NASA RASC-AL
Lunar Surface Short Habitat

Preliminary Proposal

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RASC-AL
Revolutionary Aerospace Systems Concepts Academic Linkage

Project Sponsor: NASA
Faculty Advisor: Sarah Oman

Sponsor Mentor: [Note: if any of these categories are the same person, delete the repeats]

Instructor: David Michael Willy

DISCLAIMER

This report was prepared by students as part of a university course requirement. While considerable effort has been put into the project, it is not the work of licensed engineers and has not undergone the extensive verification that is common in the profession. The information, data, conclusions, and content of this report should not be relied on or utilized without thorough, independent testing and verification. University faculty members may have been associated with this project as advisors, sponsors, or course instructors, but as such they are not responsible for the accuracy of results or conclusions.

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TABLE OF CONTENTS

[Use your word processor to delete the following Table of Contents and insert a new TOC. Include front matter (except for the cover page), body of the report, and all appendices. The Table should include four levels of headings, e.g., down to 2.2.1.3, as illustrated below. Front matter should be in Roman numerials.]

Contents

1 BACKGROUND Keerthi

1.1 Introduction

In response to Revolutionary Aerospace Systems Concepts- Academic Linckage (RASC-AL), this preliminary report discusses the initial discoveries, challenges as well as provide preliminary concepts for building a durable low-mass lunar surface habitat.

As part of a new era of space exploration, NASA's Artemis Missions will prepare humanity for the next giant leap, a manned mission Mars. The Artemis projects main objective is to establish a lunar presence by the end of 2028. Since the Apollo Missions, recent discoveries imply that space is a harsher environment for life than previously understood. A lunar presence would increase the opportunity to further science, establish lunar commerce, extract resources, and use the moon as a waystation to further exploration into space ensuring human survival.

1.2 Project Description

[Provide the sponsor's original project description, as presented at the beginning of fall term. To credit the source, precede the description with text, such as "Following is the original project description provided by the sponsor." Set the Description in a block quote (i.e., indented from the surrounding text). If the description has been changed, provide an explanation of what has changed and why.]

Following is the original project description provided by the sponsor:

> *"**DURABLE LOW-MASS LUNAR SURFACE HABITAT THEME***
>
> *After the initial Artemis mission lands the first woman and the next man on the Moon in 2024, the Artemis program will continue with longer and bolder missions on the lunar surface throughout the 2020s. A key enabling system for those future missions will be a habitat that can support crew on the lunar surface, as they continue the exploration of the Moon and prepare for future missions to Mars. To leverage developing commercial lander capabilities, NASA is interested in a low -mass habitat that can be used on the lunar surface.*
>
> *For this theme, teams will design a durable, low-mass habitat that can support a crew of 2 for 30 days at the lunar south pole, with a dry mass limit of 6,000 kg. The habitat should be ready for first use in 2028, with an annual budget of no more than $1 billion per year from 2022-2028 (including delivery to the lunar surface). Teams should create a development timeline with a realistic technology portfolio that can credibly achieve that date. The habitat should be capable of re-use, as it will serve as the starting point for expanding to greater crew capabilities on the surface, and for preparation for Mars missions. Thus, teams should identify how their habitat can be used to support both of these goals."*
>
> *-NASA RASC-AL []*

Scope

Designing, engineering, and constructing a lunar habitat unit(s) requires the most sophisticated of intricate planning. A number of factors would go into designing a fully functional livable structure. The surface environment, lunar soil variations, solar radiation, livable volume, maintaining a constant supply of necessary resources (air, water, and food), waste management are some of the many components that must be factored into the design criterion. These factors alone are not enough to design a fully functional lunar base. Issues such as brittleness due to colder temperatures, redesigning factors of safety for the moon, structural fatigue due to temperature differentials, and potential buckling/stiffening effects of internal pressurization need to be tackled eventually. Nevertheless, it offers a good base to start the design using the material and structural choices that are heavily dependent on the factors mentioned above.

As a result, the scope of the project will be limited to designing a structure that complies with the customer requirements. Heavy analysis will go into designing, engineering, and testing a structure for assembly on the lunar surface. The necessary systems and resources will be researched on and ideal subsystems will be chosen based on projected performance on the lunar surface.

2 REQUIREMENTS Aidan

[Use this section (2) to describe to the reader what is required from the project. Provide an introduction here (describing what this chapter contains) before leading into section 2.1]

Every engineering project has a goal, and with every goal comes its associated customer and engineering requirements. Customer requirements were informed by the team's faculty advisor and instructor. Weights were assigned to each customer requirement on a 1-10 scale, with astronaut safety taking main priority, followed by project feasibility. This would include budget and transport related requirements. The engineering requirements were generated to fill our customer requirements, and were all assigned measurable units, target values, and associated tolerances with each target value. Sections 2.1 and 2.2 list and describe the customer requirements and engineering requirements the team generated respectively.

2.1 Customer Requirements (CRs)

The customer requirements that applied to the project, and associated weights are listed and expanded upon below:

1. **Be Able to Support Own Weight (Weight Assigned = 8)** – The structure would need to support its own weight in order to house and protect astronauts. The team weighed this customer requirement highly because it directly effects astronaut safety.
2. **Ease of Assembly (Weight Assigned = 7) –** Astronauts would need to be able to assemble the habitat easily within a reasonable amount of time. Ease of assembly is important because astronaut's suits are difficult to work in and making small bolts or tight places to fit pieces together would make it nearly impossible for assembly on the lunar surface. The team weighted this customer requirement fairly highly, because without considering it, astronauts could potentially fail the assembly process.
3. **Supports 2 Crew Members (Weight Assigned = 6) –** This customer requirement was formed using the project description given by NASA. The team weighted this one somewhat neutrally because it didn't directly affect the safety of the astronauts, or the feasibility of the project. Although it was still important, because the habitat could not only support one astronaut as this would severely affect their mental health.
4. **Able to Fit on a Rocket (Weight Assigned = 9) –** The structure would have to be able to fit on existing rocket designs in order to be able to be transported to the moon. The team weighed this customer requirement highly because the design would be unfeasible if it is not transportable.
5. **Can be Disassembled and Reused on Lunar Surface (Weight Assigned = 4) –** This customer requirement was also formed using the project description given by NASA. One of NASA's goals was to create a habitat which could be deconstructed and stored for future missions. The team weighed this customer requirement fairly low because it did not directly affect astronaut safety, or project feasibility. Although it is an excellent goal to shoot for, it does not have a direct effect on the success of the project.
6. **Safe (Weight Assigned = 10) –** This is a more general customer requirement which encompasses all safety related requirements. It was created to skew the importance values of safety related engineering requirements in order for the team to have astronaut safety

as the priority. As stated above, this customer requirement was rated a 10 for the sole purpose of ensuring that we have safety related requirements as top priority.

7. **Comfortable (Weight Assigned = 4) –** A comfortability requirement is an excellent way to ensure that the astronauts living in the habitat for one month aren't completely cramped or otherwise uncomfortable. Although it is a nice requirement to have, it isn't rated highly because it does not affect astronaut safety, or project feasibility.
8. **Under Budget (Weight Assigned = 9)** – This customer requirement simply states that the project must come in under the specified budged given to the group. This was rated highly because it would make the project unfeasible if over budget.
9. **Payload Limits of Existing Systems (Weight Assigned = 7) –** All existing rockets have payload limits which must be met, or the habitat would be immobile. This customer requirement was generated based on the dry mass limit requirement given by NASA's description. The team rated this requirement relatively highly, as it effected the feasibility of the project; however, solutions could be created to work around it if the structure were over existing payload limits.
10. **Ready for Use in Specified Time (Weight Assigned = 6) –** This customer requirement was also created using the project description. It was rated somewhat neutrally because it had some effect on project feasibility, however it did not affect astronaut safety at all.
11. **Shield Radiation (Weight Assigned = 9) –** This requirement was created with some research being done on space radiation effects on the apollo astronauts. Shielding from radiation is absolutely necessary to guarantee the safety of the astronauts, and for this reason the team rated it very highly.
12. **Maximize Lunar Resources (Weight Assigned = 6) –** This requirement was created with the team's faculty advisor so that the team would make it a priority to include use of lunar resources. This customer requirement was rated somewhat neutrally because it did have some effect in the astronaut's safety in the form of radiation protection through utilizing the lunar regolith. It did not however, have any effect on the feasibility of the project.
13. **Innovative System or Subsystem (Weight Assigned = 5) -** This requirement was also created with the help of the team's faculty advisor to push the team towards innovative solutions. The reasoning behind this is NASA often considers innovative ideas even if they are not completely feasible because they could be made to work in the future. For this reason, the team rated this requirement neutrally, because it had no effect on astronaut safety, but creating an innovative design could help the feasibility of the project.

2.2 Engineering Requirements (ERs) Aidan

[Use this section to list and discuss the Engineering Requirements that have been developed. ER's must be verifiable, that is, specify objectively measurable parameters or conditions. **Each ER must have a target, or design-to, value with tolerance along with justification/rationale for the selected value and tolerance. Every project must include ERs relating to Reliability and Durability.**]

Add summaries as opposed to a table. Talk about weighting. Justify rational for weight.

The engineering requirements with associated units and target values with associated tolerances are listed in order of relative technical importance (RTI) below:

1. **Budget ($ per Year, 11.4% RTI) –** The budget had a target value of 1 Billion as provided by the project description, and was assigned a tolerance of 1 million. This tolerance was assigned based on 1% of the budget, as any more than this value could create issues for the feasibility of the design. This engineering requirement was created to fill the Under Budget customer need, and was rated highly because it affected nearly every aspect of the project. Going too far over budget would make the project impossible.
2. **Levels of Radiation Exposure (Millirads per Day, 11.0% RTI) –** The radiation exposure had a target value of 25 millirads per day, with a tolerance of 2 millirads per day. These values were created based off of the levels of radiation that astronauts aboard the ISS see based on the ISS crew members dosimeter readings. This engineering requirement was created to fill the Shield Radiation customer need, and was rated highly because it had a direct effect on astronaut safety.
3. **Number of Livable Days (Days, 9.2% RTI) –** The number of livable days had a target value of 30 days as provided by the project description, and had a tolerance of 1 day. This value was decided on with the limited number of resources that the astronauts could bring to the moon. More than 1 day without sustenance could cause the astronauts to get weak, and not be able to complete the mission.
4. **Livable Space (m^3, 9.2% RTI) –** The amount of livable space had a target value of 55 m^3 and a tolerance of 5 m^3. The team could not benchmark these values on the ISS because it is much larger scale than the lunar habitat, so the target value was based on values approximated by NASA's human factors research [x]. This value also accounts for supplies, equipment, and samples brought in by astronauts. The tolerance value allows the team some room for change in the overall design. This engineering requirement was rated high because the mental health and comfortability of the astronauts is important to the success of the mission.
5. **Assembly Time (min, 9.1% RTI) –** The assembly time had a target value of 360 minutes, with a tolerance of 30 minutes. The target value is set so that the astronauts don't go for an extended period of time without rest and rehydration. The tolerance value was decided on based on an upper limit of time that the team wouldn't want the astronauts to exceed as it could cause them to get weak. This engineering requirement was rated highly because the safety of the astronauts directly depended on it.

6. **Time Limit (years, 8.9% RTI) –** The time limit had a target value of 7 years with a tolerance of 0.5 years. The time limit engineering requirement was created based on the project description timeline, and also filled the Ready for use in specified time customer need. This engineering requirement was rated somewhat neutrally because without meeting a deadline, the design idea would never be implementable, however it had no affect on the safety of astronauts.

7. **Dry Mass Limit (kg, 8.6% RTI) –** The dry mass limit had a target value of 6000kg with a tolerance of 100kg. This target value was based on the project description, and its tolerance is the maximum the team was willing to go over in order to meet the payload limits of existing systems requirement. This engineering requirement was rated neutrally because it had an effect on project feasibility, but again had no effect on the safety of the astronauts.
8. **Inside Air Temperature (Celsius, 8.1% RTI) –** The inside air temperature requirement had a target value of 20 degrees Celsius and a tolerance of 3 degrees Celsius. These values were based on comfortable room temperatures. This engineering requirement was important for the comfortability and safety of the astronauts, however the team was confident that temperature regulation would be no issue with the implementation of lunar regolith along with other insulants, and so as a result was not rated as high.
9. **Inside Air Pressure (KPa, 5.9% RTI) –** The inside air pressure requirement had a target value of 101 kPa with a tolerance of 0.25 kPa. These values are based on the pressures that are used in the international space station, which is atmospheric pressure at sea level. This engineering requirement is necessary for the safety and comfortability of the astronauts.
10. **Reusable (# of Assemblies, 5.6% RTI) –** The reusability engineering requirement had a target value of 3 and a tolerance of 1. This engineering requirement was based on the project description and its target value was a goal set by the team to have the habitat be usable for 3 different missions. This value, and its tolerance is simply a goal, and is not based off of any benchmark. This engineering requirement was rated somewhat low, as it is something that was provided in the project description, but not detrimental if goals are not met.
11. **Air loss (% per day, 4.7%) –** The target value for the air loss engineering requirement was .03% per day, with a tolerance of .005%. The team wanted to lose no greater than 1% of the air within the habitat, in order to keep an adequate pressure for the astronauts. This engineering requirement was important for the comfortability and safety of the astronauts, but the effects of air loss are usually quite low in the ISS, so the team decided that it wasn't as crucial as the other habitat living conditions.
12. **Lunar Resources Used (%, 4.5% RTI) –** The target value for this engineering requirement was 15% with a tolerance of 5%. Similar to the reusability requirement, the target values and associated tolerances are based off of a goal for the team, and is not based off of any benchmark. This engineering requirement was created to fulfill the maximize lunar resources requirement, which was created with the help of the faculty advisor.

13. **Number of Novel Subsystems (#, 4.0% RTI) –** The target value for the number of novel subsystems was 2 with a tolerance value of 1. Similar to the lunar resources used requirement, the target values and associated tolerances are based off of a goal that the team set. This engineering requirement was created to fulfill the innovative system or subsystem customer need.

2.3 House of Quality (HoQ) Aidan

[Summarize project requirements in a House of Quality using the template provided on the course website. If the HoQ is small enough you may include it here as landscape or portrait. If it is too large, add the HoQ as an Appendix. Include a detailed introduction to the section and a discussion of how the HoQ has helped the team in the design process. Be specific and detailed (i.e., do not write any statements that could be applied to multiple projects besides your own). Ensure that every Engineering Requirement has a legitimate target value and tolerance to the target.]

For the Preliminary Proposal include only CRs, Weightings, ERs, Target Values (with tolerances), and approvals. Testing Procedures will be added to the next report.

Figure out how to landscape this page only. If the table still does not fit, add it in the appendix.

A House of Quality (QFD) was used to rate and evaluate the team’s customer requirements and engineering requirements. The House of Quality helped the team determine that Budget, Levels of Radiation Exposure, and Number of Livable Days were the three most technically relevant engineering requirements. This helped our team select the most important design aspects for the lunar habitat. Figure x below shows the teams House of Quality.

3 DESIGN SPACE RESEARCH Everyone

[Use this chapter to describe alternative approaches to designing your new or re-engineered system. Sources for this information include existing product descriptions, catalogs, engineering textbooks, the engineering literature, and the internet. Another very important source for some projects, especially (but not exclusively) for process re-engineering projects, is benchmarking.]

[Put introduction to Ch. 3 here detailing what the chapter contains before leading into Section 3.1.]

3.1 Literature Review

[Use this section to describe what sources were used for benchmarking and design research. This could have been done by examining similar systems, literature review, or web searches. Each student should have at least five relevant sources (academic and professional journals, books, websites, catalogs, interviews with sponsor, advisor, design tools etc.), given in the following subsections. For each source, include a summary and discuss how it specifically applies to your project design space.

How should we format this section? Should we provide the link and then do two subsections (Summary and discussion)?

3.1.1 Salar Golshan

This student aimed to focus their research on human factor requirements that would affect the design of the habitat. The research of habitat designs also proclaimed on this student throughout the initial weeks of the semester. The focus was to discover specific requirements and values that would designate parameters throughout the sustainable lunar habitat design for the scientists and astronauts.

1. Lunar Habitats: A Brief overview of issues and concepts [13]

The cylindrical module base proposal provides a great leeway for expansion. In order to land the modules on the moon and maneuver the base to the appropriate final destination on the lunar surface, a Teleoperated Rocket Crane would be incorporated. This crane would be assembled within the lunar orbit and then descent to the lunar surface. A configure of the design is illustrated below in figure [1]. [SG1]

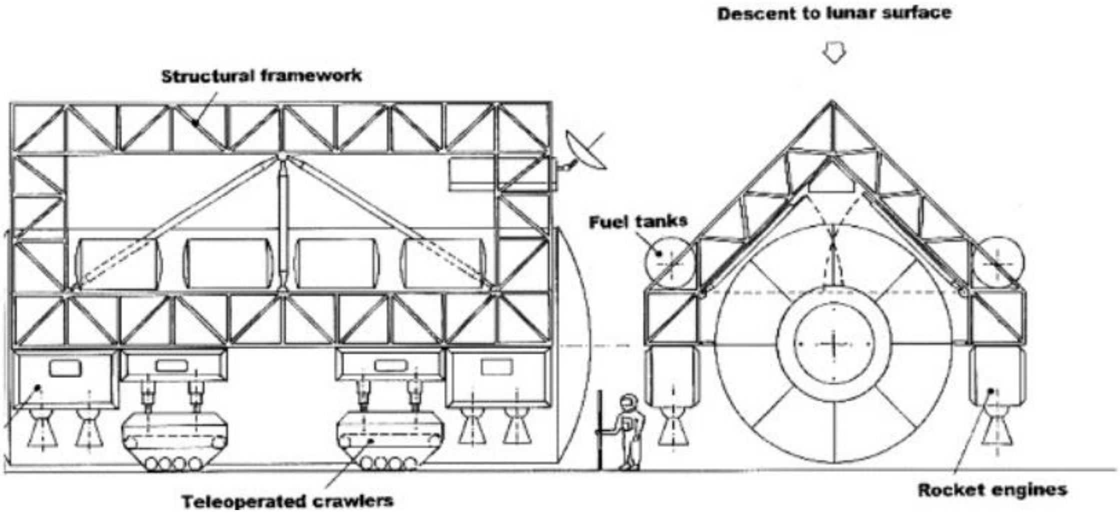


Figure 1: Teleported Rocket crane

This design will have an outer shell made out of aluminum sheets incorporated through a double shell structure to intensify the strength from micrometeorites, radiation and temperature differentials. This design will also incorporate lunar regolith for shielding. The inner height of each module will be approximately 2.8 meters tall and 4 meters in diameter.

2. A Parametric Comparison of Microgravity and Macro-gravity Habitat Design Elements-

Various equations are presented to define the minimum amount of space an astronaut would require depending on the duration and amount of crew members. Based on provided equations considering gravitational pulls across the planets, the text suggests that Mars climbing velocity is sufficient to cause the foot used to step upwards to float upwards off of the departing step almost to the next step. When observed in microgravity, humans adopt a neutral body posture which represents the lowest muscle energy equilibrium state. A figure of the thorough study of the human body posture is shown below in figure [2] [SG2]

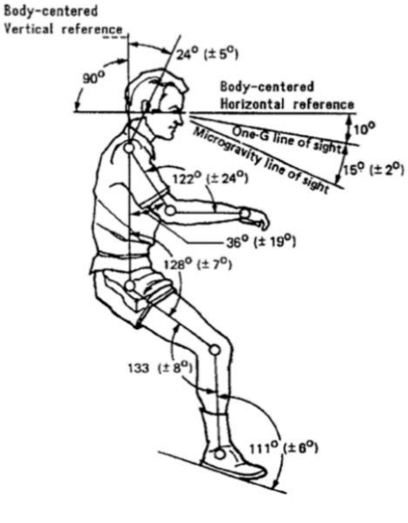


Figure 2. Human Body Posture in Low Gravity

3. Space Habitability

In an interview with 14 ISS astronauts, all 14 mentioned that habitability is an essential aspect for the success of the mission while 13 of 14 also suggested that the habitability needs improvement. The main habitability problems that the astronauts mentioned were low habitability, privacy, variability, and orientation problems due to visual chaos. The human factor habitability has a direct correlation to the psychological, sociocultural, physical and operational factors of the individual. Which in return improves the performance, quality of life, and safety of the individual. [SG3]

4. Emergencies in Space

Upon entering outer space, due to the microgravity the human body is surrounded by, a cephalad shift and equilibration of intervascular fluid is emitted on the body. There is also a 10%-20% decrease in systematic plasma volume. Throughout the initial few days where the human is adjusting to the new environment, on average a 2.5 kg body mass loss is experienced. Although 70% of astronauts experience Space motion sickness, most of the symptoms abate within 72 hours. Orthostatic hypotension caused by microgravity-induced cardiovascular changes is the most prominent space medical emergencies, implicating 2 uncertain deaths. In an emergency situation, surgical chambers that can be operated under in microgravity have been engineered that incorporate expandable clear plastic with arm ports fitted with surgical gloves. [SG4]

5. Water and Energy Dietary Requirements

Through 14 astronauts, it was determined that total water turnover before flight was 3768± 509 mL/d and 2731± 611 mL/d after flight. In flight urinary volume approximated to 1519± 859 mL/d which determined that fluid intake from food and water was 1061± 292 mL/d. NASA states that the recommended intake for fluids should range within 2000mL/d, maximum sodium intake of 3500mL/d and a minimum of 3500 mL/d of potassium. [SG5]

3.1.2 Keerthi S. Gopi-Nagaruri

Air Tight Structure design for manned vehicles [7] Feel free to drop in full citation.

Description

Space Structure designs are typically designed using elastic deformation and safety factor methods. This paper discuses an alternative method of analysis called shake down analysis where the simulations are first generated and then prototypes are tested in the lab.

Application to project

…….

Automatic Pressure Control and Load Simulation [8]

Space structures based on inflatable flexible inflatable membranes that provide the rigidity necessary as well as load disbursement. This paper discusses an automated pressure control system along with load simulation techniques.

Space Structures and Improvements [9]

This paper focuses on improvements in manned space vehicles over the years. Space travel is very complicated although a lot has been improved on, concepts such as reentry into earth's atmosphere is not a guaranteed. This paper discusses in depth on structure design of various shapes and materials for space application.

Human Factors for Small Net Habitable Volume: The case for close quarters space habitat analog.

This is a research paper that was the result of collaboration between the University of Houston and the Aeronautical University and it discusses how habitat design affects crew performance and behavioral health. The isolation, confinement, lack of privacy, necessary volume of air, water and ideal workspace are some key components taken into consideration to examine the net habitable volume (NHV) necessary for crew wellbeing on space missions. Below is the table outlined in the article that defines major psychological stressors.

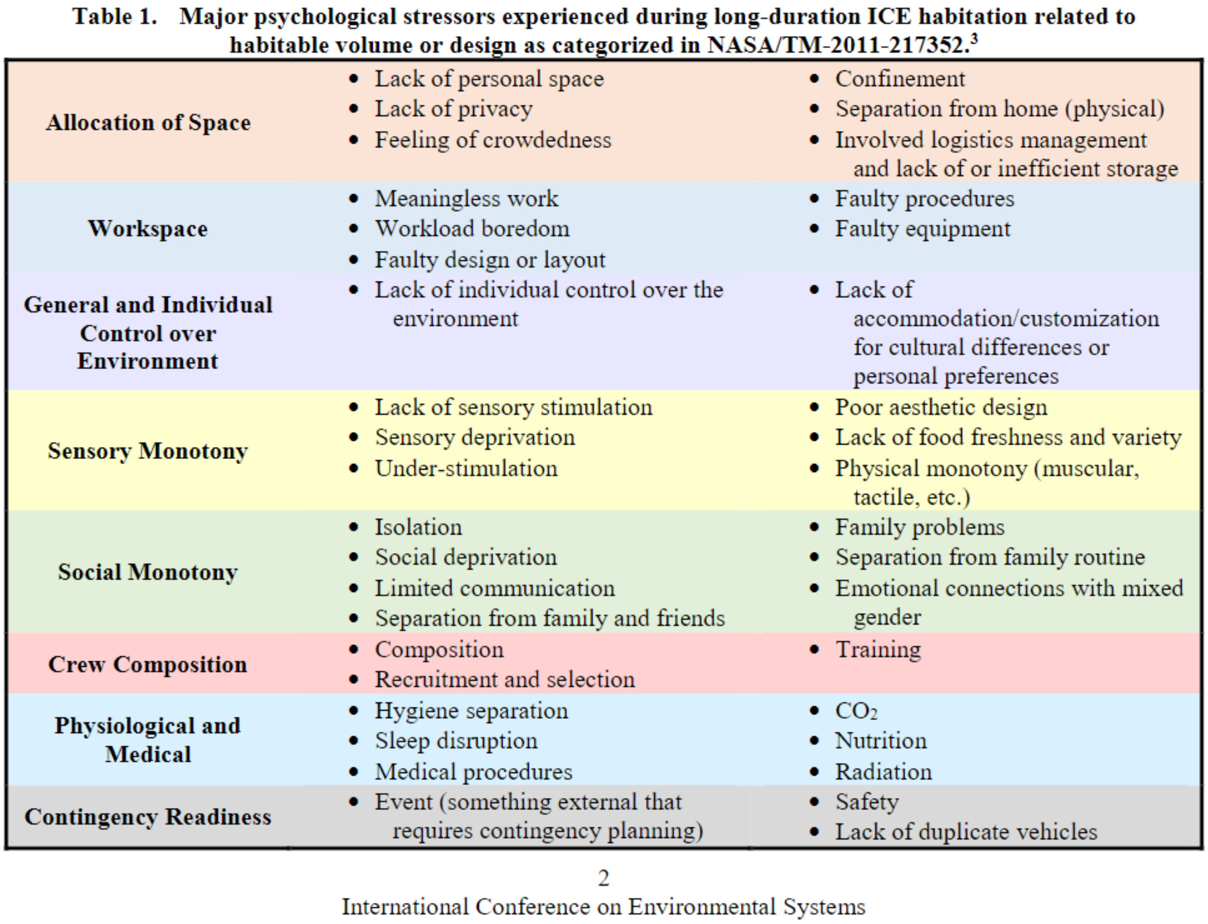


Table 1. Major psychological stressors experienced during long-duration ICE habitation related to habitable volume or design as categorized in NASA/TM-2011-217352.[3]

Allocation of Space	Lack of personal space Lack of privacy Feeling of crowdedness	Confinement Separation from home (physical) Involved logistics management and lack of or inefficient storage
Workspace	Meaningless work Workload boredom Faulty design or layout	Faulty procedures Faulty equipment
General and Individual Control over Environment	Lack of individual control over the environment	Lack of accommodation/customization for cultural differences or personal preferences
Sensory Monotony	Lack of sensory stimulation Sensory deprivation Under-stimulation	Poor aesthetic design Lack of food freshness and variety Physical monotony (muscular, tactile, etc.)
Social Monotony	Isolation Social deprivation Limited communication Separation from family and friends	Family problems Separation from family routine Emotional connections with mixed gender
Crew Composition	Composition Recruitment and selection	Training
Physiological and Medical	Hygiene separation Sleep disruption Medical procedures	CO_2 Nutrition Radiation
Contingency Readiness	Event (something external that requires contingency planning)	Safety Lack of duplicate vehicles

2
International Conference on Environmental Systems

[Citation on the way]

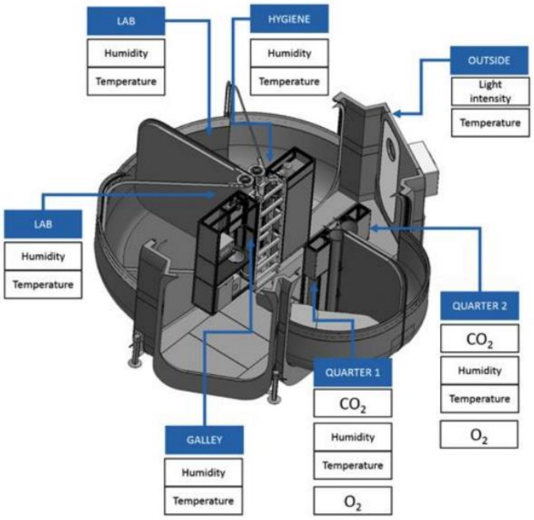
Using the table above and the harsh space conditions, the report investigates the net habitable volumes for a number of vehicles designed for various lengths and crew sizes. The report also outlines potential emergency situations such as fires, gas leaks, depressurizations and solar particle events. The report then concludes that testing small habitats such as the self-deployable habitat for extreme environments could offer solutions to emergency situations. The key figure obtained is the NHV for individuals is 25m^3 per person.

SHEE, Self-Deployable Habitat for Extreme Environments

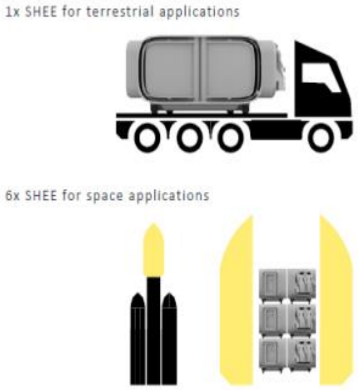
This report discusses a potential foldable structure designed for extreme environments (including space). In the folded configuration, the SHEE takes up (find the collapsible sq footage). The design incorporated interior criteria such as areas designated for Food (storage, preparation, and consumption), Hygiene, Workspace, Personal Quarters, and air lock. The design considers the NASA NHV of 25m^3 per person, as well as the current industry standards for manufacture and assembly. The figure below describes the foldable design. The figure below describes the inner layout and the necessary support system locations. The design offers key criteria for designing a habitat for a crew of 2 and how the necessary support systems would fit.

Figure : SHEE deployed and folded configurations. SHEE Consortium

Figure 2: Deployment of SHEE from folded configuration (1) to operational configuration (5).



SHEE life support systems location and measurements; *credit: SHEE Consortium, visualisation: COMEX, 2014*



3.1.3 Ryan Navarette

The focus of this team members research materials, material selection manufacturing methods and design standards in order to understand the scope of the project and create a design that meets the constraints of the project. The resources found below showcase the top fives sources the student found most effective in understanding available materials, manufacturing processes, and design standards:

1. The Space Materials DataBase (SPACEMATDB) [Ryan 1] –

   This data base provides a detailed list of 418 space ready materials and includes physical, environmental, mechanical, and thermal properties as they pertain to space applications. The data base was compiled by Dr. Antonius de Rooij, former principal metallurgist in the Materials and Process Section at the European Space Agency and has over 30 years of experience with aerospace capable materials. The data base serves as a basis for material selection, however, further research on individual materials of interest should be done.

2. Materials and Manufacturing PDF [Ryan 2] –

   In this chapter, the author describes the challenges NASA faced with the design of the Space Shuttle systems, the innovations in materials solutions and overcoming manufacturing limitations. This document provides valuable insight into innovating problem solving and the manufacturing of the space shuttle and the hurtles engineers might encounter, with insight into a possible solution. An example of the testing required for designs is shown in Figure X1, in which the tile attachment for the space shuttle via use of a nondestructive test known as acoustic emission monitoring.

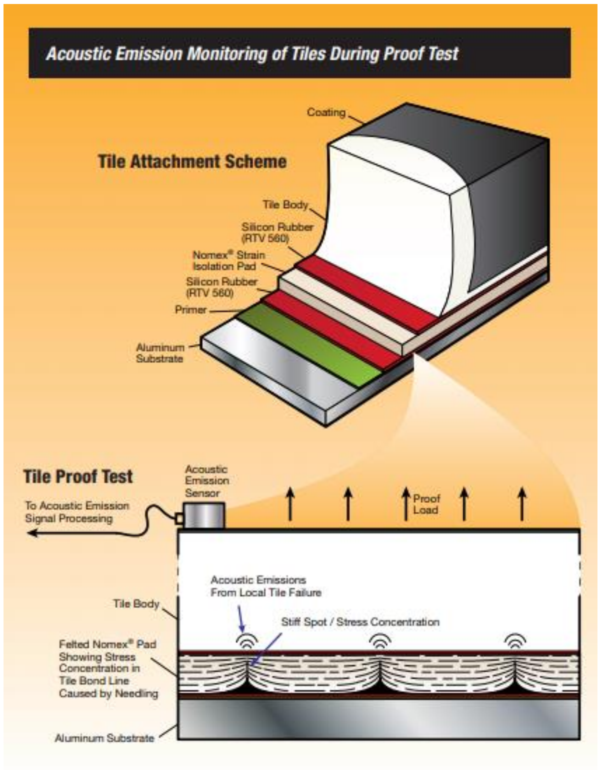


Figure X1. Acoustic Emission Monitoring of Tiles During Proof Test [Ryan 2]

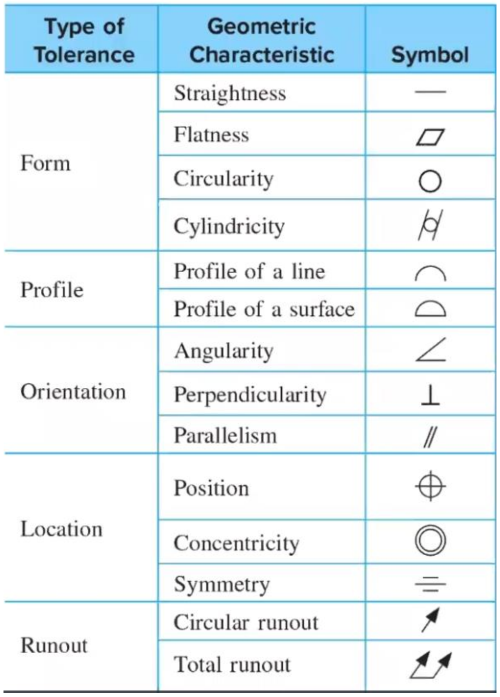
3. Introduction into Aerospace Materials [Ryan 3] –

   This book introduces the science and engineering of materials used in aerospace applications, and examines the structural materials used in airframe and propulsion systems. There significant emphasis placed on the structural materials used with in aerospace applications due to the influences on cost, performance, reliability, and safety that the materials have on these applications.

4. Fundamentals of Modern Manufacturing: Materials, Processes and Systems [Ryan 4]

   This book describes modern manufacturing processes of metals, ceramics, polymers, and composite materials. The manufacturing processes range from traditional processes that have been refined throughout the centuries and the implementation of electronics into the manufacturing processes. There is also an extensive section on Geometric Dimensioning and Tolerancing (GD&T); that covers the basics one would need to learn to properly convey design intent and properly understand manufacturing limitations. Table X1 shows typical geometric controls found in the geometric tolerance block. Figure X2 is the general set up of a geometric tolerance block. Table X2 shows the typical tolerance of common manufacturing processes covered within the book.

Table X1. Geometric Controls



Type of Tolerance	Geometric Characteristic	Symbol
Form	Straightness	⏤
	Flatness	⏥
	Circularity	○
	Cylindricity	⌭
Profile	Profile of a line	⌒
	Profile of a surface	⌓
Orientation	Angularity	∠
	Perpendicularity	⊥
	Parallelism	//
Location	Position	⌖
	Concentricity	◎
	Symmetry	⌯
Runout	Circular runout	↗
	Total runout	⌰

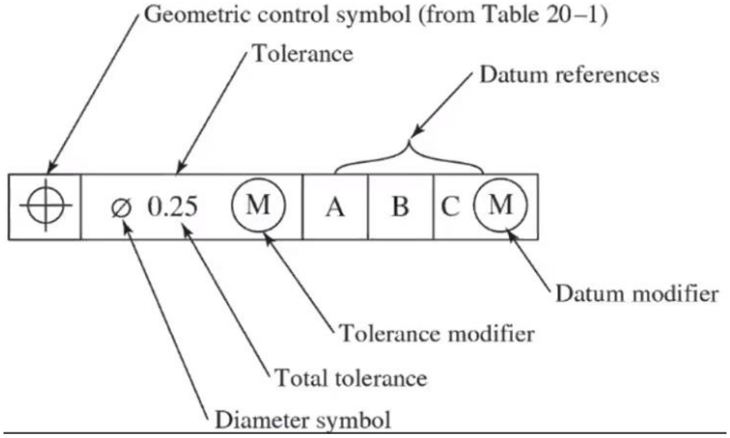
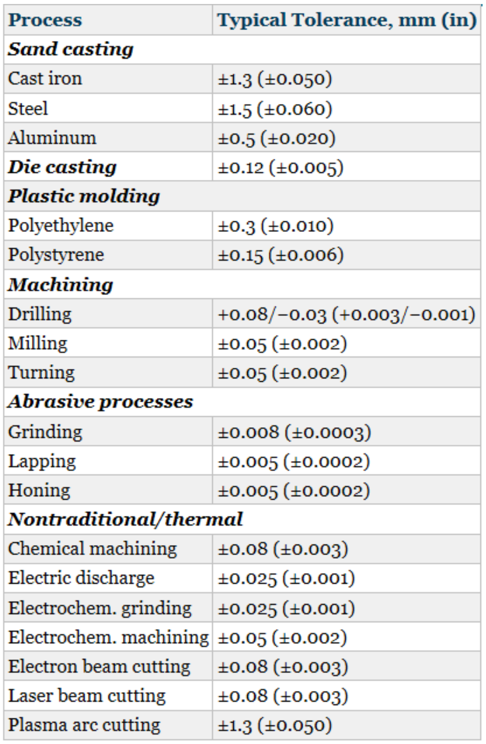


Figure X2. Feature Control Frame

Table X2. Typical Tolerance limits for various manufacturing processes



Process	Typical Tolerance, mm (in)
Sand casting	
Cast iron	±1.3 (±0.050)
Steel	±1.5 (±0.060)
Aluminum	±0.5 (±0.020)
Die casting	±0.12 (±0.005)
Plastic molding	
Polyethylene	±0.3 (±0.010)
Polystyrene	±0.15 (±0.006)
Machining	
Drilling	+0.08/−0.03 (+0.003/−0.001)
Milling	±0.05 (±0.002)
Turning	±0.05 (±0.002)
Abrasive processes	
Grinding	±0.008 (±0.0003)
Lapping	±0.005 (±0.0002)
Honing	±0.005 (±0.0002)
Nontraditional/thermal	
Chemical machining	±0.08 (±0.003)
Electric discharge	±0.025 (±0.001)
Electrochem. grinding	±0.025 (±0.001)
Electrochem. machining	±0.05 (±0.002)
Electron beam cutting	±0.08 (±0.003)
Laser beam cutting	±0.08 (±0.003)
Plasma arc cutting	±1.3 (±0.050)

5. Dimensioning and Tolerancing: ASME Y14.5-2004 [Ryan 5]

   The ASME Y14.5 2004 (or 2009) is a drawing standard created by the American Society of Mechanical Engineers (ASME) to ensure quality, reliability, and safety. This standard relies on the user to have a basic understanding of GD&T and proper designing methods. The 2004 version was created to properly convey design intent and provide a universal drawing standard that engineers from different companies and manufacturing plants may understand.

3.1.4 Aidan O’Brien

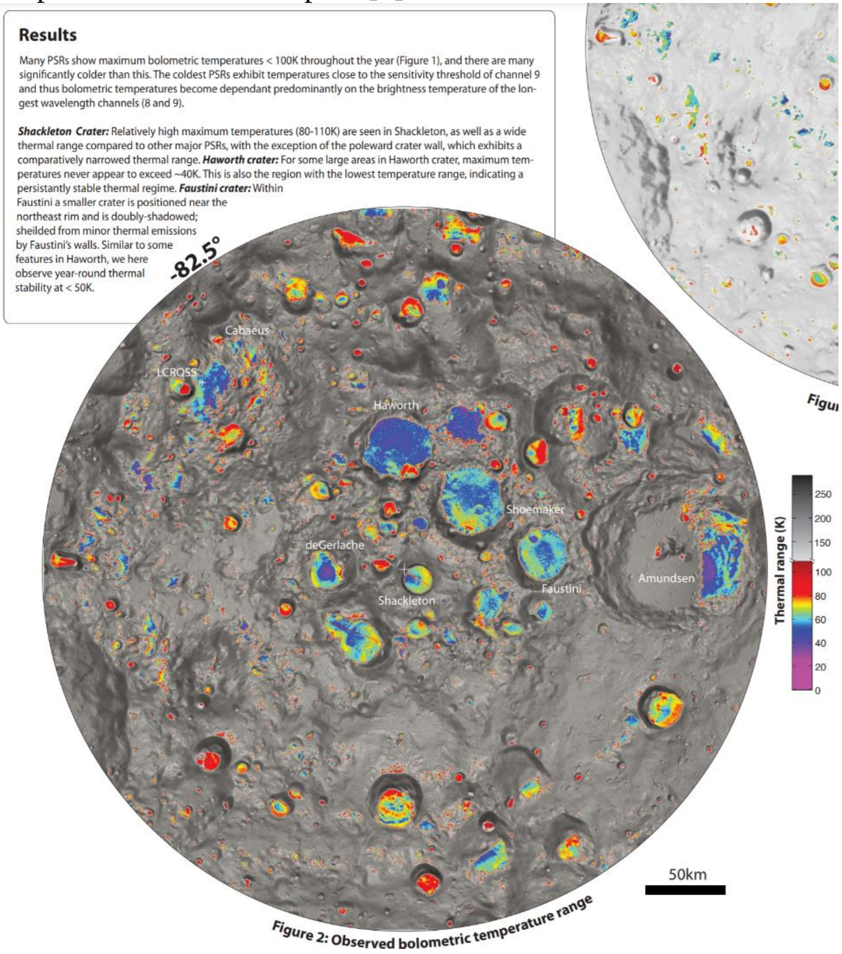
The focus for this team members research was on ambient conditions on the lunar surface, as well as the effects of space radiation on the lunar surface, and how to design around it. Listed below are the five sources that were used to understand the surface conditions and radiation amounts to design around:

1. Lunar Sourcebook: A User’s Guide to the Moon

The Lunar Sourcebook is a collection of information gathered from NASA and other research groups that contains information on seismic activity, physical properties of lunar rock and regolith, lunar heat flow, lunar dust, and the polar environment. This source will give the team information on how to design around these lunar surface conditions.

2. Thermal Extremes in Permanently Shadowed Regions at the Lunar South Pole

This source is a thermal map of the lunar south pole, which shows the temperatures in the craters as well as outside of the craters. This map gives the team a good idea of what the south pole region looks like, and what exactly what temperatures to expect anywhere in that region. This map will prove to be useful for a heat transfer analysis for the habitat. Figure xxx below shows the temperature map for the lunar south pole [x].



Results

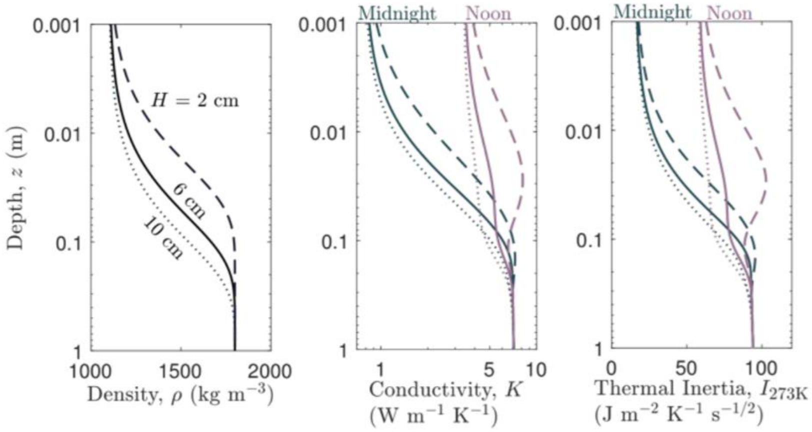
Many PSRs show maximum bolometric temperatures < 100K throughout the year (Figure 1), and there are many significantly colder than this. The coldest PSRs exhibit temperatures close to the sensitivity threshold of channel 9 and thus bolometric temperatures become dependant predominantly on the brightness temperature of the longest wavelength channels (8 and 9).

Shackleton Crater: Relatively high maximum temperatures (80-110K) are seen in Shackleton, as well as a wide thermal range compared to other major PSRs, with the exception of the poleward crater wall, which exhibits a comparatively narrowed thermal range. ***Haworth crater:*** For some large areas in Haworth crater, maximum temperatures never appear to exceed ~40K. This is also the region with the lowest temperature range, indicating a persistantly stable thermal regime. ***Faustini crater:*** Within Faustini a smaller crater is positioned near the northeast rim and is doubly-shadowed; sheilded from minor thermal emissions by Faustini's walls. Similar to some features in Haworth, we here observe year-round thermal stability at < 50K.

Figure 2: Observed bolometric temperature range

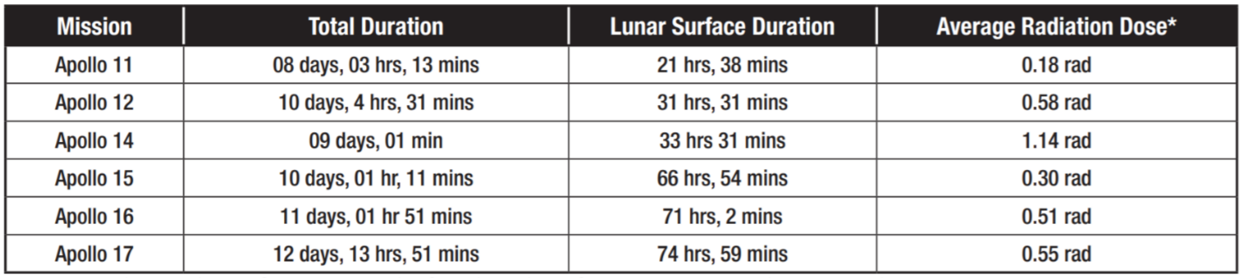
3. Global Regolith Thermophysical Properties of the Moon from the Diviner Lunar Radiometer Experiment.

This article is a useful source of information regarding the properties of the moon's regolith. This information will be necessary for running calculations for heat transfer when using regolith along the outside of the structure. Figure xxx below shows the variation in regolith density, thermal conductivity, and thermal inertia depending on the depth beneath the lunar surface, and the time of day[x].

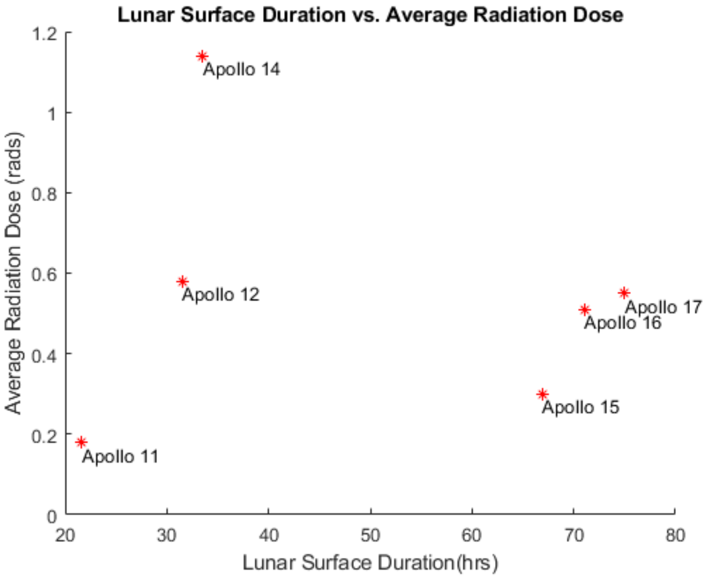


4. Space Radiation

NASA's article on space radiation discusses the effects of radiation in living organisms, and how to protect against it. It also lays out radiation exposure limits based on age and gender for astronauts. The focus of the third chapter is how to defend against deadly ionizing radiation. Most of the shields in the ISS are placed around frequently occupied areas like sleeping quarters and are typically made of a polyethylene plastic called RFX1. Another way to counteract radiation is using dietary countermeasures, which are drugs that are ingested by astronauts which help reduce the effects of ionizing radiation [x]. This source gives the team many options when considering for designing the radiation protection subsystem, and it also gives the team information on what radiation levels to expect for missions on the lunar surface. Table [x] below shows the levels of radiation astronauts received during the apollo missions, and figure [x] is a scatter plot that was created to gain a better understanding of average radiation doses that we can expect to see on the lunar surface[x].



Mission	Total Duration	Lunar Surface Duration	Average Radiation Dose*
Apollo 11	08 days, 03 hrs, 13 mins	21 hrs, 38 mins	0.18 rad
Apollo 12	10 days, 4 hrs, 31 mins	31 hrs, 31 mins	0.58 rad
Apollo 14	09 days, 01 min	33 hrs 31 mins	1.14 rad
Apollo 15	10 days, 01 hr, 11 mins	66 hrs, 54 mins	0.30 rad
Apollo 16	11 days, 01 hr 51 mins	71 hrs, 2 mins	0.51 rad
Apollo 17	12 days, 13 hrs, 51 mins	74 hrs, 59 mins	0.55 rad



5. Radiation Shielding Properties of Lunar Regolith and Regolith simulant
   This article discusses the effectiveness of lunar regolith as a radiation deterrent. It is compared to other materials like polyethylene, graphite, aluminum and lead. The main conclusions from this article were that lunar regolith is an effective solution for radiation protection, with small amounts of lunar soil providing a large protection against galactic cosmic radiation heavy ions. Work was also done to find out how the energy deposition changes with the depth of the regolith. It was found that there is a significant drop off in energy deposition 15cm deep into the regolith [x]. This information is valuable for specifying thicknesses for our outer lunar regolith shell.

3.1.5 Jelani Lamont Peay

The focus for this team member is to benchmark various existing designs of different spacecraft. It is important for our team to analyze habitats that have been used for the long-term survival of astronauts in space. The reason for this is because we need to get a better understanding of the systems and subsystems that are needed to successfully create an environment that is comfortable physically as well as psychologically for however long the duration of the astronaut's mission is.

1. Building a lunar base with 3D printing (Article)

The European Space Agency (ESA) has been working on a solution that would help protect astronauts from radiation by using 3-D printed moon dust from the lunar surface called regolith. A regolith simulant has been created for experimentation by mixing magnesium oxide and a binding salt. The ESA has successfully printed this simulant at a rate 2m/hr which proves that this task can be accomplished as shown in figure [JP 1]. For this reason, I believe that benchmarking this idea would be very beneficial to our team's progress because of regolith's ability to reduce the exposure to radiation [JP 1].

Figure 1 [JP 1] Regolith simulant

2. Protecting the Space Station from Meteoroids and Orbital Debris (Book)

The Whipple shield is a concept that was created by an astronomer named Fred Whipple in the 1940's with the intention of making a protective layer against space debris. Today it is used on the International Space Station (ISS) in several different ways that help protect the critical and non-critical components of the station. The Whipple shield is a multi-layered protective barrier that vaporizes objects that move at a very high velocity and disperses the kinetic energy and impact over the large surface area of the layers behind it. This could be very beneficial to our team because this could provide an efficient way to protect the habitat from the micrometeorites that hit the lunar surface [JP 2].

3. Astromaterials Research & Exploration Science HYPERVELOCITY IMPACT TECHNOLOGY

NASA has been doing some extensive research over the years in the area of Hypervelocity Impact Technology and has developed numerous protective shields as a result. Some of which are the Stuffed Whipple Shield, Multi-Shock Whipple Shield, and the Mesh Double Bumper Whipple Shield shown below in figures [2,3,4] respectively. There are many other ideas that are currently being researched but these three will be beneficial to our project because each of these shields has protected astronauts in the same way we intend to. Knowing the concepts work will allow us to gain a better understanding of the materials that are used for their success so that we can implement it in the same way [JP 2 JP 3 JP 4].

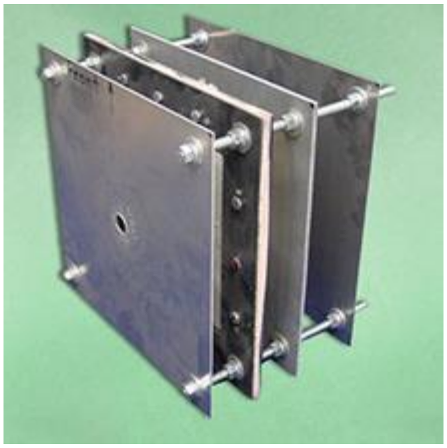


Figure 2 [JP 4] Stuffed Whipple Shield

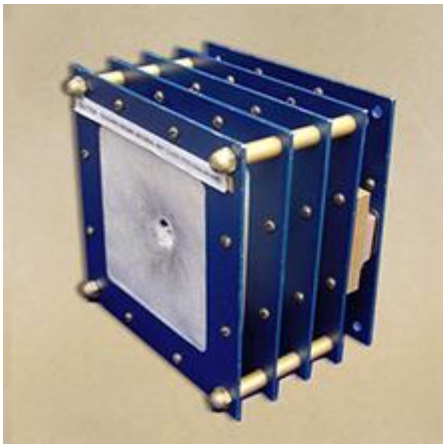


Figure 3 [JP 4] Multi-Shock Whipple Shield

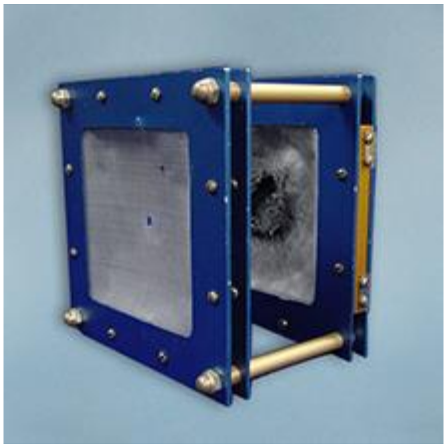


Figure 4 [JP 4] Mesh Double Bumper

4. 3M™ Nextel™ Ceramic Fibers and Textiles Technical Reference Guide

Nextel is a revolutionary material that has been used in several aerospace applications because of its strength and high heat resistance. In fact, it has been tested and used for the purpose of micrometeorite protection. This reference guide can serve as an excellent source for technical information as well as the chemical and mechanical properties of Nextel [JP 5].

5. The International Space Station (ISS) flight systems

This reference guide provides an in depth look at all the structures and subsystems that were integrated into the International Space Station (ISS). This will be a great aid in further developing our subsystems because we can benchmark all the different components to create the best habitat possible. For example, we can analyze the ISS's life support system to try to understand all the components that keep the astronauts safe as shown in figure (5) [JP 6].

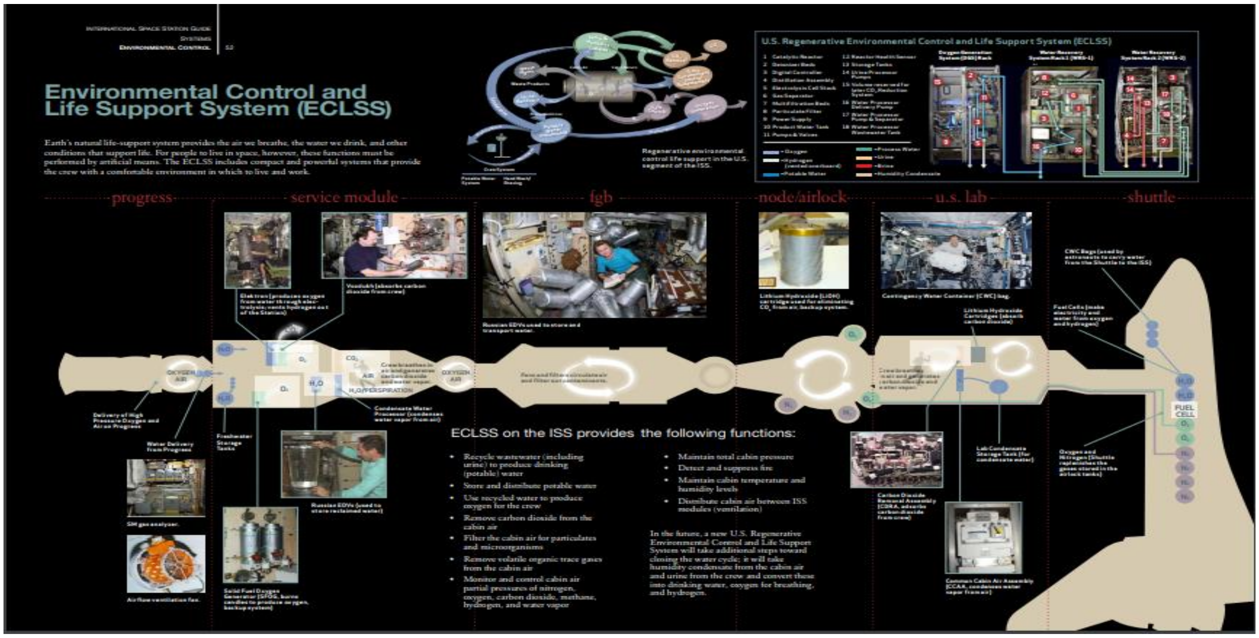


Figure 6 ISS Life Support System [JP 6]

[Explain what technical aspect of the project this student focused on and then list the 5+ relevant sources with summaries and discussions. Cite all textual information and figures.]

3.2 Benchmarking Jelani and Aidan

[Use this section to describe the benchmarking process. Benchmarking involves on-site visits to organizations, observation, and interviews with employees to see how others have approached this type of design problem. Benchmarking can also be done online through extensive research. Based on your completed Original System analysis and the Project Description, identify relevant problems / issues / opportunities that would benefit from the Benchmarking Study. More than one area of the project should be identified for benchmarking. Include the findings of the Benchmarking Study in the remaining sections of this chapter.]

So, there are no existing lunar habitats at this time. What then should we use for the system level benchmarking? In the presentation 1, we attached 5 existing concepts. Should we just do that and explain that there are no existing designs? We can also include the international space station and the lunar module. Furthermore, what system level benchmarking and sub-system level benchmarking should we use?

Use space stations, apolo mission.

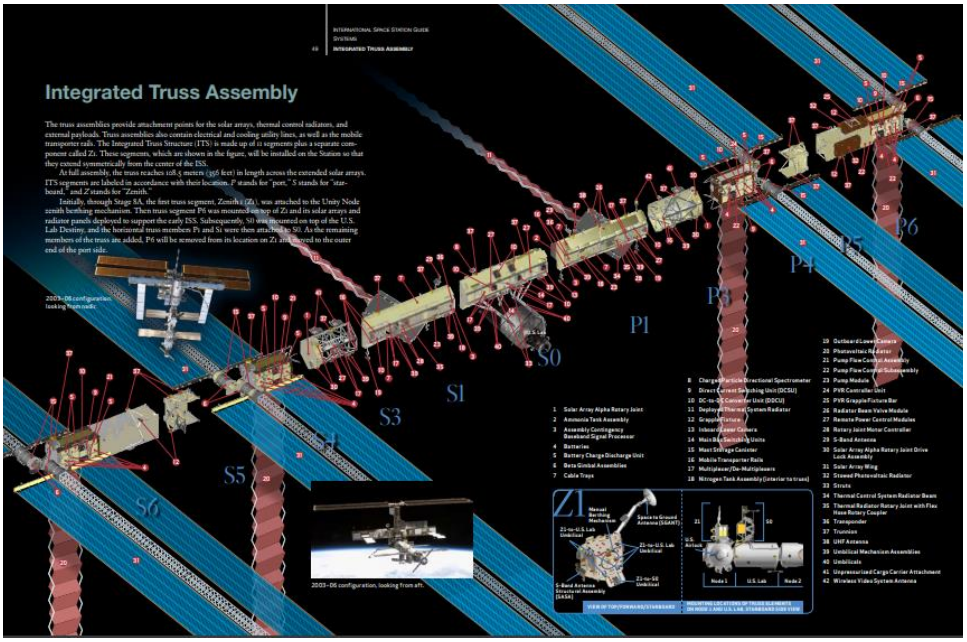
Space Habitat Subsystems. Break down the project into sub-system topics.

3.2.1 System Level Benchmarking

[Use this section to discuss existing designs that address requirements relevant to your project at the system level. For example, if you were designing a race car, one would use this section to describe entire race cars meeting similar or related requirements. List at least three system-level designs and add more as necessary. Cite the sources from which the designs were identified, including your own benchmarking results, if appropriate. Use this section to describe the rationale for your selection of the systems described in the following subsections.]

3.2.1.1 Existing Design #1: International Space Station (ISS)

The International Space Station shown in figure 7 is the result of multiple nations working together to create a modular space station for the purpose of research. It has many components to marvel at but the one that is of the most important to our team is the compartment that houses the astronauts safely. Our intrigue stems from attempting to understand how the ISS was designed to shield against radiation, micrometeorites, space debris, and how it regulates the temperature. By deepening our research, we have found that according to the National Academies Press [JP 2] the ISS is protected by over 100 different shields to ensure the safety of the ISS's components and the safety of the crew from space debris. We have also found that the ISS mitigates the amount of radiation exposure to about 1 millisieverts per day which is about how much the average human being is exposed to over the course of a year here on Earth [JP 7]. Lastly, the way the ISS regulates temperature is through a system called Active Thermal Control System (ATCS). ATCS has three subsystems which are Heat collection, Heat transportation, and Heat rejection. All three help maintain a comfortable temperature and humidity [JP 8]. Utilizing the information that has been collected about the ISS our team can mimic some of the concepts that have made the ISS a successful mission. For example, I believe that the Whipple shields are an excellent idea since the moon is consistently bombarded by micrometeorites.



Integrated Truss Assembly

The truss assemblies provide attachment points for the solar arrays, thermal control radiators, and external payloads. Truss assemblies also contain electrical and cooling utility lines, as well as the mobile transporter rails. The Integrated Truss Structure (ITS) is made up of 11 segments plus a separate component called Z1. These segments, which are shown in the figure, will be installed on the Station so that they extend symmetrically from the center of the ISS.

At full assembly, the truss reaches 108.5 meters (356 feet) in length across the extended solar arrays. ITS segments are labeled in accordance with their location. *P* stands for "port," *S* stands for "starboard," and *Z* stands for "Zenith."

Initially, through Stage 8A, the first truss segment, Zenith 1 (Z1), was attached to the Unity Node zenith berthing mechanism. Then truss segment P6 was mounted on top of Z1 and its solar arrays and radiator panels deployed to support the early ISS. Subsequently, S0 was mounted on top of the U.S. Lab Destiny, and the horizontal truss members P1 and S1 were then attached to S0. As the remaining members of the truss are added, P6 will be removed from its location on Z1 and moved to the outer end of the port side.

1 Solar Array Alpha Rotary Joint
2 Ammonia Tank Assembly
3 Assembly Contingency Baseband Signal Processor
4 Batteries
5 Battery Charge Discharge Unit
6 Beta Gimbal Assemblies
7 Cable Trays
8 Charged Particle Directional Spectrometer
9 Direct Current Switching Unit (DCSU)
10 DC-to-DC Converter Unit (DDCU)
11 Deployed Thermal System Radiator
12 Grapple Fixture
13 Inboard Lower Camera
14 Main Bus Switching Units
15 Mast Storage Canister
16 Mobile Transporter Rails
17 Multiplexer/De-Multiplexers
18 Nitrogen Tank Assembly (interior to truss)
19 Outboard Lower Camera
20 Photovoltaic Radiator
21 Pump Flow Control Assembly
22 Pump Flow Control Subassembly
23 Pump Module
24 PVR Controller Unit
25 PVR Grapple Fixture Bar
26 Radiator Beam Valve Module
27 Remote Power Control Modules
28 Rotary Joint Motor Controller
29 S-Band Antenna
30 Solar Array Alpha Rotary Joint Drive Lock Assembly
31 Solar Array Wing
32 Stowed Photovoltaic Radiator
33 Struts
34 Thermal Control System Radiator Beam
35 Thermal Radiator Rotary Joint with Flex Hose Rotary Coupler
36 Transponder
37 Trunnion
38 UHF Antenna
39 Umbilical Mechanism Assemblies
40 Umbilicals
41 Unpressurized Cargo Carrier Attachment
42 Wireless Video System Antenna

Figure 7: International Space Station [JP 6]

3.2.1.2 *Existing Design #2: Apollo 11 Lunar Module*

The Apollo 11 lunar mission is considered the precipice of human spaceflight outside of the Earth's atmosphere. The Lunar module as shown in figure 8 is an exemplary example of ingenuity and engineering because before this mission there weren't any spacecraft built for such daring tasks that needed to protect astronauts from high exposures of radiation, micrometeorites, and maintain optimal temperatures. During the design process engineers thought it would be best to align the lunar module with a skin of aluminum to shield against the high energy cosmic radiation that emanated from the sun as well as the universe itself [JP 9]. This will be helpful for our team is because we are deliberating between choosing to 3-D print regolith (lunar surface moon dust) and aluminum to shield against radiation. Furthermore, according to the National Air and Space Museum [JP 9] the Lunar Module was coated in a heat resistant nickel-steel alloy with a thickness of 0.0021072 millimeters or 0.0000833 inches. Since it was a darker colored metal, the emissivity was closer to a blackbody than a white body which allowed for a greater absorption of heat and which allowed the regulation of heat for the safety of the astronauts as seem in figure [JP 10]. Lastly, to protect from micrometeorites the lunar module used 25 layers of plastic films thinly covered in aluminum. It seems that aluminum has a variety of useful properties which should provide us with some insight as to how to keep our astronauts safe for the duration of our project.

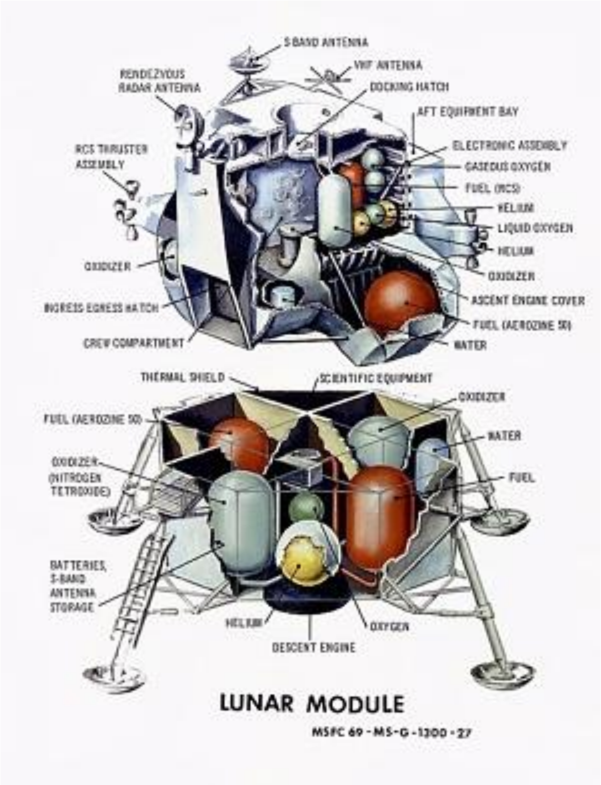


Figure 8. [JP 10]

3.2.1.3 Existing Design #3: Apollo 12 Lunar Module

The Apollo 12 lunar module was very similar to its predecessor with one exception. That exception was that it had an octagonal prism as the ascent stage. This design could be useful because one of our final concepts in our concept generation had a very similar geometrical design. If we could utilize the same methods that made that design a success whilst also integrating our subsystems (i.e., Temperature regulation, Micrometeorite protection, Radiation protection) we be able to would help protect our astronauts for the duration of the mission on the lunar surface. Lastly, one of our constraints for this project is that the lunar habitat has a dry mass of under 6000 kg. Luckily the Apollo 11 & 12 had a dry mass of 2445 kg and 2383 kg respectively. Since we know the materials that were selected to design the Apollo 11 and 12 we should be able benchmark those same materials to create a habitat that not only has a dry mass under 6000 kg but satisfies our other constraints as well [JP 11].

3.2.2 Subsystem Level Benchmarking

[Use this section to discuss existing designs that address requirements relevant to your project at the subsystem level. Under each subsystem heading, list existing designs meeting similar or related requirements. There must be at least three existing designs described under each component/subsystem.]

3.2.2.1 Subsystem #1: Shielding Protection (i.e., Micrometeorites & Space debris)

Although this subsystem is not a part of our functional model it is important because our team will be mainly focusing on the “bare-bone” structural frame and exterior. So, we need to address the various existing designs for shielding so that we can ensure the safety of our astronauts for the length of the mission.

3.2.2.1.1 Existing Design #1: Whipple Shield

The Whipple Shield as shown in figure 9 is an intuitive design created for the purpose of protecting crew members within space modules from micrometeorites and space debris. It is comprised of up to four layers starting with aluminum on the outer layer. Aluminum is a lightweight metal that is durable enough to vaporize the high velocity objects that it would encounter. The two inner layers would be comprised of either Kevlar or Nextel due to of the material's high tensile strength and low porosity. Lastly, the innermost layer is also comprised of aluminum as a failsafe just in case the object did not fully vaporize on impact with the first layer. So, to summarize if an object is moving upwards at a velocity of about 15000 m/s and impacts the shield the first layer will vaporize it until it is nothing by microscopic dust. The second layer will then provide a way for the high kinetic energy of the now disintegrated object to be dispersed over a large area rendering it harmless. Finally, the inner most layer will act as a failsafe just in case the object did not fully disintegrate on impact [JP 3 & JP 4]. This existing design would be great to benchmark off because the lunar surface is bombarded by micrometeorites at the same speed, so it is useful knowing that there is a design that has been successfully tested to withstand that kind of force.

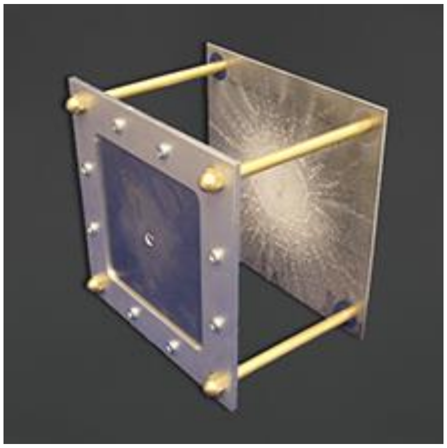


Figure 9. Whipple Shield

3.2.2.1.2 Existing Design #2: Stuffed Whipple Shield

The Stuffed Whipple Shield works in the same manner as the Whipple Shield except there are more layers between the plates of aluminum. The concept is a derivative of its predecessor and is currently being used on the ISS [JP 3 & JP 4]. This design is better suited for objects moving faster than 15000 m/s because it has more layers of Nextel in between the aluminum. Nextel is a fantastic material for this kind of application because it has a strength of close to 3000 MPa. Since it has already been tested in a hazardous environment and proven successful, we can utilize the same idea to protect our astronauts from similar dangers.

3.2.2.1.3 Existing Design #3: Multi-Shock Whipple Shield

The Multi-Shock Whipple Shield is the same concept as its predecessor the Whipple Shield with the exception that is has multiple layers of Nextel between the aluminum. Once an object impacts the shield the Nextel layers continuously shock it until it is rendered harmless. To ensure that the layers continuously shock the object the layers are evenly spaced apart to not offset the process. Using Nextel as the material between the aluminum would be useful because the material is very lightweight weighing in at 9.6g/m [JP 12]. However, economically speaking Nextel is very expensive in fact it costs $1250/kg [JP 12]. Which depending on how much we would need could strain the materials and manufacturing portion of our budget so that is something that we need to be tabulated.

3.2.2.2 Subsystem #2: Radiation Protection (i.e., Solar radiation)

Radiation is something that our team needs to analyze and prepare protective measures for because unlike the Earth the Moon does not have a magnetic field to filter out the ionizing electromagnetic waves (i.e., X-Rays, Gamma Rays, and UV Rays). This will be a difficult task because there isn't a lunar module to benchmark from, except for the ISS. The ISS, however, is partially protected by the Earth's magnetic field so we might need to add more countermeasures in our own design to successfully accommodate the astronaut's safety.

3.2.2.2.1 Existing Design #1: Polyethylene Plastic (RFX1)

RFX1 is a plastic material that is rich in both carbon and hydrogen and possesses the ability to protect astronauts from ionizing radiation. It is a derivative of Polyethylene which is rich in hydrogen and currently keeps the crewmembers of the ISS safe. This material is currently in the research and testing phase, but it may be beneficial for our team to consider this option as a solution. The reason being is according to NASA Human Research Program Engagement and Communications [JP 13] this material is 50% better at shielding against solar flares and 15% better at shielding against cosmic radiation than aluminum (which is sometimes used as a shield against radiation). Since RFX1 is comprised of hydrogen and carbon (which have a low molar mass) the chances of secondary particles dispersing after impact and harming our inhabitants decrease exponentially. As a rule of thumb, we will need to pay close attention to materials with a larger molar mass because the chance of secondary particles dispersing increases as the atomic radius increases. What also makes RFX1 an exceptional material is the fact that it can withstand up to 1×10^{12} micro-Sieverts (μSv) of radiation as shown in figure 10 [JP 14]. This will be an important characteristic since the most radiation that our design will encounter over the course of 30 days is 40320 (μSv) it is safe to say that we will be able to protect our astronauts from the adverse effects of radiation exposure [JP 15].

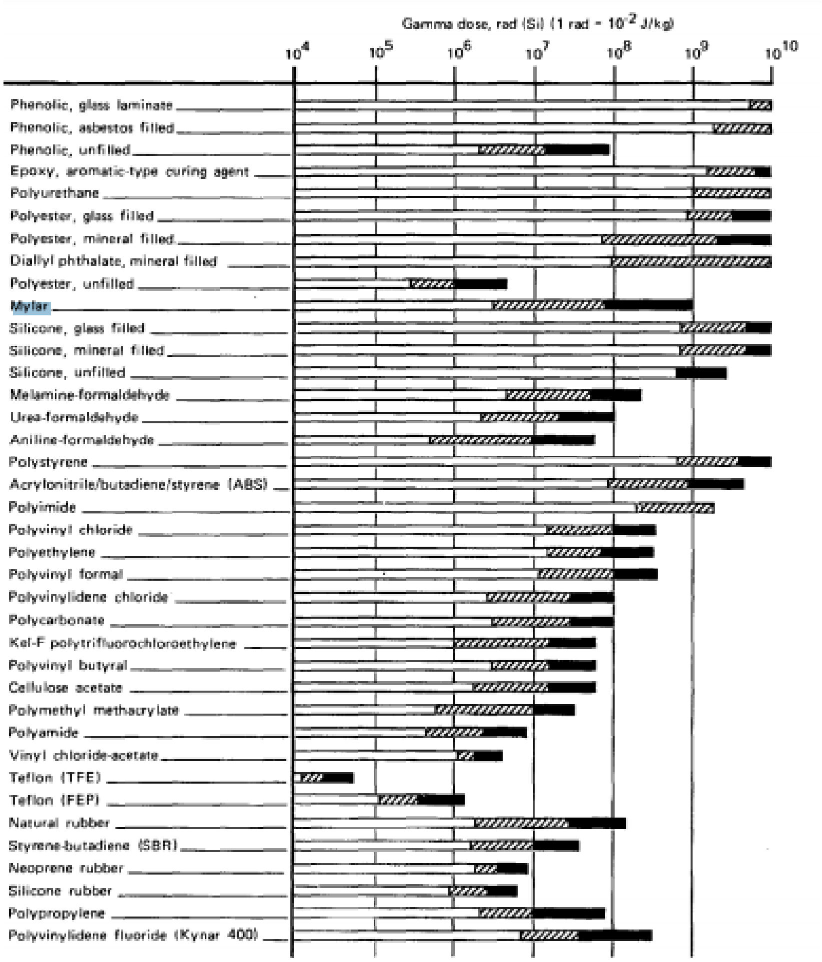


Figure 10. Gamma Radiation dose resistance [JP 14]

3.2.2.2.2 Existing Design #2: Regolith (Lunar Surface Dust)

Regolith is a fine granular substance that can be found on the surface of the moon and has a similar effectiveness in protecting against cosmic radiation. There are a couple of key differences as to why our team is considering using this material and one of those differences is its economic value. Since regolith is already on the moon all our team would need to do is 3-D print it into a usable substance instead of using a portion of our budget on another material. Another important difference is the fact that it is chemically made of light elements (Al_2O_3, CaO, Na_2O, K_2O) which have a lower chance of releasing more harmful secondary particles after impact with the shield [JP 16]. Although regolith has not been used to protect human life as of right now, there have been experiments that have proven that it has the ability block a great deal of radiation. According to the NLSI Lunar Science Conference (who uses a regolith simulant) states that regolith with a thickness 15 cm and a density of 1.9 g/cm^3 will provide an optimal amount of protection from radiation [JP 17].

3.2.2.2.3 Existing Design #3: Water Wall

Water has the potential to serve as a barrier against radiation because since it has a low density and a low molar mass it can stop neutrons from harming our astronauts. However, water does not protect against gamma rays once they meet neutrons so our team will need to have a combination of materials that can block out neutrons and gamma rays [JP 18]. Luckily a water-wall design as shown in figure 11 has been tested aboard the ISS using a protective curtain that consisted of hygienic wipes and towels at a water thickness of about 6.3 g/cm^2. To measure the difference between in radiation dose reduction the experiment was conducted on an unprotected package and a protected package. The results showed that the unprotected package had a radiation dosage of 821 μSv/day and the protected package had a radiation dosage of 575 μSv/day. This is a 37 ± 7% radiation reduction percentage which shows that water does have the capability to shield against radiation. However, our astronauts will be exposed to a greater deal of radiation because the moon does not have a magnetic field to block most radiation. So, we will need to design a barrier that can protect against neutrons as well as gamma rays [JP 19].

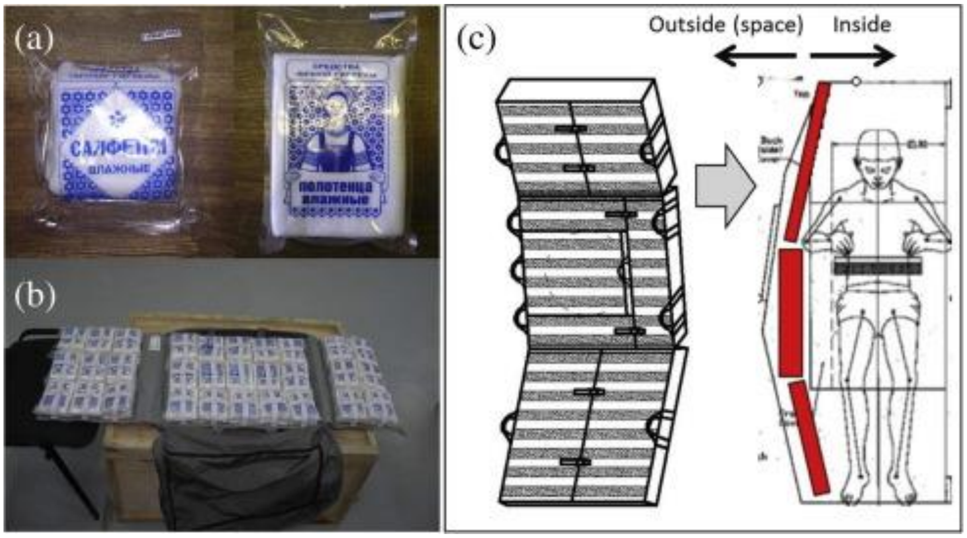


Figure 11. Water wall design test

3.2.2.3 *Subsystem #3: Temperature Regulation (i.e., Thermal Insulation)*

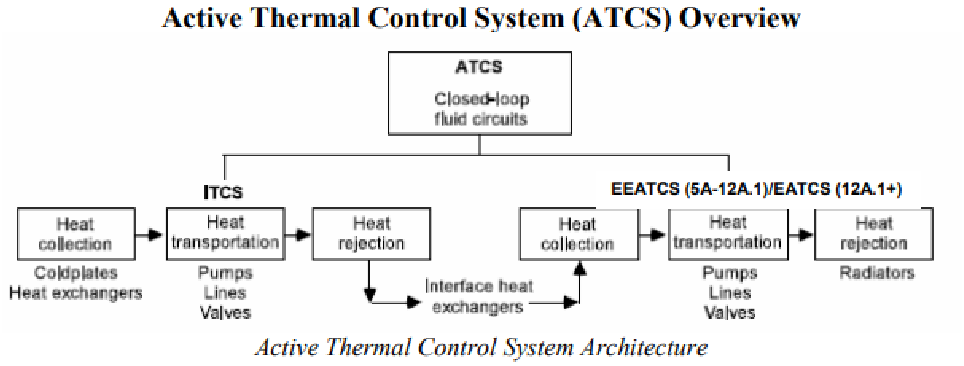
Maintaining a comfortable temperature for our team not only increases the survivability rate of our astronauts for the entirety of 30 days but can also allow other life support systems to function properly. Our team has chosen three existing designs to benchmark off that we believe will help us design a successful subsystem.

3.2.2.3.1 Existing Design #1: Passive Thermal Control System (P.T.C.S) Multi-Layer Insulation

The ISS utilizes the PTCS to keep the cabinets and electronics at a comfortable and operational temperature. The multi-layer insulation material that assists in completing this arduous task is made up of Mylar and Kapton [JP 8]. Both materials have a low thermal conductivity of 0.12 (W/m*K) and 5.24 x 10^{-3} (W/m*K) respectively [JP20, JP 21]. Since the rate of heat transfer is low because of the materials thermal properties the ISS can stay at a comfortable temperature of 24 °C [JP 8]. This can be useful for our team because we can apply the same materials in a similar fashion for our habitat since the temperature ranges from 0 – 250 (K).

3.2.2.3.2 Existing Design #2: Active Thermal Control System (A.T.C.S) Heat Collection

The ATCS aids in keeping the temperature within the ISS at an optimal level by using three subsystems which is the Heat Collection, Heat Transportation, and Heat Rejection as shown in figure 12. The Heat Collection utilizes several heat exchangers which are evenly distributed throughout the cabinets that the astronauts travel through. This is to ensure all sides of the ISS are the same temperature[JP 8]. This will be extremely helpful for our project because the temperature varies greatly throughout the surface of the south pole on the moon. So, this change in temperature is something we will need to account for.



Active Thermal Control System (ATCS) Overview

Active Thermal Control System Architecture

Figure 12. ATCS System overview [JP 22]

3.2.2.3.3 Existing Design #3: Active Thermal Control System (A.T.C.S) Heat Rejection

The Heat Rejection subsystem of the ATCS eliminates the heat that was not used from the ISS through two radiators as seen in figure 13. This task is accomplished by heating up water in closed loops of pipes during the heat of transportation phase [JP 8]. This steam is then transferred to other pipes that have ammonia within them [JP 8]. Lastly, the heated ammonia is then radiated outside the ISS and into space [JP 8]. This efficiently helps the ISS stay at an optimal operating temperature which is imperative for the duration of our project. Depending on our budget we may be able to utilize a similar system, but it may be difficult to replicate this system because we have a dry mass limit of 6000 (kg).

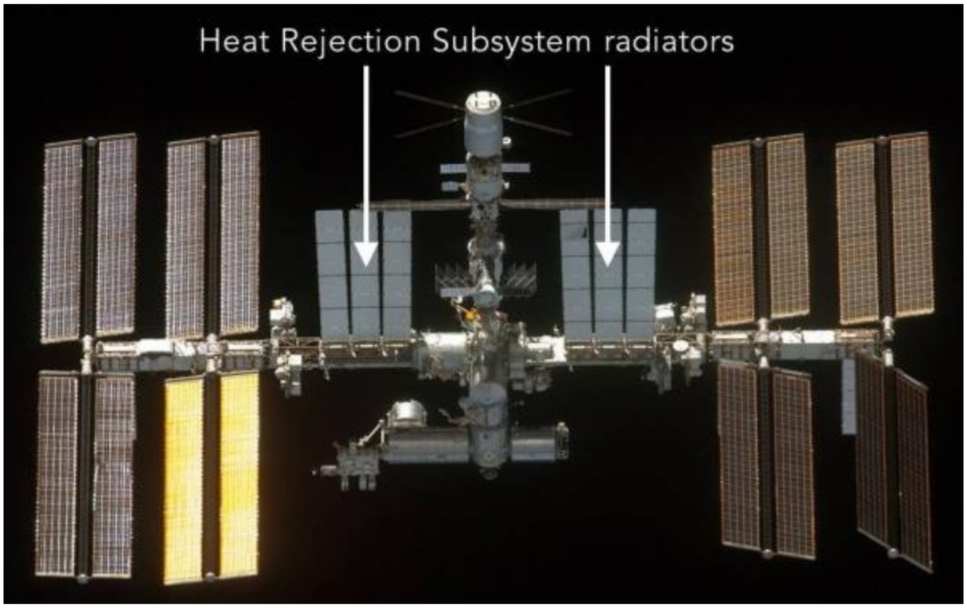


Figure 13. Heat Rejection Subsystem [JP 8]

[**Note**: Copy & paste additional headings as necessary. Be sure to update your Table of Contents.]

3.3 Functional Decomposition Aidan

[Use this section to describe a functional decomposition or system/process hierarchy of your system. Use this space to describe the main functions of the projects and elaborate on your functional decomposition process. Describe your functional decomposition in this section, including (at minimum): a Black Box Model and a Functional Model, Work-Process Diagram, or Hierarchical Task Analysis. Each subsystem listed in the previous section should be included in the functional decomposition (NOTE: Although this section shows up after subsystem benchmarking in this report, you SHOULD perform this activity before and/or concurrently with your subsystem benchmarking.) Your functional decomposition must contain at least three subsystems. For example, if you were designing a race car, your functional decomposition would include braking, steering, and suspension subsystems (among others). The content of Section 3.2.2 would then include a discussion of existing designs for (i) braking, (ii) steering, (iii) suspension, etc.]

3.3.1 Black Box Model Aidan

[Provide an introduction to this section before presenting the Black Box Model with appropriate inputs and outputs in the form of materials, energies, and signals. Include a discussion of how this model helps the team to visualize or clarify your project.]

The black box model is a diagram which analyzes the inputs and outputs of a system. This is a useful tool in the concept generation process as it illuminates the different kinds of flows to design around. The bold, heavyweight line represents the material flows, which include anything physical that takes up space entering the system. The term solids is used to describe any equipment, supplies, samples, and other physical materials that the astronauts will be bringing into the system with them. The black lightweight line is used to represent energy which flows into and out of the system. Energy can take many forms, however in this case only radiant energy from the sun, and electricity from external sources are relevant. The dashed line represents signal flows. Signals are waves which carry information, in this case radio waves are used to communicate with NASA. Figure xxx below displays the teams Black Box Model.

Figure : Black Box Model

3.3.2 Functional Model/Work-Process Diagram/Hierarchical Task Analysis

[Provide an introduction to this section before presenting the team's selected model with appropriate form based on the process diagram/model/analysis. Include a discussion of how this model helps the team to visualize or clarify your project.]

The functional model is a more detailed breakdown of the flows into and out of the system. Notice how the same input and output flows from the Black Box Model are present in this model as well. Each subsystem starts with its own import function, where the material, energy, or signal flow is imported into the system. The overall system is broken down into 5 subsystems: radiation, air and temperature regulation, astronauts and solids, radio signals and finally power. The primary function for this system is to "maintain" or preserve astronauts. Inputs of air, conditioned air, astronauts, solids, and an auditory signal for communication are required to sustain the life of the astronauts. This model was useful for get a deeper understanding of what specific subsystems accomplish. It gave the team a good idea of what subsystems to benchmark, as well as helped the team consider how these subsystems would affect the overall design. This was useful in the concept generation process. Figure xxx below shows the teams finished functional model.

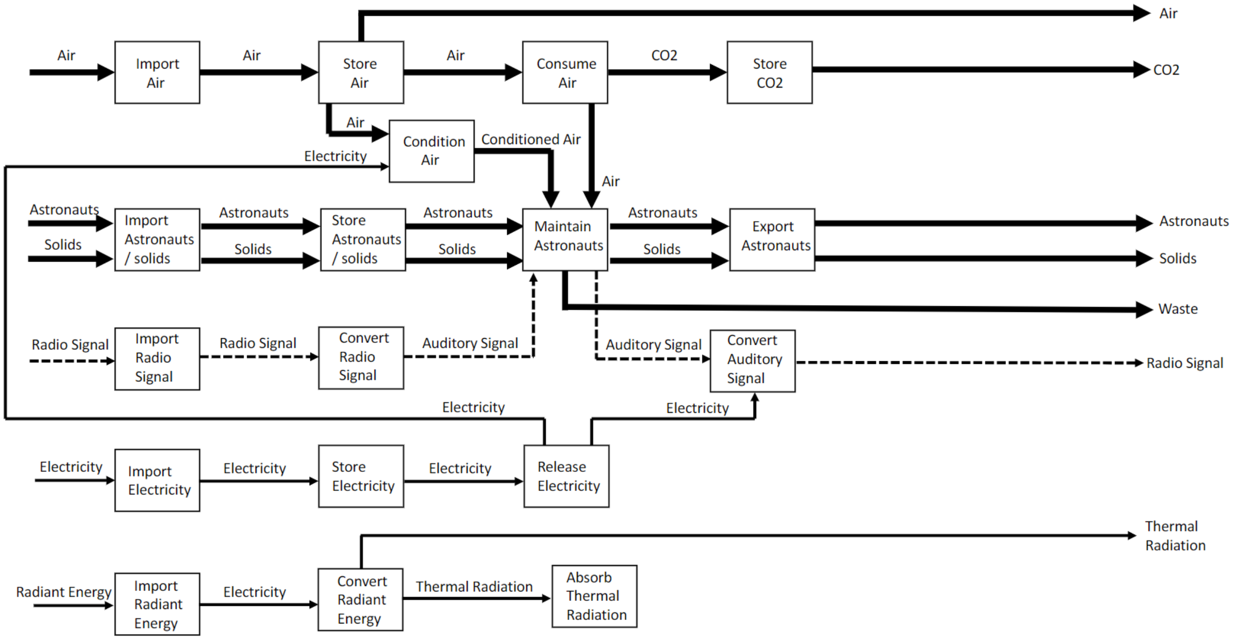


Figure : Functional Model

4 CONCEPT GENERATION Keith and Salar CAD/Pictures-Ryan

[Using the information and data collected as a result of the benchmarking, the design team should complete a group brainstorming session of how to solve the design problem(s). Provide **at least TEN distinctly different possible designs for your system, including full-system designs and sub-system designs.** List advantages and disadvantages of each using brief but compelling technical analysis. **Figures of the designs MUST be professional, i.e. no photos of sketches or lined paper sketches – scans of non-lined paper or computer-generated sketches only.**]

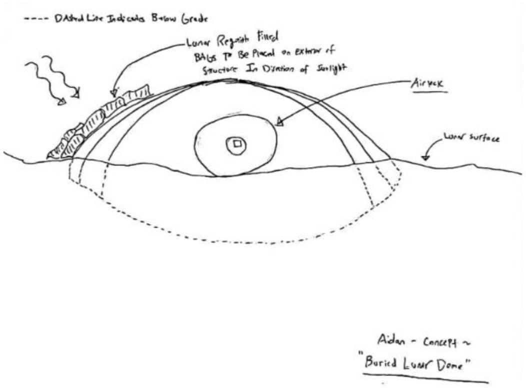
[Do not confuse these designs considered with Existing Designs. Designs considered are new concepts you generate. Existing Designs are entities that currently exist.]

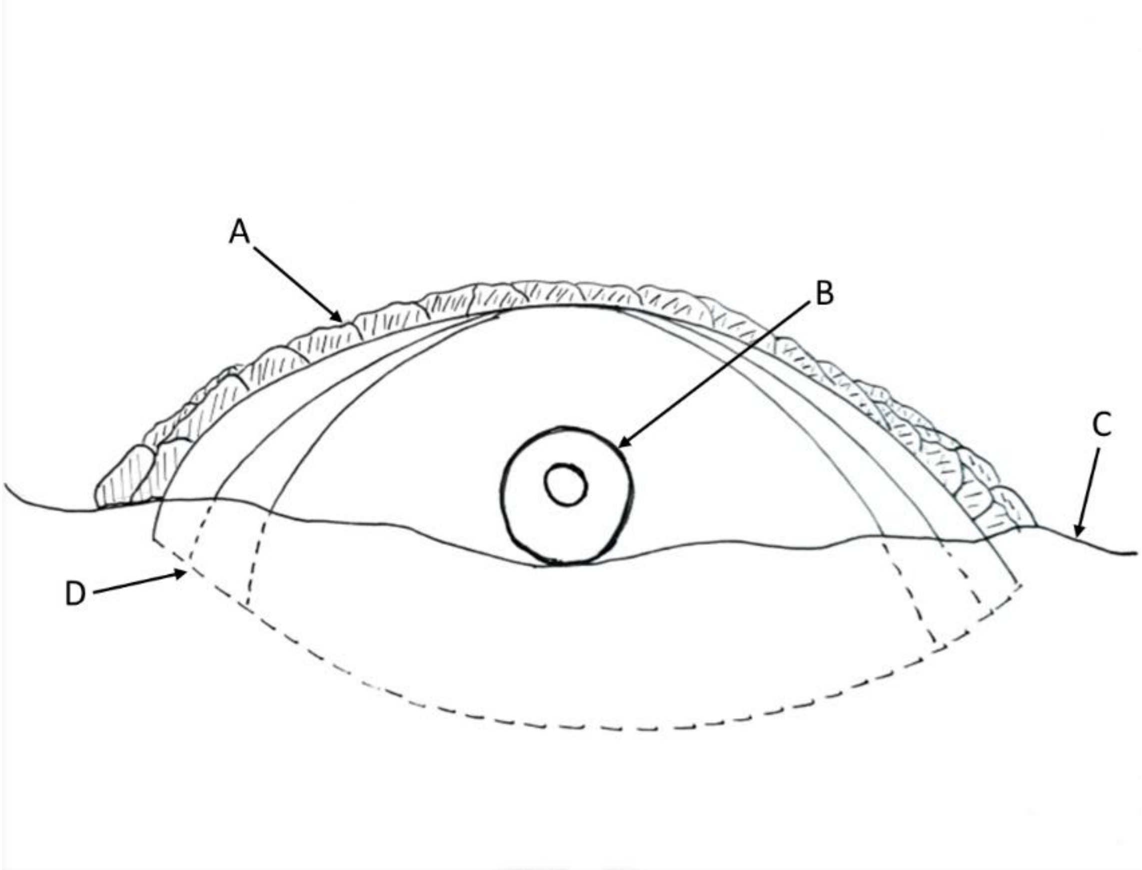
-underground

4.1 Full System Concepts Keith

The following are 10 different full system designs. The main full system problem that needs to be addressed has to do with the system structure. As a result, the full systems described below are designs of whole structures and their inner members. The designs advantages and disadvantages are listed to expand on the structures understanding. Once the structure is chosen, the complimentary sub-systems will be selected and the volume they occupy will be accounted for in the cad design.

4.1.1 Full System Design #1: Buried Lunar Dome





Legend:

A – Regolith

B – Airlock

C – Lunar surface

D – Portion below ground

Advantages:

- Easier temperature control as the structure is partially submerged into the soil.
- The regolith will offset internal pressure.
- Protection from harmful radiation.
- Room for all life support systems.

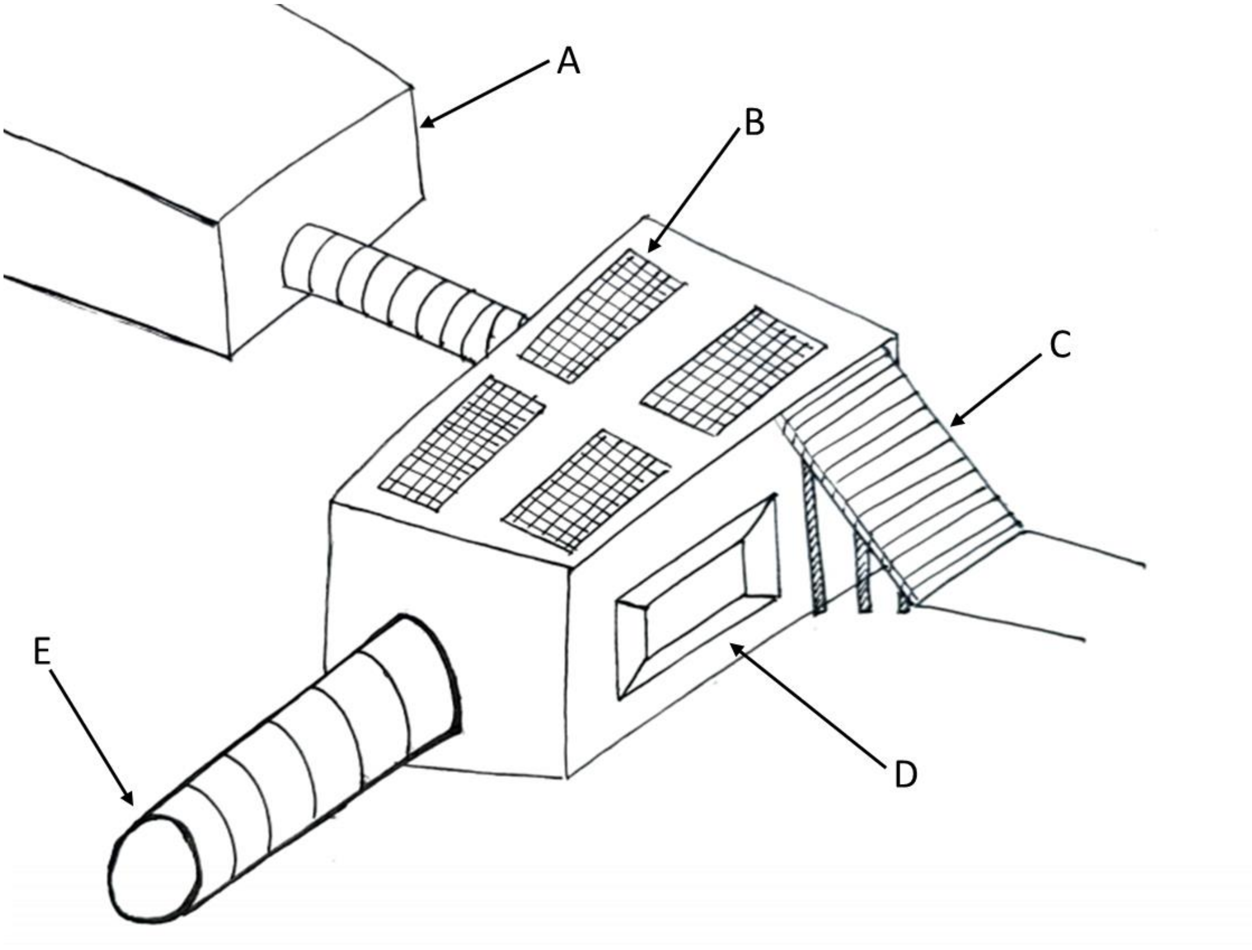
Disadvantages:

- Expensive installation
- Digging into lunar surface could be tricky.
- Structure is to be built on the lunar surface using aluminum. This could be tricky.

Description:

The is space structure is a dome that is buried into the surface of the lunar surface. Then large bags filled with lunar soil (Regolith) is then placed on the exterior of the dome in the direction of sunlight. There is an opening in the dome structure for entry/exit.

4.1.2 Full System Design #2: Space Cube



Legend:

A – Expandable structure

B – Solar panels

C – Stairs

D – Base attachment

E – Airlock

Description: The space cube structure is assembled out of prefabricated walls that will be shipped to the moon. Number of man hours spent to assemble the structure is small and the cylindrical air lock is used to house additional air and to link additional structures together.

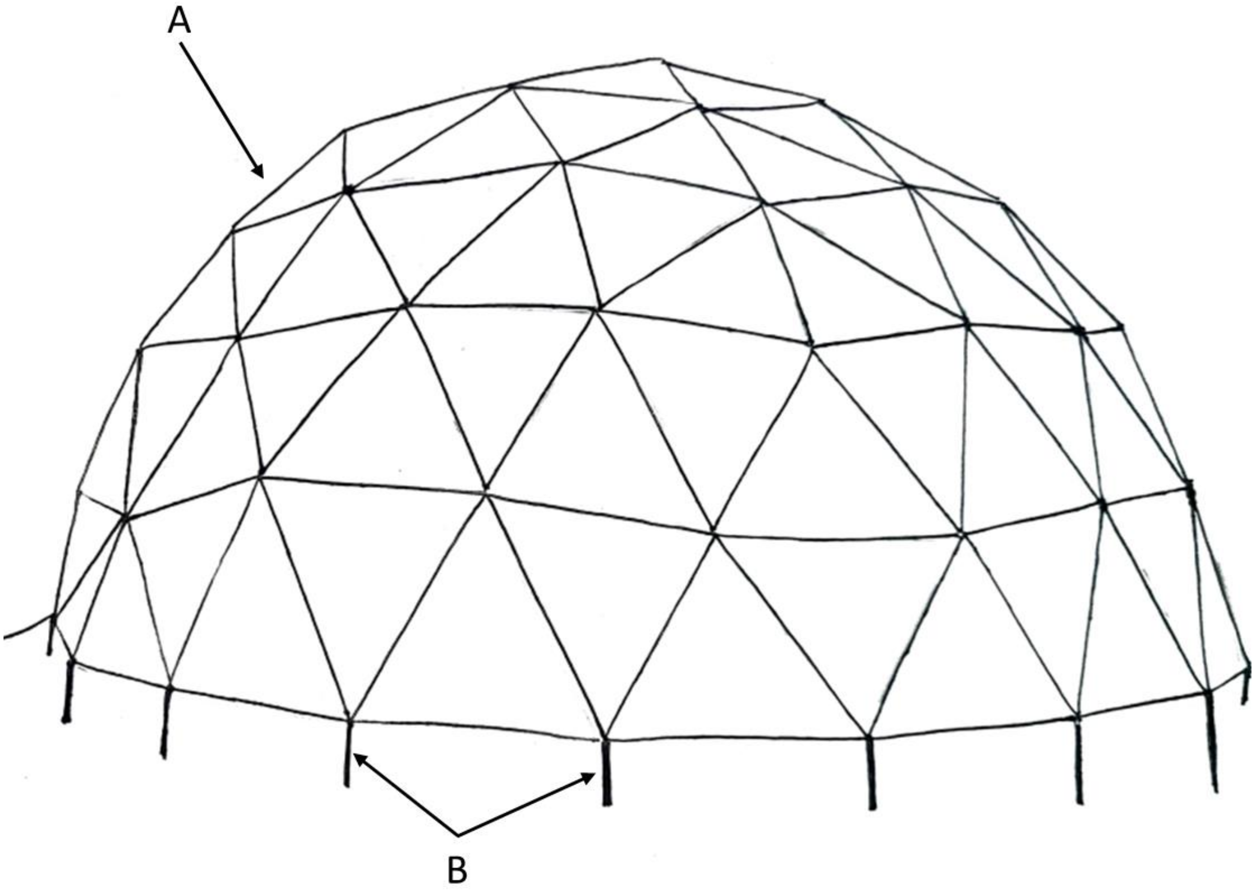
Advantages:

- Low cost
- Modular design allows for easier expansion.
- Meets minimum livable volume.

Disadvantages:

- Not reusable.
- Additional protection could be required to block radiation exposure.
- Extra strength is required to hold air pressure inside the structure.

4.1.3 Full System Design #3: Truss Structure using space grade one handed truss system



Legend:

A – triangle dome structure with regolith imbedded in the walls.

B – Pegs/stokes that are sunk into the lunar surface.

Advantages Structural integrity

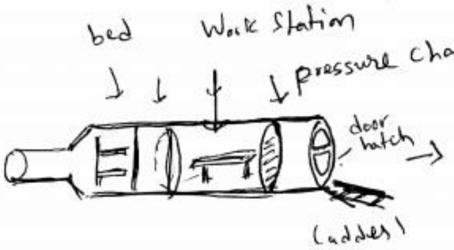
- Lots of room
- Regolith counteracts internal pressure
- Structurally more stable

Disadvantages

- Routes for expansion might be difficult after being fully constructed.
- Could be heavy and requires additional time planning to assemble the structure.
- Structure assembly could be expensive.
- Not reusable

Description: This structure is made out of trusses and beams that form a dome shape. It makes use of the one-handed truss locking mechanism developed for use on the international space station. Then the structure is anchored into the moon's surface using spokes shown in the image. The structure is then covered with metal plates and regolith on the outer layer. The regolith adds structural integrity as it puts the structure under compressive force and offsets some of the internal pressure generated from air.

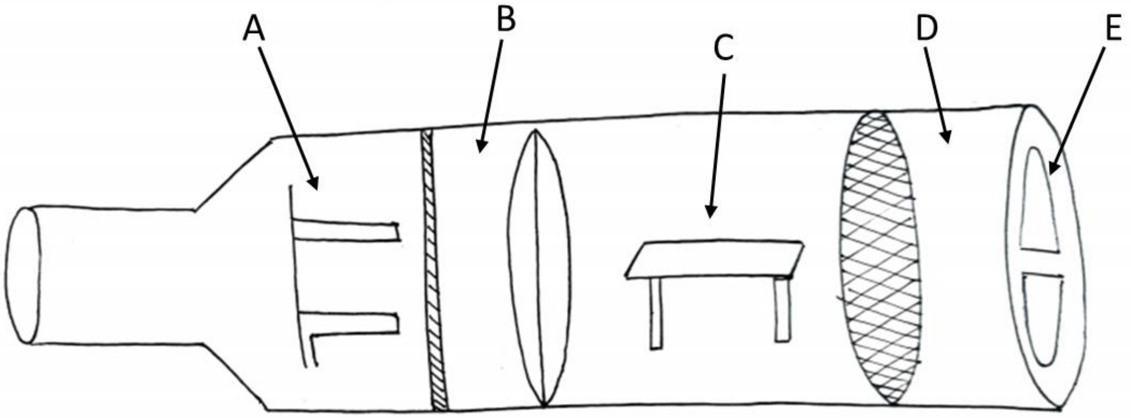
4.1.4 Full System Design #4: Coffee Mug Design



→ fits inside a rocket

→ ~~tamined~~ Modular connections for future expansion.

→ About 230 sq ft



Legend:

A – Bed

B – Shower

C – Workspace

D – Pressurized chamber

E – Door Hatch

Advantages:

- Costs less as the structure will be assembled on earth.
- Modular connections for future expansion.
- Assembled on earth would mean a more reliable testing.
- One shot trip.
- Limits radiation exposure.

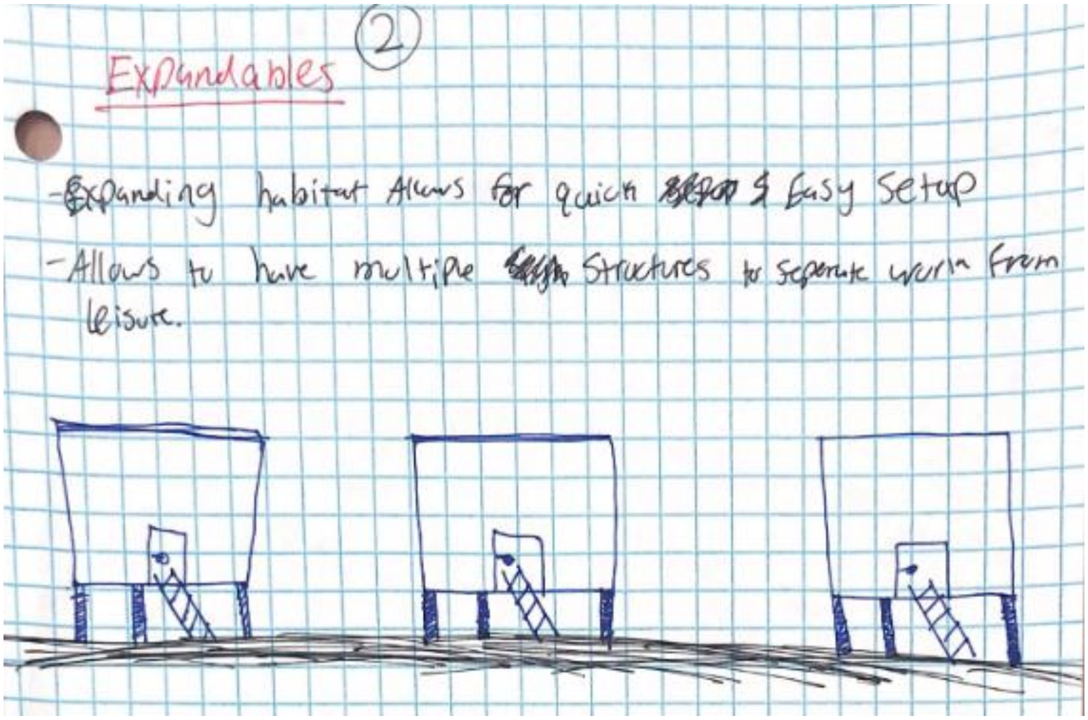
Disadvantages

- Limited living space.

- Subsystems necessary might not fit within the structure.

Description: The structure looks similar to a bottle where it is placed in the rocket fully assembled. Then the coffee mug is placed in the rocket and sent to the lunar surface and some material could be placed on top to reduce radiation exposure. The fully assembled design would mean cost savings overall.

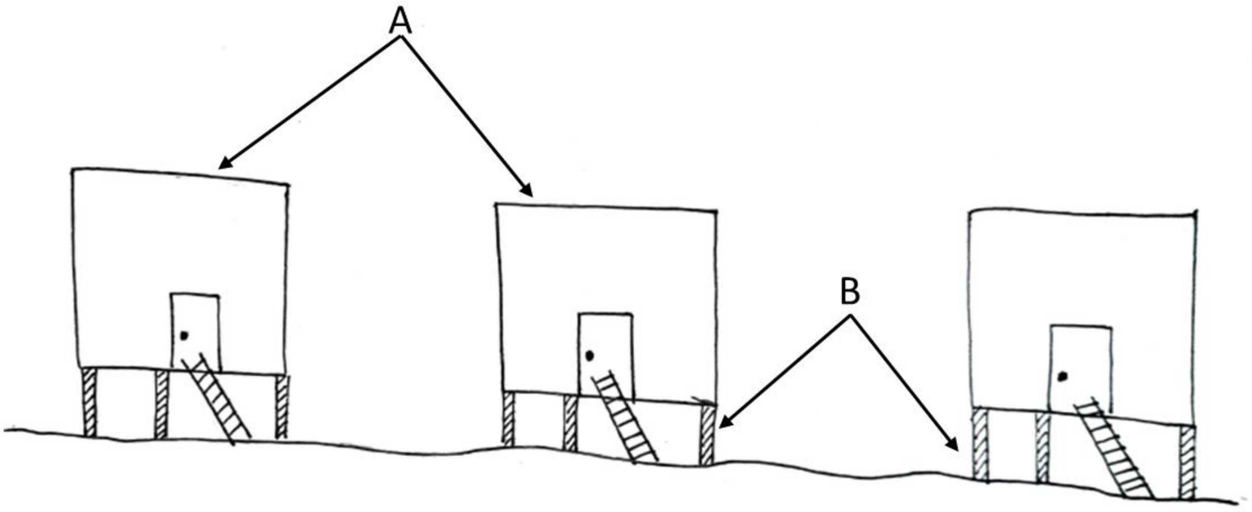
4.1.5 Full System Design #5: Space Shipping Containers



②

Expandables

- Expanding habitat Allows for quick & Easy Setup
- Allows to have multiple Structures to Seperate work from leisure.



Legend:

A – Individual structures

B – Support legs

Advantages:

- Simple design
- Low cost
- Easy expansion
- Low assembly time
- Reusable

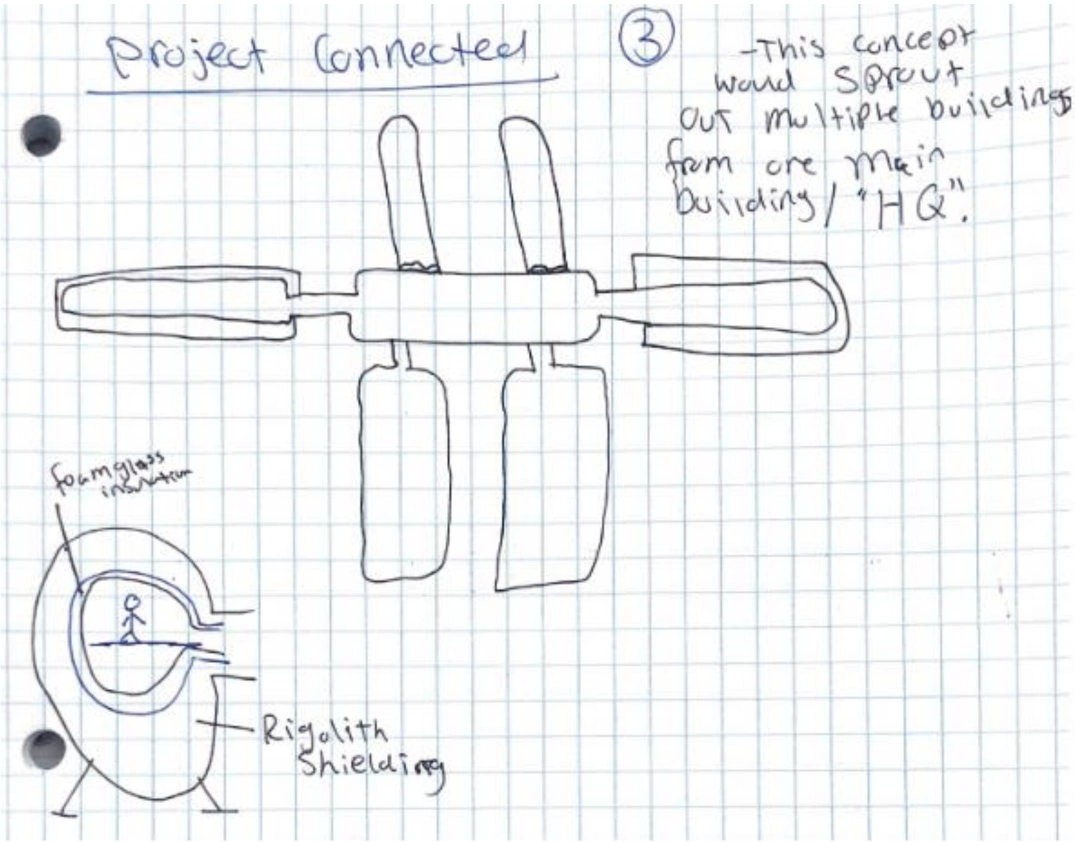
Disadvantages:

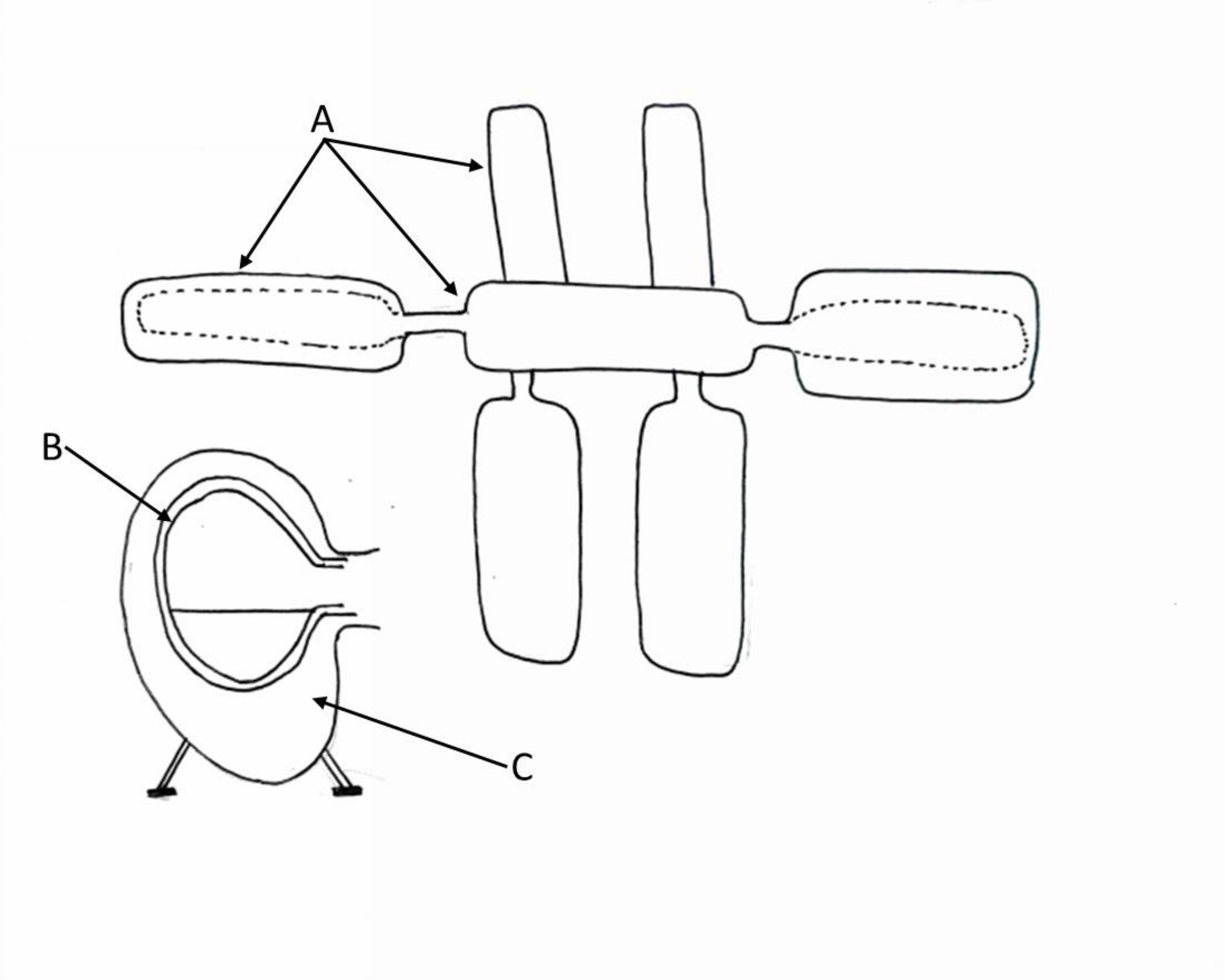
- Fitting it into a rocket might be tough.
- Temperature control is tough.
- Levels of radiation exposure will be high.

Description:

Shipping containers are very popular today. If we could repurpose them for space, it could mean huge cost savings in the long run. Although they might not be connected, the containers have a volume that is easy to design around. When placed near each other, the structures could form a small town.

4.1.6 Full System Design #6: Modular Spider





Legend:

A – Modular structures

B – Foam glass

C – Regolith shielding

Description:

This structure used a central hub as the linking base and connects to multiple little structures. The assembly time could be small as the structures could be attached in modular connections. The structure is also protected with foam glass insulation and uses regolith on the exterior.

Advantages:

Ease of assembly.

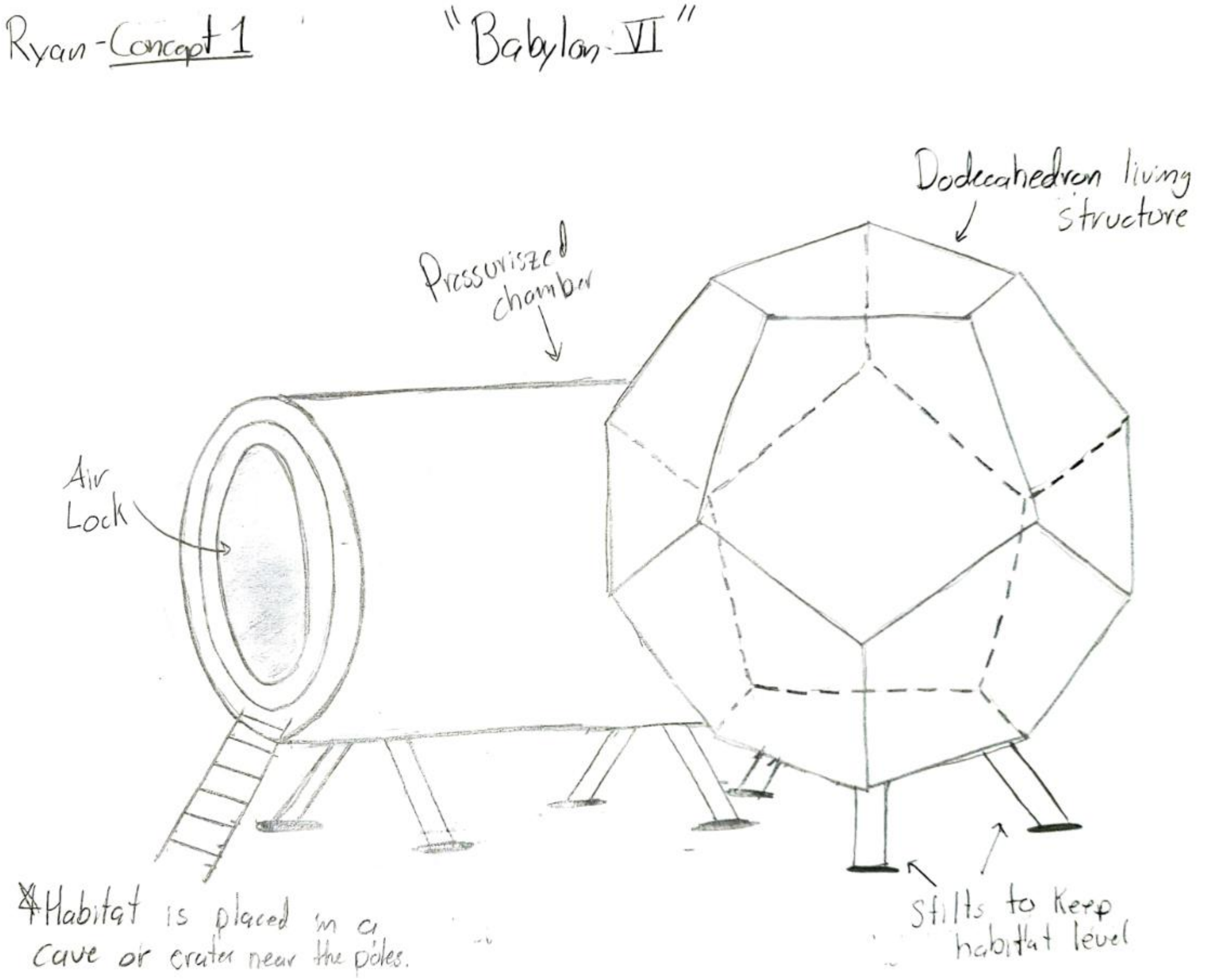
- Expandable design.
- Uses lunar resources – saves cost.
- Better performance during emergency – Crew can move to another module if one malfunctions.

- More room for a full botanical air filtration system.

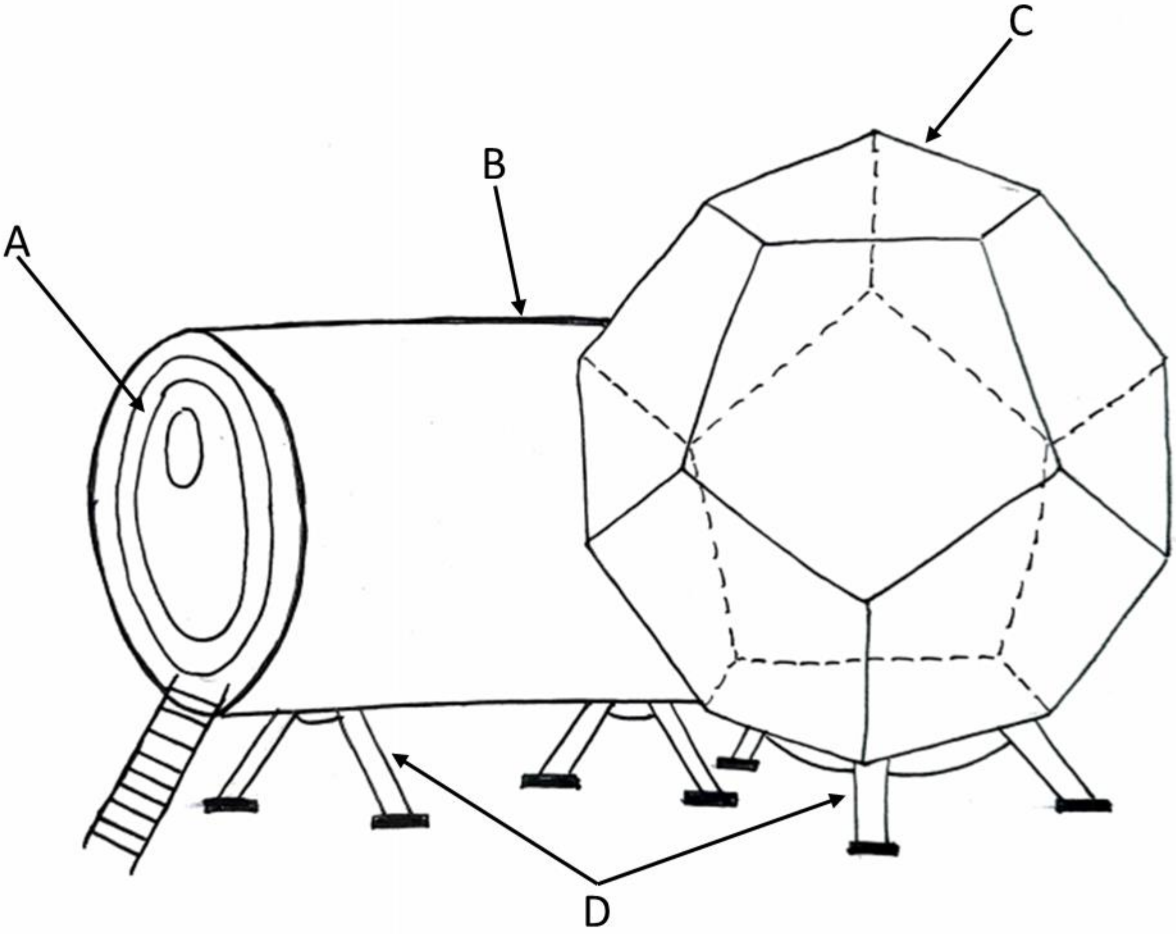
Disadvantages

- Uses more resources to cover the surface area
- Requires many more systems for additional rooms.

4.1.7 Full System Design #7:



*Habitat is placed in a cave or crater near the poles.



Legend:

A – Airlock

B – Pressurized cabin

C – Dodecahedron structure

D – Stilts

Description: The structure shown above is a combination of a dodecahedron structure with a cylindrical structure attached for entry. The Dodecahedron structure is designed to save space and add 2 floors of available space. The stilts provide added support for the structure as well as limit the thermal conduction from the ground.

Advantages

- Uses a dodecahedron structure that is structurally strong for transport and internal air pressure.
- Plenty of space for systems and human factors.
- Uses regolith to shield from harmful radiation.
- Ease of assembly
- Minimal potential for air loss due to the structural rigidity.
- Second best space saving design.
- Reusable.

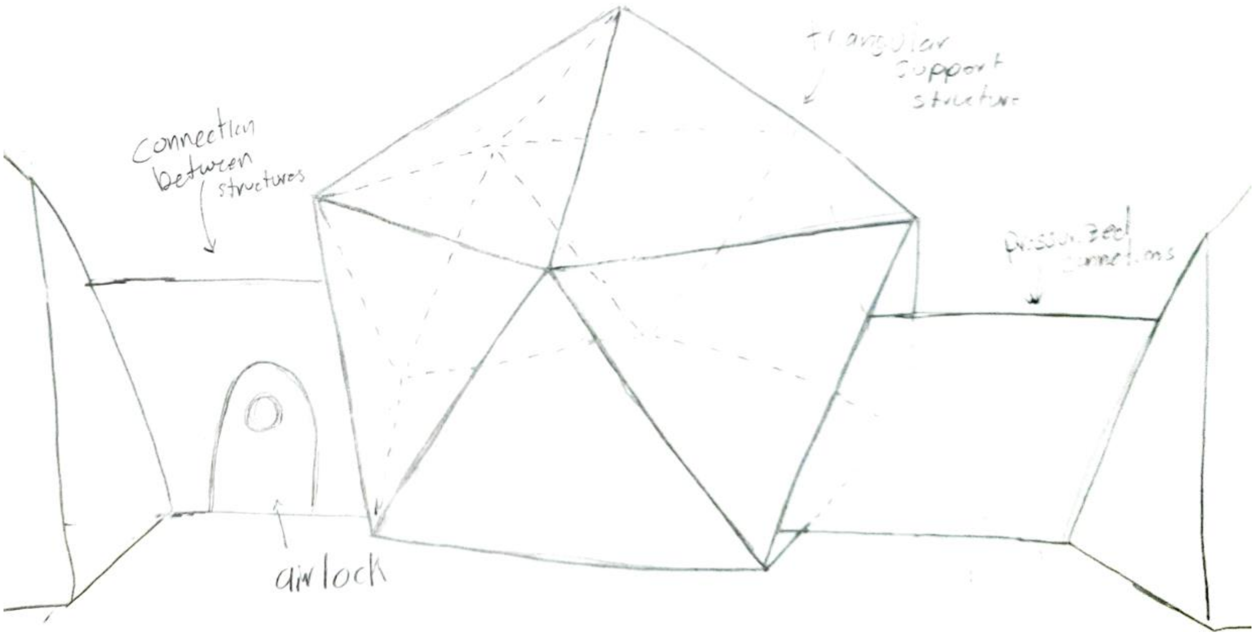
Disadvantages.

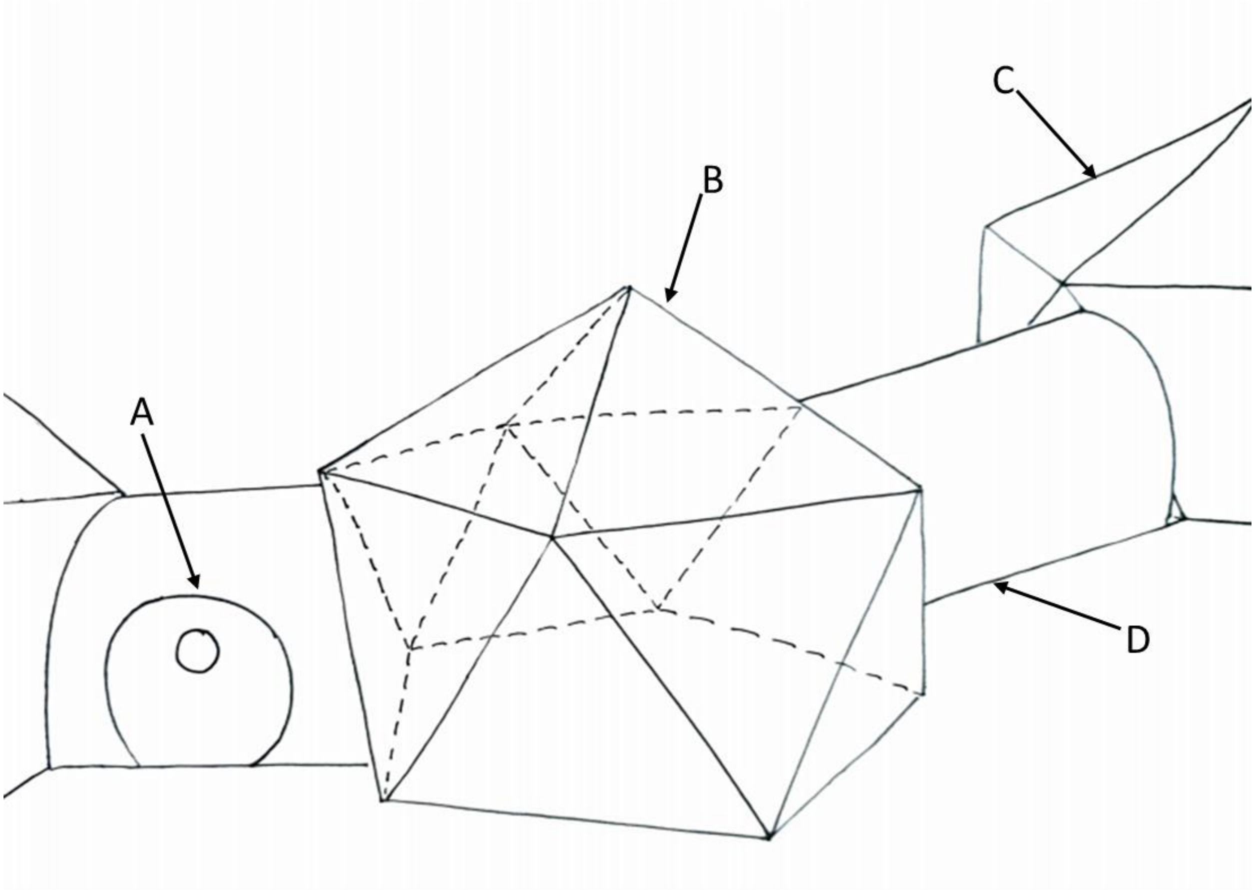
- Needs to be assembled in space; Number of man hours in space increases cost.
- Not a modular design, thus, no room for expansion.

4.1.8 Full System Design #8:

Ryan - Concept 3 "Space Valkyria"

* Each structure is modeled of an Isosahedron and are connected by air tight pathways





Legend:

A – Airlock

B – Icosahedron structure

C – Other structures

D – Pressurized connector

Description: Structure shown above is a Icosahedron structure that has a modular attachment to it. The airlock door is a cylindrical structure aiding for minimal air loss. The modular design adds extra space for additional systems.

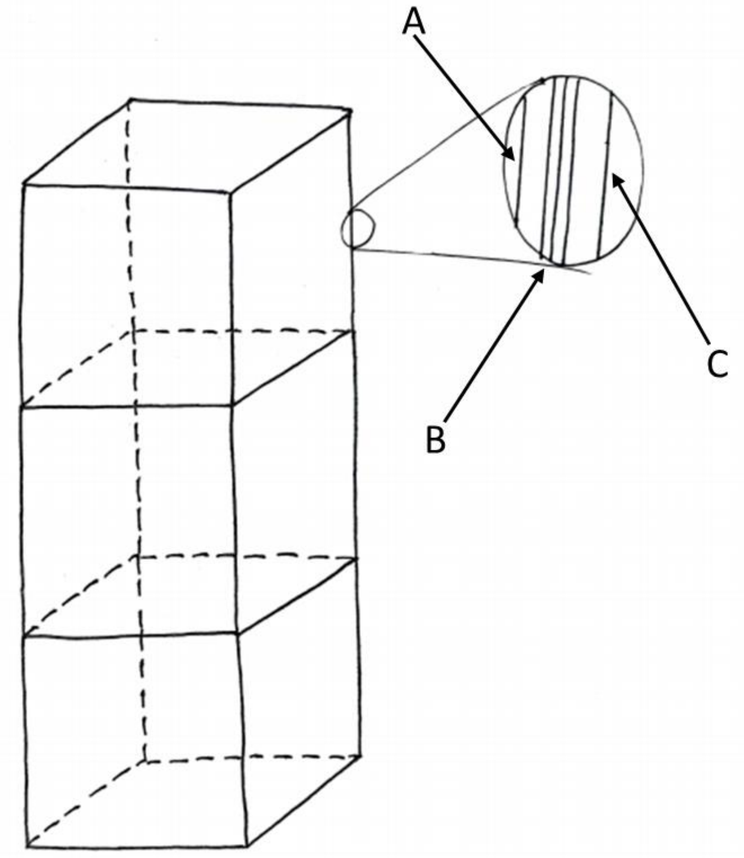
Advantages

- Uses a dodecahedron structure that is structurally strong for transport and internal air pressure.
- Plenty of space for systems and human factors.
- Uses regolith to shield from harmful radiation.
- Minimal potential for air loss due to the structural rigidity.
- Reusable.

Disadvantages.

- Needs to be assembled in space, increasing the number of man hours increasing cost.
- Not a modular design, thus, no room for expansion.
- Lengthy assembly time.
- Increases surface area which increases potential exposure to radiation.

4.1.9 Full System Design #9:



Legend:

A – Inner Aluminum wall

B – Kevlar

C – Outer Aluminum Wall

Description: the above structure is a modular cubical structure that is stackable in space. The structure is made up of Kevlar material.

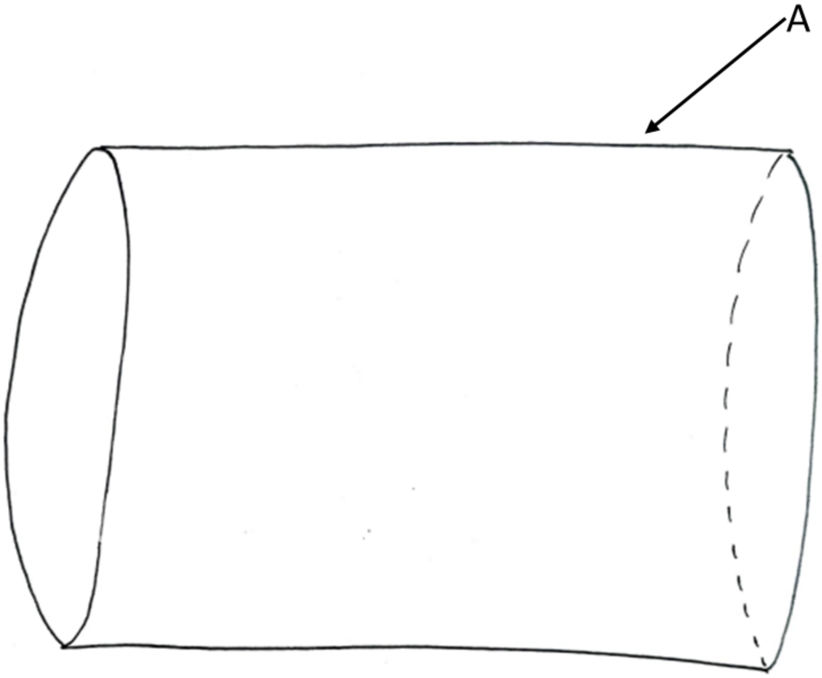
Advantages

- Stackable cubical structure.
- Kevlar is light.
- Easy to assemble on earth and transport it to the lunar surface.
- Easy to assemble on the lunar surface.
- Room for systems.
- The stackable design adds weight on to the structure resisting the air pressure at the bottom modular box.

Disadvantages.

- Not enough protection from solar radiation.
- Kevlar is expensive.
- No sub-systems present.
- Requires stairs to travel up and down.
-

4.1.10 Full System Design #10:



Legend:

A – Regolith covering

Description: The structure above is a cylinder that made out of concrete regolith. Using regolith as a base material, the concrete habitat will be structurally rigid.

Advantages:

- The regolith helps with Radiation Shielding.
- The cylindrical geometry helps spread the internal forces evenly.

Disadvantages

- The habitat is made out of concrete and concrete will require heavy labor.
- Additional materials such as cement and gravel may need to be transported to the lunar surface.
- Although the geometry helps with containing air pressure, the habitat needs constant supervision for air leaks as concrete could be porous on the lunar surface.

- Concrete absorbs heat at a much higher rate from solar radiation even with the addition of regolith.

[Describe in detail a design solution you have considered. Include a list of Pros and Cons.]

[Copy & paste additional headings, as necessary. Be sure to update your Table of Contents.]

4.2 Subsystem Concepts

[Include at least three distinctly different full-system concepts.]

4.2.1 Subsystem #1: Power Generation and Storage

[Please keep subsystems consistent with the functional decomposition and subsystem benchmarking.]

4.2.1.1 Design #1: Small Nuclear Generation: NuScale Power Module

Nuclear power generally takes up vast amounts of space and requires constant supervision by a team of engineers. However, Nuscale is developing a smaller power module for homes and factory environments. The power module is scalable to size in theory. The power module is currently in development and an operational product is due in 2024. If the technology is indeed scalable, it can be small enough to fit into the habitat. The power system also offers constant power supply and can be a suitable alternative to solar power. However, the power module has a high risk of failure as we do not yet know how the module would function on the lunar surface. The module would also produce vast amounts of water wastage.

J. Doyle, B. Haley, B. Galyean, and D. T. Ingersoll, "Highly Available Nuclear Power for Mission-Critical Applications," *Nuclear Technology*, pp. 1–16, Feb. 2020, doi: 10.1080/00295450.2019.1699382.

4.2.1.2 Design #2: Solar Panels

Solar panels utilize solar radiation to generate electrical energy. Spacecrafts typically use the radiation is two ways. First to run the sensors, to heat the habitat and to run the systems necessary for life. The other is for electric propulsion. Since the application here is for lunar habitat, propulsion is not necessary. The main advantage of solar power is that it is a constant power source, light and takes up a large surface area that would provide additional shielding from harmful radiation. Disadvantages include not being able to turn the power off and the heavy batteries necessary for storage.

[Describe in detail a design solution you have considered. Include a list of Pros and Cons.]

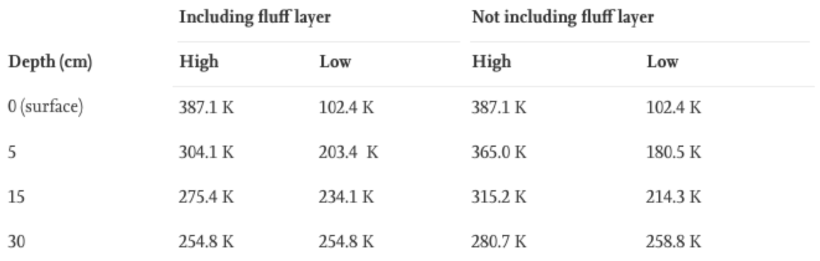
4.2.1.3 Design #3: Hydrogen Fuel Cell

Hydrogen is the most abundant material on the planet. It is a cleaner way to produce power and provides many benefits if utilized right. Hydrogen fuel cell use hydrogen reaction to produce electricity and produce water as a byproduct. It is small enough to be fitted into a habitat and provide a constant supply of power if hydrogen is present. A key disadvantage is that hydrogen and oxygen that is stored for use by the crew would be used for power instead.

4.2.2 Subsystem #2: Insulation Material

4.2.2.1 Design #1: Lunar Regolith

One of the most prominent insulation designs for the lunar habitat is using Regolith. The lunar soil has proven to be a sustainable solution through its core strength to keep the astronauts safe from the harsh conditions of the Moon and solar radiation. During the Apollo 15 and 17 missions, multiple in-depth studies were conducted on Lunar Regolith and it's been determined that the best approach to using the soil as insulation is to create two different layers amongst the insulation, a fluff layer on the outer edge and a more compacted inner insulation. [SG6] The fluff layer consists of a lower thermal conductivity ranging between 0.9×10^{-5}W/cm K at 0K and 3.0×10^{-5} W/cm K at 400K while the higher compaction level maintains a thermal conductivity of 0.93×10^{-4} W/cm K at 0K and 1.94×10^{-4} W/cm K at 400K. [SG6]. Through only 2 cm of fluff, the outer regolith layer reduces the temperature by 25% due to the higher temperature shielding. [SG6] Lunar Regolith has a prominent property of reflecting a portion of the solar radiation back out to space while absorbing a majority, the absorption constant for regolith is .87. When dry casted for 72 hours at 60 degree Celsius, the regolith has proven to sustain a compressive strength of 37.07MPa. [SG6]. Although there are many advantages to regolith, the lunar soil is only sustainable for certain objects; scientific equipment like telescopes for example cannot be covered in regolith.



	Including fluff layer		Not including fluff layer	
Depth (cm)	High	Low	High	Low
0 (surface)	387.1 K	102.4 K	387.1 K	102.4 K
5	304.1 K	203.4 K	365.0 K	180.5 K
15	275.4 K	234.1 K	315.2 K	214.3 K
30	254.8 K	254.8 K	280.7 K	258.8 K

4.2.2.2 Design #2: Multilayer Insulation (MLI)- Mylar

Thermal multilayer insulations are designed to maintain the internal temperature while reducing heat loss. MLI consist of numerous reflecting radiation shields interspaced with a low conductivity thermal spacer. [SG7] The insulation material also includes heat radiation throughout the gaseous medium while heat conduction is maintained within the spacer or contact points through the crinkled MLI exterior surface. The radiation shield of the insulation is the most prominent component of the insulation, Mylar is an extremely inexpensive material option and has been mass produced. Although, the material is extremely vulnerable to extended UV exposure. Thus, this material is more commonly used within the insulation.

4.2.2.3 Design #3: Multilayer Insulation (MLI)- Kapton

This gold-colored plastic is one of the most prominent insulator through its increasing emissivity the thicker it gets. Although Kapton (1.42 g/cm^2) is slightly heavier than Mylar (450g/m^2), the material is still more rugged and temperature resistant. Kapton has a temperature range of -276 degrees C to 400 degrees C. [SG8] Although tested to be very effective, the ISS solar array wing, aluminized in Kapton, has also degraded through undercutting erosion.

4.2.3 Subsystem #3: Environmental Control

4.2.3.1 Design #1: ISS – Water Recovery System (WRS)

The Water recovery system (WRS) on the ISS is a procedure to reclaim wastewater, cabin humidity condensate and extra vehicular activity (EVA) wastes. The system initiates with a water processor that separates free gas and solid materials such as lint, hairs, etc. then proceeds to a series of multifractional beds that extend the purification procedure of the water. [SG9] A high temperature catalytic reactor assembly removes any remaining microorganisms and organic contaminants. Typical contaminants increase the increases the conductivity of water; thus, conductivity sensors test the purity of the water. If the water does not pass the standard for health and safety of the crewmembers, the process is conducted again, then stored in a storage tank ready for use by the crewmembers. Through this process, the delivery of drinkable water sent from Earth to the ISS to support six crew members is reduced by 15,000 pounds per year. Some of the main disadvantages for this design is reclaiming above 90% of the human waste through the filtration recovery system. The reliability of this design is also at risk while having difficulty to expand.

4.2.3.2 Design #2: ISS- Oxygen Generation System (OGS)

Throughout the daily operations on the ISS, breathable oxygen is lost due to the habilitation, experimental use, airlock depressurization, module leakage, and carbon dioxide ventilation. The oxygen generation system reinstalls the lost oxygen mainly through its cell stack which electrolyzes the water provided by the WRS, yielding hydrogen and oxygen as its byproducts. [SG10] The oxygen generation system is designed to operate at cycle or continuously, providing a maximum of 20 pounds of breathable oxygen every day during continuous usage or at a normal rate of 12 pounds of breathable oxygen during cyclic usage. [SG10] The following figure provides a visual representation of the flow chart within the ISS, incorporating the WRS and OGS. Some of the challenges engineers face with this method is providing the high pressure and high purity air that would best fit the astronauts while sustaining a durable design.

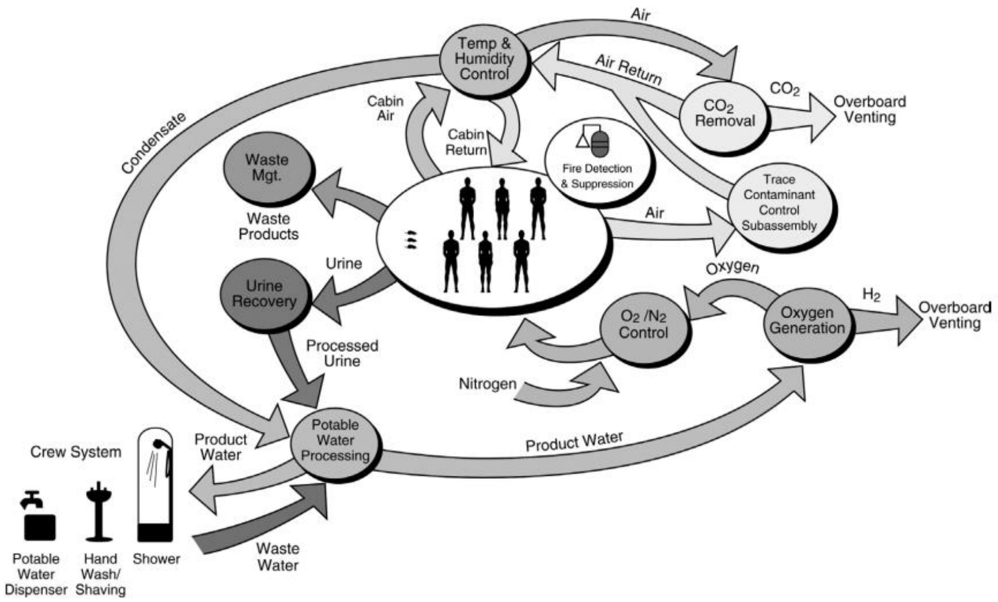


Figure XX: Regenerative Environmental Control Within ISS

4.2.3.3 Design #3: Spacecraft Atmospheric Monitor (SAM)

The spacecraft atmospheric monitor (SAM) is a mobile measurement tool used in outer space to effectively test atmospheric properties such as pressure, radiation, etc. SAM is a compacted gas chromatograph mass spectrum designed to map out organic compounds major factors of the spacecraft's atmosphere. This monitor weighs approximately 9.5 kg and has the potential to make a measure constitute analysis every 2 seconds which is a drastic decrease in time compared to its predecessor which took 3-5 hours while also decreasing in volume to 10 L which is also a 1/6 decrease. [SG11] SAM will intake common air constituents such as CH4, CO2, H2O, O2, and N2. [SG11] This design has the stability to currently run on full potential for a maximum of two years, then requiring replacements of certain components making it not very sustainably practical.

5 DESIGNS SELECTED – Keith (section) Ryan (CAD MODEL)

In this section, the Pugh matrix and the Decision matrix are provided first. Then the selected final concept is also provided with a rough cad model and the rational for the concept selection.

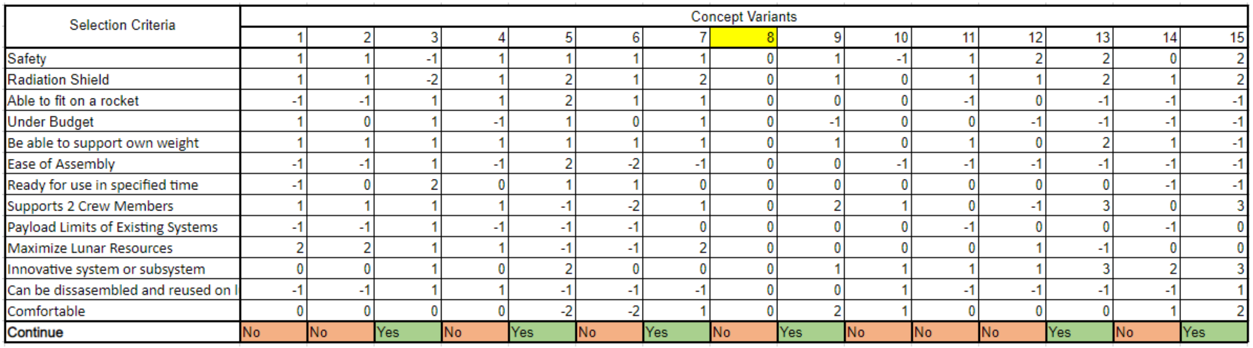
5.1 Technical Selection Criteria

Making the right decision on a concept is essential to move forward on a project. The best way to evaluate the pros and cons of a design is achieved using a Pugh matrix and Weighted Decision Matrix.

The first part of the concept selection is the Pugh Chart to narrow down concept variants for a weighted analysis. The selection criteria were taken from the list of engineering requirements in the order of importance. Then we conducted the Pugh Chart from using the concept variant 15 as the datum and assigned a score to each concept variant. The concept 8 was used as the datum to evaluate the remaining concepts. The 6 best concepts were then selected with the highest net score out of all the concept variants for the next stage of evaluation. For the first selection we choose the CV's with the highest net score out of all the CV's.

As shown below in Table Xa, the concept variants were narrowed down from fifteen to the six top concept variants. The selected concepts are highlighted in green. A full-size table is provided in the Appendix A.

Table Xa. Pugh Chart



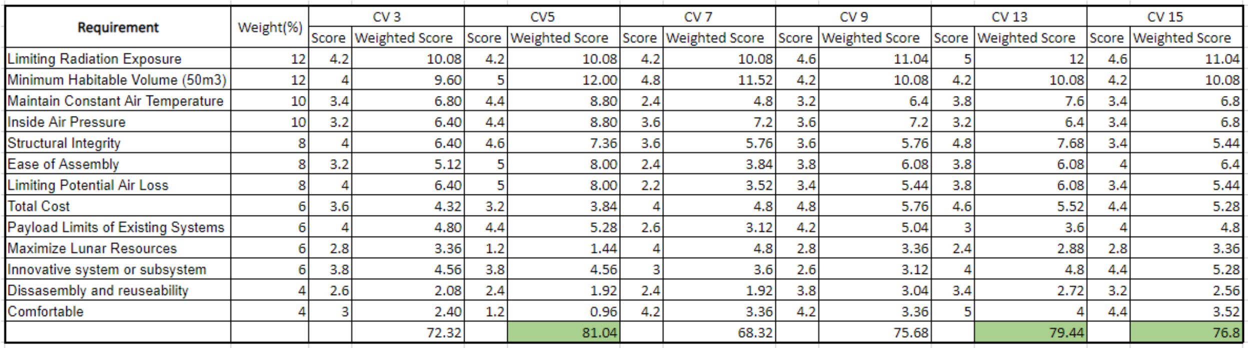
Selection Criteria	Concept Variants														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Safety	1	1	-1	1	1	1	1	0	1	-1	1	2	2	0	2
Radiation Shield	1	1	-2	1	2	1	2	0	1	0	1	1	2	1	2
Able to fit on a rocket	-1	-1	1	1	2	1	1	0	0	0	-1	0	-1	-1	-1
Under Budget	1	0	1	-1	1	0	1	0	-1	0	0	-1	-1	-1	-1
Be able to support own weight	1	1	1	1	1	1	1	0	1	0	1	0	2	1	-1
Ease of Assembly	-1	-1	1	-1	2	-2	-1	0	0	-1	-1	-1	-1	-1	-1
Ready for use in specified time	-1	0	2	0	1	1	0	0	0	0	0	0	0	-1	-1
Supports 2 Crew Members	1	1	1	1	-1	-2	1	0	2	1	0	-1	3	0	3
Payload Limits of Existing Systems	-1	-1	1	-1	-1	-1	0	0	0	0	-1	0	0	-1	0
Maximize Lunar Resources	2	2	1	1	-1	-1	2	0	0	0	0	1	-1	0	0
Innovative system or subsystem	0	0	1	0	2	0	0	0	1	1	1	1	3	2	3
Can be dissasembled and reused on l	-1	-1	1	1	-1	-1	-1	0	0	1	-1	-1	-1	-1	1
Comfortable	0	0	0	0	-2	-2	1	0	2	1	0	0	0	1	2
Continue	No	No	Yes	No	Yes	No	Yes	No	Yes	No	No	No	Yes	No	Yes

The next stage of selection is the weighted Decision Matrix. The top six concept variants, as chosen by the Pugh Chart, are then evaluated for each criterion. There are a total of fourteen weighted requirements and the individual criteria were weighted according to the importance for the scope of the project and the concept variants are evaluated according to that weighted criteria as shown in Table Xb. The criteria for the decision differ from those used for the Pugh Chart. In the Pugh matrix, the team looked at how the concepts differ from one another. As a result, the team chose the general customer requirements to use in the comparison. In the Decision Matrix, the criteria was selected based upon the engineering requirements and modified to compare how each design would satisfy the criteria the best. The weighted Decision Matrix is presented in Table Xc.

Table Xb: Weighted Requirements

Requirement	Weight(%)
Limiting Radiation Exposure	12
Minimum Habitable Volume (50m3)	12
Maintain Constant Air Temperature	10
Inside Air Pressure	10
Structural Integrity	8
Ease of Assembly	8
Limiting Potential Air Loss	8
Total Cost	6
Payload Limits of Existing Systems	6
Maximize Lunar Resources	6
Innovative system or subsystem	6
Disassembly and reusability	4
Comfortable	4

Table Xc : Weighted Decision Matrix



Requirement	Weight(%)	CV 3		CV5		CV 7		CV 9		CV 13		CV 15	
		Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Limiting Radiation Exposure	12	4.2	10.08	4.2	10.08	4.2	10.08	4.6	11.04	5	12	4.6	11.04
Minimum Habitable Volume (50m3)	12	4	9.60	5	12.00	4.8	11.52	4.2	10.08	4.2	10.08	4.2	10.08
Maintain Constant Air Temperature	10	3.4	6.80	4.4	8.80	2.4	4.8	3.2	6.4	3.8	7.6	3.4	6.8
Inside Air Pressure	10	3.2	6.40	4.4	8.80	3.6	7.2	3.6	7.2	3.2	6.4	3.4	6.8
Structural Integrity	8	4	6.40	4.6	7.36	3.6	5.76	3.6	5.76	4.8	7.68	3.4	5.44
Ease of Assembly	8	3.2	5.12	5	8.00	2.4	3.84	3.8	6.08	3.8	6.08	4	6.4
Limiting Potential Air Loss	8	4	6.40	5	8.00	2.2	3.52	3.4	5.44	3.8	6.08	3.4	5.44
Total Cost	6	3.6	4.32	3.2	3.84	4	4.8	4.8	5.76	4.6	5.52	4.4	5.28
Payload Limits of Existing Systems	6	4	4.80	4.4	5.28	2.6	3.12	4.2	5.04	3	3.6	4	4.8
Maximize Lunar Resources	6	2.8	3.36	1.2	1.44	4	4.8	2.8	3.36	2.4	2.88	2.8	3.36
Innovative system or subsystem	6	3.8	4.56	3.8	4.56	3	3.6	2.6	3.12	4	4.8	4.4	5.28
Dissasembly and reuseability	4	2.6	2.08	2.4	1.92	2.4	1.92	3.8	3.04	3.4	2.72	3.2	2.56
Comfortable	4	3	2.40	1.2	0.96	4.2	3.36	4.2	3.36	5	4	4.4	3.52
			72.32		81.04		68.32		75.68		79.44		76.8

As shown in the Tables above, the selected concepts are the concept variant 5 (CV5) and concept variant 13 (CV13). Initially, CV5 was favorited for the overall versatility of the design. However, after analyzing CV13, it was realized that some of its advantages could be combined with CV5 to make for a complete well-rounded design. A key advantage of CV13, compared to that of the other concepts, is the ideal use of space and a sturdy structural integrity achieved by using a dodecahedron support structure. Furthermore, the potential ease of combining multiple structures to form a modular design could not be overlooked. These two advantages prompted us to combine CV5 and CV13 to form the final selected design. A detailed prelimiary Computer Automated Design (CAD) model can be found in Figures XA to XD and a description of the design are provided below.

5.2 Rationale for Design Selection

Final Design Selected: Modular Space Capsule

Design Description: The design shown below is named the Modular Space Capsule. As shown below the on the outside is a big cylinder with a window section at the end. The design is generated from CV5 and CV13 and is designed for versatility with assembly. The structure is manufactured on earth and initially assembled on earth for testing. After the testing process, the structure could be taken apart and shipped to space in rockets in modular sections for assembly in space, or on the moon. Another option is to place the structure in a rocket fully assembled and transport it to the lunar site of interest. Currently, all the sub-systems necessary to support 2 individuals exist inside the structure. In addition, the capsule is designed to be a expandable via the airlock chamber where it could use a coupling chamber to connect to extra modules if necessary.

A list of the top four human factors as described by the research as described in section 3.1.2 is presented below:

1. Net Habitable Volume

   The generated concept structure must adhere to the minimum habitable volume (NHV) to accommodate for a safe livable area. According to human factors research, our net habitable volume for 2 individuals for 30 days is 55 +/- 5 cubic meters. This net volume not including the air lock chamber is 3m x 7.5m x 2.5m (width x length x height). This results in a volume of 56.25 cubic meters. The structure is divided in three quadrants based on human factors research. As shown in the figure below, the first quadrant is separated for necessary subsystems. The second quadrant is separated for the workspace and the last quadrant is separated for the living quarters.

2. Workspace

   The workspace area is in the second quadrant of the final concept design. The workspace accounts for laboratory equipment and storage of materials collected on the lunar surface.

3. Main Systems Area

   The subsystem area contains the air management system, water purification system, power storage, temperature control system and pressure management system. The waste management system is planned to be placed in the hygiene area.

4. Personal Living Quarter

   The personal living quarter consists of the capsule bunk bed area, the food preparation area, and a hygiene area. The waste management system and water purification systems are located in this quarter.

The rational justifying the selection of the final concept for the design selection was based on the main criteria as described above in the criteria ranking. The reasons why the selected design sufficiently achieves most of the criteria compared to that of the other designs is discussed below:

Regolith is an ideal insulation material that is abundantly present on the lunar surface as it is efficient at shielding the structure from harmful radiation. As a result, this material has been used in multiple designs in varying capacity. The chosen method of application here is to pack it in bags and place it around the structure and then spray the regolith into the remaining crevices. Regolith also compresses down on the structure helping negate the internal air pressure. Furthermore, regolith will not be added to the dry mass limit of the structure allowing for additional overall cost savings as this material is readily available on the lunar surface and does not need to be transported on a rocket from earth unlike the structure. The structure also uses ultra-lightweight mylar for emergency shielding if the regolith is blown away due to unexpected events.

The structure meets minimum habitable volume requirement and allows room for expansion if needed. The design also provides adequate space for all the systems to function allowing for an entire section of the floor to be used for air and water filtration systems. As seen in the cross section of the generated.

The structure is small enough to fit inside a rocket and is manufactured on earth. This means it could be assembled on earth to be transported to the lunar surface as a whole or it could be assembled on the lunar surface. The structure also uses the space grade circular tubing truss attachment that is capable of one-handed assembly. This shortens the assembly process.

The geometry of the structure is made from a honeycomb structure which helps save the most space while also being structurally rigid. The structure also distributes the internal air pressure evenly throughout the structure minimizing air loss. In addition, the honeycomb structure also handles the massive vibrations from the rocket’s acceleration better than any other structure.

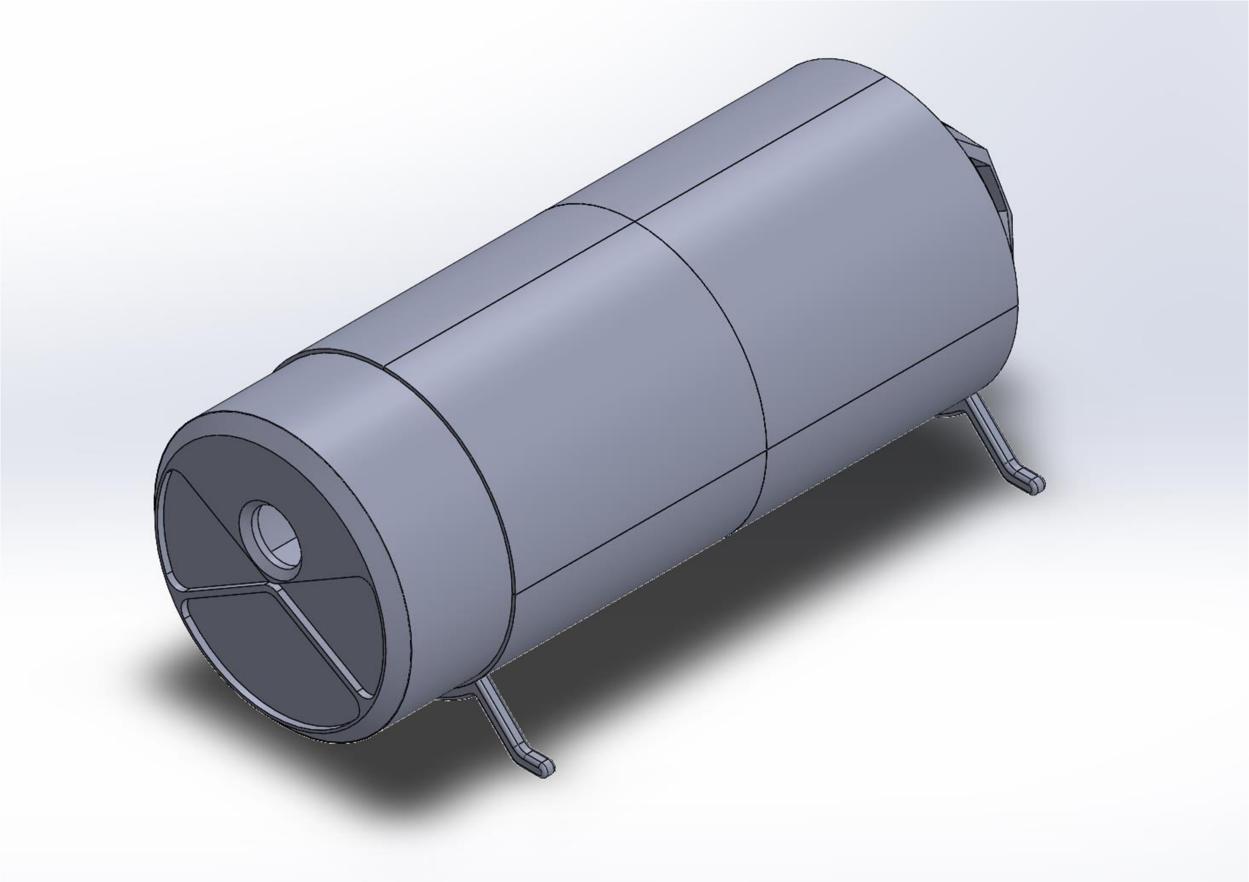


Figure XA. Isometric view of the front of the preliminary CAD model generated in SOLIDWORKS.

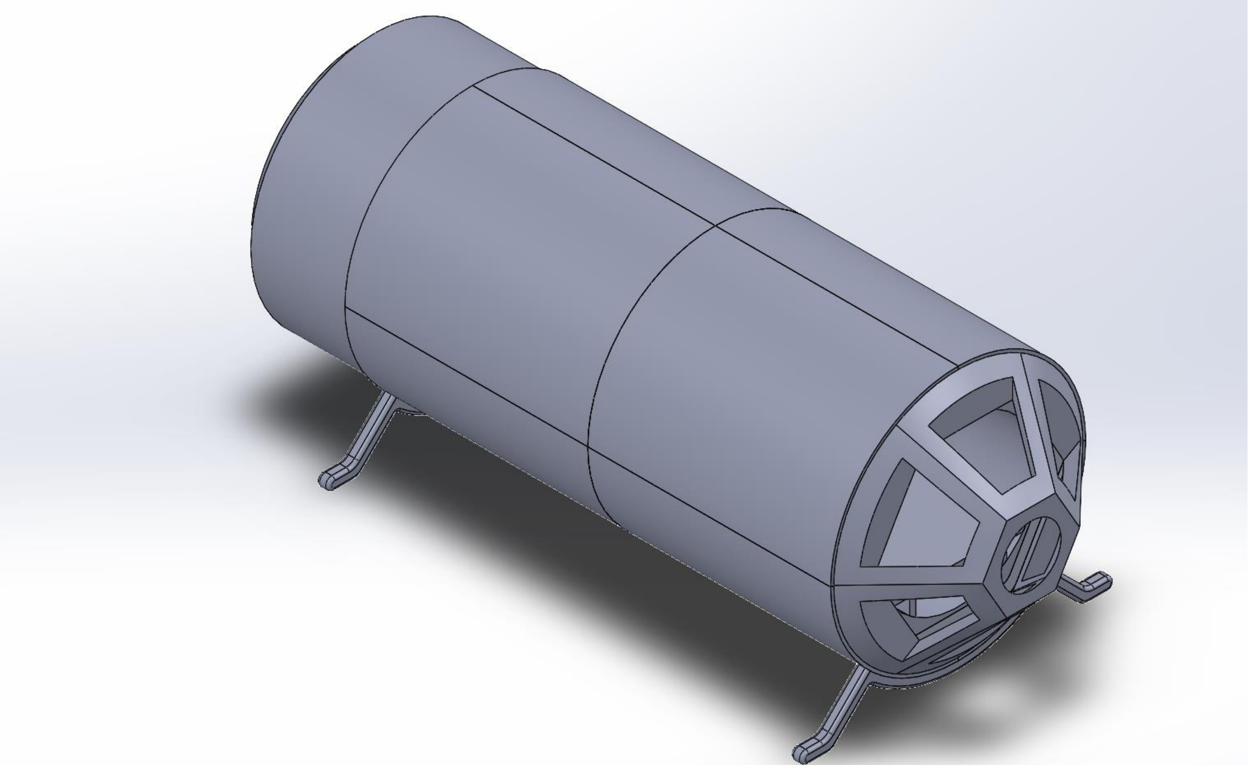


Figure XB. Isometric view of the rear of the preliminary CAD model generated in SOLIDWORKS.

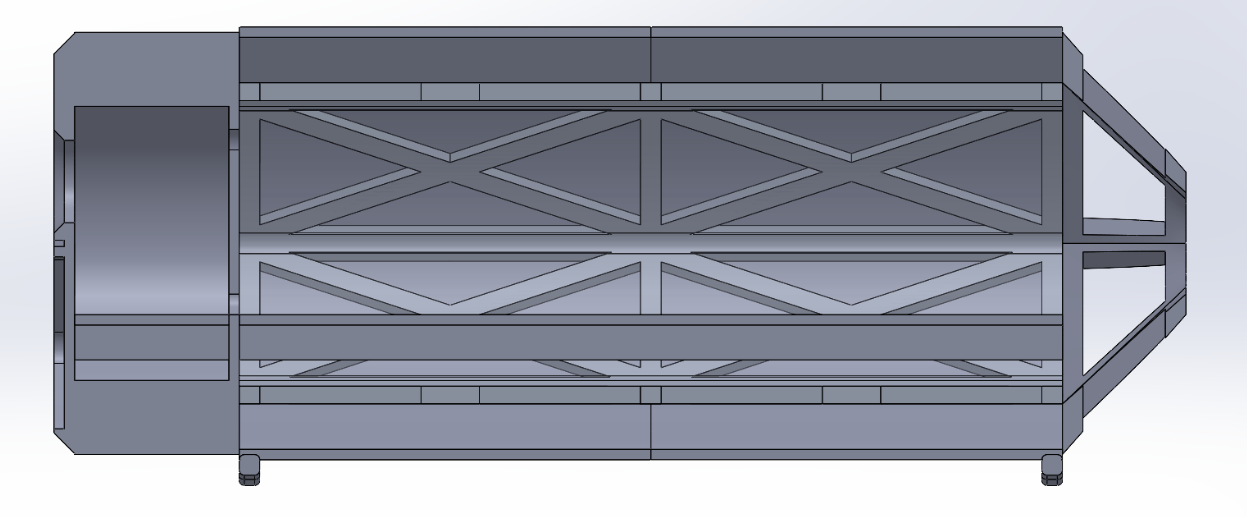


Figure XC. Cross-section of the preliminary CAD model generated in SOLIDWORKS.

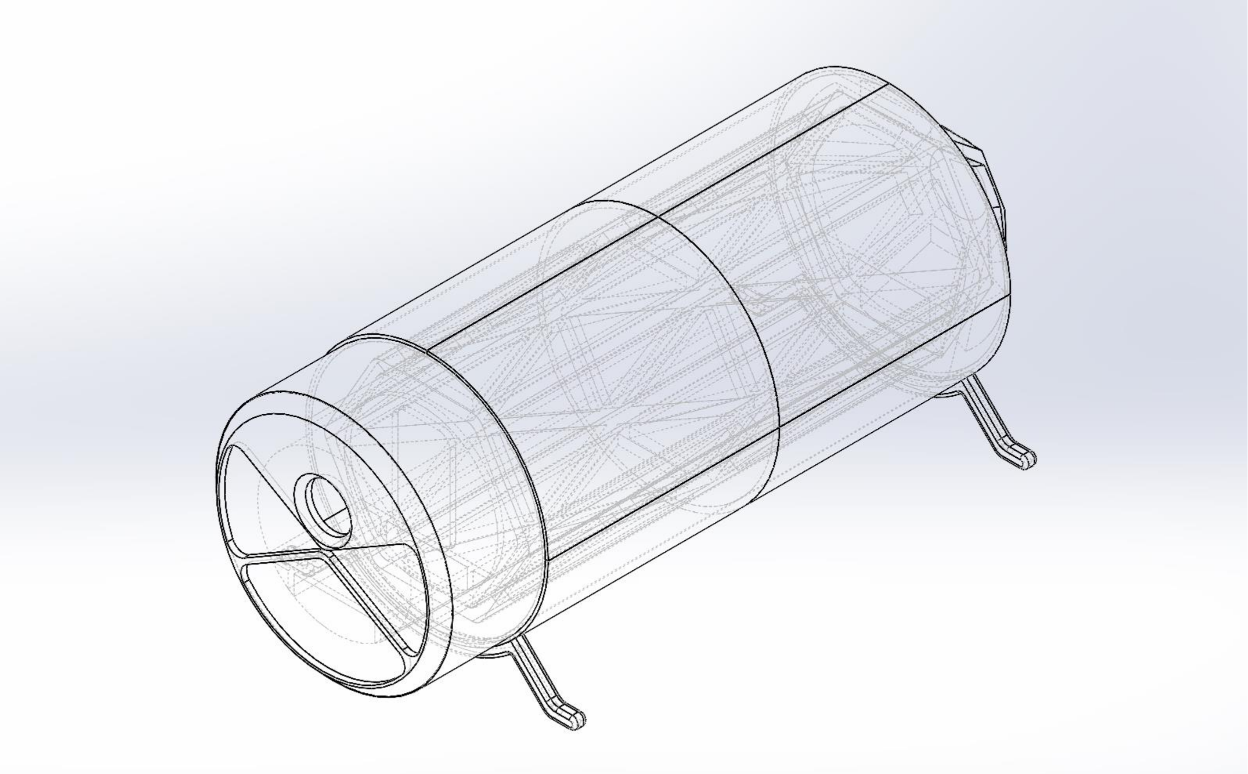


Figure X. Skeleton (hidden lines shown) isometric view of the front of the preliminary CAD model generated in SOLIDWORKS

6 REFERENCES Everyone

[Include here all references cited, following the reference style described in the syllabus. There should only be one Reference list in this report, so all individual section or subsection reference lists must be compiled here with the main report references. If you wish to include a bibliography, which lists not only references cited but other relevant literature, include it as an Appendix.]

[Keith1]
Zhao, Bing, Hu, Jianhui, Chen, Wujun, Chen, Jianwen, Qiu, Zhenyu, Zhou, Jinyu, and Gao, Chengjun. "An Automatic System for Pressure Control and Load Simulation of Inflatable Membrane Structure." Automation in Construction 90 (2018): 58-66. Web.

[Keith2]
Li, Weijie, Zeng, Fuming, Chen, Geng, Deng, Yuanbin, Liu, Guoqing, Zhang, Xiaoyu, Bezold, Alexander, and Broeckmann, Christoph. "Shakedown Analysis for Structural Design Applied to a Manned Airtight Module." The International Journal of Pressure Vessels and Piping 162 (2018): 11-18. Web.

[Keith3]
Advances in Space Science and Technology. Volume 3. United Kingdom ed. 1961. Advances in Space Science and Technology. Web
[Keith4]
[1]
V. Disher, T. Kobrick, and R. Kring, “Human Factors for Small Net Habitable Volume: The Case for a Close-Quarter Space Habitat Analog,” 2017. [Online]. Available: https://commons.erau.edu/cgi/viewcontent.cgi?article=1591&context=publication.

[Keith5]
[1]
“Self-deployable Habitat for Extreme Environments | SHEE, Self-Deployable Habitat for Extreme Environments,” 2015. Accessed: Mar. 06, 2021. [Online]. Available: https://www.shee.eu/pdf/SHEE_Summary.pdf.

[Ryan 1]
D. A. de Rooij, Space Materials Database. Materials data for space applications. [Online]. Available: https://www.spacematdb.com/. [Accessed: 01-Feb-2021]

[Ryan 2]
G. Chapline, "Materials and Manufacturing", Nasa.gov, 2021. [Online]. Available: https://www.nasa.gov/centers/johnson/pdf/584729main_Wings-ch4c-pgs200-225.pdf. [Accessed: 01- Feb- 2021].

[Ryan 3]

A. P. Mouritz, Introduction into Aerospace Materials. Reston, VA: Woodhead Publishing , 2012. [Accessed: 01- Feb- 2021

[Ryan 4]
M. P. Groover, Fundamentals of Modern Manufacturing: Material, Processes and Systems, 7th ed, Willey's

[Ryan 5]
ASME, Dimensioning and Tolerancing: ASME Y14.5-2004, American Society of Mechanical Engineers, 2004

[Jelani 1] "Building a lunar base with 3D printing," ESA, 31-Jan-2013. [Online]. Available: http://www.esa.int/Enabling_Support/Space_Engineering_Technology/Building_a_lunar_base_with_3D_printing. [Accessed: 06-Mar-2021].

[Jelani 2] National Research Council, "Read 'Protecting the Space Station from Meteoroids and Orbital Debris' at NAP.edu," National Academies Press: OpenBook. [Online]. Available: https://www.nap.edu/read/5532/chapter/6. [Accessed: 06-Mar-2021].

[Jelani 3] N. Scharping, in *What Can Stop a Speeding Bullet? A Whipple Shield, Of Course*, .

[Jelani 4] https://hvit.jsc.nasa.gov/shield-development/
"ARES HyperVelocity Impact Technology," NASA. [Online]. Available: https://hvit.jsc.nasa.gov/shield-development/. [Accessed: 05-Mar-2021].

[Jelani 5]

https://multimedia.3m.com/mws/media/1327055O/3m-nextel-technical-reference-guide.pdf
"3M™ Nextel™ Ceramic Fibers and Textiles Technical Reference Guide," 01-Nov-2018. [Online]. Available: https://multimedia.3m.com/mws/media/1327055O/3m-nextel-technical-reference-guide.pdf. [Accessed: 05-Mar-2021].

[Jelani 6] "The International Space Station (ISS) flight systems." [Online]. Available: https://www.nasa.gov/pdf/167129main_Systems.pdf. [Accessed: 05-Mar-2021].

[Jelani 7] E. Samuel, "Space station radiation shields 'disappointing'," New Scientist, 23-Oct-2002. [Online]. Available: https://www.newscientist.com/article/dn2956-space-station-radiation-shields-disappointing/. [Accessed: 06-Mar-2021].

[Jelani 8] https://letstalkscience.ca/educational-resources/backgrounders/temperature-on-earth-and-on-iss Let's Talk Science and S. 23, "Temperature on Earth and on the ISS," Let's Talk Science, 23-Sep-2019. [Online]. Available: https://letstalkscience.ca/educational-resources/backgrounders/temperature-on-earth-and-on-iss. [Accessed: 06-Mar-2021].

[Jelani 9] “About the Spacecraft,” About the Spacecraft | National Air and Space Museum. [Online]. Available: https://airandspace.si.edu/exhibitions/apollo-to-the-moon/online/apollo-11/about-the-spacecraft.cfm. [Accessed: 06-Mar-2021].

[Jelani 10] D. R. Williams, “Apollo 11 Lunar Module / EASEP,” NASA Space Science Data Coordinated Archive. [Online]. Available: https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1969-059C#:~:text=The%20lunar%20module%20was%20a,held%202376%20kg%20of%20propellan. [Accessed: 05-Mar-2021].
t.

[Jelani 11] D. R. Williams, “Apollo 12 Lunar Module / ALSEP,” Space Science Data Coordinated Archive. [Online]. Available: https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1969-099C. [Accessed: 05-Mar-2021].

[Jelani 12] “Read ‘Ceramic Fibers and Coatings: Advanced Materials for the Twenty-First Century’ at NAP.edu,” National Academies Press: OpenBook. [Online]. Available: https://www.nap.edu/read/6042/chapter/9#79. [Accessed: 06-Mar-2021].

[Jelani 13] “Space Radiation.” [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/space_radiation_ebook.pdf . [Accessed: 05-Mar-2021].

[Jelani 14] Shulman and Ginell, “NUCLEAR AND SPACE RADIATION EFFECTS ON MATERIALS .” [Online]. Available: https://www.nrc.gov/docs/ML1533/ML15334A202.pdf. [Accessed: 05-Mar-2021].

[Jelani 15] https://www.space.com/moon-radiation-dose-for-astronauts-measured#:~:text=Astronauts%20hopping%20about%20on%20the,surface%2C%20study%20team%20members%20said.
M. Wall, “We now know exactly how much radiation astronauts will face on the moon,” Space.com, 28-Sep-2020. [Online]. Available: https://www.space.com/moon-radiation-dose-for-astronauts-measured#:~:text=Astronauts%20hopping%20about%20on%20the,surface%2C%20study%20team%20members%20said. [Accessed: 06-Mar-2021].

[Jelani 16]
https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/RG020i004p00761#:~:text=The%20chemical%20composition%20of%20the,FeO%2C%20MnO%2C%20and%20Sc.

Pipike, Simon, and Paul, “The lunar regolith: Chemistry, mineralogy, and petrology,” Advancing Earth and Space Science, 14-Jun-2014. [Online]. Available: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/RG020i004p00761#:~:text=The%20chemical%20composition%20of%20the,FeO%2C%20MnO%2C%20and%20Sc. [Accessed: 05-Mar-2021].

[Jelani 17] J. Miller, L. A. Taylor, M. DiGiuseppe, L. H. Heilbronn, G. Sanders , and C. J. Zeitlin, “RADIATION SHIELDING PROPERTIES OF LUNAR REGOLITH AND REGOLITH SIMULANT. ,” NLSI Lunar Science Conference, 2008. [Online]. Available: http://lasp.colorado.edu/~horanyi/nlsi/AMES_2008/NLSC2008_abstracts/numbered%20abstracts/2028.pdf. [Accessed: 05-Mar-2021].

[Jelani 18] Person, *Radiation Shielding Materials - A Guide*. [Online]. Available: https://www.thomasnet.com/articles/plant-facility-equipment/radiation-shielding-materials/. [Accessed: 06-Mar-2021].

[Jelani 19] S. Kodaira, R. V. Tolochek, I. Ambrozova, H. Kawashima, N. Yasuda, M. Kurano, H. Kitamura, Y. Uchihori, I. Kobayashi, H. Hakamada, A. Suzuki, I. S. Kartsev, E. N. Yarmanova, I. V. Nikolaev, and V. A. Shurshakov, “Verification of shielding effect by the water-filled materials for space radiation in the International Space Station using passive dosimeters,” Advances in Space Research, 24-Oct-2013. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0273117713006522. [Accessed: 06-Mar-2021].

[Jelani 20] Polyimide. [Online]. Available: http://www.mit.edu/~6.777/matprops/polyimide.htm. [Accessed: 06-Mar-2021].

[Jelani 21] D. J. Benford, T. J. Powers , and S. H. Mosley, “Cryogenics,” Thermal conductivity of Kapton tape. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0011227598001258#:~:text=The%. [Accessed: 05-Mar-2021].

[Jelani 22] “Active Thermal Control System (ATCS) Overview.” [Online]. Available: https://www.nasa.gov/pdf/473486main_iss_atcs_overview.pdf. [Accessed: 05-Mar-2021].

[SG1]

H. Benaroya, “Lunar habitats: A brief overview of issues and concepts,” *REACH*, 12-Aug-2018. [Online]. Available:

https://www.sciencedirect.com/science/article/pii/S2352309318300014. [Accessed: 27-Mar-2021].

[SG2]

Akin, David L. “A Parametric Comparison of Microgravity and Macrogravity Habitat Design Elements” [Online]. Available: https://pdfs.semanticscholar.org/c408/a494c667c842e278cc05ad1fd442ca95ba20.pdf [Accessed: 28-Feb-2021].

[SG3]

Lane, Helen. “Astronaut Health and Performance” 08-Jun-2015. [Online]. Available: https://www.nasa.gov/centers/johnson/pdf/584739main_Wings-ch5d-pgs370-407.pdf

C. Montes, K. Broussard, M. Gongre, N. Simicevic, J. Mejia, J. Tham, E. Allouche, and G. Davis, “Evaluation of lunar regolith geopolymer binder as a radioactive shielding material for space exploration applications,” *Advances in Space Research*, 08-Jun-2015. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0273117715004019. [Accessed: 27-Feb-2021].

[SG4]

Google Search. [Online]. Available: https://www.google.com/search?sxsrf=ALeKk02QRAhZyE9Wq73THCylyO8GhZO9GA%3A1615002040560&q=4.%09Emergencies%2Bin%2BSpace%2BUpon%2Bentering%2Bouter%2Bspace%2C%2Bdue%2Bto%2Bthe%2Bmicrogravity%2Bthe%2Bhuman%2Bbody%2Bis%2Bsurrounded%2Bby%2C%2Ba%2Bcephalad%2Bshift%2Band%2Bequilibration%2Bof%2Bintravascular%2Bfluid&spell=1&sa=X&ved=2ahUKEwjMkMG335rvAhWUHTQIHaE8DhIQBSgAegQIERAw&biw=828&bih=746. [Accessed: 27-Mar-2021].

SG[5]

C.-S. Kang, “Multilayer Insulation for Spacecraft Applications,” *COSPAR Colloquia Series*, 02-Sep-2007. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0964274999800237. [Accessed: 28-Feb-2021].

[SG6]

R. B. Malla and K. M. Brown, “Determination of temperature variation on lunar surface and subsurface for habitat analysis and design,” *Acta Astronautica*, 04-Nov-2014. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0094576514004160. [Accessed: 27-Feb-2021].

[SG7]

B. Dunbar, “Human Needs: Sustaining Life During Exploration,” *NASA*. [Online]. Available: https://www.nasa.gov/vision/earth/everydaylife/jamestown-needs-fs.html. [Accessed: 27-Feb-2021].

[SG8]

“International Space Station Environmental Control and Life Support System,” *NASA*, May-2008. [Online]. Available: https://www.nasa.gov/centers/marshall/pdf/104840main_eclss.pdf. [Accessed: 02-Mar-2021].

[SG9]

S. Madzunkov, S. B. Bae, R. W., J. Gill, R. Schaefer, E. Neidholdt, M. L. Homer, D. Nikolić, R. D. Kidd, and M. Darrach, “Progress Report on the Spacecraft Atmosphere Monitor,” *Researchgate.net*, 14-Jul-2016. [Online]. Available: https://www.researchgate.net/profile/Dragan-Nikolic/publication/305427049_ICES2016-284-Pres-ResearchGate/links/578e571f08ae81b4466ec305/ICES2016-284-Pres-ResearchGate.pdf. [Accessed: 02-Mar-2021].

[SG10]

C. Ellis, H. Morrison, and N. Nickel, “15 years of progress on the International Space Station - ,” *The Brock Press*, 03-Nov-2015. [Online]. Available: https://www.brockpress.com/mars-the-space-station/. [Accessed: 25-Feb-2021].

[SG11]

Kriss J. Kennedy, Chair Leslie Alexander, Rob Landis, Diane Linne, Carole Mclemore, Edgardo Santiago-Maldonado. “DRAFT Human Exploration Destination Systems Roadmap” National Aeronautics and Space Administration [Online]. Available: https://www.brockpress.com/mars-the-space-station/. [Accessed: 25-Feb-2021].

7 APPENDICES

[Use Appendices to include lengthy technical details or other content that would otherwise break up the text of the main body of the report. These can contain engineering calculations, engineering drawings, bills of materials, current system analyses, and surveys or questionnaires. Letter the Appendices and provide descriptive titles. For example: Appendix A-House of Quality, Appendix B- Budget Analysis, etc.]

7.1 Appendix A: Descriptive Title

7.2 Appendix B: Descriptive Title