

Minimum Functionality Lunar Habitat Element Design: Requirements and Definition of an Initial Human Establishment on the Moon

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ABSTRACT

This paper summarizes the activities of the University of Maryland Space Systems Laboratory in performing a design study for a minimum functionality lunar habitat element for NASA's Exploration Systems Mission Directorate. By creating and deploying a survey to personnel experienced in Earth analogues, primarily shipboard and Antarctic habitats, a list of critical habitat functions was established, along with their relative importance and their impact on systems design/implementation. Based on a review of relevant past literature and the survey results, four habitat concepts were developed, focused on interior space layout and preliminary systems sizing. Those concepts were then evaluated for habitability through virtual reality (VR) techniques and merged into a single design. Trade studies were conducted on habitat systems, and the final design was synthesized based on all of the results. A full scale functional mockup of the final concept was fabricated which along with neutral buoyancy partial gravity testing allowed more realistic human factors studies and the validation of the VR techniques used previously.

INTRODUCTION

In August 2008, NASA awarded the University of Maryland Space Systems Laboratory a contract to design a

minimum functional habitat for the Constellation lunar exploration program. One of three similar contracts awarded in parallel, the purpose of this study was to define the minimum requirements for an extended-stay lunar habitat, to be used as a "jumping-off" point for informed decisions on the marginal costs and benefits of adding capabilities over and above those required for the minimal system.

This approach paralleled that taken by the NASA Exploration Systems Architecture Study (ESAS), which decided on the basic transportation architecture and spacecraft configurations for the Constellation program. Rather than design an "all-up" vehicle, which could easily wind up overweight and requiring expensive downscoping, the approach taken was to define the minimum lunar habitat element which could meet the most basic requirements of the program. Given this minimum as a baseline, subsequent trade studies could be performed to evaluate enhanced capabilities by adding systems beyond the minimum set, quantified by the marginal costs and complexities of the added components. This would allow for logical decisions on which augmentations are worth their additional costs.

The basic minimum function set, as presented by the sponsor, included:

- a crew of four, drawn from the anthropometric data base of current U.S. astronauts
- a 28-Earth-day nominal mission duration, with a 30-day contingency
- access for extravehicular operations, with mitigation of dust hazards in and around the habitat
- sufficient radiation protection to meet NASA's overall loss of crew probability limit of 0.001 per mission
- assumption of the availability of the rest of the current planned Constellation architecture for the outpost which includes the habitat
- designs were to include the capability for augmentation and extension to more demanding mission goals
- total habitat mass of no more than 7000 kg
- 30% O₂ atmosphere at a total pressure of 8 psi

Beyond this simple list, it was the responsibility of the study contractors to decide on what constituted the detailed form of a "minimum functional habitat", and to produce a design concept which could be used as a development baseline while assessing additional capabilities. To extend this list of requirements, the University of Maryland created a rudimentary concept of operations which was used to evolve additional design constraints.

Critical habitat design issues are predicated on the level of extravehicular operations, particularly in the number of ingresses and egresses and the mode adopted. Since this habitat is to be used for exploration activities, the UMD team assumed that there would be a two-person EVA every day throughout the 28-day nominal mission. Due to the severe problems of controlling dust intrusion at this level of EVA operations, a further decision was made to baseline the use of suitports for nominal operations. Although currently at a low technology readiness level (TRL), suitports offer the advantages of negligible atmosphere loss with each cycle and no dust infiltration to the habitat with normal use. Since it will be necessary to bring items into and out of the pressurized volume, including suits for maintenance and repair, the design team also established a requirement for a conventional airlock, which was assumed to be inflatable. Nominal mission operations assumed an airlock cycle on a weekly basis. Since the 30-day contingency requirement was included as a "waiting out" period for another launch window back to Earth, no allocation of resources was made for EVA operations during this time.

HABITABILITY IN CONFINED AND AUSTERE ENVIRONMENTS

The study of habitability crosses engineering, physiological, and psychological disciplines. Habitability does not have an agreed-upon definition, but in general terms it is the relationship between humans and their environment,

or more precisely, the suitability of an environment for the acceptable performance of humans [1] [2]. Habitability can be divided into three hierarchical levels: (1) health and safety, (2) function and efficiency, and (3) psychological well-being [2]. The first level of habitability is provided by the habitat's structural and life support systems. The second level of habitability requires an optimization of the human-machine interfaces within the habitat, where special attention is given to habitat layout and automated mission support systems. The third level of habitability is affected by crew selection, mission duration, available area/volume per person, habitat layout, stress levels, and other psychological factors. Although a minimum functional habitat is sparse compared to an outpost design, it should nevertheless provide features that help to achieve adequate levels of human performance for the duration of the mission.

Providing for health and safety is accomplished by the structural and life support systems in a habitat. The requirements for maintaining the health and safety of the crew are detailed in NASA's Man-System Integration Standard [5]. Satisfying only these requirements creates a habitat whose function is simply to support life. To achieve higher levels of habitability and performance, consideration should be given to the functional layout and psychological aspects of the habitat and the crew. Baggerman in [6] notes that the "environment in which the crew works and lives has been a primary issue since Expedition 1" and has been rated as one of the top five issues to rectify. Based on the literature, this issue can be ascribed to poor zoning of functional areas. Figure 1 below provides a zoning of functional areas based on their individual or group use and their respective noise levels.

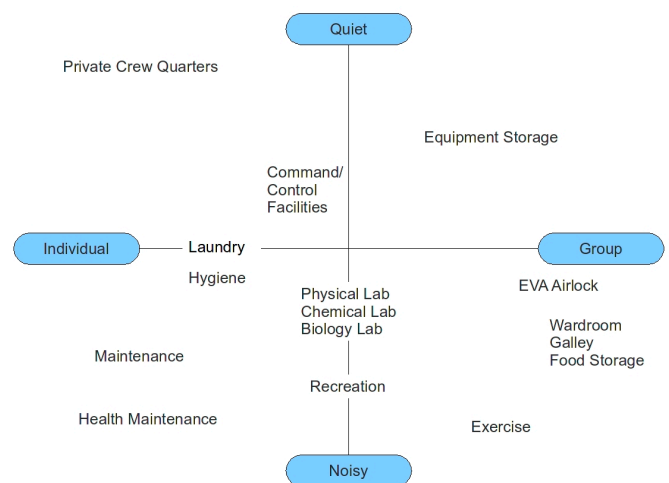


Figure 1: Functional Areas by Noise Level and Privacy Level [3]

Although this zoning provides a good rule of thumb for arranging the spaces within the habitat, it is but one aspect of a proper design. Other factors that should be addressed are the total size of the space, the percent of total time within the space, and the crew flow or interaction between the spaces. Parker in [7] divides the habitat

into four functional areas, and provides volumes for each space. Additionally Schowalter and Malone in [4] provide a breakdown of time per activity, and present a flow diagram for crew activities. Figure 2 below reveals the interactions between different activities.

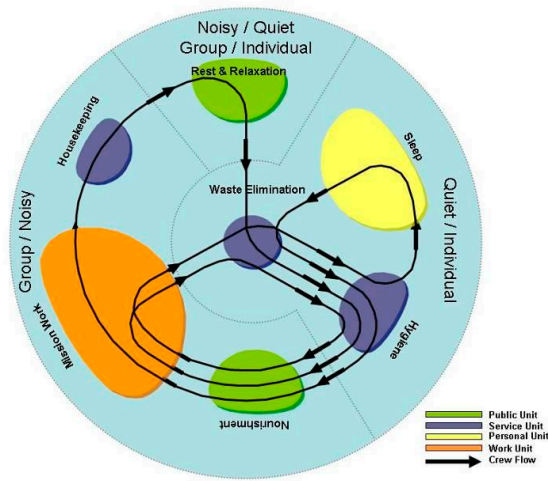


Figure 2: Combined Habitability Approach: Zoning, Unit and Flow [4]

From this view, certain design traits become evident. First, it may be useful to group the waste elimination and hygiene activities into one area, and place them near where the sleeping activity occurs. This area should be acoustically isolated from noises above 40 dB. Secondly, mission, nourishment, and housekeeping activities can be grouped into a common functional area. Acoustic dampening of noises above 50 dB within this area will help facilitate team communication and cohesion, resulting in improved performance and morale. Finally, because of the varied nature of rest and relaxation activities, they should not take up their own dedicated area, but should be allocated between the two primary functional spaces. Addressing the functional layout, relative size, and crew flow of the habitat contributes to Preiser's second level of habitability. The highest level of habitability, psychological well being, requires that crew morale be considered in the design of the habitat.

One indirect contributor to crew morale is the amount of space per person, which is key to providing a sense of privacy and personal territory. The amount of required space, however, varies for each crew member, and can be difficult to assess a priori [7]. Cabin sizing for conceptual habitats is frequently done heuristically, with little physical or psychological justification, and a notable lack of consensus in the literature. Cabin layout and crew size, as drivers of psychological well being, are likely at least as important as total cabin volume [8]. For some missions, a sense of personal space can be achieved with nothing more than a personal storage locker. However, because of the mission duration, it is expected that a habitat intended for a 28-day nominal mission would require more space for privacy. At minimum, these private spaces could potentially be provided by a combination of the individual

sleeping quarters and the personal hygiene facility.

Another contributor to morale is personal hygiene and habitat cleanliness. The personal hygiene facility should be equipped for personal grooming and for collecting, processing, and disposing of body and other waste [7]. At a minimum, it can be nothing more than a private area where a crew member can clean themselves with water and a cloth [7]. Similarly, it is equally important from a psychological and physiological perspective to keep the living spaces clear of equipment and debris.

Mealtime is also key to crew morale. For the crew, mealtime is a major social activity, where experiences are shared and problems resolved [7]. Finally, communication with family and friends provides a morale boost and contributes to mental stability [7]. Clearly, to provide a habitable environment, designers must consider the crew's health and safety, the efficient use of space for mission operations, and the crew's mental state. All of these factors contribute to high crew performance and should be considered in the design of a minimal functional habitat.

PAST DESIGNS

Data on mission duration and volume per crew member from several past proposed lunar habitat designs are plotted in Figure 3. As can be readily seen, the allocated volumes vary widely across mission durations. As no strong relationship exists for all habitat designs, the data are separated into two sets, based on the mass of the habitat. Only two of the precedent designs examined had a mass below the 7000 kg limit imposed for this study, therefore, a 10,000 kg mass was used as the dividing line between small and large habitats.

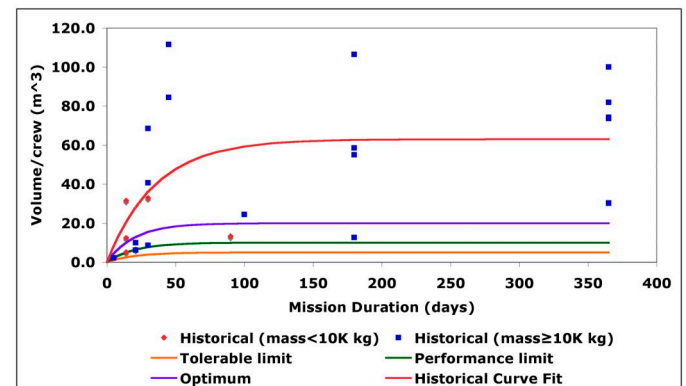


Figure 3: Habitat Volume vs Mission Duration

This analysis provides an interesting perspective on the "traditional" Celentano curves matching volume per crew member to the duration of the mission. Eight of the selected data points fall below Celentano's "optimum" asymptote of 20 m³ per crew member; five are at or below the "performance limit" of 10 m³ per person. The four 30-day missions from the data set have specific volumes of 8.7 m³, 32.8 m³, 40.5 m³, and 68.4 m³ per person for

an average of 37.8 m³ per person. However, these same design examples have habitat mass estimates of 11,790 kg, 9700 kg, 17,060 kg, and 25,410 kg respectively, for an average mass estimate of 15,720 kg – more than a factor of two higher than the mass limit imposed for this study.

DATA ACQUISITION AND ANALYSIS

METHODOLOGY

Rather than making a priori assumptions about habitability, the University of Maryland design team adopted a formal methodology to obtain data on critical habitability elements. First, a list of features considered important to habitability was generated from the literature review. This list of features was then ranked in importance using an Analytic Hierarchy Process, based on the input of test subjects with experience in restricted habitation environments on Earth, such as undersea and Antarctica. The results of that process were used as inputs to a Quality Function Deployment matrix, in which relationships were established between habitat features (as they impact the crew), and design features/systems. This process resulted in a vector of importance values for various design features/systems, intended for use within the trade space to assist in determining the impact of system alternatives on overall habitability. In this way, a minimum habitat design can be achieved which provides an acceptable level of habitability for its crew.

ANALYTICAL HIERARCHY PROCESS IMPLEMENTATION

In order to determine the relative importance of the habitability functions, an Analytic Hierarchy Process (AHP) was used. The Analytic Hierarchy Process is a method of determining the relative importance of a series of parameters, based on a series of subjective pairwise rankings. To perform an AHP on a given set of n parameters, an $n \times n$ matrix is created, with the value of each element (i, j) corresponding to the relative importance of parameter i with respect to parameter j . By definition, the diagonal elements are equal to one, and the value of each element (j, i) is equal to the reciprocal of the value of its conjugate element (i, j) . Thus, only $\frac{n^2 - n}{2}$ elements must be known in order to fully populate the matrix. The values of these elements may be determined through survey responses of relevant subjects, in which subjective statements of the form “parameter A is [some degree more or less] important than parameter B ” are converted to numerical values.

For a fully populated AHP matrix, the importance values of the parameters are contained in the normalized principal eigenvector of the matrix. A consistency value for the matrix can be determined by dividing the matrix size n by the principal eigenvalue, with a consistency of 100% indicating a totally consistent matrix. A consistency less than 90% can indicate that the subject was confused about the definitions of the parameters or the instructions for com-

pleting the pairwise comparisons. By using these consistencies to weight the average importance values, the most reliable data can be emphasized.

In a multi-level AHP hierarchy, the importance values of related parameters in a sub-matrix are multiplied by the importance value of the matrix as a whole, to arrive at a global importance value for each parameter. Because the principal eigenvector is normalized for each matrix in the hierarchy, the sum of the parameter values across any level of the hierarchy will be one. Multi-level AHPs increase the number of features which can be examined, while keeping the overall size of the AHP matrices within reason for a survey. The drawback to this approach is that it reduces redundancy of information. However, for any AHP matrix with at least four parameters, there exists at least twice as much information as is strictly necessary to populate the matrix. Thus, the trade-off is between superfluous redundancy in a single-level AHP, and extending the survey to cover more features with a multi-level approach.

To determine which features were most crucial to habitation, an online survey was generated, which consisted of ninety pair-wise ranking questions on a list of thirty-four habitat features generated from the literature review. It was assumed that minimum life support would be provided; thus, the habitat features considered in the survey focused on the functionality, efficiency, and psychological well-being of the crew. A two-level AHP with a total of eight matrices and thirty-four parameters was generated, as illustrated in Figure 4. The top level matrix ranked the relative importance of the following areas: health and hygiene, communications, general environmental quality, non-physical recreation space, exercise space, work space, and sleeping/resting space.

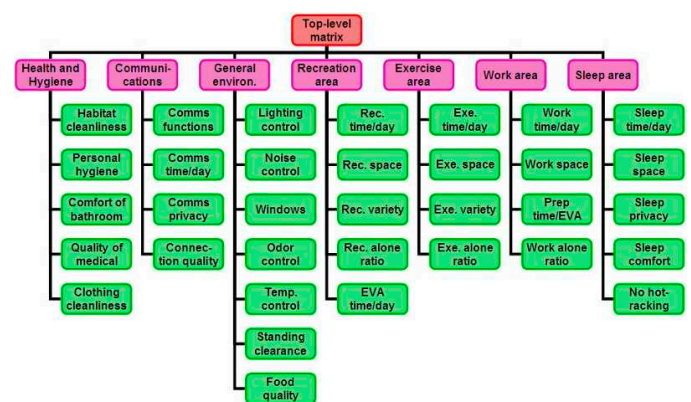


Figure 4: AHP Survey parameters map

The ideal target populations for the survey were populations with experience in remote and/or confined environments believed to be analogous to the lunar surface habitat environment. These populations include astronauts, submariners, ship crew, Arctic/Antarctic research scientists, and engineers and designers of space habitats.



Table 1: Demographics of survey respondents

By Nationality	By Environment	By Age Group
American (15)	Submarine (19)	≤40 years
Italian (11)	Ship (11)	> 40 years
French (2)	Arctic/Antarctic base(3)	
Romanian (1)	Other (2)	

Our final survey demographics are summarized in Table 1 where it can be seen that we were able to acquire responses from all populations except for astronauts.

Survey respondents were asked to envision a scenario in which they were one of four crew members in an unspecified isolated, confined environment for a period of one month, with a limited ability to leave the habitat for brief periods of time. Respondents were told that their habitat would, at a bare minimum, support life, and that the goal of ranking the specified features was to maximize crew productivity and psychological well-being.

AHP ANALYSIS

In converting the survey data to AHP matrices, numerical weights were applied to the subjective pairwise comparisons as described in Table 2. For each of the twenty-nine respondents, and for each matrix within the response, a vector of importance values and a consistency value were generated using the method described above. The importance value of each habitat feature was averaged across all survey respondents, weighted by matrix consistency, to generate cumulative importance values for the habitat features, which are presented in Figure 5.

Table 2: Subjective assessment weights

Subjective assessment	Weight ($= \frac{\text{feature 2}}{\text{feature 1}}$)
"Feature 1 is much more important than feature 2"	$2^{-3.0} = 0.125$
"Feature 1 is moderately more important than feature 2"	$2^{-1.5} = 0.354$
"Feature 1 is slightly more important than feature 2"	$2^{-0.5} = 0.707$
"Feature 1 is about as important as feature 2"	$2^{0.0} = 1.000$
"Feature 1 is slightly less important than feature 2"	$2^{0.5} = 1.414$
"Feature 1 is moderately less important than feature 2"	$2^{1.5} = 2.828$
"Feature 1 is much less important than feature 2"	$2^{3.0} = 8.000$

An overall consistency was computed for each respondent by taking an average of that respondent's matrix consistencies, weighted by the number of pairwise comparisons in each matrix. Consistency varied greatly between respondents, although the average consistency of the respondents was greater than 90% for all matrices. The average consistency over all respondents and matrices was 92.5%. The most consistent matrix was "work space", at 96.6%. The least consistent matrix was "general environmental quality" at 90.3%.

The most important habitat feature was "no hot racking", defined as the practice of assigning more than one crew member to a bed or "rack" to reduce berthing space, at 2.3 times the importance of the average feature, and 6.5 times the importance of the least important feature. Quality of

Table 3: Statistically Significant Variances to 95% Confidence

Demographic	Feature	Difference in mean
French	EVA time/day	+26.3%
French	Exercise alone ratio	-11.9%
American	Quality of communications	-5.3%
Ship crew	Quality of personal hygiene	+0.9%
Ship crew	Quality of medical facilities	+1.3%
Ship crew	Recreation alone-time ratio	-0.8%
Ship crew	Sleep privacy	+0.3%
Submariners	Bathroom comfort	-0.6%
Age 40+	Communications privacy	-1.4%
Age 40+	Temperature control	-0.8%

medical facilities, communications connection quality, and personal hygiene round out the highest ranked functions. Work time and work space were also highly ranked, with respondents indicating an average preference for 9.4 work hours per day. This indicates that providing an ability for the crew to perform useful work is especially important to the overall habitability of an environment. At the opposite extreme, the data indicate that non-physical recreation features were considered especially unimportant. Lighting quality and windows were the least important features, with windows ranked at 0.35 the importance of the average feature. The top seven features account for more than one third of the total importance; The top twelve features account for more than half of the total importance.

The average coefficient of variation across all respondents for all features was 73.4%, implying that there is a great deal of difference from person to person in how important the considered habitat features are. It should thus be noted that a habitat design based on general results may not be optimal for all crew members, and the preferences of individual crews should be taken into account in selecting a habitat configuration for a particular mission.

An analysis of variance (ANOVA) was performed to identify statistically significant differences in responses across demographics, including age, nationality, and type of experience. Table 3 lists the statistically significant variances between specific demographics and their complementary sets, as well as the difference in weighted mean between the two sets.

As the table 3 shows, the statistically significant variances mostly represent small variations in the mean importance of the respective features. This indicates that demographic variation is not likely to play a significant role in determining design, at least among the populations which responded to the survey.

Performing ANOVA between astronauts and analogue populations could be used to justify the statistical relevance of analogue populations. Unfortunately, there were no astronaut respondents to the survey. The analogue environments considered in the survey may be of limited fidelity to the space environment, due to several factors.

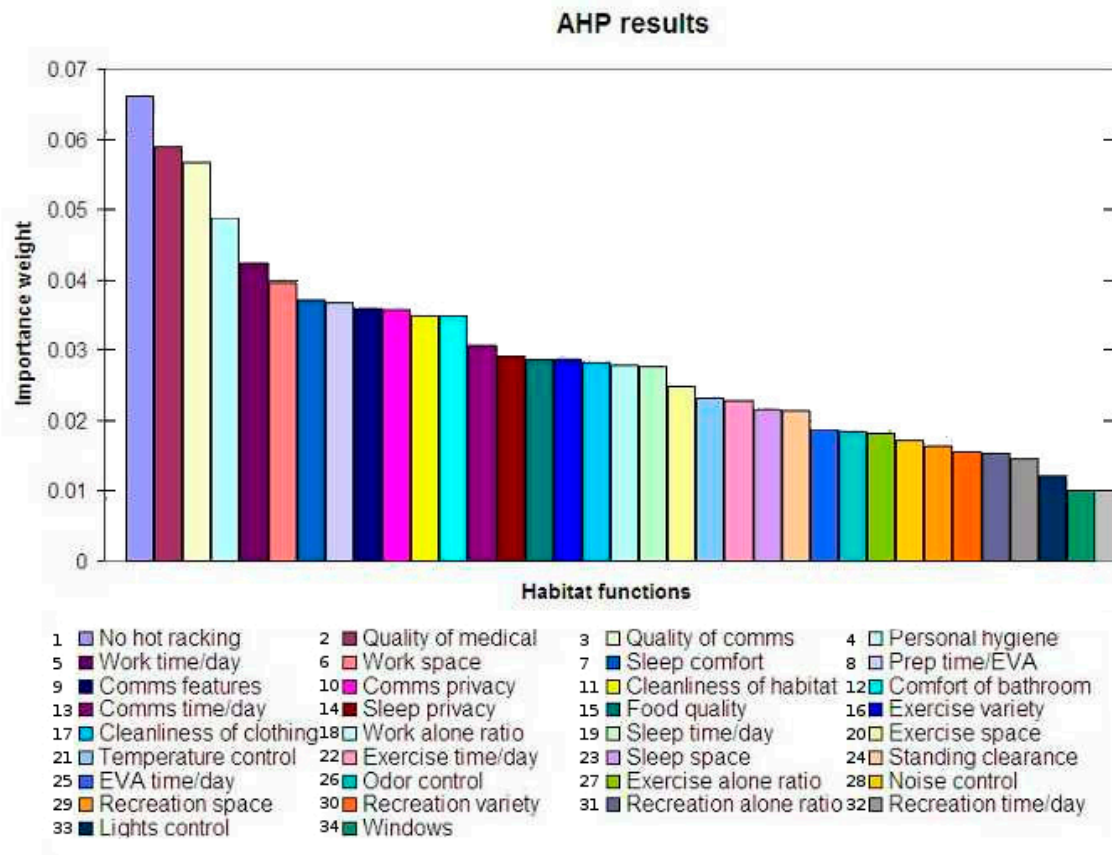


Figure 5: Cumulative importance values

- Windows may be less important in environments with a static view or no view at all, such as submarines and ships.
- Analogue environments do not account for any effects that reduced gravity may have on the importance of habitat features.
- The ability to leave the habitat environment during EVA may impact the importance of some habitat features. This effect is not accounted for in analogue environments.

These potential limitations of fidelity were not evident in the collected survey data. However, more data would be needed to identify any effects that these and other factors may have on respondents with experience in analogue environments. In particular, larger samples of analogue populations would be required, in addition to samples of the astronaut population, in order to identify and correct for all statistically significant variations between analogue and space/planetary surface environments.

QUALITY FUNCTION DEPLOYMENT

Quality Function Deployment (QFD) is a technique for mapping system users demands (in this case, AHP-ranked habitat functions) to design features, based on subjective assessments of the strength of the relationships between demands and design features. QFD can

be useful in determining the benefit of adding an extra unit of mass, volume, or other resource to a given system or subsystem, beyond that required for basic operation of the system. (In the case of a minimum functional habitat, basic operation is defined as supporting life for the duration of the reference mission.)

In determining the most important design features for a minimum functional habitat, twenty-eight AHP-ranked habitat functions were mapped to fifty-three design features. (six AHP functions which were assumed to have little design impact were excluded from the QFD.) Each intersection of AHP function and design feature was assigned a strength of relationship between zero and nine, with all other design features assumed constant. The relationship strengths were multiplied by the importance values of the respective habitat features, as determined in the AHP. These importance-weighted strengths were summed for each design feature, to yield an importance value for that design feature. The normalized importance values of the most important twenty design features are presented in Table 4.

Total habitable volume was found to be the most important design feature among the features considered. This reflects the versatility of habitable volume; an extra unit of volume within the habitat could potentially be used to help achieve any of several AHP habitat functions. The same is true of electrical power, which ranked second.

Table 4: QFD Top Twenty Design Feature Importance Values

Rank	Design Feature	Importance Value
1	Total habitable volume	0.0632
2	Electrical power	0.0602
3	Running water	0.0555
4	Particle/odor/micro-organism filtration	0.0499
5	Earth downlink data-rate	0.0491
6	Closed-loop water	0.0406
7	Humidity	0.0395
8	Frequency of clothing changes	0.0349
9	Accessible storage volume	0.0304
10	Total noise produced by all systems	0.0280
11	Number of controllable lighting zones	0.0257
12	Heat removal rate	0.0229
13	Communication features	0.0217
14	Ventilation rate	0.0217
15	Acoustic isolation of sleep space	0.0204
16	Volume re-allocatable for medical use	0.0203
17	Complexity of first aid facility	0.0203
18	Medical sensors/diagnostic equipment	0.0203
19	Sponge bath vs. shower	0.0195
20	Communications quality	0.0195

Intercorrelation exists between design features which is not addressed by this method. For example, a number of the design features considered are dependent in turn on the available electrical power. To supplement the value of a QFD, the degree of correlation between pairs of design features are often recorded in a correlation matrix, which can be useful in identifying relationships between design features and independent underlying design variables. Creating such a correlation matrix would be a logical extension of the work performed in this study.

Those interested in the full survey results and data analysis are referred to the final report of the ESMD study [9].

PRELIMINARY CONCEPTS

The primary objective of this study was to produce a conceptual design for a minimum functionality habitation element based on a minimum set of functions that are required to perform the reference mission. Realistically, such an element may never fly, but the minimum set of functions identified would provide the backbone for crew accommodations on the lunar surface, as well as provide growth options for lunar surface systems. Minimum func-

tionality as a design philosophy begins with an element that deliberately meets only the minimum set of functions required to perform the mission, and no more than that. Such an element:

- Does not consider contingencies, nor does it have added redundancy (i.e., it is a single string implementation).
- Enables a process that can add safety, reliability and other functionality to the element with informed cost, risk and performance deltas

- Does not need to meet full operational standards; it is for concept development only

INITIAL CONCEPT

The first proposed habitat concept reflects the initial assumptions and requirements that it must provide self-contained life support, radiation shielding and EVA support. The habitat consists of a volume containing all the necessary supplies (food, O₂, water, etc.).

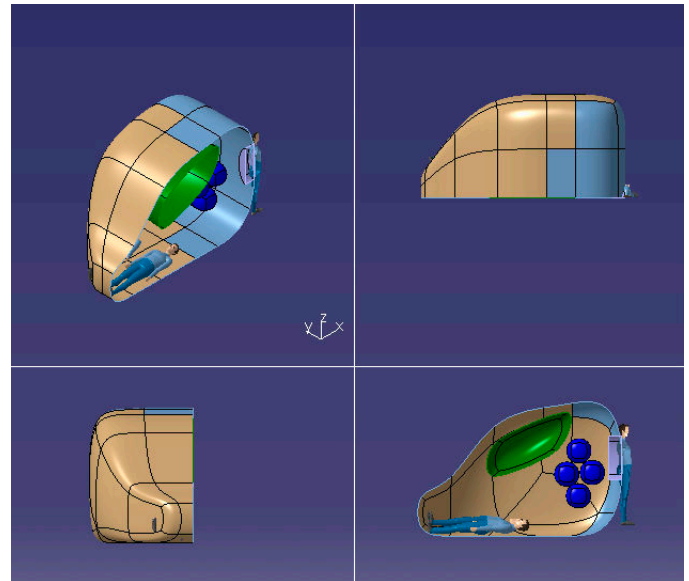


Figure 6: Initial Concept

The interior volume and overall shape are a result of the attempt to minimize interior volume and therefore system mass as much as possible. The tapered shape allows for the crew to lay down while only a limited section of the entire habitat allows for standing. One could see it as a very similar concept to traditional tents. This concept was used only to set a baseline design to refer to during our initial trade studies and subsequent design concepts. Following the preliminary design, three more concepts were developed by dividing the design space based on the operational scenario and be expected to pre-existing support equipment on which the system can rely.

LUNAR PUP-TENT

The Lunar Pup-Tent (LPT) concept finds its operational application in those contingency scenarios where crew survival is the only objective. After a critical failure in a primary system such as a main habitat or a lunar rover, the LPT is designed to buy time for either an outpost-based or an Earth-based rescue mission. As a consequence of those initial assumptions, the LPT is designed to be as simple (and hence reliable), as light, and as small as possible while guaranteeing crew survival. The LPT provides crew survival for a maximum duration of 28 days for a crew of 4. From the first level requirements, the life support system is dimensioned to operate at a nominal