Planetary Resource & In-Situ Material Habitat Outfitting for Space Exploration (PRISM-HOUSE)

SPRS 592 – Space Resources Project II

Final Report

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1. Introduction

The Colorado School of Mines (CSM) was awarded a project under the Moon to Mars eXploration Systems and Habitation (M2M X-Hab) Academic Innovation Challenge on June 10, 2021 for the proposed Planetary Resource & In-Situ Material Habitat Outfitting for Space Exploration (PRISM-HOUSE) lunar habitat system. The project deliverables have been executed concurrently with coursework in the CSM Space Resources program, specifically for the Space Resources Project I & II classes. A team was established in the fall semester of 2021 and a Systems Engineering process was followed to brainstorm initial concepts, determine objectives, flow down top-level requirements, and identify areas for which the project could best further the understanding of the overall system through targeted detailed design and design evaluation testing. This report summarizes the overall project, as well as specific work completed in the spring semester of 2022.

PRISM-HOUSE is a lunar habitat system that is deployed on the lunar surface robotically and supports safe, long-term human occupancy while maximizing the use of in-situ resources and minimizing the mass of supplies and equipment that must be delivered from Earth. In this report, the team provides an overview and description of the objectives, the system, and how the current design was selected from various alternatives, as well as the resulting products of systems engineering tasks such as product and specification trees and flow-down requirements. A review of current risks and planned mitigation are reviewed. Four key PRISM-HOUSE systems are explored: the inflatable Habitat, External Structures & Environmental Protection (ESEP), Human Interior Goods (HIG), and ECLSS & Remote Outfitting (E&RO); for each, the team provides a detailed system description and an overview of analyses performed supporting final design, followed by a review of each Design Evaluation Test (DET) performed and resulting conclusions. The report closes with a suggestion of next steps.

2. System Objectives and Analysis of Alternatives

2.1. Objectives & Measures of Effectiveness

The initial proposed goal of the PRISM-HOUSE project was in response to the NASA-requested topic of “Make It or Take It?: Approaches to Outfit an Inflatable Habitat,” and was “to investigate all outfitting components necessary for a safe, livable, inflatable lunar habitat.” [1] The Objectives of a project should flow down from the top-level, single goal into categories that directly support achieving that goal, and further into sub-categories each of which support their own parent objective, creating an Objectives Tree. Each design decision and requirement can then be tied back to an objective to demonstrate the purpose and value of that decision. The high-level Objectives Tree established by the PRISM-HOUSE team is shown in Figure 1.

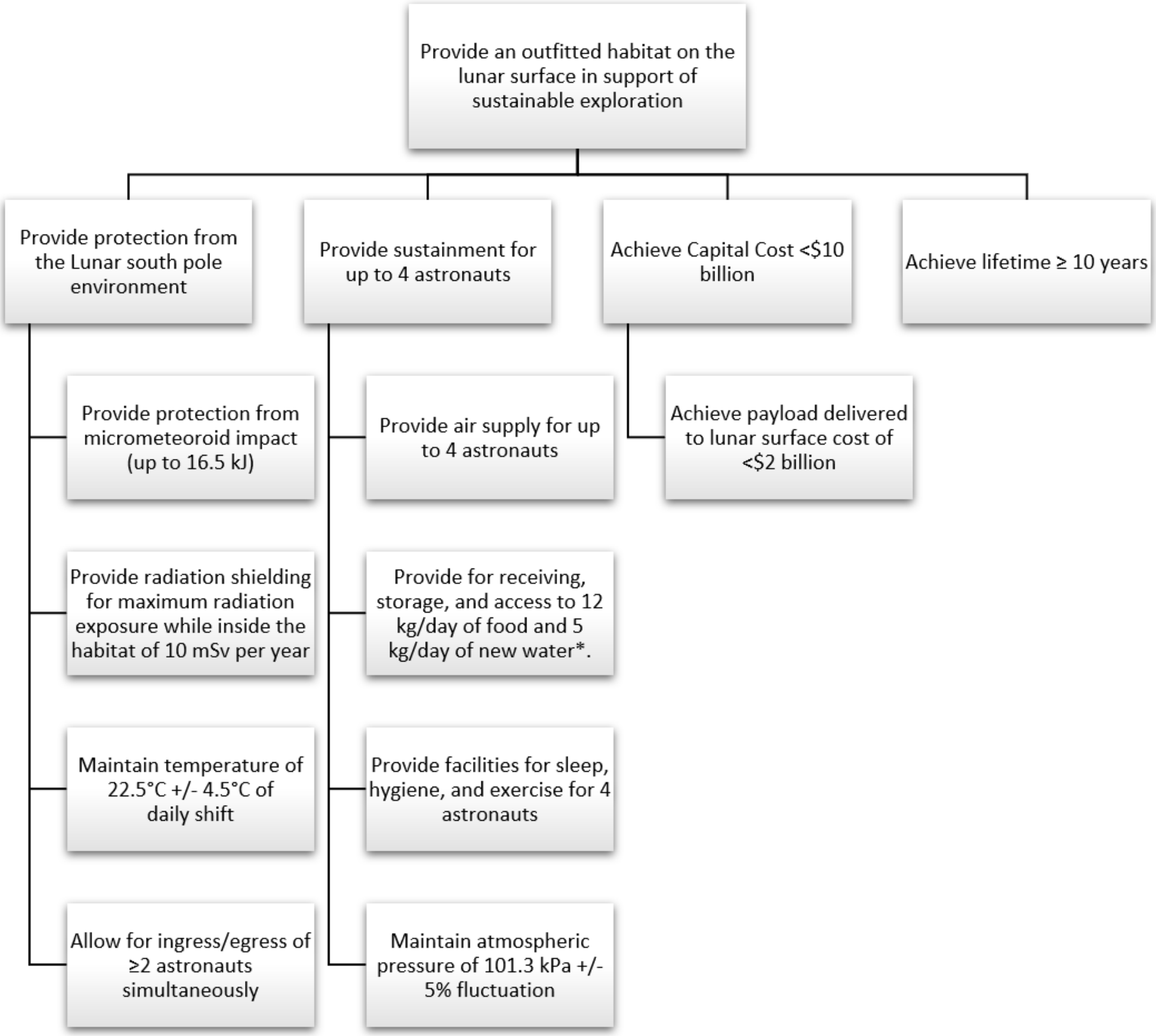


Figure 1: PRISM-HOUSE Lunar Habitat Objectives Tree

Based on these objectives, measures of effectiveness (MOEs) were established which supported continued design and provided a method to determine how well the system meets the stated objectives. These MOEs have been updated as result of conclusion of detailed design and testing, and consist of the following:

1) Protection from micrometeoroid impacts of 16.5 kJ or less
    a) Includes ongoing maintenance after impacts
2) Radiation exposure of 10 mSv or less per year
    a) Per astronaut (International Standards of radiation exposure limits)
    b) Maximize habitat geometry and materials for shielding
3) Sustainment of 4 astronauts
    a) Storage and preparation of water and food
    b) Includes all required living facilities
4) Allows for safe ingress/egress of astronauts

    a) Minimum of two in the case of an injured astronaut requiring assistance
5) Produce regolith-based interior goods to outfit habitat living requirements
    a) Products safe for human contact, safe to use for food, durable
6) Lifetime > 10 years
    a) High durability and/or the capability to perform repairs
7) Cost < $10 billion
    a) Includes launch cost and development costs
8) Assembly, Installation, and Commissioning time < 1 year
    a) Total time from initial landing to astronaut-ready
    b) 6-month maximum external shell construction period
    c) 9-month maximum time to initial ECLSS operation and habitat safe for astronauts
9) Use of in-situ materials for >50% of final system mass
    a) Includes mass of all system components used to meet requirements on the lunar surface
    b) Excludes launch, landing, and transit vehicles
10) Comply with NASA Human Health & Performance Requirements
    a) Includes social and mental health and habitability

2.2. Analysis of Alternatives

During brainstorming, many ideas were generated for achieving the project objectives. To determine the best concepts to carry forward into detailed design, an Analysis of Alternatives was performed by generating performance criteria and associated weight of importance of each criterion to the overall project objectives. Each concept category was evaluated against these criteria, and the resulting table is shown in Figure 2. Items are rated from 1 (worst) to 5 (best), with the highest overall score representing the most promising alternative.

Habitat Alternatives	**Risk**	**Mass**	**Cost**	**Power**	**Lifetime**	**Total**
Category Weight	5	4	2	1	2	-
Class 1 Hard Modules	5	1	5	5	3	50
Class 2 Inflatables, 0% ISRU	4	2	4	4	2	44
Class 2.2 Inflatables, 20% ISRU	3	3	3	4	4	45
Class 2.5 Inflatables, 50% ISRU	3	5	3	3	4	52
Class 3 100% ISRU	1	5	1	1	4	36

Figure 2: Analysis of Alternatives

Risk, as defined for this analysis, is based on the general magnitude of overall risk for both development and operation relative to the current state of the art. Power is evaluated as relative magnitude of maximum and average power required. The Mass category evaluates only the mass of the system that must be delivered from Earth.

The “Class 2.5” structure received the highest score and was selected for detailed design. Given the constraints of the analysis of alternatives and general trend of the evaluation, it is assumed that future reduction in risk (via technology development) of ISRU technologies will further reduce mass required to be delivered from Earth, favoring designs even closer to a full “Class 3” type.

3. Functional Tree & Product Tree

A functional tree was developed to determine the primary functions the system must be able to perform to meet the system objectives and MOEs. These functions include both initial deployment and long-term operation and maintenance. The PRISM-HOUSE Functional Tree is shown in Figure 3.

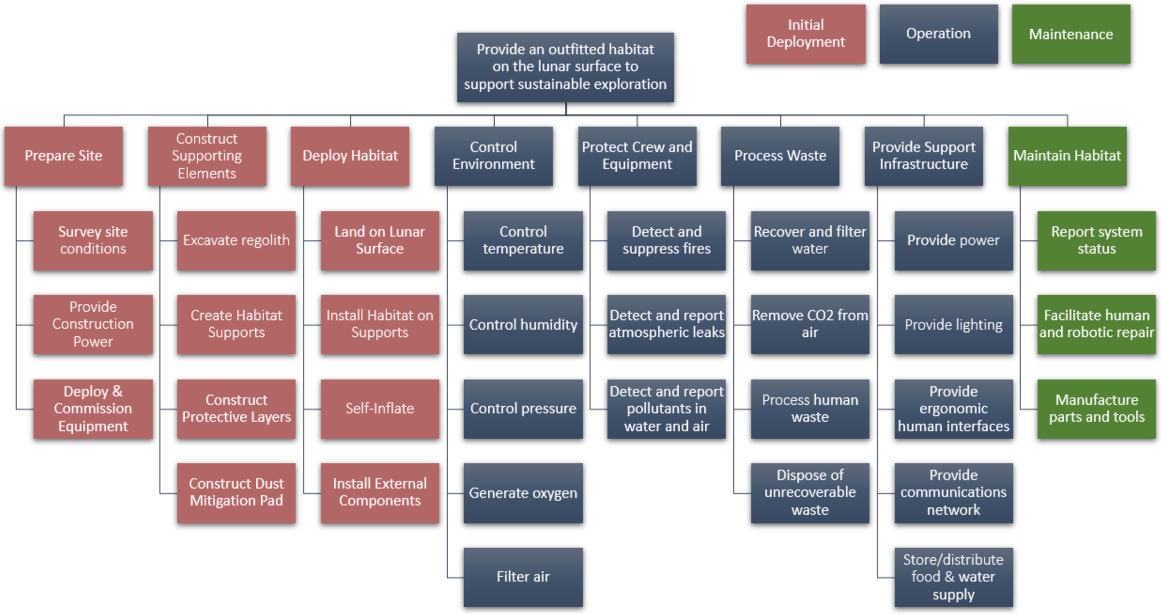


Figure 3: PRISM-HOUSE Habitat Functional Tree

Each of these functions must be performed by some combination of equipment, software, personnel, processes, etc. These items are considered Products and are summarized in a Product Tree. Importantly, the Product Tree includes all products of the system, which can provide all functions listed in the Functional Tree. Note that single products can serve multiple functions, and single functions can be achieved through the use of multiple products. The PRISM-HOUSE Product Tree is shown in Figure 4.

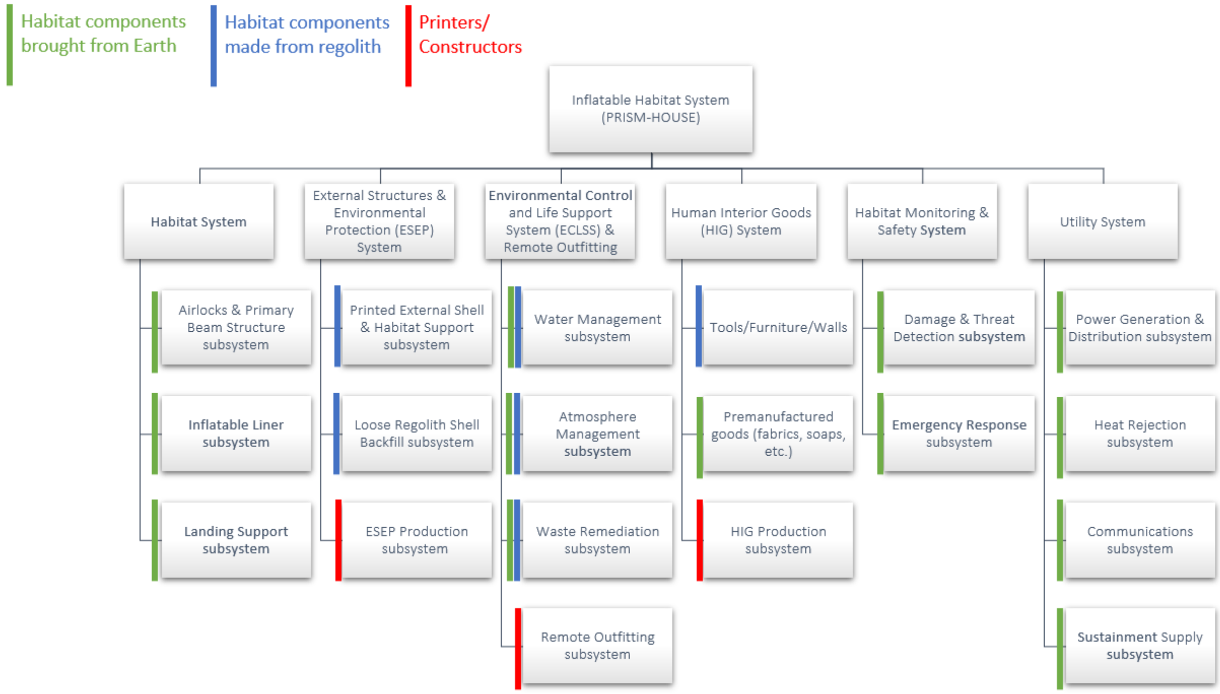


Figure 4: PRISM-HOUSE Habitat Product Tree

4. System Description and Concept of Operations

4.1. Top Level Requirements

The functional and product trees lead the team to define top level requirements for the system (Table 1). These requirements were defined for four primary systems, which were determined from the logical grouping of the Product Tree. More detailed requirements are provided for each system in subsequent sections of this report, and the complete Requirements document generated for the project can be found in Appendix A: Final Requirements.

Table 1: Top Level Requirements

Req ID	Requirement
1	External Structures & Environmental Protection (ESEP) System
1.1	The ESEP System shall function on the lunar surface environment.
1.4	The ESEP System shall utilize additive manufacturing methods.
1.5	The ESEP System shall consume 60kW of power or less on average for a 1-hour period during operation
1.6	The ESEP System shall provide a protect the internal habitat from external hazards
2	Human Interior Goods (HIG) System
2.1	The HIG System shall function within the constraints of the PRISM-HOUSE habitat
2.2	The HIG Production Subsystem shall fabricate components, parts, and other items to offset mass delivery from Earth by 25%
3	Environmental Control and Life Support System & Remote Outfitting (E&RO)
3.1	The E&RO system shall control environment and process waste for up to four astronauts
3.2	The E&RO system shall interface with other PRISM habitat subsystems to allow function of all ECLSS equipment
3.3	The E&RO system shall complete installation and commissioning prior to astronaut arrival
4	PRISM-HOUSE Habitat (PHH) System
4.1	The PHH system shall function in the protected lunar surface environment
4.2	The PHH system shall be capable of installation inside the ESEP Protective Shell
4.3	The PHH system shall be compatible with structural components produced by the HIG system

4.2. System Description

To achieve previously stated objectives and MOEs, provide the products and functions discussed, and meet established top-level requirements, the team proposes a lunar habitat system that is deployed on the lunar surface robotically and supports safe, long-term human occupancy while maximizing the use of in-situ resources and minimizing the mass of supplies and equipment that must be delivered from Earth. The system consists of pre-manufactured components which are delivered to the lunar surface using commercially available services. These components include all equipment necessary to prepare the surface, gather necessary materials such as lunar regolith, robotically deploy the habitat, construct all in-situ subsystems, support long-term operations, and the habitat itself (

Figure 5). The system also includes the components constructed on the lunar surface, such as external protection and interior goods.

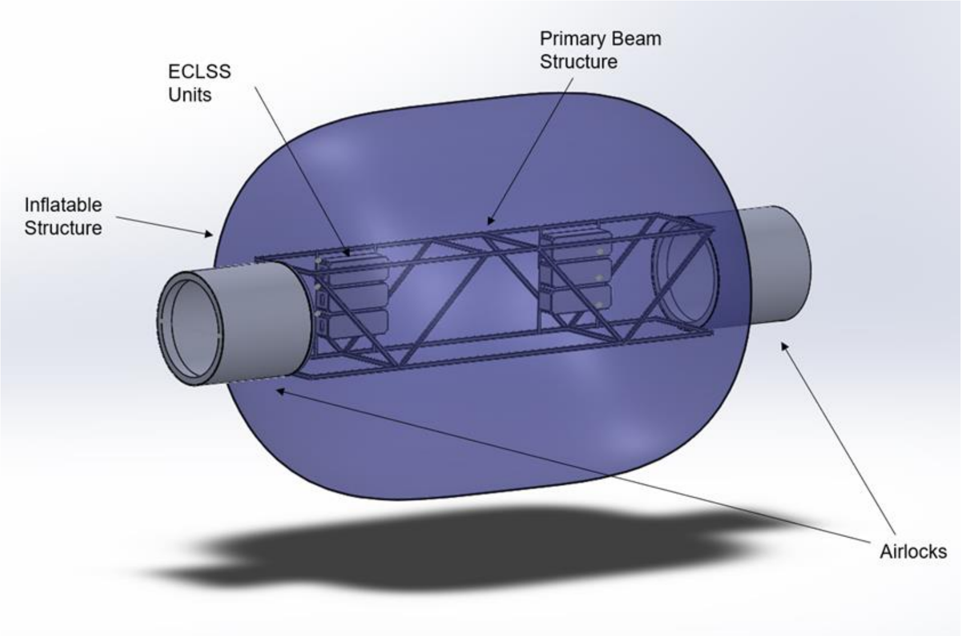


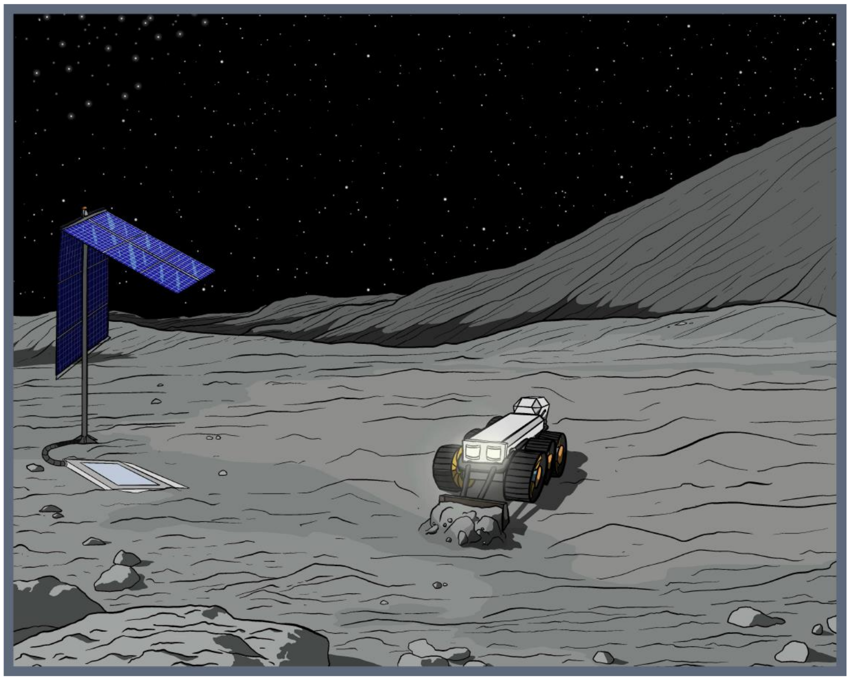
Figure 5: Structural Components and Pre-Manufactured ECLSS

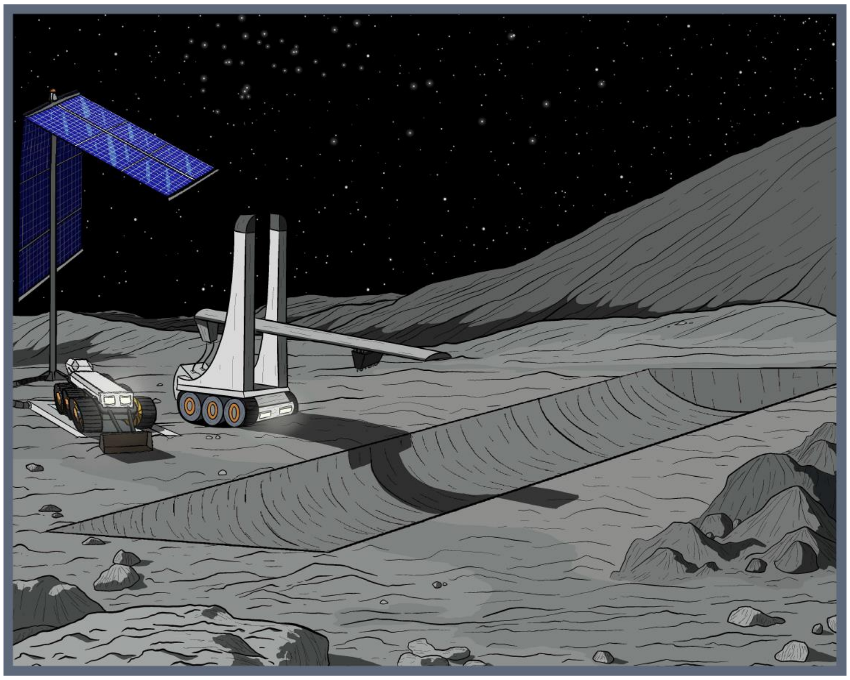
The four primary systems which make up PRISM HOUSE are described in detail in subsequent sections of this report, but the following Concept of Operations provides a high-level overview of the complete system.

4.3. Concept of Operations

Equipment Delivery

Upon landing, robotic investigation of nearby areas will be used to determine the optimal location of the habitat. Initial power infrastructure (solar array, rover charging station) will be brought online and various equipment robotically unpackaged. The habitat itself will remain in an undeployed state at this time or be delivered on a later lunar landing.



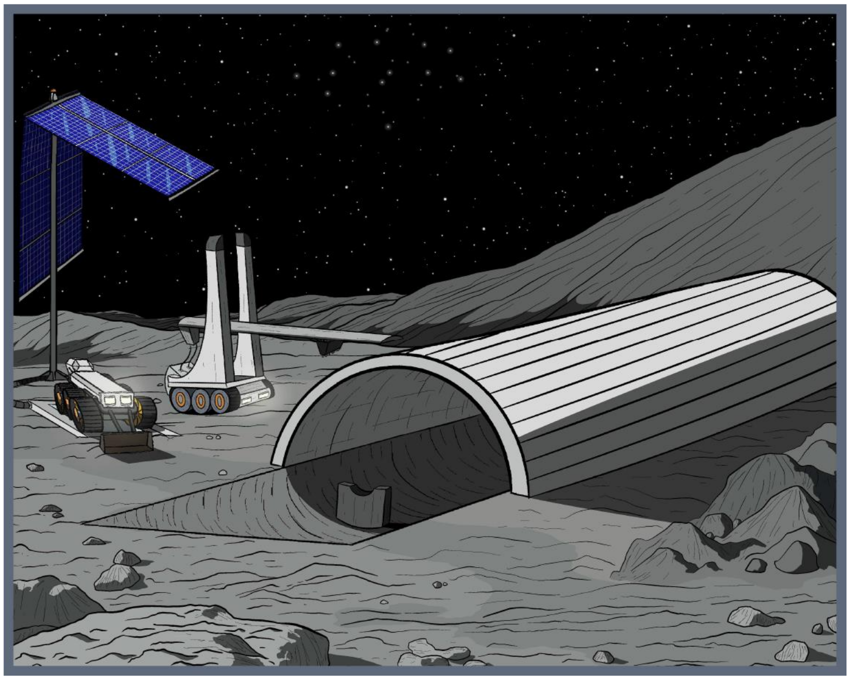


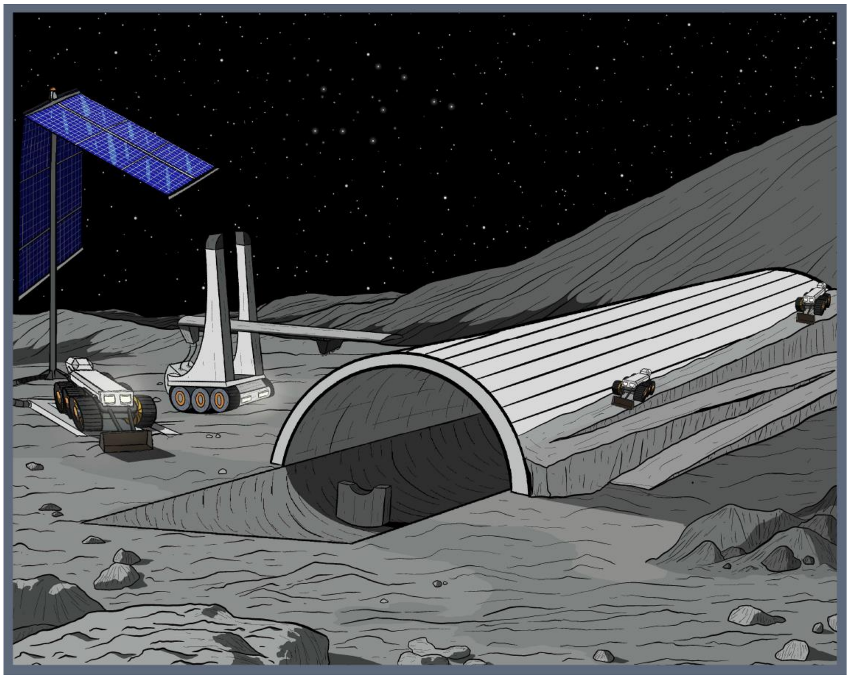
Trenching & Printer Setup

Trenching begins to make room for the lower half of the inflatable habitat, as well as provide feedstock for the external printer. The external printer is brought online and commissioned.

External Shell & Habitat Support Printing

The external printer creates the support shell on which loose regolith will be piled in the next step. It also creates the supports for the airlocks of the habitat, allowing the habitat to be deployed with no lunar surface contact other than the printed supports.



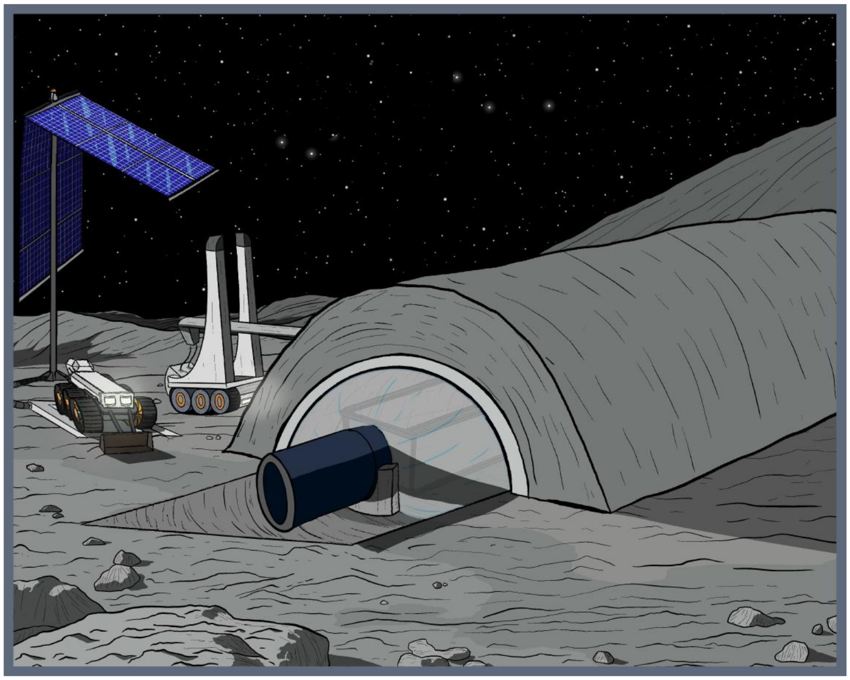


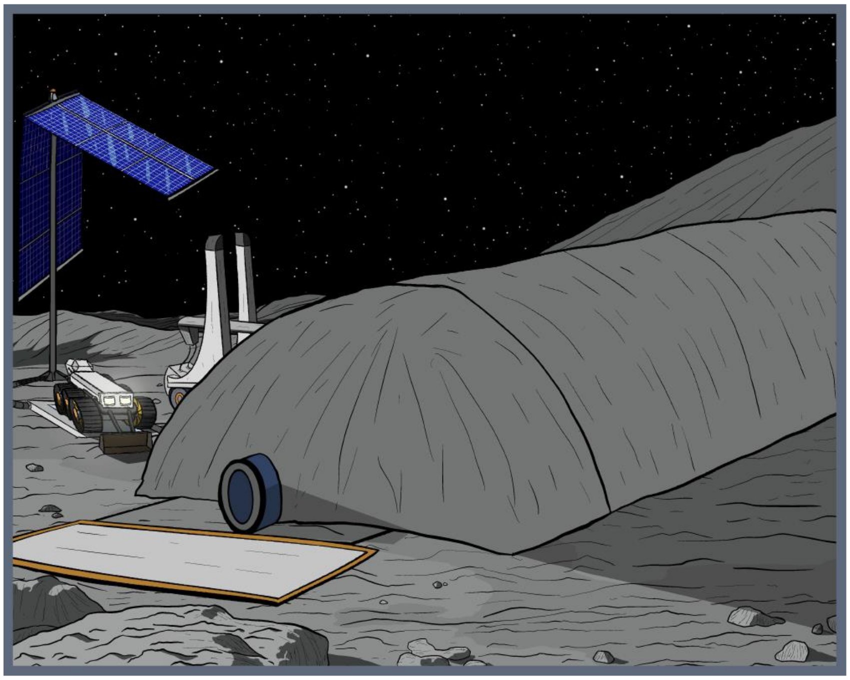
Loose Regolith Shell Creation

Loose regolith is moved into position over the printed shell. This could be conducted by rovers, as shown in the photo, or other conveyance systems as discussed in the following sections. While indicated as series steps for simplicity, this process could actually be performed in parallel with the shell printing, with the loose regolith follow the completion of each linear section of the shell.

Habitat Installation and Inflation

Once the shell and loose regolith are installed, the habitat can be moved into place on the printed habitat supports and inflated. At this stage, pressure performance of the habitat and installation tolerances (such as the gap between the inflatable surface and the printed shell) can be evaluated and, if necessary, modified, prior to moving on to the next step.





End Cap Printing & Loose Regolith Completion

A hemispherical shell with gap for the habitat airlock is installed, followed by transport of loose regolith to cover the ends of the habitat. The external printer creates a solid pad at the airlock exit for dust mitigation. At this stage, the remaining ECLSS systems (heat rejection, communications, and additional power) are installed external to the habitat and connected to the habitat via cables and hoses.

Commissioning & Operation

All habitat functions are tested and commissioned prior to astronaut arrival and long-term operation. The rovers and external printer are available for repairs, maintenance, and operation. The Human Interior Goods printer is available to create necessary interior products to supplement human occupancy, safety, and comfort of the habitat.

5. Risk Management

5.1. Risk Identification

The operationally limited and extreme environment of the lunar surface comes with many inherent risks. Additional risks are introduced by our required phases of deployment, excavation, production, and sustainment, with the ultimate requirement of supporting living astronauts becoming a culmination of all derived and implicit risks. The process of risk management began with identify risks affecting the habitat and assessing their probability and impact.

5.2. Risk Assessment

Assessing our risks and plotting their likelihood and consequence on a risk matrix provided an estimate of their projected impact on the habitat. Power and energy requirements were the most significant risks to address, while other significant risks included manufacturing systems functioning properly on the Moon through the duration of the habitat life, mitigating lunar dust, deploying the habitat successfully, and being able to excavate regolith within a given time schedule.

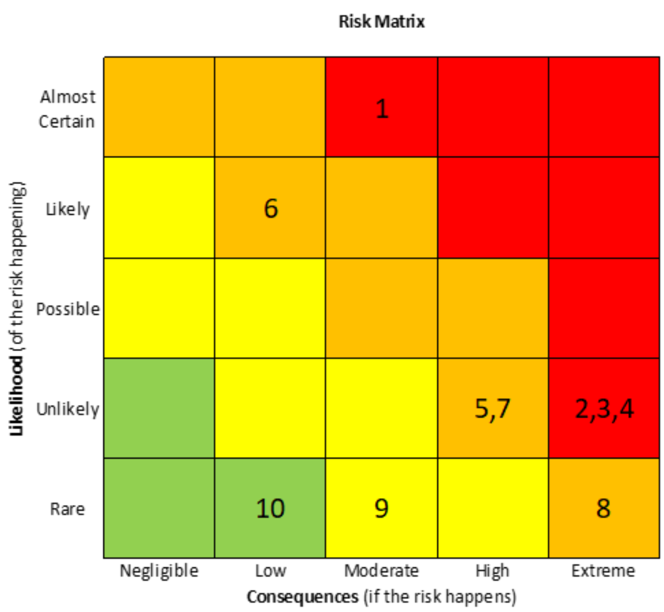
Risk #	Category	Risk	
1	Development	Power and energy requirements exceed mass / launch count requirements	
2	Operational	Lunar dust within habitat atmosphere exceeds ECLSS filtration limits	
3	Operational	Manufacturing systems (3D printers) degrade and fail to meet longevity + redundancy requirements	
4	Operational	Inflatable is punctured during deployment, operation, or maintenance	
5	Operational	Lunar radiation or micrometeorite environment is more severe than currently predicted	
6	Development	Internal complexity of ECLSS installation exceeds capability of rovers	
7	Operational	Regolith requires excessive effort to produce suitable particle size for feedstock requirements	
8	Development	Vulnerability to impacts, radiation exposure, and redundant seals in transitory areas of ingress/egress	
9	Operational	Regolith-based printed products are found not to be food safe	
10	Development	Excavation rate insufficient for phased deployment requirements	

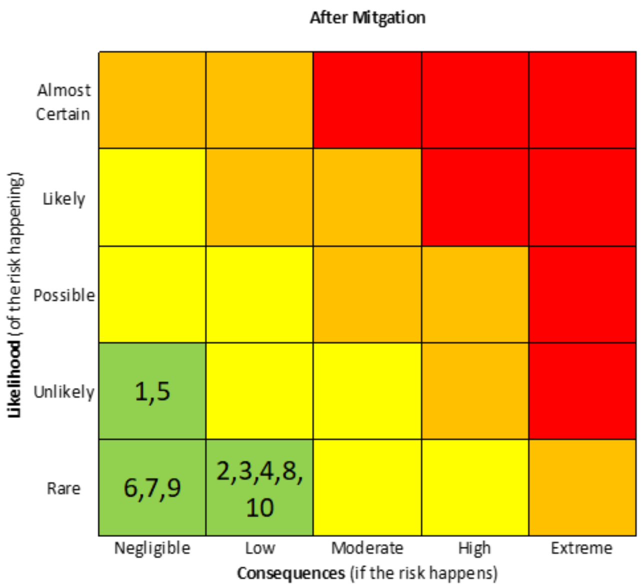
Figure 6: Risk Assessment risk matrix

5.3. Risk Handling

Between the risk handling methods of avoid, mitigate, transfer, and accept, it was most important to identify those which would be mitigated and accepted, in order to work them into the design as early as possible. Power was decided to be transferred – all power and energy requirements will be purchased from suppliers on the lunar surface, and the design requirements will instead be centered on interfacing with those purchased power systems. This will give the habitat the best chance of being designed with a focus on lunar surface and human living requirements, then become efficient on power use based on a purchase and cost perspective. Avoided risks included those derived from sensitive components that cannot risk any extent of failure: avoiding the inflatable membrane's contact with regolith, avoiding ECLSS being set up onsite (install in advance of deployment), and avoiding manufacturing printers with limited feedstock input capabilities. The remaining mitigated and accepted risks are outlined in the Risk Mitigation matrix below.

5.4. Risk Mitigation

Mitigated and accepted risks were identified early on, not only to be incorporated into the design, but also to structure the design and evaluation test plan respectively. The additional data provided by a risk-conscious test plan enables a technical and quantified approach to risk mitigation through continual design improvement. All engineered designs will need to reliably operate on the lunar environment with redundancy, repairability, and effectiveness. Highlighting the risks which need to be mitigated is critical to evaluating the future prototypes that will be built and ensure they meet the requirements to reduce risk for the lifespan of the mission.

Risk #	Mitigation	
1	Transfer - purchase power from other supplier	
2	Mitigate - plan to provide extra filtering equipment and increased resupply if needed	
3	Mitigate - if performance is degrading faster than expected, print extra parts in advance to allow time for deployment of new equipment	
4	Avoid - design inflatable to not have contact with regolith	
5	Mitigate - ESEP printer can expand external shell beyond original design as needed	
6	Avoid - install as much ECLSS in correct location prior to launch	
7	Avoid - design printers that accept wide range of feedstock sizes	
8	Mitigate - redundant / conservative design	
9	Mitigate - test wide range of potential lunar materials so that any combination of actual materials is acceptable	
10	Accept	

After Mitgation

Likelihood (of the risk happening)	Negligible	Low	Moderate	High	Extreme
Almost Certain	🟧	🟧	🟥	🟥	🟥
Likely	🟨	🟧	🟧	🟥	🟥
Possible	🟨	🟨	🟧	🟧	🟥
Unlikely	🟩 1,5	🟨	🟨	🟧	🟥
Rare	🟩 6,7,9	🟩 2,3,4,8, 10	🟨	🟨	🟧

Consequences (if the risk happens)

Figure 7: Risk Mitigation risk matrix

6. Habitat

6.1. Description

The PRISM-HOUSE Habitat itself consists of the internal structural components supporting all subsystems installed under the ESEPS shell, the inflatable outer layer, the airlocks on either end to provide safe access of personnel and equipment, and any supporting infrastructure to allow safe landing and installation under the external regolith shell. An early trade analysis (see Inflatable Interface Trade Analysis) resulted in the decision to not allow the external inflatable surface to come into contact with any lunar regolith surface. This allows the inflatable requirements to fall more in line with the current state of the art and mitigates risks related to lack of knowledge of lunar regolith abrasion properties at the lunar south pole, the intended location of the PRISM-HOUSE habitat. However, it requires the full mass of the habitat and all internal components and personnel to be supported only by the airlocks on either end of the habitat and the truss structure connecting them. This drives the structural requirements of the internal habitat members between the two airlocks, as well as the structural requirements of the supports which hold the airlocks above the regolith and act as the interface between the airlocks and the lunar surface. To save mass, these supports will be created by the External Structures printer (see Section 7).

Internal to the Habitat, the minimum infrastructure will include structural members spanning the two airlocks, on which all other equipment will be mounted. The inflatable surface material will be stowed around the structural members prior to inflation, to minimize form factor of the habitat for launch and installation. Floors, walls, and doors can be pre-installed in volumes available prior to inflation. For volumes available only after inflation, a combination of astronaut-installed additional structural members provided with the habitat and items printed by the Human Interior Goods system will be used. Components and subsystems required for construction and installation (such as the rovers and initial power sources) can also be transported inside the pre-deployed habitat.

The airlocks provide all interfaces between the habitat and other systems, as well as the lunar surface. All communications, power, and fluid connections to external equipment are connected on the outer-most airlock ring. The airlock body itself is in contact with the printed lunar regolith supports. The airlock also provides safe transition for personnel and equipment from the vacuum of the lunar surface to the pressurized interior habitat (and vice versa).

6.2. Requirements

The PRISM-HOUSE Habitat (PHH) System requirements were determined after other primary systems and are therefore flowed-down and frequently constrained by those systems. The primary requirements are shown below in Table 2, and the full requirements document can be found in Appendix A.

Table 2: PRISM-HOUSE Habitat (PHH) Requirements

Req ID	Requirement
4.1	The PHH system shall function in the protected lunar surface environment
4.1.1	The PHH System shall function in a vacuum.
4.1.2	The PHH System shall remain functional between 110K and 395K.
4.2	The PHH system shall be capable of installation inside the ESEP Protective Shell
4.2.1	The PHH system shall be capable of locomotion while the inflatable is undeployed
4.2.2	The PHH system shall have maximum dimensions of 2.5m x 2.5m x 14.5m while undeployed
4.3	The PHH system shall be compatible with structural components produced by the HIG system
4.4	The deployed PHH system shall allow all relevant ECLSS requirements to be met
4.4.1	The PHH inflatable subsystem shall meet ECLSS pressure requirements
4.4.2	The PHH System shall meet NASA reliability requirements for human spaceflight
4.4.3	The PHH System shall only come into contact any part of the lunar surface (printed or loose regolith) at the airlocks

6.3. Analysis

Structural Analysis

$F = center\ point\ load$ (N)
$L = beam\ length$ (m)
$E = Modulus\ of\ Elasticity$ (Pa)
$A = beam\ cross\ section$ (m^2)
$n = proportional\ axial\ force$ (%)
$N = member\ axial\ force$ (N)
$K = Buckling\ Factor$
$q = distributed\ load$ (N/m)

$$\text{Max main deflection} = \sum \frac{nNL}{EI}$$

$$\text{Critical Buckling Load} = \frac{\pi^2 EI}{(KL)^2}$$

$$\text{Max side deflection} = \frac{qL^4}{8EI}$$

Figure 8: Structural Equations

The purpose of this analysis was to determine the minimum mass required for this structure while still minimizing deflection and withstanding gravitational loading. Figure 9 shows the simplified beam model used for the calculations, and variables and equations utilized are provided in Figure 8. The results show that 31,000 kg can be supported on a truss structure spanning 10m with a mass of 450kg while only deflecting 1.6mm and reaching a stress of 11% of max loading before permanent deformation of the beams, assuming a material of Aluminum 6061-T4. This is possible primarily due to the reduced gravity of the lunar environment, and does not include an analysis of launch vibrations, launch accelerations, or Earth's gravitational forces. While it is not expected that the final habitat structure will follow this same beam design, this analysis provides a rough order of magnitude estimate of the material required to achieve the requirement which only allows the airlocks to come into contact with the lunar surface. The low-mass result led the PRISM-HOUSE team to consider the spanned support habitat design a feasible approach.

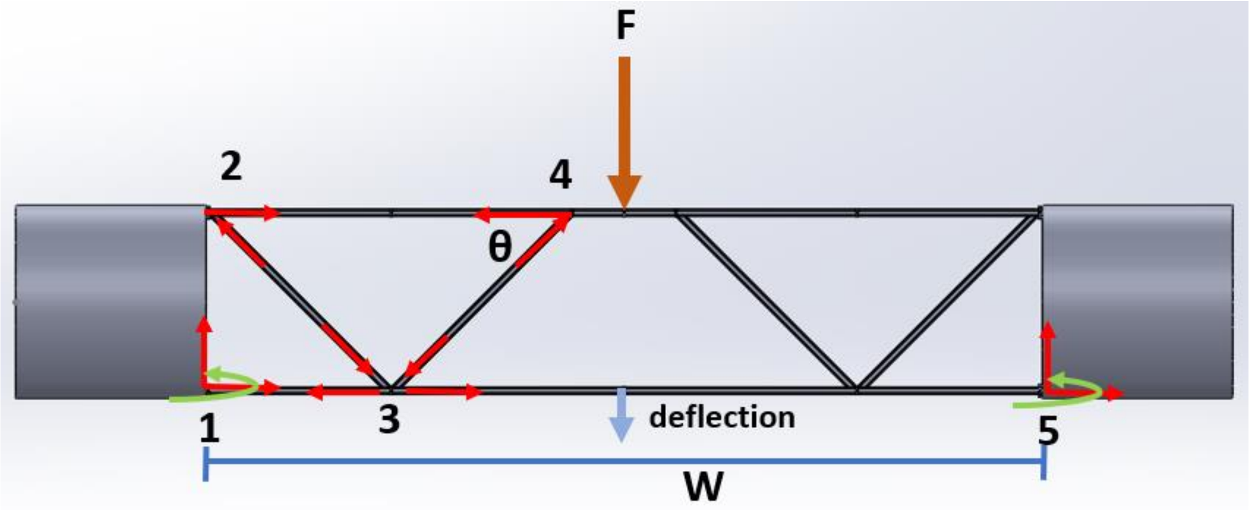


Figure 9: Simplified Beam Model

Inflatable Interface Trade Analysis

The primary consideration when evaluating whether the inflatable habitat should be in contact with the printed shell was the mechanical loading on the printed layer. A simplified schematic of the forces is shown in Figure 10. In the non-contact scenario, the shell is self-supporting and loaded in compression. In this scenario, compressive stress is lowest at the crown and highest at the base. It can be calculated as the weight of the arch divided by the contact area. [2] A worst-case evaluation of this loading, which assumed the full weight of regolith in the ESEP system (see Section 7.3) was supported by the arch, led to a calculated compressive load of 0.64 MPa which should be well within the material limits. However, in the contact scenario at the weakest point – the crown of the arch, there is a substantial net upwards force on the printed shell. A simple hoop stress calculation yields a 1.4 MPa *tensile* stress within the section, which will only be counteracted by a small portion of the arch mass. Bumps or bulges on the interior surface as well as print layer delamination would produce stress concentration points, greatly increasing local stresses. Ceramic materials are weak in tension, so the ultimate tensile strength of these materials is much lower than their strength in compression. The overall lower force within the printed material, as well as the reduced requirements on surface finish led to the decision to avoid contact with the regolith and printed shell. Avoiding contact has a few additional benefits outside of stress. Firstly, it greatly reduces the risk of puncture from rubbing or sharp edges on the printed structure, which eliminates the need for an outer puncture-resistant layer and reduces habitat mass. Secondly, the gap between the habitat and shell allows for inspection and potential repairs to either the inflatable habitat or the shell.

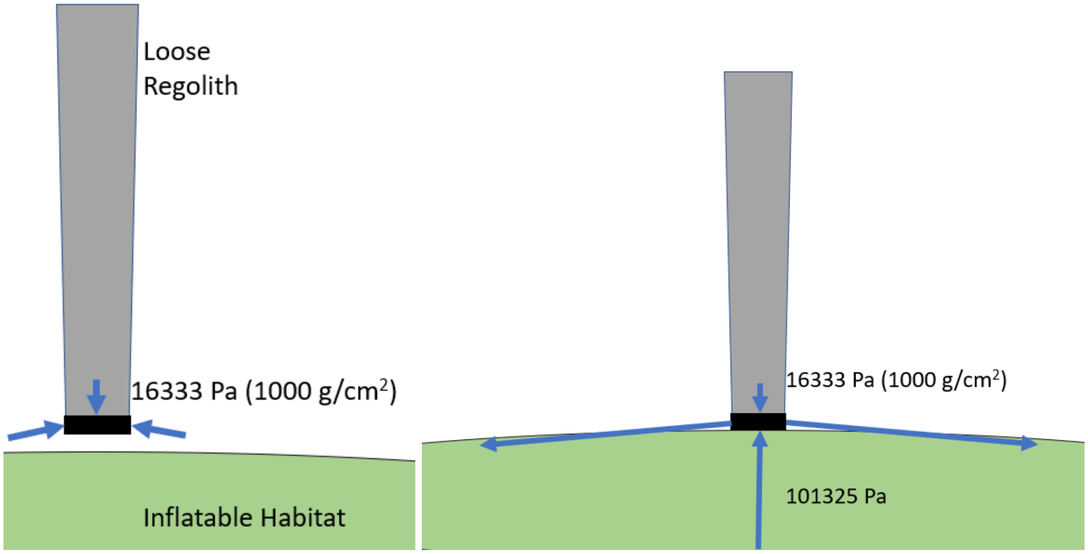


Figure 10: Schematic of loading in the non-contact (left) and contact (right) scenarios. In the non-contact scenario, the arch is loaded under compressive force, while in the contact scenario, the arch is loaded under tension and experiences much higher magnitude forces.

7. External Structures & Environmental Protection System

7.1. Description

The External Structures & Environmental Protection (ESEP) system provides protection from radiation and micrometeorites, allows access to and from the habitat for personnel and equipment, provides structural support for the habitat, and provides an internal usable volume of sufficient dimensions to allow full inflation of the habitat. It also includes all equipment required to manufacture the system in-situ at the lunar surface.

Figure 11: Concept art for the Olympus printer under development by ICON [3]

The primary component of the ESEP system is the external 3D printer, which is modeled after a technology under development by ICON (Figure 11). [3] The printer melts or sinters processed, loose regolith in layers, allowing construction of three-dimensional shapes, such as a half-cylindrical shell as shown in the ConOps.

This printer also creates the supports for the airlocks located on either end of the habitat, which are the only interface between the habitat and the lunar surface. This allows the habitat inflatable surface to avoid direct contact with lunar regolith, resulting in simpler design. However, it requires the printed habitat supports to withstand significant loading. The ESEP printer is anticipated to be able to create robust enough supports to achieve this requirement.

Excavation rovers are then used to excavate and move loose regolith on top of the half-cylindrical shell. This process can be completed in layers, to allow temporary access paths for rovers to all areas where regolith is required. The current design calls for a simple pile of regolith at a natural angle of repose for the final state (see Regolith Printing section) so precise placement of regolith is not required. This is an area of possible trades and flexibility on rover design. The driving requirement is the rate of regolith movement required; how the regolith is moved (rovers, conveyors, line and bucket systems, etc.) can be determined by the best available technology at project start. The process for regolith piling can begin as soon as a single section of the printed shell is complete, allowing the rovers and external printer to operate nearly in parallel during construction.

Once the main shell and regolith layers are complete, the habitat is installed in place on the habitat supports. This may be achieved through the function of the habitat itself (such as wheels attached to the airlocks) or via the use of rovers, depending on the technology utilized for excavation.

After habitat installation, an end-cap is printed by the external printer is a partial spherical shape with a cutout section for the airlock. Regolith is then backfilled over this shell in a similar manner to previous loose regolith movement. Finally, a smooth pad is printed by the external printer to assist in dust mitigation.

During operation & maintenance, the rovers can be used to add loose regolith to areas as needed, as well as remove regolith to provide access to the printed shell for repairs by the external printer.

7.2. Requirements

The most constraining ESEP requirements (Table 3) are related to using additive manufacturing methods, protecting the internal habitat from external hazards, and doing so with minimal power usage. The printing rate is directly proportional to the power usage and efficiency of the printer, so a high achieved efficiency in regolith printing technology has a big effect on the overall risk, cost, and duration of construction of the PRISM-HOUSE system.

Table 3: External Structures & Environmental Protection (ESEP) System Requirements

Req ID	Requirement
1.1	The ESEP System shall function on the lunar surface environment.
1.3	The ESEP System shall interface with other PRISM habitat subsystems to allow function of all passthroughs and sensors.
1.3.1	The ESEP System subsystem shall produce a structure with a 2.5m minimum opening for the habitat airlock
1.4	The ESEP System shall utilize additive manufacturing methods.
1.4.2	The ESEP System shall be capable of receiving up to 1000 kg/day of regolith for additive manufacturing.
1.4.3	The ESEP System shall be capable of receiving up to 7000 kg/day of regolith for regolith infill.
1.5	The ESEP System shall consume 60kW of power or less on average for a 1-hour period during operation
1.6	The ESEP System shall provide a protect the internal habitat from external hazards
1.6.1	The ESEP Production Subsystem shall produce a structure that is capable of stopping a micrometeoroid impact up to 16.5kJ without compromising the structural integrity of the shell.
1.6.2	The ESEP Production Subsystem shall produce a structure that limits the maximum internal radiation exposure to 10 mSv or less per year. This will be measured as the weighted average radiation measured in room in the habitat with weighting based on anticipated astronaut time in rooms.
1.8	The ESEP Production Subsystem shall produce a structure with an internal habitable area of at least 150 square meters with a minimum height of 3m

7.3. Analysis

Impact Analysis

The lunar surface experiences a steady flux of micrometeoroids which the habitat needs to be protected from. The 16.2kJ impact spec is based on a once-in-a-century impact on a habitat with a surface area of 500 m2 at maximum velocity (18 km/s) and is equivalent to a 0.1g impactor. This was determined from data from the Lunar Source book and a copy of the chart is shown in Figure 12 below. [4] It is noted that "[f]or meteoroid masses of about 1 g, craters of centimeter scale and somewhat lesser depth are formed" (Section 3.10.3). Note that this is an impactor 10x larger than that required by the system specification. Thus, to meet impact requirements, a protective layer of regolith at least 10cm thick across the habitat would be sufficient to protect from all expected impacts. It is worth noting that micrometeoroid flux rate is largely determined by extrapolation so there is potential for some variation in actual flux. However, as shown in the following sections, regolith thickness is predominantly driven by radiation shielding needs, so regolith thickness should be several orders of magnitude greater than necessary solely for impact protection.

Figure 12: Micrometeoroid flux on the lunar surface with estimated once-in-a-century impactor of a habitat with 500m^2 of surface area is shown on the chart. [4]

Regolith Excavation & Transport Logistics

The reduced gravity of the lunar environment creates significant challenges for the mass and horizontal forces that are driving performance factors in excavation equipment. The excavation rover design must be able to move any composition of regolith that is encountered to include scraping, loading, and breaking up irregular clusters. An excavation rover capable of handling all of these requirements will have a wide front blade for scraping, rear mechanical jackhammer for break up, and a top hauling bay which can be loaded with regolith to increase rover mass. This diverse design will allow for a full spectrum of excavation and hauling operations, as needed. Initial bulk regolith excavation from the formation of the trench will be set aside to be utilized for infill of the habitat's final ESEP protective covering, as well as berm walls as additional protection in the area of operations.

Having a fleet of excavation rovers not only provides redundancy, but also a more productive flow of operations. As active rovers are excavating, inactive rovers can recharge power or receive maintenance to ensure continual operations. A rotation of active rovers will maximize excavation rate and provide additional rovers as backups when failures occur. A robust and reliable fleet of excavation rovers will include a maintenance bay, wireless (inductive) charging station, and the ability to print repair parts from regolith. Priorities for repair parts are durable components which are in frequent abrasive contact with regolith such as wheels and digging blades.

It is worth nothing that RASSOR 1 is an excavator designed for reduced gravity environments which is commonly discussed for lunar excavation. Unfortunately, the quantity of material required for the ESEP system is beyond the capabilities of this excavation system. To meet a 6-month timeline for fabrication of the ESEP system, more than 30 RASSOR 1's would be required. [5] Additionally, the RASSOR 1 system is not well suited to the longer transport distances or deep excavation required leading to inefficient operation and further increase the number required. A larger and more capable rover would be better suited to this task. The habitat excavation requirements highlight the need for a fleet of multifunctional excavation rovers with an improved rate of excavation compared with currently operational rover technology.

Regolith Printing

The ESEP external shell printing rate is determined by the geometry and thickness of the shell, the power usage of the printer, and the efficiency by which the printer uses that power to melt and form regolith. A brief summary of each calculation is provided below, followed by the resulting printer power required to meet the target printing rate.

The printed external shell is a hollow half-cylinder with roughly quarter spherical end caps. The cylinder is sized such that it can fit the inflated internal habitat with 0.5m of gap space between the inflatable and the internal wall of the shell. The thickness of the shell is estimated at approximately 381mm, based on initial predictions of structural shapes the printer can make and the way those shapes can printed to result in the required arch-like shapes. These printed shapes are also assumed to not be fully solid, but rather have a relative density of ~57%. This results in a shell that has a maximum length of ~24m and is 10.5m in diameter, with a total printed material volume of 85m^3.

The power required to print the regolith can be estimated using heat transfer equations and knowledge of the regolith density, heat capacity, and melting point. By using a heat capacity value of 1715 J/g [6], a melting temperature of 1245°C, and a regolith density of 1.7 g/cm^3 [7], 1kW of power is capable of melting 0.34 cm^3/s of regolith. However, the printer will not be 100% efficient and will lose heat to space, conduction, and auxiliary electrical loads. Assuming a 50% printer efficiency, the maximum deposition rate of the printer is assumed to be 0.17 cm^3/s per 1kW nameplate rating of the printer.

In order to achieve the requirement of a 6-month maximum printing time of the external shell, the total nameplate of the external printer(s) must be approximately 55kW (Figure 13).

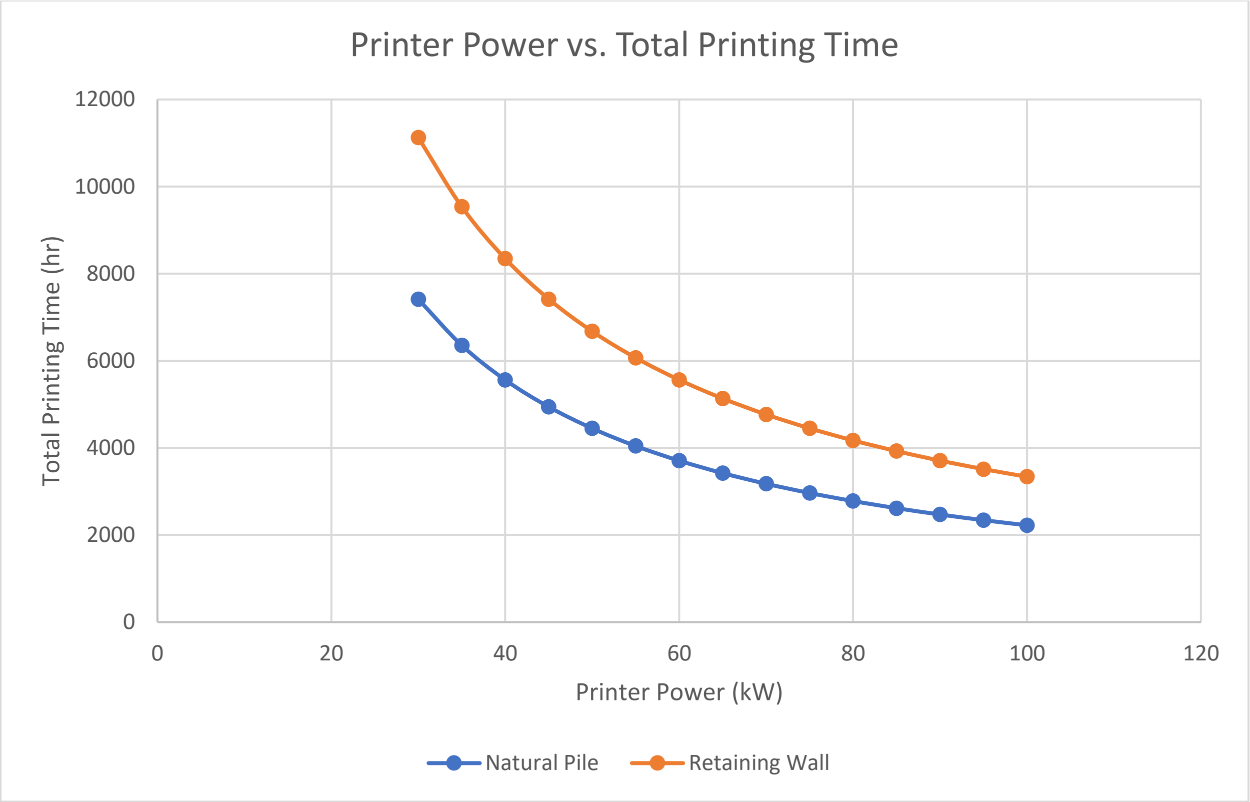


Figure 13: External Printer Power vs. Total Shell Printing Time

The other primary component of the ESEP shell is the loose regolith layer on top of the printed shell. This layer must be a minimum of 5m thick, and will take the shape of a simple pile with a slope equivalent to the regolith angle of repose, assumed to be 58° [8]. The thickness was determined by following the recommendation from R. Moses' Lunar Surface Innovation Consortium (LSIC) 2021 presentation to achieve approximately 1000 g/cm^2 thickness [9] and considers the density of both the loose regolith and densified, printed regolith shell. It should also be noted that while the angle of repose value chosen is based on the measurement from a single Apollo 14 sample, it is in the same range as other angle of repose predictions for lunar regolith and the results of this analysis are not sensitive in the range of likely angle of repose values (see Figure 14). The volume of regolith required can then be determined from simple geometry and trigonometry equations, shown in Figure 15. Note that θ represents the angle of repose, and "r" represents the radius of the printed cylindrical shell. In this scenario, the total volume of loose regolith that must be provided is 2,890m^3. To match the 6-month shell printing time (as the operations could be completed roughly in parallel, as the printer finishes each section), this would require a regolith transport rate of approximately 0.7m^3/hr (assuming round the clock operation).

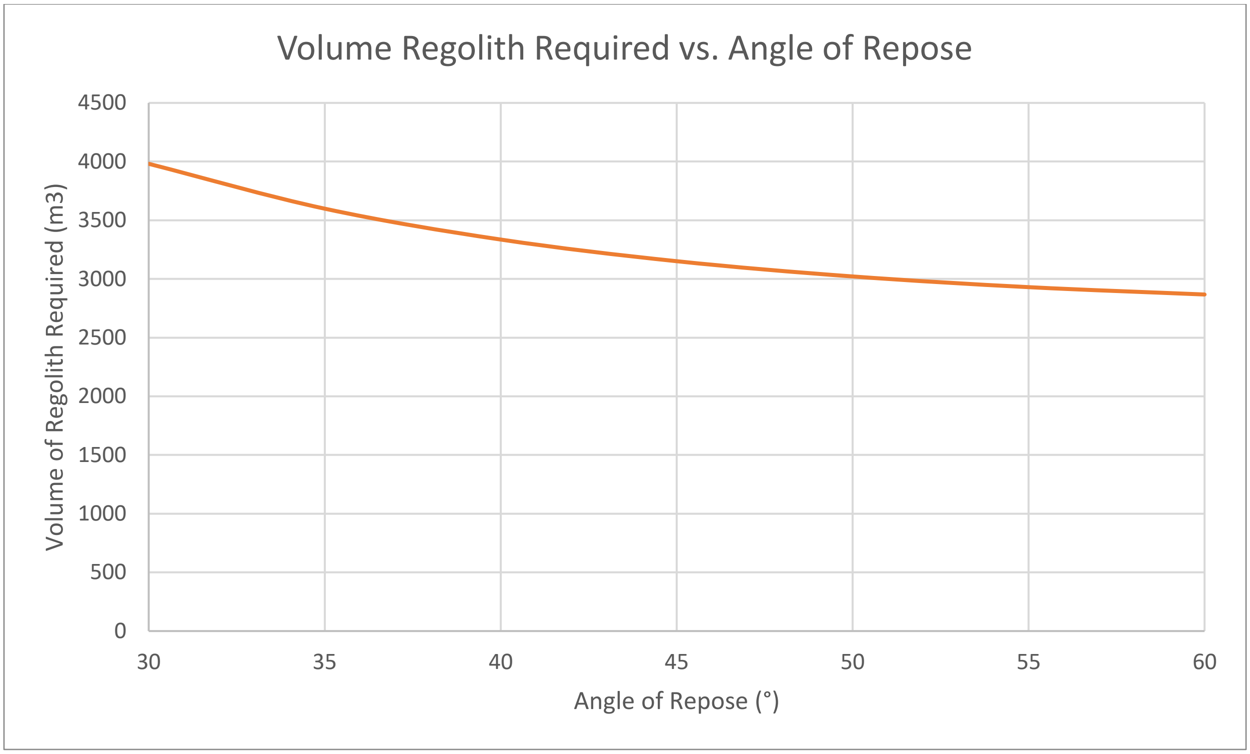


Figure 14: Volume of Loose Regolith Required vs. Angle of Repose

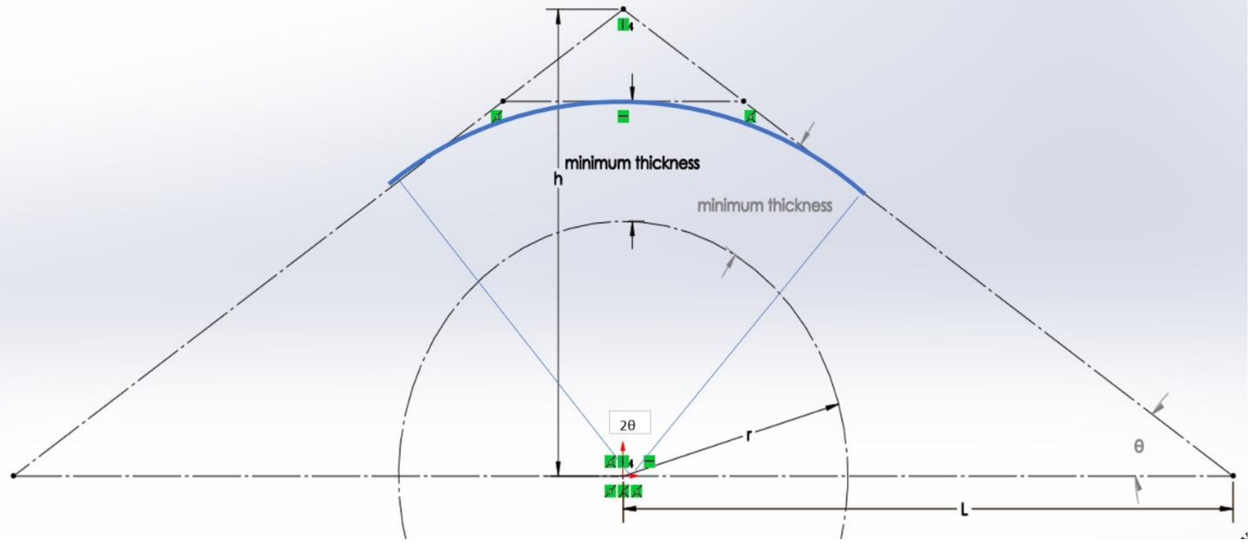


Figure 15: Loose Pile Option for Loose Regolith Shell

Lastly, a trade analysis was completed to see if additional printed regolith material could offset loose regolith transport and save time (or printer power) as compared to the base case. A geometry was proposed for “retaining walls”, which would be printed by the external printer 5m from the inner shell (the minimum required loose regolith thickness) and tall enough to support the regolith at its natural angle of repose. The resulting geometry is shown in Figure 16. This increased the printed regolith volume requirement by 40m^3 and reduced the loose regolith volume requirement by 91m^3. To hit the 6-

month printing timeline, the total power of the printer(s) would now need to be approximately 75kW, and the loose regolith movement rate would effectively bet the same. It was concluded that the simple pile option was the preferable choice.

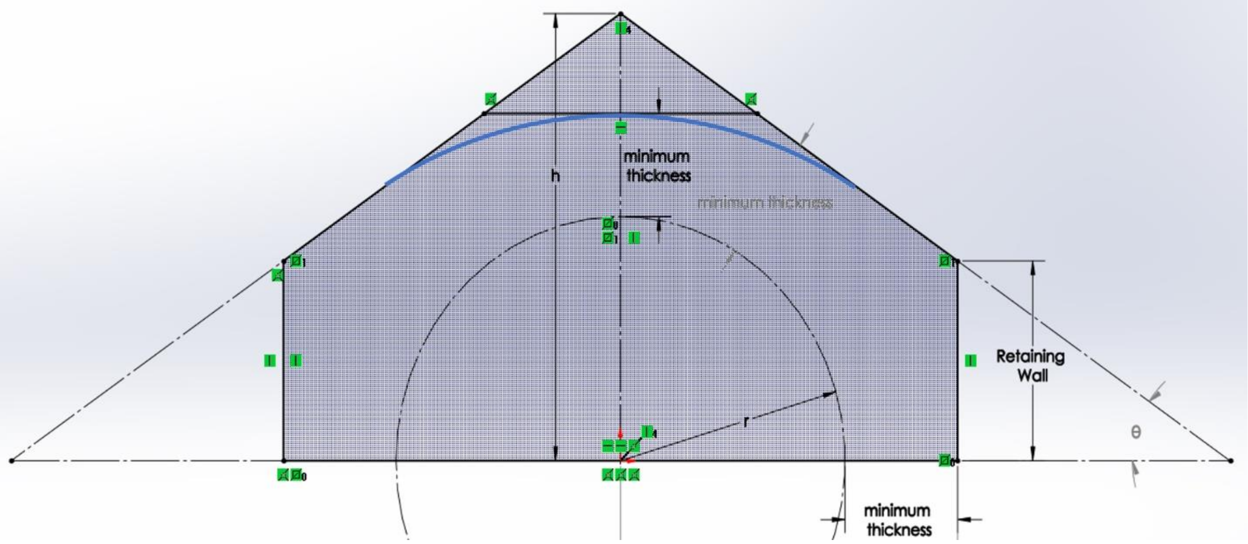


Figure 16: Retaining Wall Option for Loose Regolith Shell

Viewports and Windows

Feedback from NASA has indicated that viewports are important for psychological health of astronauts. As previously discussed, substantial shielding is required to protect from the harsh radiation environment on the Moon. Unfortunately, a traditional window would effectively place a hole in the shielding, greatly reducing the overall protection. Several solutions were considered to provide a similar effect without compromising radiation protection. A full analysis of alternatives is shown in Table 4.

Radiation Shielding Windows

Conceptually, the simplest solution of providing a viewport without compromising radiation shielding would be to produce windows thick enough to provide reasonable shielding. These would likely need to have similar area-density to regolith at 1000 g/cm^2. Glass has a density of roughly 2.5 g/cm^3, [10] which would lead to a window 2.5m thick. Even a relatively small window would be hundreds of kilograms and would be prohibitively expensive to launch. Producing glass clear enough to see through at this thickness would be technically challenging, even on Earth. Attempting such a task in-situ without the necessary deposits of high purity quartz would be nearly impossible with present technology. Although not a major concern, the thermal conductivity of a solid block of glass is higher than bulk regolith and could potentially increase thermal control requirements.

Periscope Viewport

An alternative solution considered was a periscope-style design. This would consist of a pair of offset tubes with a pair of mirrors in the middle to transmit light. A schematic of the design is shown in Figure 17. The mirrors would be produced from a material which is reflective to visible light but transparent to high energy radiation, allowing the radiation to continue into the loose regolith layer and be absorbed. Due to the long length of such a periscope, an un-magnified image would shrink by a factor of ~12x through the length of the tube, meaning that a window 40x40cm would appear to have a visible image less than 3.4x3.4cm. This would require magnification optics which would need to be brought from Earth, however, the tube body could be produced in-situ using the large-scale printer. One potential concern is secondary radiation produced from GCB. Further evaluation will be needed to ensure this would not be emitted into the tube and reducing the effectiveness of the shielding.

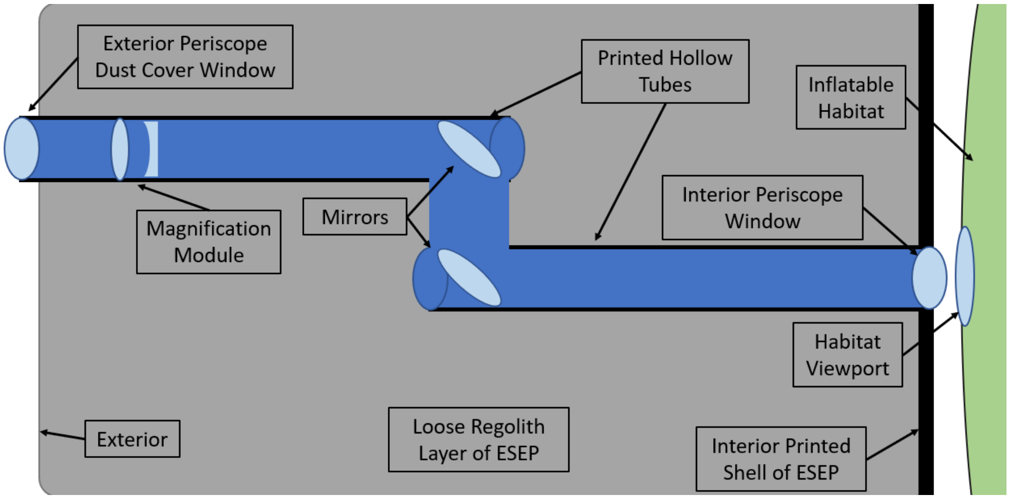


Figure 17: Schematic of a periscope-style design. Grey and black regions are loose and consolidated regolith respectively, produced via ISRU. Dark blue is hollow tube sections, light blue are windows and lens elements brought from Earth.

Live Camera System

A live view camera system provides an effect similar to a window without requiring a passthrough to the exterior. Such a system would consist of several cameras place on the outside of the habitat, paired to a set of monitors within the habitat. Cables could be run around the base of the habitat to utilize the airlock passthroughs, allowing for easy installation and repair. The system would be low in mass and could potentially share components with other systems, such as cameras for remote monitoring, or monitors for displaying equipment readouts. An assortment of flight-tested camera hardware already exists so such a system would be relatively easy to implement. However, the system does require steady power and ceases to function if power is lost, which could lead to safety risks if these systems are relied on for mission critical tasks. Additionally, some research has shown that virtual windows provide less psychological benefit than traditional windows. [11] While this research is still in its early stages, it should be further evaluated before such a system is relied on as the only viewport option. The Crew Health and Performance Exploration Analog (CHAPEA) mission 1, utilizing the ICON produced Mars Dune Alpha and being run by Johnson Space Center, is operating with screens acting as windows. The results of this analog test, which will conclude in Fall of 2023, will be helpful in determining the degree to which screens may be used as windows in a future habitat. [12] [13]

Fiber Optic Imaging

The final option considered here is fiber optic imaging. This technology consists of a bundle of extremely fine fiber optic cables which are used to transmit an image. While an individual fiber is only capable of transmitting a single color of light, by bundling thousands of fibers together, an image can be assembled. This technology is most commonly encountered today in endoscopes for minimally invasive surgery. The systems flexibility, power-free operation, and relatively small feed through diameter, have recently led to its incorporation into military vehicles as a backup gun sight, such as the system produced by Nedinsco Venlo. [14] Their system has options for optical fibers up to 4.5m and a mass around 10kg, in a military specification (MIL-STD-810F) package, meaning the technology is capable of handling harsh environments. A system could be installed into the lunar habitat similar to the periscope design with a lens viewport on the exterior and a display window on the interior. The narrow passthrough diameter minimizes the hole in the radiation shielding and the solid optical fiber also acts as a radiation absorber. One drawback of a fiber optic system is the intensity of light transmitted through the fibers is low, resulting in a dimmer final image. In addition, the quantity and density of fibers needed to create an image is roughly proportional to the size of the final image. Therefore, short of creating an exterior viewpoint the size of a full window (which would have similar excessive mass issues as a standard window), the final size of a fiber optic based viewport would be smaller and low resolution.

Summary

As shown in Table 4, the fiber optic system was chosen as the most promising standalone design for ambient lighting. The minimal effect on radiation shielding, low system mass, and ability to operate without power are substantial benefits over other technologies. In practice, this system would likely be deployed along with a suite of live cameras on the habitat exterior for monitoring by Earth-based ground crews as well as lighting solutions to meet other needs, such as natural ambient lighting to give the habitat the sense of time passing. Due to polar locations lacking a true day and night cycle, natural ambient lighting would need to be limited to common areas and avoid sleeping areas. A combination of solutions could help offset the negatives of each.

Over the long term, an expansion of the habitat could attach a cupola-style Class I module to the secondary airlock of the habitat. While this would result in higher radiation exposures, it could be visited for short periods of time and would not compromise the protection of the main astronaut living and working quarters.

Viewport Option	**Shielding**	**System Mass**	**Power Consumption**	**Technologic Difficulty**	**Total Score**
Weight	**5**	**4**	**2**	**2**	**-**
Standard Window	1	4	3	5	**39**
Shielded (thick) Window	5	1	4	1	**41**
Periscope	4	4*	5	3	**52**
Live Cameras	5	5	1	5	**59**
Fiber Optic	5	4	5	4	**61**

*Table 4: Analysis of alternatives for various window designs. *The periscope concept is the only window design which can be partially produced using ISRU, mitigating some of the mass requirements*

8. Human Interior Goods (HIG) System

8.1. Description

The Human Interior Goods (HIG) system provides the ability to produce PRISM-HOUSE component parts on the lunar surface and to create many of those parts from lunar regolith and constituent materials.

The system consists of a variety of 3D printers, including those that utilize only feedstock brought from Earth as well as printers which provide a terrestrial-based binder which allows lunar regolith to be used as the primary feedstock. The components that can be produced include:

- Human interface equipment such as chairs, walls, floors, doors, and tables.
- Tools and utensils such as plates, cups, eating utensils, wrenches, pliers.
- Replacement components of other systems such as ECLSS, communications, rovers, printers.
- Flexibility for science and operations support for designs developed at a later date.

HIG printers will vary in size, capability, power usage, and printing environment based on the needs of the specific print. Small components can be printed in a typical flat bed, enclosed printer utilizing plastics, for example, while larger items such as tables and chairs will be better printed utilizing a free-form 6-axis arm printer with binder-supported regolith (Figure 18). This technology is what was used by our industry partner, Branch Technology, to create a prototype stool for human use (see Section 10.2).

Figure 18: Free-form 6-axis printer technology [15]

The HIG system is the only major system of PRISM-HOUSE that will not be operated until astronaut arrival. By not requiring the system to be up and running prior to human occupancy, the subsystems of HIG can be flexible and the order of printing operations can be decided on the fly and adjusted. As the habitat will contain only minimal infrastructure internally to support daily astronaut activities, the first priority of HIG will likely be to print walls & floors (which can be attached to internal structural members of the habitat), chairs, tables, and similar items.

8.2. Requirements

The primary constraining requirements for the HIG System (Table 5) are the ability to operate inside the limited space inside the habitat, the ability to utilize (at least partially) lunar regolith as a feedstock, and the ability to fabricate components suitable for human interaction (which includes meeting NASA's strict and lengthy requirements for flight hardware located inside human-rated vessels).

Table 5: Human Interior Goods (HIG) System Requirements

Req ID	Requirement
2.1	The HIG System shall function within the constraints of the PRISM-HOUSE habitat
2.1.1	The HIG System shall consume 20kW of power or less on average for a 1-hour period during operation
2.1.2	The HIG System shall have a mass less than 140 kg.
2.1.3	The HIG System freeform printer shall be less than 1.5m x 1m x 0.5m in size when shutdown.
2.1.4	The HIG System freeform printer shall have a minimum build volume of 2m x 1m x 1m
2.1.8	The HIG System shall be capable of utilizing in-situ material feedstock for additive manufacturing processes.
2.2	The HIG Production Subsystem shall fabricate components, parts, and other items to offset mass delivery from Earth by 25%
2.2.2	The HIG Production Subsystem shall produce products suitable for ergonomic and safe human interaction

8.3. Analysis

Product Needs and Printing Frequency – Maintenance Considerations

The frequency of use, wear and interactions of each component will drive maintenance requirements for each habitat component. Those maintenance considerations then become important factors that dictate the priority and frequency of product types being produced. Habitat components can be further delineated by three classes of use: Consumable, Durable, or Structural. Consumable components will be regularly produced and replaced, as their frequent use and interactions will degrade them quickly. Durable components with moderate wear can be replaced or repaired, depending on their operational status after inspection. Finally, structural components must be repaired as habitat functionality relies upon them and immediate repair is the only option. A long term maintenance plan includes regular inspection and scheduled maintenance to maximize longevity of all components.

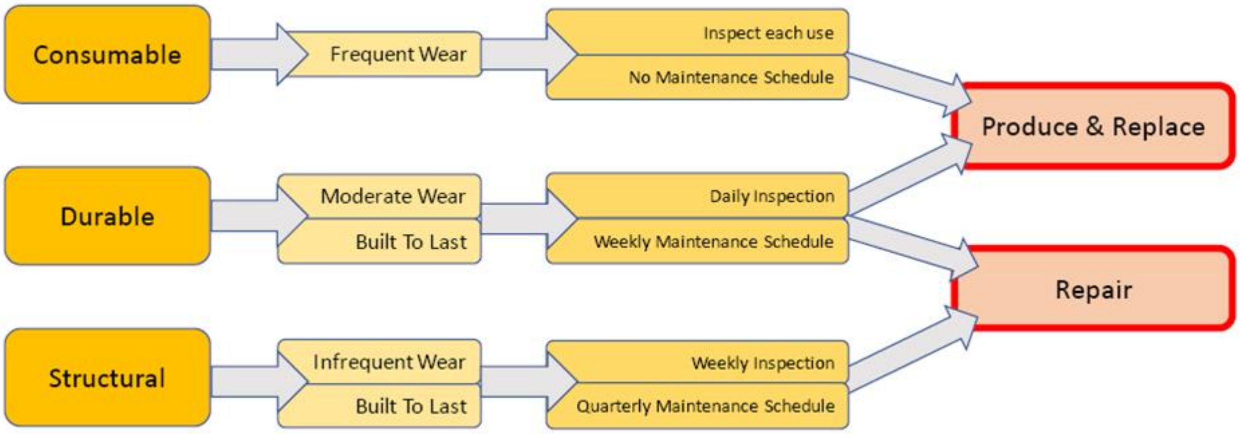


Figure 19: Habitat maintenance classes

9. Environmental Control & Life Support System (ECLSS) and Remote Outfitting (E&RO)

9.1. Description

Environmental Control & Life Support Systems (ECLSS) are well established for space habitats, most notably at the International Space Station (ISS). The PRISM-HOUSE team partnered with Axiom Space, who recently completed the first fully commercial spaceflight to the ISS and is in development of their own private space station, to determine ECLSS requirements. A second partner, Collins Aerospace, was consulted to identify a technology solution for meeting these requirements in the PRISM-HOUSE habitat. They proposed a modular solution utilizing a proprietary ECLSS "pallet" design, for which each of the required subsystems are enclosed in one or more standard containers with the same dimensions, mounting points, and interfaces for power, communications, and fluids. The PRISM-HOUSE lunar habitat has assumed the use of these ECLSS pallets for all internal components of the system. They will be pre-installed in the stowed habitat, including all necessary power, communications, and fluid connections. Upon habitat deployment on the lunar surface, the only connections that will need to be made are through the habitat airlock interface to the external systems.

The ECLSS external systems include any items that are unable to function underneath the protective regolith shell. These include communications, solar power arrays, and heat rejection surfaces. A top-level requirement of the system is complete ECLSS commissioning and operation prior to astronaut arrival, so these systems must be installed remotely. The PRISM-HOUSE will utilize a combination of self-deploying units and robotic rovers to achieve this. Upon landing, ECLSS rovers will survey the ideal locations for external ECLSS equipment and transport the equipment units in stowed position to their final locations. The units can self-deploy to their final operating positions, then the rovers can attach necessary cables and hoses between the units and the external interface of the habitat (once deployed) on the airlock.

One example of a self-deploying external ECLSS system is the product envisioned by the NASA NSPIRES Vertical Solar Array Technology (VSAT) solicitation [16]. The project requests "autonomously deployable and relocatable lunar surface solar arrays for future missions", and shows the arrays being installed by rovers as an example (Figure 20). For the purposes of the PRISM-HOUSE habitat, it is assumed that the communications and heat rejection external systems would be installed in a similar manner.

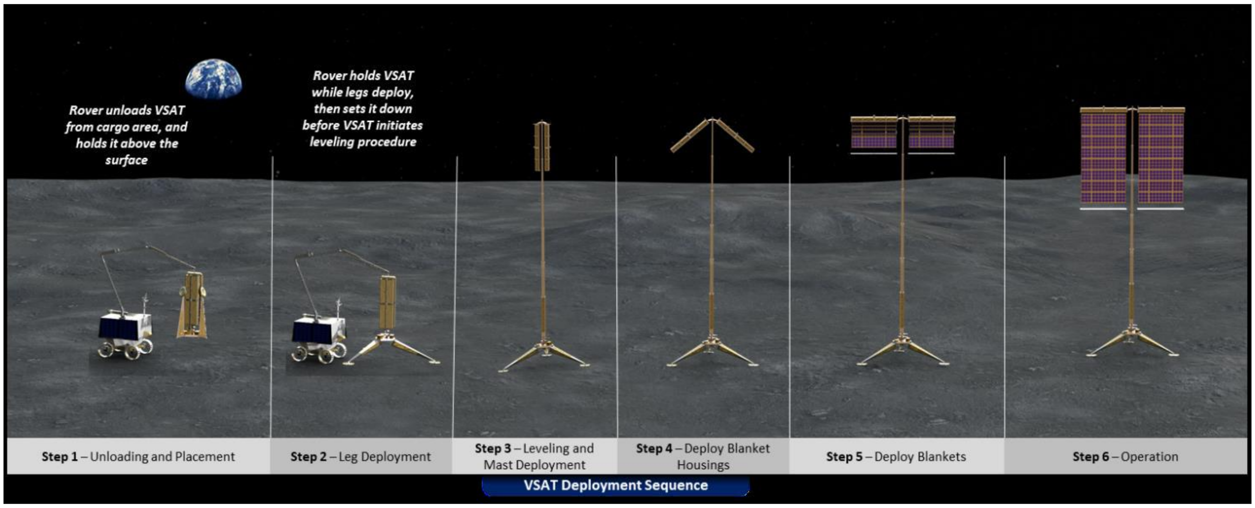


Figure 20: NASA VSAT Deployment Example

9.2. Requirements

While onerous, the ECLSS requirements are well established by NASA and private industry, well researched, have high Technology Readiness Level (TRL) and are required for many other programs and projects; this results in lower risk to the PRISM-HOUSE system. Therefore, the most constraining requirements for E&RO are related to the functionality of the rovers that will place the external components required for the ECLSS to operate (Table 6).

Table 6: Environmental Control and Life Support System (ECLSS) and Remote Outfitting Requirements

Req ID	Requirement
3.1	The E&RO system shall control environment and process waste for up to four astronauts
3.1.1	The ECLSS System shall maintain an atmosphere that meets or exceeds NASA-STD-3001-Vol2-6.2 (Internal Atmosphere)
3.1.2	The ECLSS System shall provide water to meet NASA-STD-3001-Vol2-6.3 (Water) while crew are present.
3.1.3	The ECLSS System shall provide waste collection and storage to meet NASA-STD-3001-Vol2-7.3 (Body Waste Management) while crew are present.
3.1.4	The ECLSS System shall limit the levels of lunar dust particles in the atmosphere per NASA-STD-3001, 6.4.4.2 (Lunar Dust Contamination)
3.2	The E&RO system shall interface with other PRISM habitat subsystems to allow function of all ECLSS equipment
3.3	The E&RO system shall complete installation and commissioning prior to astronaut arrival
3.3.1	Remote Outfitting mobility devices shall have an operational time before recharging of greater than 10 hours
3.3.2	Remote Outfitting manipulation devices shall be capable of motion determined by at least 2 degrees of freedom
3.3.3	Remote Outfitting manipulation devices shall be capable of positioning up to a 750kg mass with dimensions of 3m x 3m x 3m to a precision of +/- 5cm
3.3.4	Remote Outfitting mobility and manipulation devices shall be capable of tele-operation from earth-based operational centers
3.3.5	The Remote Outfitting Subsystem shall be capable of operation in lunar surface environmental conditions including day/night cycle

9.3. Analysis

Rover Tipping Calculations

The rovers used for ECLSS external components will need to be capable of picking up the units and traversing the lunar surface without tipping over or dropping the load. A simplified rover model consists of the wheelbase, the center of mass of the rover, and the center of mass of the load being lifted (Figure 21).

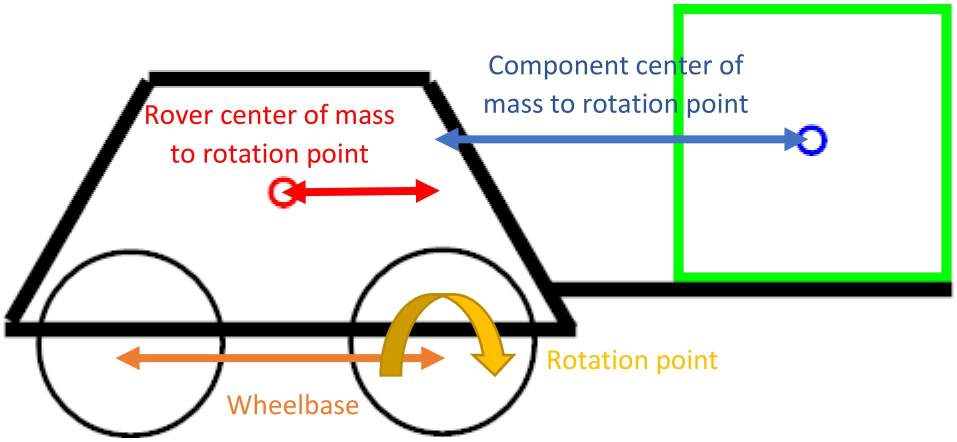


Figure 21: Simplified Rover Tipping Model

In this model, the product of the weight of the rover and the rover center of mass distance from the front wheels must be greater than the product of the weight of the component and the component center of mass distance from the front wheels. Assuming roughly similar distances of center of mass from the front wheels, a simple solution like this would work well for rovers that are more massive than the components they are lifting. However, it is possible for the PRISM-HOUSE system (and for many space systems in general) for the rovers to be lighter than the components they are required to interface with due to efforts to minimize rover mass and therefore launch costs. Therefore, it is recommended that the PRISM-HOUSE Remote Outfitting rovers utilize a system by which the center of mass of the component can be placed within the wheelbase when lifted. In this scenario, the increased weight of the rover on the lunar surface actually adds to rover traction, increasing the rover ability to traverse the surface with the component. An example of a rover of this type is shown in Figure 22.

Figure 22: Astrobotic FLEX (Flexible Logistics & Exploration) Rover [17]

Quantitative Analysis – Power

The total power usage of the PRISM-HOUSE habitat will include continuous and intermittent loads which are either critical or non-critical to astronaut survival. The overall nameplate in kW for the power system is determined by the size of the continuous loads plus the highest-power non-critical intermittent load. This assumes that multiple high-power non-critical loads will not be operated simultaneously. The battery storage size is determined by the total energy that needs to be stored to allow the habitat to survive the periodic lunar nights at the lunar south pole. It is assumed that this storage is utilized as needed to support power draw over the nameplate value when needed, as the lunar night durations and times are predictable and can be prepared for.

Table 7 shows the nameplate power requirements assumed for all system equipment and the quantitative inputs and results of the power analysis, including a system nameplate of 85kW, battery storage size of 300kWh, and a total mass of ~2000kg, assuming about 300kg of distribution and auxiliary equipment.

Table 7: Power Requirements and Calculations

Key Powered Equipment			
External Structure Printer	55	kW	Based on 6-month maximum printing time
Internal Products Printer	20	kW	Terrestrial freeform printer equivalent
ECLSS devices	15	kW	Rough estimate volume-adjusted from ISS
Communications	2.5	kW	Conservative estimate
Thermal Control	9.9	kW	Assuming 216kW absorbed energy shedding at 4.58%
Electronics, Lights	5	kW	5x typical home use (conservative)
Solar Panel Area Required			
Solar constant	1361	W/m2	
Panel effeciency	25%		ISS is 14%, Juno spacecraft is 28%
Conditional adjustment	75%		Cosine losses, tracking losses, downtime
Sunlight available	75%		H. Noda, et. al.*
Desired maximum required power	84.9	kW	ESEP printer, ECLSS, Thermal Control, Electronics/Lights
Power density of solar power units	136	W/kg	From NASA VSAT Solicitation
Solar power unit mass	624	kg	To run equipment without using battery backups
Panel Area	444	m2	
Storage			
Duration of longest night	5	days	Linne, et. al.**
Minimum power (occupied)	22.5	kW	electronics, lights, ECLSS, communications
Storage needed	2700	kWh	minimum power times duration of longest night
Battery energy density	300	Wh/kg	Optimistic state of the art
Battery roundtrip efficiency	92%		Optimistic state of the art
Mass of batteries	9783	kg	Storage needed divided by battery energy density
Minimum power (unoccupied)	2.5	kW	Communications only
Storage needed	300	kWh	minimum power times duration of longest night
Mass of batteries	1087	kg	Storage needed divided by battery energy density

* [18] ** [19]

The storage calculation provides two potential options for surviving extended periods without sunlight; the first option is with human occupation, the second is without. Both options assume non-critical loads are not operated during this time period. Given the high mass of battery systems, the unoccupied habitat option was selected for PRISM-HOUSE. Assuming site conditions similar to that of the high ridge near Shackleton Crater, the habitat would need to be evacuated 2-3 times over a 4 month period, for a maximum of 5 days at a time, and with no evacuations for ~8 months of the year (See Linne, et. al., slide 5/50 [19]).

External printer power calculations can be found in Section 7.3 under Regolith Printing.

The estimate for powering a heat rejection system is based on the amount of solar energy absorbed by the habitat, worst-case, and assuming a fractional overhead on that energy to reject it to space. The amount of solar energy absorbed is based on the surface area of exposed loose regolith outside the habitat, the solar constant of 1361 W/m^2, and an assumed lunar albedo of 12%. The fractional overhead was roughly estimated from a summary of the ISS Active Thermal Control System, considered by the PRISM-HOUSE team as the current state of the art [20].

The power requirement is a significant constraint for the PRISM-HOUSE system. It is possible that an alternative solution, such as nuclear small modular reactor (SMR) would be better suited to the system requirements. An alternative power supply solution is required if the intent is to keep the habitat occupied at all times.

10. Design Evaluation Test Plan

10.1. External Structure and Environmental Protection

A sample of printed lunar regolith simulant (CSM-LHT-1) was produced for the project using a prototype printer being developed at ICON, to demonstrate a potential technology used for printing the ESEP inner shell. This printer uses a laser to locally melt a pool of regolith. The laser is then scanned across the regolith surface to produce a layer of consolidated material. Once completed, a layer of regolith is spread over the top of the consolidated material and the process is repeated. This system is effectively a laser powder bed fusion system, albeit with a unique feedstock material. To better understand the power consumption that a printer system would require, a test part was produced (Figure 23). A design was chosen which would generate several layers of different geometry and in-fill to examine various printing conditions.

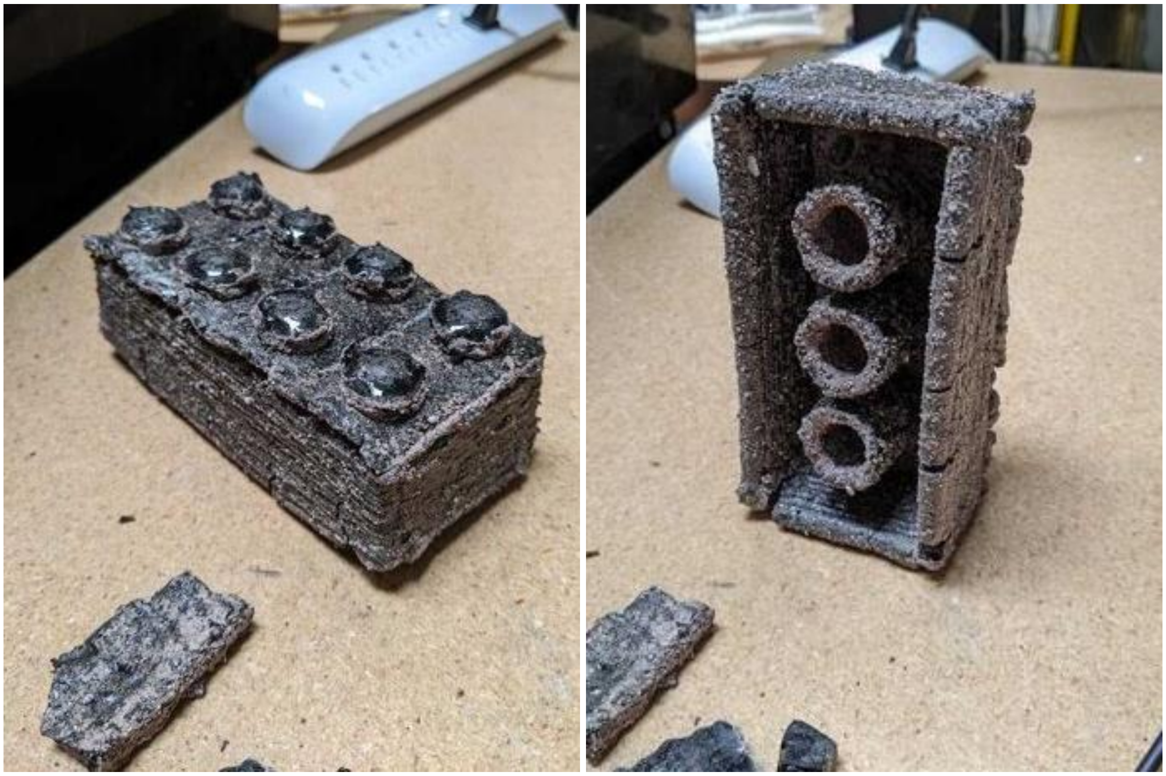


Figure 23: Photos of the test sample printed at ICON. Layer geometry was designed to produce a structure with a variety of in-fill percentages.

10.2. Human Interior Goods

Branch Technologies utilizes a freeform additive manufacturing process that enables them to print large matrix components which maximize strength while minimizing material feedstock mass; achieving an optimized strength-to-weight ratio. It is known as their Cellular Fabrication (C-Fab) technology, which allows for increased flexibility and freeform construction. They have proven this technology terrestrially and are in the process of adapting it to lunar use. Their terrestrial process relies on mixing a binder with feedstock, and ISRU-produced binders are being sought for lunar use. Research is being conducted by Stanford University on microbially produced binders that could be grown on-site, but it is still in the research phase and a product with this ISRU binder was not available for testing. Instead, a test print was conducted of the freeform printing method in order to validate the method for suitable interior goods.

To evaluate the strength of the test print, a loading test was devised to evaluate the structural strength of the test print. The test print was sequentially loaded with 20.4 kg (45 lbs) cast iron weights to determine the maximum structural load the design was capable of. Once loaded to a weight level, the stool was gently rocked to ±5° to evaluate the stiffness of the structure. The stool was loaded to a total mass of 183.6 kg (405 lbs) and did not experience failure. This is representative of an equivalent lunar total mass of 1101 kg (2430 lbs), well above the maximum expected loading of a stool. Although the test print remained structurally sound and was likely capable of supporting higher loads, the testing was stopped at this mass due to concerns about safety. Photos of the test print at several intervals of testing are shown in (Figure 25) below. Branch Technology's test print was found to be both structurally sound and lightweight. If the same product can be achieved with the microbial binder, then it will be able to produce interior goods to furnish the habitat.

Figure 24: Design and photo of the test Forma stool printed by Branch Technology.

Figure 25: Loading testing of the test print stool at 20.4 kg (45 lbs), 81.6 kg (180 lbs), and 183.6 kg (405 lbs) from left to right respectively. Testing was stopped at 183 kg.

10.3. Food Safety Testing of Printed Regolith

Introduction

Lunar regolith is chemically similar to terrestrial clays as shown in Table 8. Additional oxides found in regolith are often added to clays to control melting point (calcia and magnesia) and color (iron and titanium). Conceivably then, vitrified regolith could be used similar to terrestrial clays for the production of food ware such as plates, bowls, and cups, for astronaut use. To ensure that produced good would be safe for use, a series of tests on samples of additively manufactured regolith were developed. Tests were developed based on FDA practices for testing glazed ceramic ware, specifically the *Element Analysis Manual for Food and Related Products*, which utilizes ASTM C 738-94 "Standard Test Method for Lead and Cadmium Extracted from Glazed Ceramic Surfaces". [21] [22] These methods are designed specifically for testing the glaze coatings on pottery vessels and work by filling a vessel with leaching acid solution so that only the interior of a vessel is measured. Because vitrified regolith ware will not have a glaze coating it was deemed more appropriate to measure surface and bulk leaching behavior of this material to determine which elements would leach from the samples. Bulk leaching tests the leaching behavior of the interior of the samples, which would help characterize the risk associated with a cracked or chipped vessel.

Experimental Procedure

Samples of vitrified extruded regolith simulant were received from Outward Technologies. Samples produced from two different lunar simulants were tested: JSC-1A, a lunar mare simulant, and CSM-LHT-1, a lunar highlands simulant. Representative samples of each are shown in Figure 26. Visually, the JSC-1A samples were fully vitrified and showed an elongated form, while the CSM-LHT-1 samples had a vitrified shell and a partially vitrified interior. To measure surface leaching, a sample between 7.2g and 7.5g of each material was selected and weighed. To analyze bulk leaching a similar weight sample of each material was selected and roughly crushed to expose the interior of the extruded beads. Care was taken during crushing to ensure that metal tools did not come in contact with samples to prevent metal contamination. Photos of the samples prior to leaching are shown in Figure 27 and Figure 28. Each sample was placed into a low density polyethylene (LDPE) bottle and fully submerged in 100.0g (+1.0/-0.0) of a 4% solution of food-grade acetic acid. Lids were placed onto the bottles and lightly closed to reduce evaporation losses and were placed out of direct light in a 21°C room. A sample of the acid solution was also placed into a bottle as a control. Full data of sample mass can be found in Table 9. After 24 hours (±15 min) a 10mL sample of each leach solution was transferred to a plastic test tube and stored in a refrigerated sample storage area for several days prior to testing. Samples were tested using a Dionex brand ion chromatography machine.

Figure 26: Example of the as-received vitrified simulant. JSC-1A material is shown at top, CSM-LHT-1 is shown below

Figure 27: Samples tested in surface leaching. JSC-1A material is shown at top, CSM-LHT-1 is shown below

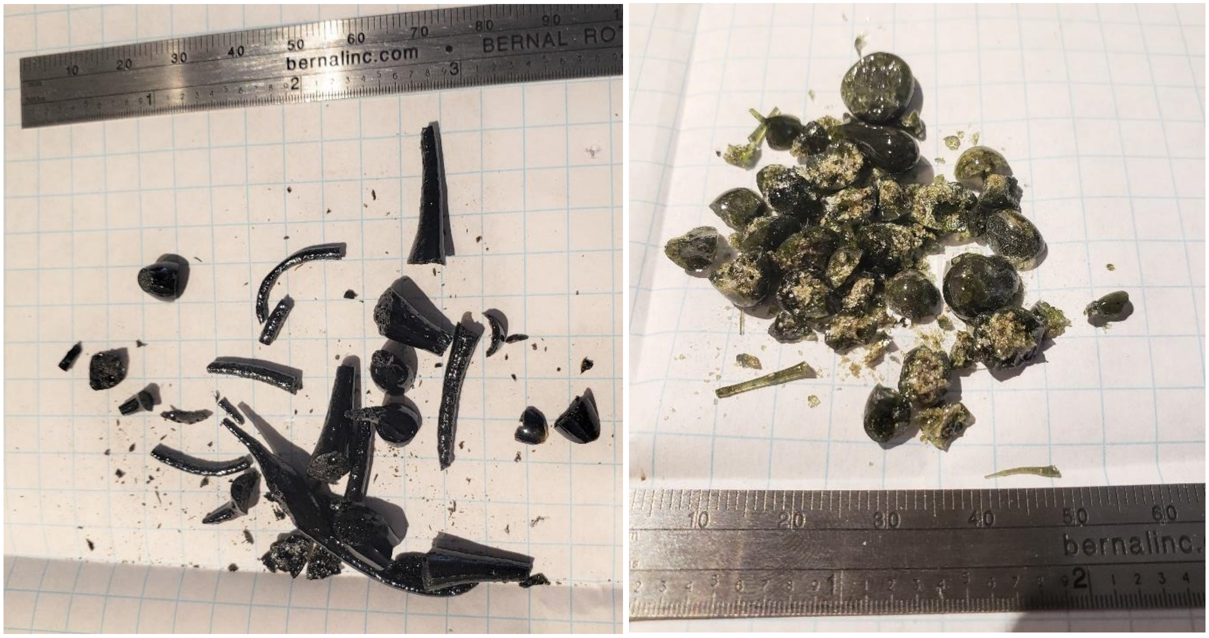


Figure 28: Samples of crushed material. JSC-1A material is shown at left, CSM-LHT-1 is shown at right

Results

Full results will be provided in a supplemental report. During transfer of the solutions from the leaching vessels to the test tubes, both crushed samples had a noticeable sulfur-aroma which may indicate sulfur leaching from the samples into the solution. This aroma was not observed in the control sample or surface leaching samples. No visible erosion of the samples was observed.

Discussion

Full discussion will be provided in a supplemental report. As previously mentioned, limits for element leaching from ceramics only exist for lead and cadmium. Drinking water limits were investigated to examine some existing element limits. Several international bodies do provide limits on drinking water levels of the elements found in lunar regolith but, at present, there are no listed limits by US regulatory bodies. [23] A chart comparing various organizations limits on drinking water contaminant levels is provided in Figure 29. Unfortunately, drinking water limits may not be appropriate for this study, due to the substantial difference in consumption rate of drinking water and highly acidic food.

Future Work

Determination of upper limits for elements will be important in understanding if this material will be suitable for food ware applications. Due to the adverse effects of heavy metals on the human body, having a detailed understanding the minor metals found in the regolith feedstock being used for producing vessels will be important. Additional tests on additional simulants would provide greater fidelity to the data.

Figure 29: Permissible limits of drinking water quality, reproduced from [23]

Major Elements\ Weight %	Highlands [24]	Maria [24]	CSM-LHT-1 [25]	JSC-1A [25]	Kaolinite [26]
Oxygen	45	45	45.2	44.2	55.8
Silicon	21	21	22.4	22.2	21.8
Aluminum	13	5	12.1	8.5	20.9
Calcium	10	8	11.4	7.5	-
Iron	6	15	4.0	8.0	-
Magnesium	5.5	5.5	1.1	4.7	-
Titanium	<1	1-5	1.8	0.9	-

Table 8: Elemental composition of lunar regolith and lunar simulants compared to kaolinite, a precursor mineral to clay

Sample Number	Simulant	Sample Form	Sample Mass (g)	Leachant Mass (g)
1	JSC-1A	Whole	7.31	100.4
2	JSC-1A	Crushed	7.27	100.4
3	CSM-LHT-1	Whole	7.42	100.6
4	CSM-LHT-1	Crushed	7.30	100.9
5	NA	Control	0.00	100.8

Table 9: Sample masses of leaching samples

10.4. ECLSS & Remote Outfitting

Introduction

The E&RO system's primary driving requirement is completion of commissioning and operation of the ECLSS prior to astronaut arrival. While many of the life support components can be pre-installed in the habitat, several components must be installed outside of the regolith shell to properly function. These components will have a small, dense form factor prior to deployment for ease of transport. Rovers will then transport these items from the landing site to their final locations, then connect power, communications, and fluid hoses as needed.

To complete this task, the rovers will require lifting capability, remote/automated operation, and ability to traverse various conditions in lunar regolith. However, it is believed that the most constraining requirement will be the level of precision required in the rover movement to interface with the external components and cables/hoses during installation. To better understand this requirement, a test was performed utilizing a prototype lunar rover, a mockup of an ECLSS external component, and varying surface conditions while measuring the time of each operation and total energy consumption of the rover. The objective of the test is to evaluate how appropriate the established requirements for the rover movement degrees of freedom (DOF) are; the more flexibility the rover is required to have in movement and precision, the greater the expense, mass, and risk.

Experimental Procedure

The high-level test concept was to create a manipulator device which was adjustable in 3 degrees of freedom (2 in translation and 1 in rotation) and attach it to a rover, then simulate interfacing with a mockup of an external component and record how many degrees of freedom were required to be used to complete the interface. The test would then be repeated for various relative positions of the rover and component, as well as various terrain scenarios.

To achieve this, the PRISM-HOUSE team partnered with Lunar Outpost, a private company developing the most advanced lunar rovers in the industry and which has been awarded several contracts by NASA and other partners to complete missions with their rovers on the lunar surface. Lunar Outpost offered the use of a prototype rover with similar form factor and function as their future flight units for the test.

A manipulator arm was designed which could be securely attached to the Lunar Outpost rover and would provide the three degrees of freedom required (Figure 30). The team chose to represent this with a forklift-style design; it should be noted that this is not intended to represent the form of an actual lunar manipulator, but rather a method of testing the relative importance of each degree of freedom. It is assumed that the actual lunar manipulator would need to be designed in close coordination with the interfaces of the external components themselves, but that the relationship between the required degrees of freedom would be similar.

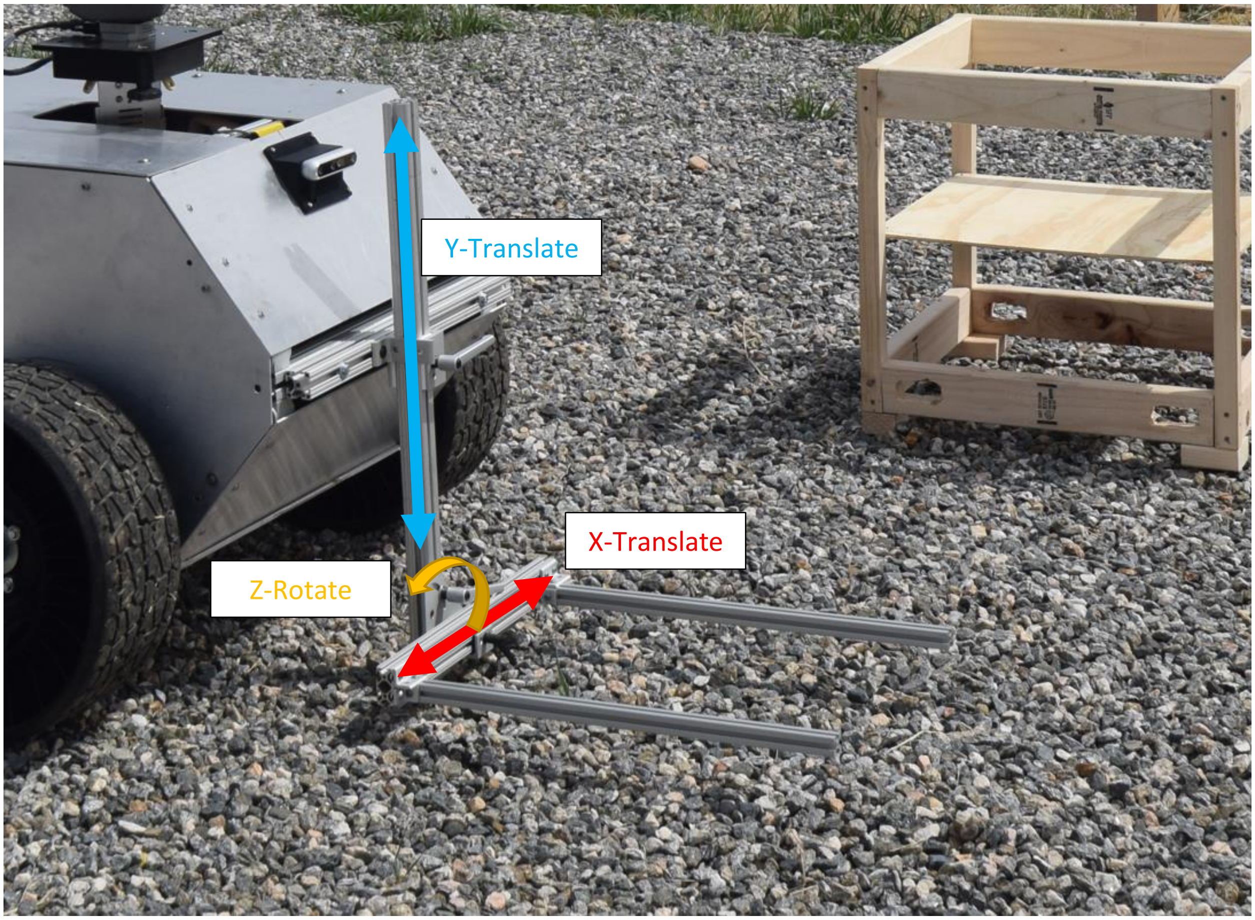


Figure 30: Manipulator Degrees of Freedom

The external component mockup was designed to have the appropriate interface points for line up with the manipulator, as well as have a similar approximate size relative to the Lunar Outpost rover as the real external components on the lunar surface might have to the flight rover. While the Vertical Solar Array (VSAT) design mentioned in a previous section is the most advanced example of an external component at this time, the NASA Vertical Solar Technology (VSAT) award is in progress and companies are competing for future awards - so information on this was difficult to obtain. However, the PRISM-

HOUSE team was able to receive feedback from one company stating that the approximate density of the VSAT unit would be around 400 kg/m^3. After adjusting for the approximate size and mass of the Lunar Outpost rover, the component mockup was designed as a cube 600mm long on each side.

The test surface was intended to be somewhat “loose” to represent lunar regolith, but the constituent materials and relative particle size was not considered critical to the test results.

The test procedure consisted of placement of the external component on the test surface in a position relative to the rover and recording the distance, angle, and any other notes relevant to the setup such as if the component is uphill or downhill of the rover, or placed intentionally unevenly. A timer was started, and a Lunar Outpost team member attempted to drive to the rover to interface with the external component. If the interface was not possible given the position of the manipulator, the Lunar Outpost team member requested assistance from another person in manually adjusting one or more of the manipulator degrees of freedom to better align the interfaces, then would again attempt interface. This was repeated until interface was completed, and the timer was stopped. Throughout each test, the c amperage drawn by the each of the 4 rover motors was recorded. Lastly, several tests were performed driving the rover at various speeds and under loading while record motor amperage.

Results & Discussion

The test was performed on April 28, 2022 in a test area on the campus of Colorado School of Mines. The testing surface was a layer of crushed stone approximately ½” – 1” in size and 4” thick. The surface had not been compacted directly and could shift slightly when walked on or driven on by the rover.

In total, 9 tests were performed, which are summarized in Table 10.

Table 10: Rover Interface Test Results

				DOF Used					
Test	Starting Dist (ft)	Starting Rot. (°)	Other Starting Notes	X	Y	Z	Duration (s)	Avg Power (W)	Energy Used (J)
1	8	0	Rover driving downhill				43	193	4298
2	8	0	Rover driving uphill		x		48	191	8445
3	5	90	Both rover and component on side slope		x	x	112	235	13694
4	10	180	Rover had to navigate an obstacle to reach the component		x		103	161	10263
5	3	90	One side of the component placed higher than the other (tilted)		x	x	105	190	16655
6	N/A	N/A	Long rover drive test, no component interface				114	261	29230
7	N/A	N/A	Maximum rover speed test, no component interface				105	304	29236
8	9	0	Rover/component interface test while operator utilizing only the video feed from rover		x		90	231	17402
9	N/A	N/a	Rover drive test with 52kg loading				116	254	27685

Operationally, the ability of the rover operator to interface with the component was easier than anticipated. The first interface required no adjustment of the manipulator and took less than a minute. Even though the rover/manipulator was not perfectly aligned with the component, the component shifted and slid across the test surface to correct this misalignment. It is unknown if the material properties and surface friction on the lunar surface as well as the traction required by the rover would allow for this in actual operation and is noted an area for potential future research.

Another empirical observation from several tests was the lack of clearance of the manipulator relative to the test surface while driving. Small undulations in terrain or a general uphill rover travel direction caused the manipulator to drag along the test surface. The assistant was required to raise the manipulator for the bulk of the drive, then lower the manipulator after reaching the component. This extra movement is extraneous and could be avoided by raising the interface point with the component.

In general, the Y-translation degree of freedom was the most utilized. This was partly due to the interface point being too close to the test surface as described above, but also because this degree of freedom cannot be modified by the rover at all. The X-translation was not required for any test, as the rover was capable of precise enough movement to align this dimension utilizing the rover wheels only.

Surprisingly, although the Z-rotation degree of freedom required precise alignment of the center of rotation of the manipulator to the center point between the two holes in the component, the rover operator was able to easily achieve this on multiple occasions. This axis was also not required for most tests, as the angle at which the component sat on the test surface was usually the same angle as the rover itself. In test 5, this angle was deliberately offset from the rover, and interface was still achieved in under 2 minutes (see Figure 31).

Figure 31: Rover Test #5 Interface

Test 8 was similar to Test 1, but the rover operator was only allowed to utilize the feed from the rover's front-facing cameras. This was intended to simulate the information that might be available to tele-operation personnel from Earth for the lunar mission (see Figure 32). While this was just a single test, it roughly doubled the time to interface. The rover operator gave qualitative feedback that it would be helpful to adjust the field of view of the camera and potentially add cameras from below the manipulator, to provide additional assistance in interface success.

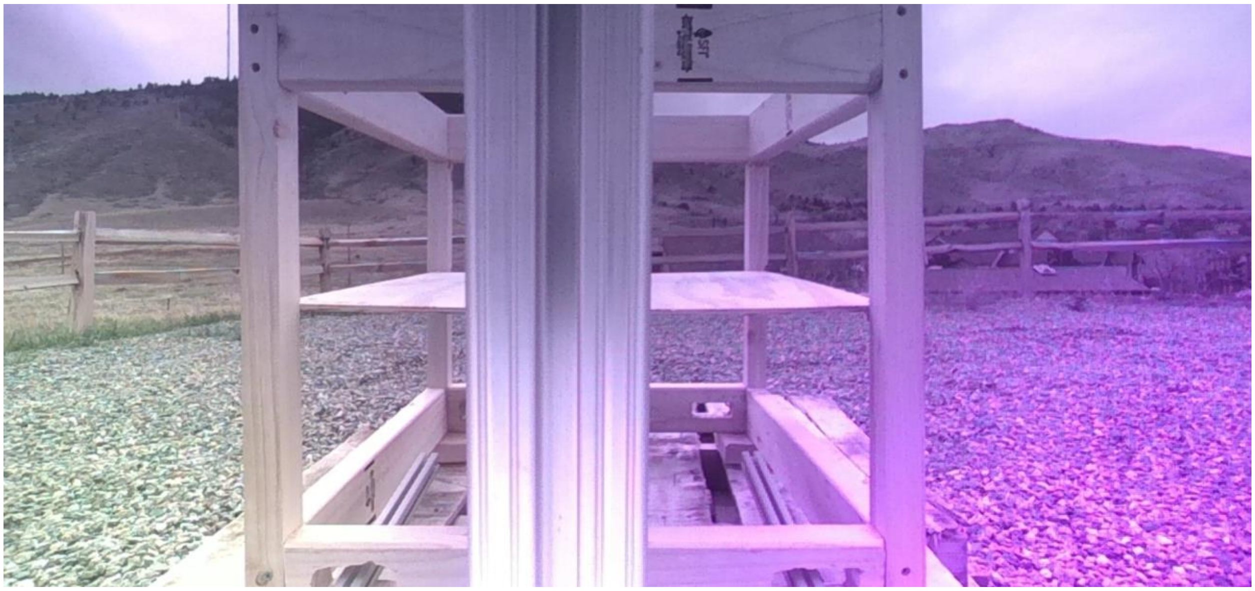


Figure 32: Rover Test #8 Interface (Rover Camera view)

For Test 9, the manipulator was modified to be able to support ~50kg, and the rover was driven around the test surface to determine if the energy usage of the rover was significantly changed compared to the unloaded condition (See Figure 33).

Figure 33: Rover Test #9 Setup (with 50kg load)

Final motor amperage data was provided by Lunar Outpost after post-processing to remove extraneous readings. This data was correlated to the start and stop timestamps recorded during testing to determine specific values associated with each test. The data was recorded in 1-sec intervals, so by correlating the amperage values to the rover motor DC operating voltage of 48V and integrating, total energy used could be approximated. Average power is also determined using a similar method.

After review and analysis of the results of the test, he PRISM-HOUSE team has arrived at the following conclusions:

- Each additional degree of freedom (beyond 1) required to achieve interface results in a step change increase in time required to interface. In practice, it seems that the operator attempted to align one axis completely prior to moving on to the next axis alignment.
- The energy usage of the rover was more dependent on speed and did not seem to fluctuate significantly due to uphill/downhill traverse nor due to loading. This result is likely due to the use of high-torque servomotors for the wheels and is an assumption the team believes will carry through to the actual flight units.
- Tele-operation via the use of cameras will increase the required time to interface, regardless of the number of degrees of freedom required.
- The power requirement for the lunar rover can be determined through the use of unitless scaling vectors described in Slonaker, J. et. Al [27]. After adjusting for lunar gravity as well as the required increased size of the PRISM-HOUSE rover as compared to the Lunar Outpost test unit, it can be shown that that the flight unit will use approximately 50% more power than the test unit when moving at the same speed. Therefore, the estimated power usage of the rover during operation is approximately 250 x 150% = 375W. This is for locomotion only and does not include heating, communications, actuation of manipulators, or any other systems.

Recommendations & Future Work

Based on the results of the test, the PRISM-HOUSE team recommends that the interfaces for external components be designed such that:

1. The interface location is given enough clearance height from the lunar surface to eliminate potential conflict between the rover manipulator and the rover surface.
2. Automation of the rover manipulator can be used to eliminate operator alignment of one axis at a time.
3. Off-nominal forces from the rover manipulator self-correct alignment to lessen precision requirements on the manipulator itself (similar to forklifts and pallets on Earth).
4. Rover camera feeds provide at least two viewpoints of the manipulator and interface points to aid in faster interface.

Future work related to rover testing can include testing in a lunar regolith simulant to better estimate rover power usage and testing of actual manipulator / component interfaces.

11. Next Steps

11.1. Work by the Team

The team has several activities planned within the month. A final report to the NASA sponsors is due in June 2022. While care has been taken to avoid sharing proprietary information, prior to releasing this report the team will provide relevant sections to company sponsors for review. In addition, a tour of Johnson Space Center (JSC) in Houston is planned for June 2nd. This had been delayed due to COVID-19 restrictions but, at time of writing, JSC was listed as Open at Stage 1, which allows public tours. An animation is currently in progress to provide video material as a final product to carry forward for PRISM-HOUSE. The team will use all current products as a reference for ongoing and future work.

11.2. Future Work

As noted under the individual test sections, there are several avenues to explore for additional work on the tests. The Food Safety Testing found that only limited standards exist for element leaching and particulate residue. Development of safe leaching levels will be important for determining if these materials can be used for food ware. Additionally, as heavy metals have the most detrimental effect on health, characterization of trace metals content in the regolith near the proposed habitat site will be essential before the material can be used in contact with food. The ECLSS & Remote Outfitting tests would gain further fidelity when tested in lunar simulants. Repeating the tests with a powered 3+ axis manipulator and multiple operators would provide additional details on task difficulty. Dedicated work on an interface tool optimized for the lunar environment would be another avenue which will be important for lunar outfitting activities.

In addition to extensions on the tests run, some additional areas for further study were identified. As noted in the ESEP analysis, radiation analysis was based on data from a presentation at LSIC. [9] A more in-depth analysis would be a ray-tracing style radiation model such as that provided by NASA's On-Line Tool for the Assessment of Radiation In Space (OLTARIS). The team attempted to import models of the habitat into the software but ran into several issues. Particularly, the software has issues with sharp corners and does not have a visualization tool to ensure that a model has been successfully imported and run. This may not be an issue for those with extensive radiation modeling experience who can readily recognize values outside of the expected range but make it very difficult for novice users. The addition of visualization aids to the software could greatly improve the usability. In addition, the current software defines total radiation exposure at a single point, where an understanding of the total volume and potential areas of high radiation spots would be more useful for the project work. While it is possible to simulate enough cases using OLTARIS to potentially acquire this data, it was outside of the budget and time constraints available. However, given that radiation exposure limit assumptions drive regolith thickness in our design, which is the primary driver of the time and power required to construct the habitat, further investigation into the true radiation exposure level of an occupant could help drive down overall requirements and timelines.

Excavation rate and print rate are the two most significant time demands for habitat installation. Due to the relatively short timeline of this project and the ongoing work by NASA, universities, and private entities on both of these topics, they were not extensively explored in this study. The successful development of these technologies will be key to the success of the PRISM-HOUSE system, to include an extensive fleet of highly capable excavation rovers and printers with diversified use cases. If the technologies under development are not capable of meeting the rates cited in this report, substantial further research will be necessary.

12. Conclusion

Human occupation of the lunar surface is no simple task, with requirements for protection and stability in numerous interdisciplinary domains. The logistics of preparing the site, the mechanics necessary for production of ISRU components, the challenges in habitat deployment, and the requirements to sustain it, are all major areas that will require extensive testing and validation. This report serves as an initial design analysis to set the foundation for ongoing development of an ISRU-based lunar habitat.

PRISM-HOUSE is a lunar habitat system that is deployed on the lunar surface robotically and supports safe, long-term human occupancy while maximizing the use of in-situ resources and minimizing the mass of supplies and equipment that must be delivered from Earth. The necessary subsystems to meet the stated objectives and the analysis performed on each have been highlighted by this report through analysis and design. A set of tests were conducted to collect data to inform updated requirements and contribute to the mitigation of risks. Finally, remaining gaps were noted, and next steps suggested.

The PRISM-HOUSE team would like to thank the Colorado School of Mines Space Resources Program, the professors and fellow students of SPRS591/592, the NASA X-Hab team, and all of our industry partners for contributing to the success of the project.

13. References

[1] C. Dreyer, G. Sowers and A. Abbud-Madrid, "Proposal: Planetary Resource & In-Situ Material Habitat Outfitting for Space Exploration (PRISM-HOUSE)," NASA X-Hab Solicitation Response, Golden, CO, 2021.

[2] A. Dutton, "Domes of Different Geometries," University of Edinburgh, 2013. [Online]. Available: https://concretedomestructures.weebly.com/analysis-of-domes.html. [Accessed May 2022].

[3] ICON, "Project Olympus," 2022. [Online]. Available: https://www.iconbuild.com/technology/space. [Accessed May 2022].

[4] D. S. McKay, G. Heiken, A. Basu, G. Blanford, S. Simon, R. Reedy, B. M. French and J. Papike, "The Lunar Regolith," in *Lunar Source Book*, New York, Cambridge University Press, 1991.

[5] R. P. Muller, R. E. Cox, T. Ebert, J. D. Smith, J. M. Schuler and A. J. Nick, "Regolith Advanced Surface Systems Operations Robot (RASSOR)," *IEEE,* 2013.

[6] R. Leth-Miller, A. Jensen, P. J. L. Glarbog, P. Hansen and S. Jørgensen, "Experimental investigation and modelling of heat capacity, heat of fusion and melting interval of rocks," *Thermochimica Acta,* vol. 406, no. 1-2, pp. 129-142, 2003.

[7] G. H. Heiken, D. T. Vaniman and B. M. French, Lunar Sourcebook, Cambridge University Press, 1991.

[8] C. I. Calle and C. Buhler, "MEASUREMENT OF THE ANGLE OF REPOSE OF APOLLO 14 LUNAR SAMPLE 14163," in *The Impact of Lunar Dust on Human Exploration*, Houston, TX, 2020.

[9] R. Moses, "Mars Mission Scenarios Suggesting Requirements for GCR Shielding, Surface Excavation & Construction," in *Lunar Surface Innovation Consortium*, Hampton, VA, 2021.

[10] Saint-Gobain, "Physical Properties of Glass," [Online]. Available: https://uk.saint-gobain-building-glass.com/en-gb/architects/physical-properties. [Accessed May 2022].

[11] P. Kahn, R. Severson and J. Ruckert, "The Human Relation With Nature and Technological Nature," *Current Direction in Psycological Sciences,* vol. 18, no. 1, pp. 37-42, 2009.

[12] NASA, "NASA CHAPEA," 2021. [Online]. Available: https://www.nasa.gov/chapea.

[13] ICON, "Mars Dune Alpha," 2021. [Online]. Available: https://www.iconbuild.com/technology/mars-dune-alpha.

[14] Nedinsco Venlo, "Datasheet: Python Back-up Sight," 2021. [Online]. Available: https://nedinsco.com/wp-content/uploads/Nedinsco_Datasheet_Backupsight-07-2021.pdf. [Accessed May 2022].

[15] Branch Technology, "Matrix Freeform Polymer," [Online]. Available: https://branchtechnology.com/products#1632046578583-ab51dae2-5a941632153286244. [Accessed 5 May 2022].

[16] NASA, "Lunar Vertical Solar Array Technology," 31 March 2021. [Online]. Available: https://nspires.nasaprs.com/external/solicitations/summary.do?solId=%7b68A7EFE3-1B4F-5AA1-A169-119D97C8DB8F. [Accessed 7 May 2022].

[17] J. Matthews, "FLEX: Flexible Logistics & Exploration Rover," in *Lunar Surface Innovation Consoritum Spring Meeting*, Laurel, MD, 2022.

[18] H. Noda, H. Araki, S. Goossens, Y. Ishihara, K. Matsumoto, S. Tazawa, N. Kawano and S. Sasaki, "Illumination conditions at the lunar polar regions by KAGUYA(SELENE) laser altimeter," *Geophysical Research Letters,* vol. 35, no. L24203, 2008.

[19] D. Linne, J. Kleinhenz, L. Sibille, J. Schuler, N. Suzuki, L. Moore, S. Oleson, A. Colozza and E. Turnbull, "Oxygen Produciton System for Refueling Human Landing System Elements," in *10th Joint Meeting of the Space Resources Roundtable / Plantary and Terrestrial Mining and Sciences Symposium*, Golden, CO, 2019.

[20] IDS Business Support, Communications and Community Affairs, "Active Thermal Control System (ATCS) Overview," [Online]. Available: https://www.nasa.gov/pdf/473486main_iss_atcs_overview.pdf. [Accessed 09 May 2022].

[21] J. Cheng, "4.6 Inductively Coupled Plasma–Optical Emission Spectrometric Determination of Cadmium and Lead Extracted from Ceramic Foodware, Version 1.0," in *Elemental Analysis Manual for Food and Related Products*, US Food and Drug Administartion, 2020, p. 28.

[22] ASTM International, "ASTM C 738-94, "Standard Test Method for Lead and Cadmium Extracted from Glazed Ceramic Surfaces"," 2006.

[23] M. Kumar and A. Puri, "A review of permissible limits of drinking water," *Indian J Occup Environ Med.,* vol. 16, no. 1, pp. 40-44, 2012.

[24] L. Haskin and P. Warren, "Lunar Chemistry," in *Lunar Sourcebook*, New York, Cambridge University Press, 1991.

[25] K. Cannon, "Planetary Simulant Database," Colorado School of Mines, 2022. [Online]. Available: https://simulantdb.com/. [Accessed May 2022].

[26] D. Barthelmy, "Kaolinite Mineral Data," Mineralogy Database, [Online]. Available: http://www.webmineral.com/data/Kaolinite.shtml. [Accessed May 2022].

[27] J. Slonaker, D. C. Motley, Q. Zhang, S. Townsend, C. Senatore, K. Iagnemma and K. Kamrin, "General scaling relations for locomotion in granular media," *Physical Review,* vol. 95, no. 052901, 2017.

14. List of Appendices

Appendix A: Final Requirements

Appendix A

Lvl1	Lvl2	Lvl3	Lvl4	Req ID	Requirement	NASA Technology Taxonomy Category	High level filter	Section filter
x				1	External Structures & Environmental Protection (ESEP) System		H	
	x			1.1	The ESEP System shall function on the lunar surface environment.	TX07.2.3 – Surface Construction and Assembly	H	1
		x		1.1.1	The ESEP System shall function in a vacuum.	TX06.6.3 – Habitability and Environment		
		x		1.1.2	The ESEP System shall remain functional between 110K and 395K.	TX06.6.3 – Habitability and Environment		
		x		1.1.3	The ESEP Production subsystem shall withstand micrometeorite impact up to sizes of [TBD]			
	x			1.2	The ESEP System cost shall not exceed [TBD].	TX06.6.4 – Operations Effectiveness		
	x			1.3	The ESEP System shall interface with other PRISM habitat subsystems to allow function of all passthroughs and sensors.	TX12 – Mechanical Systems		1
		x		1.3.1	The ESEP System subsystem shall produce a structure with a 2.5m minimum opening for the habitat airlock	TX12.3.1 – Deployables, Docking, and Interfaces		1
	x			1.4	The ESEP System shall utilize additive manufacturing methods.	TX07.2.2 – In-situ Manufacturing, Maintenance, and Repair	H	1
		x		1.4.1	The ESEP System shall be capable of using a lunar regolith-based composition as feedstock.	TX07.1.2 – Resource Acquisition, Isolation, and Preparation		
		x		1.4.2	The ESEP System shall be capable of receiving up to 1000 kg/day of regolith for additive manufacturing.	TX07.1.2 – Resource Acquisition, Isolation, and Preparation		1
		x		1.4.3	The ESEP System shall be capable of receiving up to 7000 kg/day of regolith for regolith infill.	TX07.1.2 – Resource Acquisition, Isolation, and Preparation		1
	x			1.5	The ESEP System shall consume 60kW of power or less on average for a 1-hour period during operation	TX03.3.1 – Management and Control	H	1

(use H for high-level section, 4 for habitat, 1 for ESEP, 2 for HIG, 3 for ECLSS)

	x			1.6	The ESEP System shall provide a protect the internal habitat from external hazards		H	1
		x		1.6.1	The ESEP Production Subsystem shall produce a structure that is capable of stopping a micrometeoroid impact up to 16.5kJ without compromising the structural integrity of the shell.	TX06.6.3 – Habitability and Environment		1
			x	1.6.1.1	The ESEP Production Subsystem shall produce an outer shell structure that is capable of being repaired in the event of an impact at or below the threshold energy.	TX06.6.6 – Maintainability and Supportability		
		x		1.6.2	The ESEP Production Subsystem shall produce a structure that limits the maximum internal radiation exposure to 10 mSv or less per year. This will be measured as the weighted average radiation measured in room in the habitat with weighting based on anticipated astronaut time in rooms.	TX06.5.3 – Protection Systems		1
		x		1.6.3	The ESEP Production Subsystem shall produce a structure that is capable of maintaining an interior temperature of 22.5°C +/- 20°C of daily shift.	TX06.6.3 – Habitability and Environment		
	x			1.7	The ESEP Production Subsystem shall produce a structure with a Mean Time to Repair of 5 years			
		x		1.7.1	The ESEP Production Subsystem shall produce a structure that is capable of maintaining structural integrity for 10 years.	TX12.3.7 – Mechanism Life Extension Systems		
		x		1.7.2	The ESEP Production Subsystem shall produce a structure that is capable of maintaining a short-term internal pressure of 124 kPa.	TX06.1.4 – Habitation Systems		
		x		1.7.3	The ESEP Production Subsystem shall produce a structure that is self-supporting	TX06.1.4 – Habitation Systems		

	x			1.8	The ESEP Production Subsystem shall produce a structure with an internal habitable area of at least 150 square meters with a minimum height of 3m	TX06.1.4 – Habitation Systems		1
x				2	Human Interior Goods (HIG) System		H	
	x			2.1	The HIG System shall function within the constraints of the PRISM-HOUSE habitat	TX07.2.3 – Surface Construction and Assembly	H	2
		x		2.1.1	The HIG System shall consume 20kW of power or less on average for a 1-hour period during operation	TX03.3.1 – Management and Control		2
		x		2.1.2	The HIG System shall have a mass less than 140 kg.	TX04.4.1 – Multi-modal and proximate interaction		2
		x		2.1.3	The HIG System freeform printer shall be less than 1.5m x 1m x 0.5m in size when shutdown.	TX04.4.1 – Multi-modal and proximate interaction		2
		x		2.1.4	The HIG System freeform printer shall have a minimum build volume of 2m x 1m x 1m	TX04.4.1 – Multi-modal and proximate interaction		2
		x		2.1.5	The HIG System shall be able to function in a vacuum.	TX07.2.2 – In-situ Manufacturing, Maintenance, and Repair		
		x		2.1.6	The HIG System shall be able to function in the 180K to 310K temperature range and survive a 24-hour exposure to a temperature of 110K	TX07.2.3 – Surface Construction and Assembly		
		x		2.1.7	The HIG System shall have modular parts, with durable components able to be replaced as needed.	TX04.6.1 – Modularity, Commonality, and Interfaces		
		x		2.1.8	The HIG System shall be capable of utilizing in-situ material feedstock for additive manufacturing processes.	TX07.1.4 – Resource Processing for Production of Feedstock Materials		2
		x		2.1.9	The HIG System cost shall not exceed [TBD].	TX06.6.4 – Operations Effectiveness		
		x		2.1.10	The HIG Production Subsystem shall be able to interface with PRISM-HOUSE power system connections.	TX04.6.1 – Modularity, Commonality, and Interfaces		
	x			2.2	The HIG Production Subsystem shall fabricate components, parts, and other items to offset mass delivery from Earth by 25%	TX07.2.2 – In-situ Manufacturing, Maintenance, and Repair	H	2

		x		2.2.1	The HIG Production Subsystem shall produce products with a minimum lifespan of 10 years.	TX07.2.2 – In-situ Manufacturing, Maintenance, and Repair		
		x		2.2.2	The HIG Production Subsystem shall produce products suitable for ergonomic and safe human interaction	TX06.6.3 – Habitability and Environment		2
			x	2.2.2.1	The HIG Production Subsystem shall produce products which can withstand a constant downward force of 750N	TX06.6.3 – Habitability and Environment		
			x	2.2.2.2	The HIG Production Subsystem shall produce products to a dimensional tolerance of +/- 5mm	TX06.6.3 – Habitability and Environment		
			x	2.2.2.3	The HIG Production Subsystem shall produce products adhering to Pressurized Payloads Interface Requirements Document section 3.12.8.2	TX06.6.5 – Integrated Systems Safety		
		x		2.2.3	The HIG Production Subsystem shall be capable of producing products based on data input files in [TBD] formats	TX04.4.2 – Distributed Collaboration and Coordination		
		x		2.2.4	The HIG Production Subsystem shall be capable of producing products suitable for replacement of 10% of the mass of other PRISM habitat subsystems	TX07.2.2 – In-situ Manufacturing, Maintenance, and Repair		
x				3	Environmental Control and Life Support System & Remote Outfitting (E&RO)		H	
	x			3.1	The E&RO system shall control environment and process waste for up to four astronauts	TX06 – Human Health, Life Support, and Habitation Systems	H	3
		x		3.1.1	The ECLSS System shall maintain an atmosphere that meets or exceeds NASA-STD-3001-Vol2-6.2 (Internal Atmosphere)	TX06.1.1 – Atmosphere Revitalization		3
		x		3.1.2	The ECLSS System shall provide water to meet NASA-STD-3001-Vol2-6.3 (Water) while crew are present.	TX06.1.2 – Water Recovery and Management		3

		x		3.1.3	The ECLSS System shall provide waste collection and storage to meet NASA-STD-3001-Vol2-7.3 (Body Waste Management) while crew are present.	TX06.1.3 – Waste Management		3
			x	3.1.3.1	The ECLSS System shall remove water from the collected waste and be capable of storing up to 36kg of dewatered waste.	TX06.1.3 – Waste Management		
		x		3.1.4	The ECLSS System shall limit the levels of lunar dust particles in the atmosphere per NASA-STD-3001, 6.4.4.2 (Lunar Dust Contamination)	TX07.2.5 – Particulate Contamination Prevention and Mitigation		3
	x			3.2	The E&RO system shall interface with other PRISM habitat subsystems to allow function of all ECLSS equipment	TX12 – Mechanical Systems	H	3
		x		3.2.1	The ECLSS System shall provide thermal regulation of operational equipment to 25°C +/- 15°C	TX12.3.1 – Deployables, Docking, and Interfaces		
		x		3.2.2	The ECLSS System shall connect to external power and communication systems utilizing standard connections	TX12.3.1 – Deployables, Docking, and Interfaces		
		x		3.2.3	ECLSS equipment shall operate in at least 1 horizontal and 1 vertical orientation relative to gravity	TX12.3.1 – Deployables, Docking, and Interfaces		
		x		3.2.4	ECLSS equipment shall be self-contained in enclosures not to exceed 1.5m x 0.5m x 0.5m each	TX12.3.1 – Deployables, Docking, and Interfaces		
			x	3.2.4.1	ECLSS enclosures shall interface with printed-regolith structures via no more than 4 securement locations	TX12.3.1 – Deployables, Docking, and Interfaces		
			x	3.2.4.2	ECLSS enclosures shall all have the same maximum dimensions, securement design, and power and communications interfaces.	TX12.3.1 – Deployables, Docking, and Interfaces		
			x	3.2.4.3	ECLSS enclosures shall have a mass of less than 50kg	TX12.3.1 – Deployables, Docking, and Interfaces		
	x			3.3	The E&RO system shall complete installation and commissioning prior to astronaut arrival	TX04 – Robotic Systems	H	3

		x		3.3.1	Remote Outfitting mobility devices shall have an operational time before recharging of greater than 10 hours	TX04.2.4 – Surface Mobility		3
		x		3.3.2	Remote Outfitting manipulation devices shall be capable of motion determined by at least 2 degrees of freedom	TX04.3.1 – Dexterous Manipulation		3
		x		3.3.3	Remote Outfitting manipulation devices shall be capable of positioning up to a 750kg mass with dimensions of 3m x 3m x 3m to a precision of +/- 5cm	TX04.3.1 – Dexterous Manipulation		3
		x		3.3.4	Remote Outfitting mobility and manipulation devices shall be capable of tele-operation from earth-based operational centers	TX04.4.3 – Remote Interaction		3
		x		3.3.5	The Remote Outfitting Subsystem shall be capable of operation in lunar surface environmental conditions including day/night cycle	TX04.2.5 – Robot Navigation and Path Planning		3
	x			3.4	The E&RO system costs shall not exceed [TBD].	TX06.6.4 – Operations Effectiveness		
x				4	PRISM-HOUSE Habitat (PHH) System		H	
	x			4.1	The PHH system shall function in the protected lunar surface environment		H	4
		x		4.1.1	The PHH System shall function in a vacuum.			4
		x		4.1.2	The PHH System shall remain functional between 110K and 395K.			4
	x			4.2	The PHH system shall be capable of installation inside the ESEP Protective Shell		H	4
		x		4.2.1	The PHH system shall be capable of locomotion while the inflatable is undeployed			4
		x		4.2.2	The PHH system shall have maximum dimensions of 2.5m x 2.5m x 14.5m while undeployed			4
	x			4.3	The PHH system shall be compatible with structural components produced by the HIG system		H	4

	x			4.4	The deployed PHH system shall allow all relevant ECLSS requirements to be met			4
		x		4.4.1	The PHH inflatable subsystem shall meet ECLSS pressure requirements			4
		x		4.4.2	The PHH System shall meet NASA reliability requirements for human spaceflight			4
		x		4.4.3	The PHH System shall only come into contact any part of the lunar surface (printed or loose regolith) at the airlocks			4

SUPPLEMENTAL REPORT

xHab – Food Safety Testing of Printed Regolith – Results Supplement

Peter Corwin, Michael Forlife, Thao Nguyen, Deven O'Rourke

Elements, values in mg/L	Si	Al	Ca	Fe	Mg	Ti	S	Cu	F	Hg	Cd	Se	As	Pb	Zn	Cr
US-EPA	-	-	-	-	-	-	-	1.3	4	0.002	0.005	0.05	0.05	-	-	0.1
WHO	-	-	75	0.1	50	-	-	1	1.5	0.001	0.005	0.01	0.05	0.05	5	-
FDA Elemental Analysis Manual 4.6	-	-	-	-	-	-	-	-	-	-	0.001/ 0.006	-	-	0.005/ 0.030	-	-
JSC-1A Nominal Composition	22.2	8.5	7.5	8	4.7	0.9	-	-	-	-	-	-	-	-	-	-
Control	1.034	0.012	6.342	0.007	2.403	-	3.075	0.005	-	-	0.001	0.092	*	0.010	0.171	*
JSC-1A-Solid	15.639	4.911	15.249	2.992	6.483	-	3.263	0.021	-	-	0.001	0.089	*	*	0.190	0.003
JSC-1A-Crushed	21.847	8.565	21.182	11.947	8.497	-	3.708	0.024	-	-	0.002	0.073	*	*	0.227	0.005
CSM-LHT-1 Nominal Composition	22.4	12.1	11.4	4.0	1.1	1.8	-	-	-	-	-	-	-	-	-	-
Control	1.034	0.012	6.342	0.007	2.403	-	3.075	0.005	-	-	0.001	0.092	*	0.010	0.171	*
CSM-LHT-1-Solid	19.544	11.113	19.157	6.913	7.090	-	3.212	0.007	-	-	0.002	0.071	*	*	0.185	0.012
CSM-LHT-1-Crushed	15.052	6.871	18.728	11.126	8.787	-	2.992	0.007	-	-	0.002	0.066	*	*	0.209	0.013

Dashes (-) indicate no data was collected or value exists for the entry. Entry's with asterixis (*) indicate values which fell below the detection of the ICP machine.

The results of the leaching tests on printed regolith simulant are shown in the table above. Nominal starting compositions are listed for comparison purposes. Also included is the US Environmental Protection Agency (EPA) and World Health Organization (WHO) water quality standards, and the FDA's listed values for lead and cadmium leaching. Only the WHO places limits on elements found in high concentration in the regolith simulants, specifically on calcium, iron, and magnesium. Only iron was found to be above the WHO limits for drinking water, although it should be noted that using drinking water standards may not be appropriate for this scenario. Iron is a necessary dietary supplement so small concentrations on an occasional basis may not be as harmful as frequent consumption with drinking water. Additional work to set appropriate limits may be worth further research.

For the elements in the nominal starting compositions, all of them showed increased concentration after leaching versus the control sample. JSC-1A material showed increased leaching on the crushed material due to the higher surface area, with the most notable change observed for iron. While most other elements showed concentration increases between 30-90%, iron increased roughly 4x increase in concentration after leaching. CSM-LHT-1 material however showed decreases in concentration for silicon and aluminum in the crushed material, despite the higher surface area. Iron showed a nearly 2x increase on crushed material. No significant pickup of elements outside the nominal composition were observed, although slight increases in sulfur and copper were observed in the JSC-1A samples.

For crushed material, the difference in iron concentration may indicate a microstructural segregation of an iron-rich phase within the sample. If iron-rich phase were protected by the outer surface of the JSC-1A material, this may be an explanation for why such low values were observed for leached JSC-1A material in the solid condition. The apparent glassiness of the JSC-1A material versus the more granular interior structure in the interior of the CSM-LHT-1 sample may explain the leaching difference between the two simulants, with a glassy smooth surface offering less area for leaching. Further work on microstructural characterization, potentially including Energy Dispersive X-Ray Spectroscopy (EDS) on a Scanning Electron Microscope (SEM) would help to understand why this iron concentration spike was observed.

On a practical level, if the iron leaching is determined to fall within safe levels, this material would be safe for food use, even if chipped. Full vitrification of the bead is recommended to reduce leaching, especially if chipping occurs.