a viable alternative to complex regenerative or ISRU technologies.

ISRU and logistical resupply are compared to standard open loop and regenerative schemes in Figure 9. The plot shows only general trends and does not reflect any detailed heuristic analysis of these technologies. In the case of ISRU, there can be no heuristic analysis because ISRU has not been attempted at this mission scale. However, the trends displayed do illustrate some key points about these ECLSS consumable strategies. An open-loop system (everything is launched on-board in tanks and cannot be recovered after use) results in the greatest launch mass, and consumables are depleted at a fairly constant rate throughout the mission. Closed-loop regenerative technologies require less initial consumable mass (though there will be additional dry mass for the equipment) and depletes at a slower rate, because some percentage of the consumables are recycled. An ideal closed-loop trend would simply be a horizontal line, but in reality, there is always some leakage or some waste material that cannot be recycled. ISRU is initially similar to the open-loop trend because the processing will have a start-up lag phase. Once processing is in full swing, consumable mass is added into the system as needed; however, the trend is still not flat because not all required consumables can be obtained *in situ*, so these must still be drained from storage or regenerated through partial close-loop technology. Finally, the resupply strategy allows for less initial consumable mass than open-loop but may have a similar depletion rate. Periodically (every six months, in this example), a resupply operation results in a sharp spike in available ECLSS consumables.

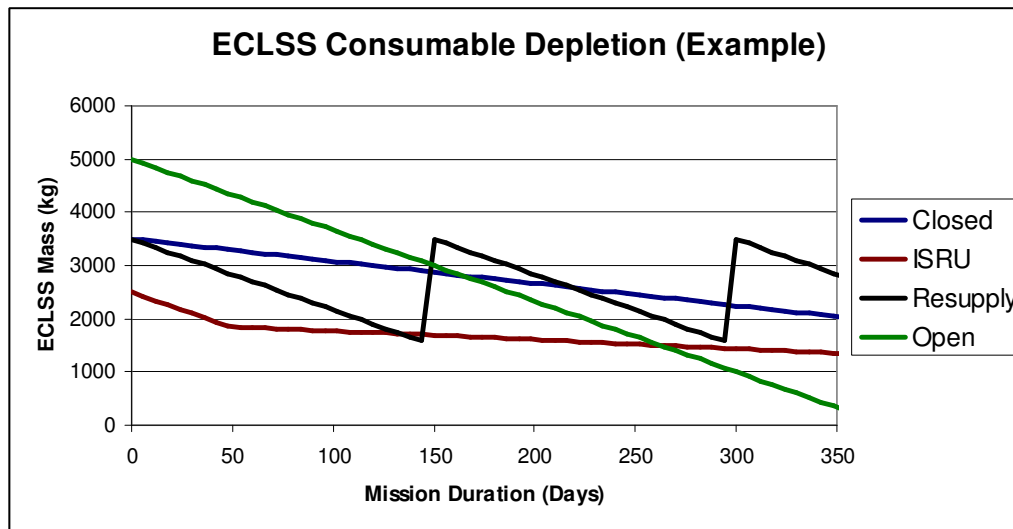


Figure 9: Representative Trends of ECLSS Consumable Mass Depletion

5.2 Translating Mass to Volume

Creating an early mass budget of a proposed spacecraft provides a measure to determine the top level mission parameters. The mass budget for different subsystems can be heuristically derived and is a good way to see the relative proportions that the spacecraft will need. Once subsystem mass is determined, it can be translated into other parameters that are useful to the designers such as power, maintenance, thermal, attitude determination, and volume requirements. For example, a top level thermal analysis can be performed based on the total mass of the system and other input parameters, so that the designers can predict whether the system will run too hot or cold. If such a case exists, steps can be made to impact early design decisions in order to mitigate the issue.

For the PISCES application, the mass budget was determined by compiling heuristic data from previous human missions and is shown in Figure 10 below. It can be seen that 15% of the spacecraft dry mass is devoted to the combination of ECLSS and related Crew Accommodations. This is an important understanding to realize early in the project, that just over a seventh of the vehicle mass is allocated to crew support equipment, much of which is inside the habitat. To get a better indication of how this mass will affect the PISCES Lunar Outpost Analogue, the

mass values can next be converted to volume. Table 1 below shows how the mass parameters predicted for PISCES in section 5.1 translate into volume in a worst-case, open-loop configuration.

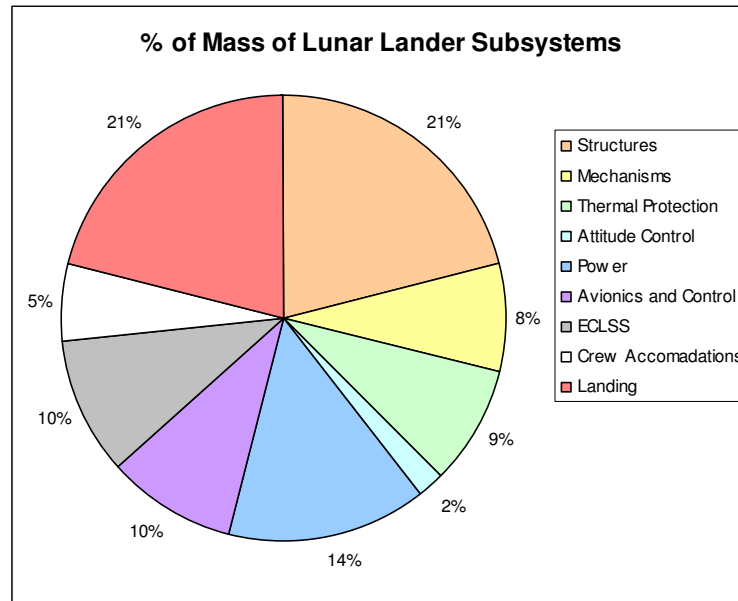


Figure 10: Typical subsystem mass breakdown for human spacecraft [Larson]

Table 1: PISCES ECLSS mass- 4 crew, 180 days

ECLSS Parameter	Mass, kg	Volume, m ³
LiOH	1260	0.9
H ₂ O Tank + H ₂ O	2570	2.8
O ₂ Tank + O ₂	2599	2.0
Food	1656	1.3
Human Factors	1478	1.0
Equipment / Tools	398	0.3
Total	9962	8.2

Once a volume analysis for the PISCES ECLSS is defined, it can be compared to the relative volume of the entire outpost. Figure 11 shows a NASA standard for determining total habitual volume for varying crew sizes and mission duration. For the PISCES application, it could be estimated that the optimal volume for the crew would be 80m³, with the minimum for nominal performance volume of 48m³ and for an absolute limit of 20m³. When these volumes are compared with the PISCES estimates as seen in Table 2, it can be seen that 9-30% of the habitual volume needs to be reserved for the ECLSS consumables.

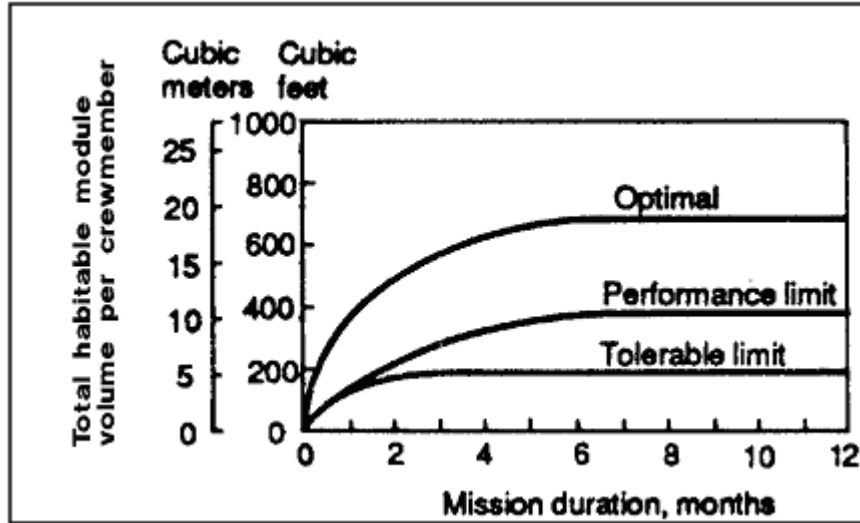


Figure 11: Envelope geometry for crew functions [NASA-STD-3000]

Table 2: Percent of ECLSS volume compared to total habitual volume

ECLSS % of Total Vehicle Volume	
Crew Tolerable Volume	29.2%
Performance Volume	14.6%
Optimal Volume	9.3%

5.3 ECLSS Maintenance Operations

In conjunction with the mass analysis being performed at our Lunar-MARS facility, work is being performed to better understand the maintenance and operations requirements that ECLSS puts on the crew members. In previous manned space programs, ECLSS maintenance has been generally underestimated prior to flight, and the maintenance activities represent a significant portion of crew time and effort, even on modern spacecraft such as the International Space Station (Russell et al., 2006; Russell and Klaus, 2007). Daily crew time for ConOps (the science and/or exploration objectives) is 24 hours minus sleep time, personal hygiene time, and general housekeeping (ECLSS maintenance). Programmatically, reducing sleep or personal time is not an option. Thus, if ECLSS maintenance requires more time than anticipated, the crew time devoted to the actual purpose of the mission, ConOps, will directly suffer. This underestimating effect has been observed and characterized among the crews of the International Space Station (Russell et al., 2006) as outlined in Figure 12.

General category	Required crew time on a work day, hr/CM/24hr-d		Required crew time during the work shift on a work day, hr/wk	
	Mission operations	Planning and coordination:	0.5	Medical operations:
	Work preparation:	1.5	Onboard training:	4.0
	Work shift (shared):	6.5	Public affairs office:	<4.5
	Total:	≤8.5	Utilization operations:	>20.0
Personal maintenance	Presleep:	2.0	Not applicable	
	Sleep:	8.5		
	Postsleep:	1.5		
	Exercise:	2.5		
	Midday meal:	1.0		
	Total:	15.5		
Habitat maintenance	Work shift (shared):	6.5	Housekeeping (per CM):	4.0
	Shared:	≤6.5	on the two rest days per week	

Figure 12: Required crew time from the ISS-Ground-Rules document placed into one of the three activity categories on workday and rest days. [Russell, J., Klaus, D. and Mosher, T.]

The PISCES Lunar Outpost analogue has a unique opportunity to better understand and classify the ECLSS operational and maintenance requirements. By using the analogue to run realistic operational scenarios, the predicted housekeeping and maintenance time needs can be built into the simulation timeline. This process would be iterative, so that as the ECLSS becomes better defined, the PISCES analogue can modify the design and give real-time feedback to the NASA team as to the resultant time impact on other mission objectives. In conjunction with this work, the Lunar-MARS team can also contribute to this effort and provide the linkage between the ECLSS work being performed at the University of Colorado, University of Hilo, and NASA.

5.4 Lunar Lander Extensibility

The current Lunar Lander concept involves undocking the Ascent module upon departure from the lunar surface. This means that a significant portion of the original landing vehicle will be abandoned on the Moon, because it is not worth the additional rocket fuel that would be required to bring it back to Earth. Due to the expense of launching any mass to the lunar surface, there is a potential benefit to reusing the abandoned hardware in subsequent Lunar Lander or Lunar Outpost missions. For instance, the Lunar Lander's Habitat module might later be connected to the Lunar Outpost to increase the latter facility's operating infrastructure and habitable volume.

Whether such extensibility concepts become a reality depends on programmatic decisions that may not be finalized until a decade or more from now. For instance, there may be scientific reasons to build the Lunar Outpost on a different part of the Moon than any of the Lunar Lander sites. Nevertheless, the cost to enable extensibility may be quite low relative to the future launch costs it might defray. Therefore, vehicle interfaces and other aspects of extensibility must be developed now, during the Lunar Lander development, as it will be too late to change anything on the Lunar Lander design by the time Lunar Outpost development begins. Therefore, the Lunar Lander should be designed with extensibility in mind, within reasonable bounds, and then at some point in the future, the Lunar Outpost can be developed to be "backwards compatible" with the abandoned hardware.

CU Lunar-MARS is in a unique position to assist PISCES with extensibility studies between our Lunar Lander mockup and the Lunar Outpost analogue in Hawaii. Extensibility concepts could be prototyped concurrently between the two facilities, with a focus on how to implement extensible features from the Lunar Lander via trade studies and how best to exploit the benefits in the Lunar Outpost. These studies could eventually lead to recommendations being made to NASA on whether extensibility is a justifiable concern for the development of these programs, and if so, just how much importance should be attached to extensibility in high-level trade studies and budgeting.

5.5 Bioregenerative ECLSS

A recommended long-term objective for PISCES is to facilitate research and operational simulations for bioregenerative ECLSS. Although hard data is not readily available because a bioregenerative ECLSS has never

been implemented on any realistically scaled space mission, the viability of cultivating vegetation (as well as lower life forms such as algae or bacteria) can be illustrated with a “break even” plot. Bioregenerative ECLSS is similar to any closed-loop ECLSS technology in that it requires higher initial mass but reduces consumable mass needed over time. Therefore, a break even point can be estimated at which the consumable mass saved from using bioregenerative ECLSS exceeds the additional mass needed to support the organisms. Most studies put this break even point at somewhere between six months and one year. Therefore, bioregenerative ECLSS is not likely to become viable until missions to Mars for a given single mission, but may prove beneficial to sequentially overlapping crews in the Lunar Outpost.

Potential benefits of bioregenerative ECLSS are numerous and diverse. (Mitchell, 1994; Wheeler, et al., 1996; Salisbury, et al., 1997) Plants can provide healthy food for the crew, including natural vitamins that may not be preserved in frozen, canned, or dehydrated food. Through photosynthesis, plants respire water that requires relatively little processing to become potable. Plants also remove carbon dioxide from the atmosphere and generate oxygen, two processes that must otherwise be performed by complex machinery in closed environments. Plants may also provide psychological benefits to crew members in an otherwise sterile outpost or spacecraft.

Due to the lack of research and experience in growing plants in space or on extraterrestrial surfaces, a strong case can be made for using the Lunar Outpost to conduct long-term studies and preparation for the use of bioregenerative ECLSS on subsequent missions to Mars. Simulating this subsystem would add not only to the volume requirements inside the analogue but also real operational demands during the simulation, as considerable work is needed to maintain food-bearing vegetation. Including bioregenerative ECLSS at a later stage of the Lunar Outpost Analogue development would provide an extra layer of demonstration to the PISCES simulation, because inadequate supply and/or maintenance of the subsystem will have directly observable consequences – the plants will underperform or die.

6 Evidence of Commitment

The CU Lunar-MARS program has a strong history at the University and is growing in support continuously within the Aerospace Engineering Sciences department as part of its Bioastronautics curriculum focus. The following sections briefly describe various facets of the program’s continued support base.

6.1 Undergraduate and Graduate Student Involvement

As mentioned above, the CU Lunar-MARS program began as a defined entity during the 2006-2007 academic year, with 4 undergraduate and 12 graduate students participating in various aspects of the project. There are currently 2 undergraduate and 7 graduate students continuing with the project during the summer term, and 4 current PhD students are also directly or indirectly involved with the facility as part of their doctoral thesis research. In addition, several incoming juniors and seniors have expressed interest in conducting a Senior Design Project based on this facility in the coming year(s).

6.2 Department and Faculty Involvement

As the mockup progresses to increasing levels of fidelity, opportunities arise for involvement in an increasing number of disciplines. Several potential collaborators in multiple departments of the College of Engineering and Applied Science have already expressed interest utilizing the mockup as it becomes available; including professors in the Aerospace Engineering Sciences, Civil, Environmental and Architectural Engineering, and Mechanical Engineering. Additionally, the Colorado Space Grant Consortium has expressed interest in becoming involved with the Lunar-MARS project:

“The Colorado Space Grant Consortium would like to explore future collaborations related to his [Dr. Klaus’s] human space systems research. Space Grant is primarily involved with satellite development but we would like to explore other space systems including research and development related to Project Constellation. As Space Grant’s primary mission is to train interdisciplinary engineers to prepare them for NASA and the Aerospace community’s future workforce, collaboration with Prof. Klaus would help us meet our program goals.”

-- Chris Koehler, Director and Brian Sanders, Student Research Coordinator, Colorado Space Grant

6.3 Dedicated Funds

Funding proposals for the Lunar-MARS program are on-going. To date, approximately \$15,000 have been committed to the program. Continued support in future years is expected from these and additional sources, particularly from the Marlar Foundation:

“Funds from the Marlar Foundation have been provided in support of this effort on the level of \$12k-15k for 2006/07 with the likely potential for up to 4 additional years of funding at this level or higher.” -- Pat Sullivan, Director, Corporate & Foundation Relations

In addition to project-level funding, various independent student grants have been awarded to support individual work in conjunction with the Lunar-MARS program. These include, but are not limited to, Undergraduate Research Opportunities Program (UROP) and Engineering Excellence Foundation (EEF) funds in support of both hardware development and operational environment training/development in support of Lunar-MARS activities.

6.4 Publications and Proceedings

In addition to this PISCES paper, a number of related publications have been produced in association with the work performed on the Lunar-MARS program. In the years of paper studies leading up to the construction of the Lunar-MARS hardware mockup, 12 journal articles, 4 peer-reviewed conference papers, and 6 conference presentations have been published on related spacecraft design topics, each with student co-authors. In addition, a student-published paper focused on the educational value of the mockup was presented at the AIAA Region V Student Paper Conference during March of 2007 and was awarded 3rd place in the team division.

6.5 K-12 and Community Outreach

The development of a K-12 outreach effort as part of the CU Lunar-MARS Program enables students to understand the process and importance of developing space missions. It may even inspire them to steer their futures in the direction of the space program, academically, politically, or both. With the right group of students and the right stimulus from the Lunar-MARS representatives, simulating a “visit to the moon” with youths becomes a valuable educational activity. Through this vignette, they become not only involved with the VSE, but also excited and intrigued by it. Six Outreach Events have been conducted in conjunction with the Lunar-MARS program to date. Typically each of these events hosted 15-30 attendees, including K-12 and undergraduate students, parents, mentors and organizers. Activities in this area have already been pursued both with the use of instruction plans and without. The Lunar-MARS program has identified and utilized a number of activities developed by NASA, including “Moon Mining” and “Cleaning Water” available from the NASA Kid’s Science News Network (KSNN). These activities encourage the students utilize the scientific method in an investigation of a technology to be used on the moon: mining ilmenite and recycling/purifying wastewater, respectively.

Additionally, televised coverage of the project by Shaun Boyd from CBS Denver Channel 4 News aired locally on May 1st 2007 and was syndicated in news broadcasts and publications nationwide.



Figure 13: Outreach Activities with the University of Colorado Lunar-MARS

7 Conclusion

The CU Lunar-MARS program has established a body of work in developing lunar analogue hardware and systems engineering requirements with the goal to iteratively provide design recommendations to NASA. We began by analyzing NASA's "Lunar Exploration Objectives" to derive realistic Lunar Lander-specific ConOps and system-level design requirements. (NASA, 2006) A full-scale mockup of the Lunar Lander was built at CU to facilitate hardware requirements and operational scenario development. The hardware is being revised in parallel with requirements development and provides a feedback loop into the process. In addition, we have developed a top-level mass analysis scheme to assist our research in sizing the different subsystems as well as determining important variables such as maintenance time and volume. This has become useful as it gives insight to design issues early within the design phase. As the NASA vehicle becomes better defined, the lunar analogue can be improved while simultaneously sending experienced knowledge back to NASA. As this iterative process progresses, the analogue and the finalized NASA vehicle designs converge and become dependent on each other's critical drivers. We propose to apply this same process to aid with effective utilization of the PISCES facility.

Specifically, we propose to assist the PISCES program in the following ways: provide an analysis of projected ECLSS mass and volume requirements for the PISCES analogue research station; develop guidelines for ECLSS maintenance, which is historically underestimated and directly impacts the crew's ability to achieve primary mission objectives; assess extensibility concepts for utilizing Lunar Lander hardware abandoned on the lunar surface in later Lunar Outpost missions and examine the possibility of implementing a functional test bed for bioregenerative or other advanced life support concepts well-suited for long duration missions. **Finally, we propose to assist the PISCES effort by establishing a firm link between the University of Hilo, University of Colorado and NASA from where experience in space habitat design, lunar mockup practice and spacecraft designers can iteratively work together to create a realistic and efficient end result.** The CU Lunar-MARS program has the funding, student involvement, experience, and enthusiasm necessary to accomplish these goals.

The general strategy of CU Lunar-MARS is to stay several steps ahead of current design efforts in NASA's Constellation Program, providing architecture, concept, and configuration studies from the earliest NASA architecture announcements through each vehicle's CDR phase. Therefore, we are currently focusing on the Lunar Lander; once that project matures and reaches CDR, our team will transition to analysis of the Lunar Outpost, and ultimately, the Mars expedition. We will be able to use the cumulative expertise and methods honed during our Lunar Lander work to achieve even more with the Lunar Outpost. This long-term strategy places CU Lunar-MARS in an advantageous position to work with PISCES and develop common practices between the Lunar Lander and Lunar Outpost analogues. It is in our best interest to learn about the Lunar Outpost now so that we are better prepared to fully transition into that study in the future. Conversely, we can use our experience with the Lunar Lander to accelerate and improve the PISCES studies and to establish synergistic links (such as hardware extensibility) between the two programs. Similarly, we hope to assist PISCES in using the Lunar Outpost analogue to study potential links between the real Lunar Outpost facility and NASA's future Mars expeditions. The proposed long-term goal of simulating bioregenerative ECLSS at PISCES is one example of the link between the Lunar Outpost and Mars missions.

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