Omond House
Lunar Base Camp

Team Name: The Fighting Mongooses

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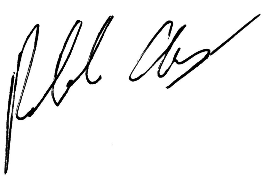
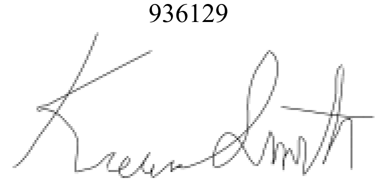
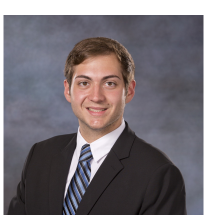
 Pablo Anguiano	1109099 	 Kieran Smith	936129 
 Matthew Sconzo	998788 	 **Faculty Advisor:** Adam Nokes	

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List of Acronyms

AIAA	American Institute of Aeronautics and Astronautics
AMCM	Advance Mission Cost Model
ARED	Advanced Resistive Device
ATHLETE	All-Terrain Hex-Limbed Extra-Terrestrial Explorer
BFO	Blood Forming Organ
C&DH	Command and Data Handling
CAMRAS	CO2 And Moisture Removing Amine Swingbed
CER	Cost Estimating Relationship
CME	Coronal Mass Ejection
COTS	Commercial Off The Shelf
DDT&E	Design Development Test and Evaluation
DSN	Deep Space Network
ECLSS	Environmental Controls and Life Support Systems
EL1	Earth-Moon Lagrange Point
EVA	Extra-Vehicular Activity
GCR	Galactic Cosmic Radiation
IDA	International Docking Adaptor
ISS	International Space Station
LADEE	Lunar Atmosphere and Dust Environment Explorer
LEO	Low Earth Orbit
LLO	Low Lunar Orbit
LLOC	Lunar Lasercomms Operations Center
LLST	Lunar Lasercom Space Terminal
LRO	Lunar Reconnaissance Orbiter
MMOD	Micrometeoroid Orbital Debris
MPV	Mass, Power, Volume
MMSEV	Multi-Mission Space Exploration Vehicle
NASA	National Aeronautics & Space Administration
NEN	Near Earth Network
NRHO	Near Rectilinear Halo Orbit
PCEC	Project Cost Estimating Capability

PMAD	Power Management and Distribution
RFP	Request For Proposal
SPE	Solar Particle Event
TFU	Theoretical First Unit
TLI	Trans Lunar Injection
TOF	Time of Flight
TRL	Technology Readiness Level
ULA	United Launch Alliance
VPCAR	Vapor Phase Catalytic Ammonia Removal

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1. Executive Summary

As the National Aeronautics & Space Administration (NASA) and the entire space industry sets its sights on Mars as the next target for human exploration, revisiting the Moon has recently become a topic of discussion as a staging point for future deep space missions. There is a heavy interest in exploring the lunar surface and utilizing lunar resources. The deployment of a lunar base camp is the first step towards establishing a permanent human presence in space, as it would provide engineers and astronauts with valuable experience in extraterrestrial exploration. The objective of this paper is to deliver a proposal for a lunar base camp design.

Requirements for this base camp were provided by the American Institute of Aeronautics and Astronautics. The main requirements are for the detailed design of a fully functional lunar base camp for a planned lunar expedition in 2031. The base camp shall sustain a crew of four for a 45 day mission, and the crew will perform a series of tests regarding deep space exploration and surface habitability systems. The lunar lander for the crew will be government supplied, and the crew must transition within 72 hours from the landing vehicle to the lunar base camp. The mission operations, including the launch, orbit transfer, station keeping, and maneuvers necessary to deliver the base camp components to the lunar surface are all described in detail in this report. The design includes all of the necessary systems to launch and deploy the base camp elements to the lunar surface. The cost of the mission also shall not exceed $12 Billion (in FY19), including costs from the start of the program to the end of the 45 day mission. This budget includes estimated technology advancement costs for technology not yet in existence but feasibly will be by 2031. It also includes launch costs to deploy base camp systems, but it does not include cost of human expedition mission and associated lander/ascent stage.

The name chosen for the base camp and the mission that surrounds it is Omond House Lunar Base Camp. This was the name of the first permanently inhabited settlement in Antarctica, a scientific station established in 1903. Like its namesake was located on Earth's south pole, Omond House Lunar Base Camp will be located at the South Pole of the Moon, near Shackleton Crater. The mission's landing spot inspires the name, but more inspiring is what the name represents. The original Omond House, now renamed Base Orcadas, is the first of its kind and is still in use today. The permanence, longevity, and lifelong commitment to scientific discovery that Omond House embodies is admirable. Omond house Lunar Base Camp intends to perpetuate these ideals by taking the name of this historic icon.

The lunar south pole, near Shackleton Crater was chosen specifically for its favorable illumination conditions and potential for scientific operations. The rim of the crater receives continuous sunlight for about half of the year, making it a viable location for a solar powered base camp. Shackleton Crater and the surrounding areas also offer a plethora of scientific opportunities. More details on the reasoning for the location can be seen in Section 3 of this report.

One of the biggest obstacles in designing this base camp is the lack of heritage, since there has not been a permanent human settlement on an extraterrestrial planetary body before. Long-term habitats for human spaceflight do however exist in the form of the International Space Station (ISS) habitation modules. The habitat will be a self-contained module that is pre-outfitted with life-support systems and radiation shielding. Section 4 contains more information on the habitat. Figure 1.1 shows a rendering of the overall base camp design.

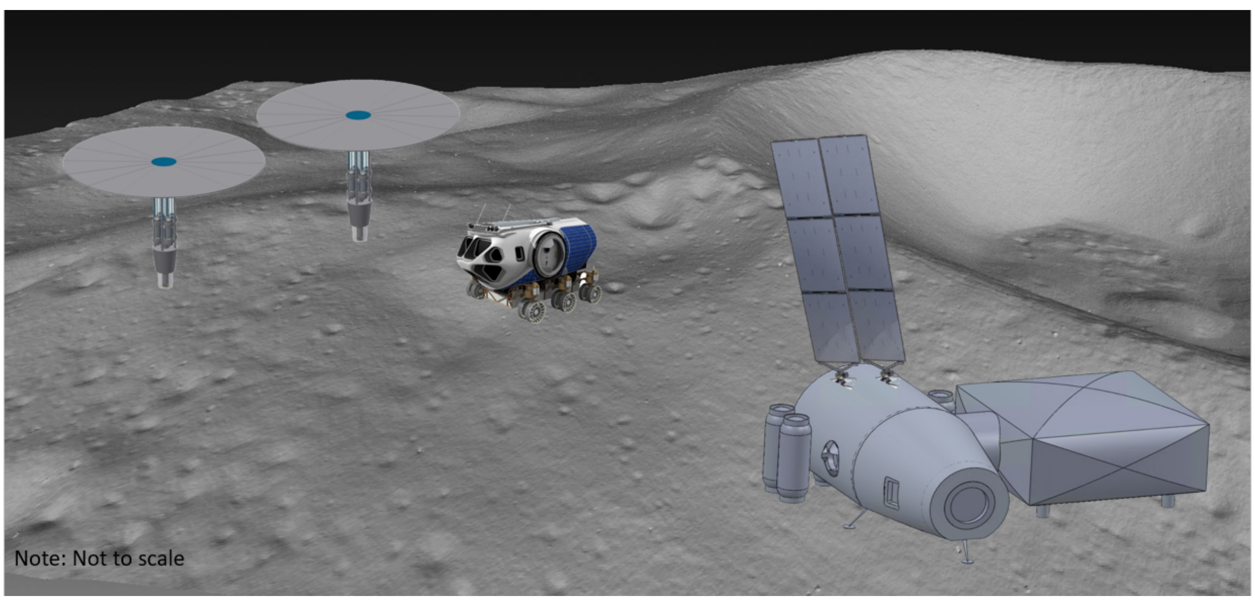


Fig. 1.1: CAD Rendering of Omond House.

Supporting a crew of four for 45 days involves many critical decisions to make regarding life support systems of the base camp. A partially closed-loop regenerative life support system will be used in the base camp to provide the crew with water and air and to remove crew waste products. Reusing some waste products will reduce mass requirements for future missions and will enable the testing of candidate technologies for future use in deep-space exploration. A partially closed-loop system allows the life-support system to implement current and well-proven technologies. More details on the life-support system, as well as the food, medical, and psychological needs of the crew can be found in Section 5. To satisfy power requirements, as found in trade studies explained in Section 6, Omond House will use nuclear and photovoltaic power for the base camp.

For communication, Omond House's communications network will incorporate both S-band radio communications and laser communications. S-band was selected for the primary communications network to provide robust and continuous communication with Earth. The laser communications terminal provides the capability to achieve high data rates at relatively low power cost. Section 7 discusses the details of the communications system of the base camp.

To get the components of the base camp to the surface of the Moon, there will be five separate launches of SpaceX Falcon Heavies that will carry all necessary components to the Moon. Each payload will enter a Low-Energy Trans-Lunar Injection (TLI) to reach the Moon. This trajectory minimizes fuel cost and allows for a precise and accurate descent to the Shackleton Crater landing site. A detailed breakdown of the launches can be found in Sections 10 and 11.

A preliminary schedule can be found in Section 11 of the report. Figure 1.2 shows a Concept of Operations diagram of the trajectory for each launch for the habitat. This schedule would place the first launch in May 2030 and the last launch in August later that same year. With an estimated time of flight of three months for each launch, all components will reach the surface of the Moon by November of 2030, meeting the requirement of the base camp being operational by December 31st, 2030.

Three costing methods were used when budgeting for the mission. These models were commercial off the shelf (COTS) pricing, NASA's Advanced Mission Cost Model (AMCM), and cost-estimating relationships (CER). The current best estimate of the cost is $10.2 billion dollars, or 85% of the allocated budget. The full cost breakdown can be found in Section 10 of the report.

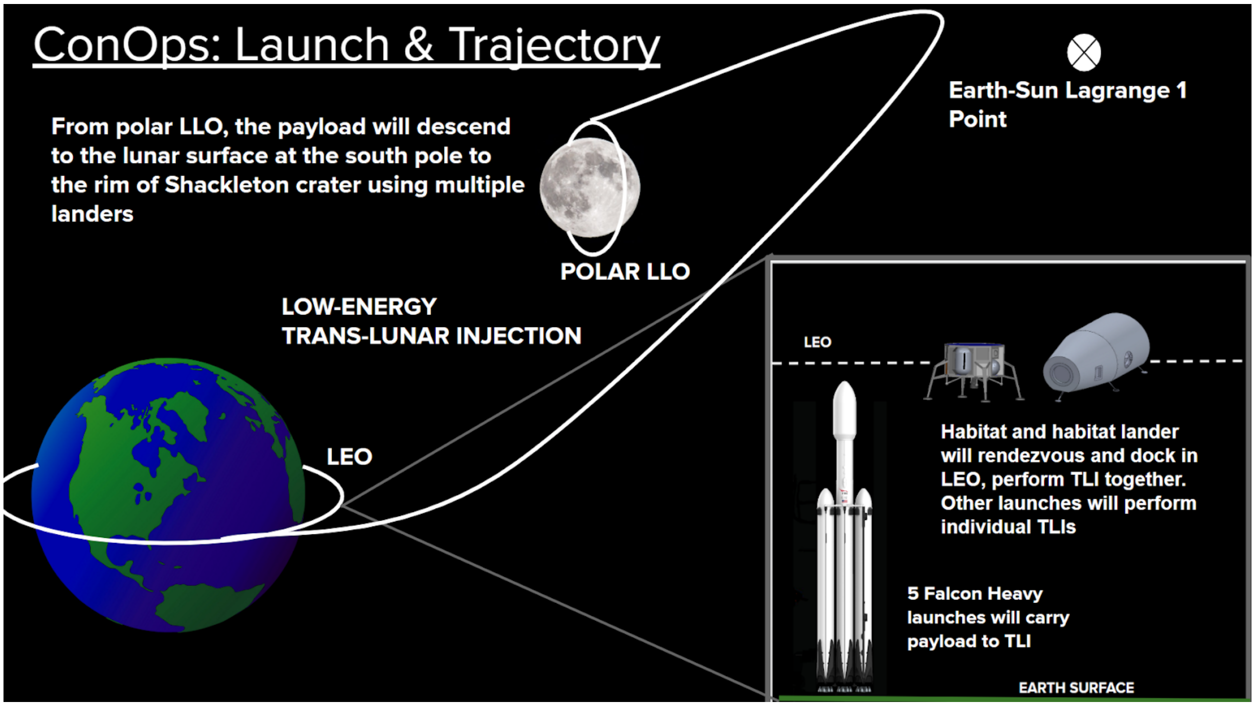


Fig. 1.2: ConOps Diagram of Launch and Trajectory for Omond House.

The design of this base camp also takes into consideration the potential for the base camp to be expanded to accommodate more crew for longer duration in subsequent expeditions. Throughout the report are considerations of various activities, resources, and systems that future exploration missions to other solar system destinations would require and how the base camp would help enable those missions.

The entirety of the past school year has been dedicated to the development and refinement of Omond House Lunar Base Camp to meet all requirements of the Request for Proposal (RFP). A compliance matrix explaining how the requirements have been addressed can be found in Section 12. The following proposal aims to capture all the effort poured into this base camp throughout the course of its design, and we would like to thank the reviewers for their time spent in examining our work.

2. Mission Description

The purpose of this section is to discuss the mission described by the American Institute of Aeronautics and Astronautics (AIAA) RFP for the Crewed Lunar Base camp mission design. The RFP for this competition states that the purpose of the competition is to develop an innovative idea and engineering design to commercially procure a fully functional lunar base camp for a planned lunar expedition in 2031. Even though NASA's long term mission planning goal is Mars exploration, numerous exploration missions can be conducted in cis-lunar space that can assist NASA in preparing for future missions. More specifically, NASA and its international partners are highly interested in the potential of utilizing lunar resources and lunar surface exploration. A base on the lunar surface would provide two main benefits: giving astronauts the opportunity to gain experience and potentially supplying resources which could then be utilized to support Mars missions in the future. Therefore, the extensibility of this base camp design is one of the most crucial factors for this mission.

Along with providing extensibility to future deep space exploration missions, the RFP also specifies other requirements that a successful design must address. The proposed base camp should sustain a crew of four for a period of 45 days on the lunar surface. The crew will perform a series of tests of surface habitability systems and deep space exploration in order to gain knowledge, experience, and assist in planning future exploration missions. The base camp must be ready to receive the first expedition crew no later than December 31, 2030. The crew themselves will arrive on the surface in a government supplied lunar lander which can support the crew for 72 hours after landing. This will help facilitate the transition of the crew from lander to base camp. The crew lander and ascent stage is not a part of the base camp design. The 45 day mission then begins after the crew of four transitions fully from the landing vehicle to the lunar base camp. The location of the base camp should be chosen to maximize crew survivability, scientific return, and potential extensibility to enable future deep space missions. The base camp should also have the ability to be expanded in order to accomodate more crew for longer duration in subsequent expeditions. Lastly, the design should also consider the various activities, resources, and systems that future exploration missions to other solar system destinations would require and how the base camp would help enable those missions.

In addition to a detailed engineering design of a lunar base camp, the proposed design also should include a definition of mission operations, including launch, orbit transfer, station keeping, and other maneuvers necessary to deliver the base camp components to the lunar surface. The design therefore must include all of the necessary systems to launch and deploy the base camp elements to the lunar surface. Trade studies on system options at the system and subsystem level must be performed to demonstrate the fitness of the chosen base camp design. Advanced technology that has not been flight tested can be used, but the cost, schedule, and risk consideration of utilizing advanced technology must be discussed and budgeted. The budget of the initial mission design is $12 Billion US Dollar (in FY19) from the start of the program to the human expedition, including Design Development Test and Evaluation (DDT&E) and Theoretical First Unit (TFU) costs of all of the base camp elements.

It is also necessary to discuss the selection of subsystem components, including mass, power, and volume, and how the design requirements drove the decisions made. The RFP also states that the report must discuss the estimated lifetime of each of the components, determine the lifetime of the system and number of surface expeditions the base camp can sustain, and detail the potential upgrades and expansions that are available with the design and how extensibility and longevity considerations impacted the design choices. It should also be detailed how the base camp components will be packaged, launched, deployed to the lunar surface, whether any on-orbit or on-surface assembly or rendezvous of components will be required, and what systems would be required to assist in the delivery of the components to the lunar surface.

3. Location and Scientific Operations

3.1 Lunar Environment

Before choosing a landing site, it is important to understand the fundamentals of the lunar environment. There are three key differences between the environment of the Moon and Earth. First, there is less gravity on the Moon. The acceleration of gravity on the Moon is 1.623 m/s^2, which is about six times less than Earth. Second, there is a tenuous exosphere, meaning there is less protection from radiation and meteoroids. This leads to the third difference: extreme temperature fluctuations [1].

The moon has a relatively low declination angle with respect to its near circular orbit around the Earth, which means there is less change in illumination conditions, particularly at the poles. The moon is about 398,000 km away from Earth on average. For the Apollo missions, it took about three days to get to the moon. Another significant factor is the soil that covers the surface of the moon, also known as lunar regolith. This regolith is made up of meteorite-generated fragmented debris that is jagged due to lack of erosion, clings to most everything, and can even pose a health hazard to astronauts.

Because tenuous exosphere means temperature fluxuations, the moon is second only to the planet Mercury when it comes to extreme thermal environments [1]. Figure 3.1 shown below is a graph from the DIVINER Instrument on the Lunar Reconnaissance Orbiter (LRO) that shows the temperature fluxuations at different latitudes.

The temperatures reach over 350K (170°F) around the equator and reach as low as about 50K (-370°F) at the poles. Similarly, the largest fluctuation occurs near the equator, while the smallest change in temperature occurs at the poles. A comparison of the thermal conditions on the moon and the Earth is shown in Table 3.1 below.

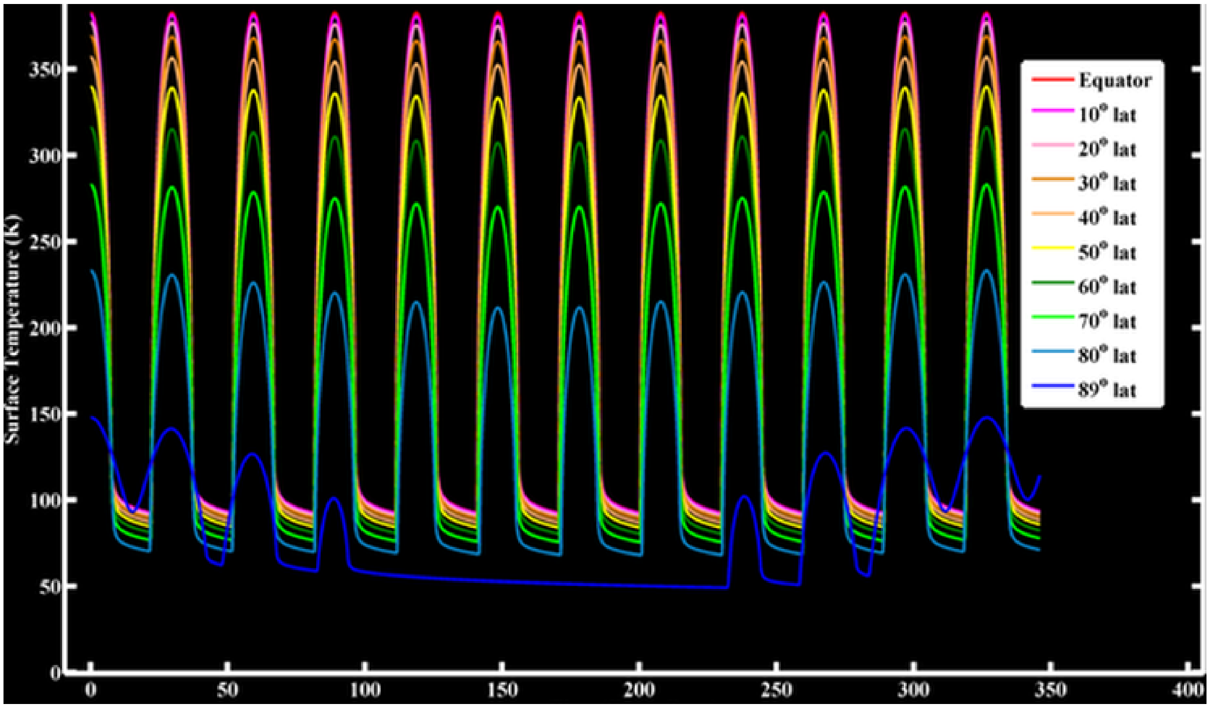


Fig. 3.1: Temperature fluxuations at different lunar latitudes [1].

	Moon	Earth
Equator Average Temperature (K)	~206K (390K at noon; ~95 K at midnight)	~299K (303K at noon, ~295K at midnight)
Polar Average Temperature (K)	~98K (outside of shadow)	~256K (North Pole) ~230K (South Pole)
Minimum Temperature (K)	~25K (Hermite Crater)	~184K (Vostok Station, Antartica)
Maximum Temperature (K)	~410K (small equatorial craters)	~331K (El Azizia, Libya)

Table 3.1: Moon and Earth Thermal Conditions from Diviner [1].

The moon's average temperature at the equator is comparable to Earth, which is one of the reasons the Apollo missions chose to land at this latitude. However, the lunar poles are much colder than the poles of the Earth, particularly the areas that have never seen sunlight [1].

3.2 Base Camp Location

Despite the colder temperatures, the location of the base camp was selected to be at the lunar south pole, specifically the rim of Shackleton crater. A temperature map of the lunar south pole is shown in Figure 3.2.

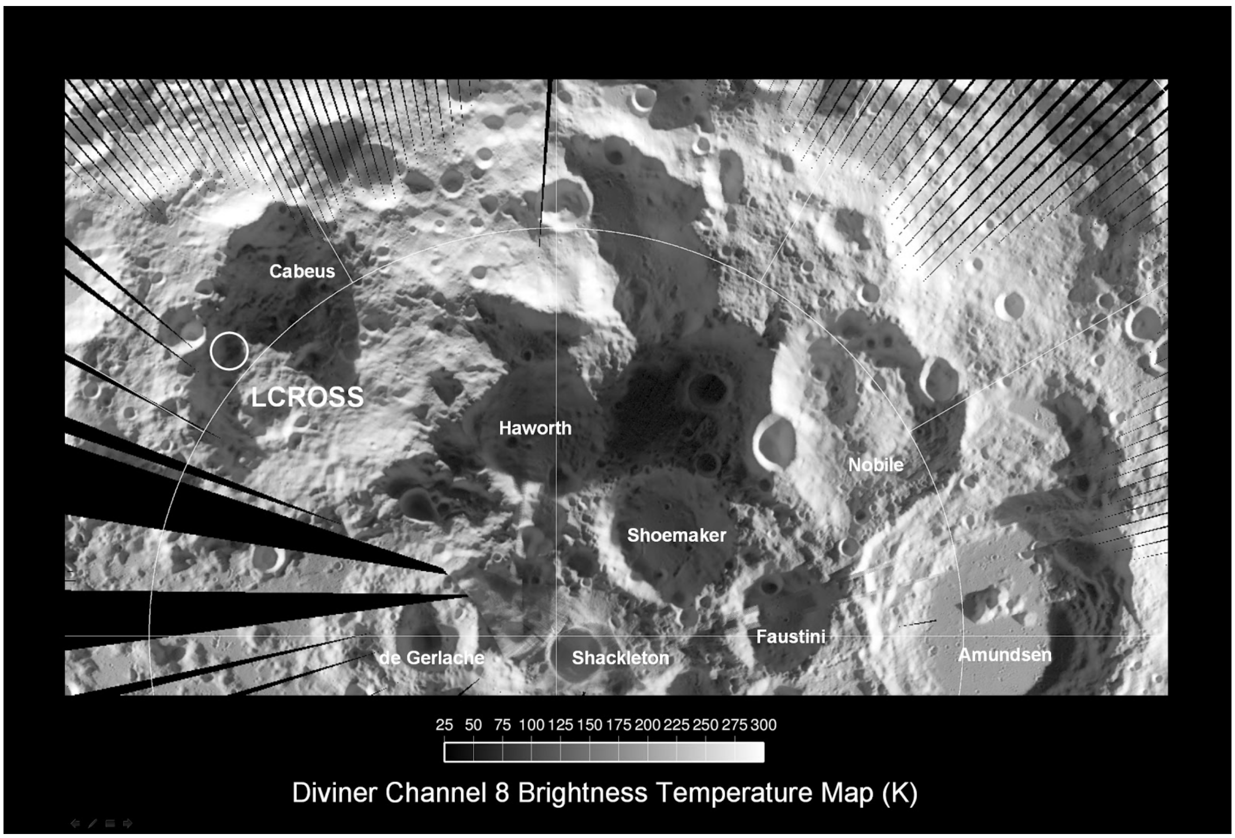


Fig. 3.2: South Pole Temperature Map [2].

The crater itself is near permanent shadow most of the year, making it one of the coldest darkest places in the entire solar system. The interior is two miles deep and in permanent shadow, and the crater is 12.5 miles across. Although the interior is cold and dark, the rim of the crater has some of the brightest places on the moon. Part of the rim of the crater receives continuous sunlight for about half of the year [3].

The superior sunlight makes Shackleton a great place for solar power. Due to the declination angle, the south pole has relatively constant thermal conditions when compared to the rest of the moon. The consistent temperatures in the shadowed craters is ideal for potential cryogenic storage, while the illuminated regions are ideal for people. The average estimated temperature in shadowed polar craters is 40K, while the average estimated temperatures in other polar areas is 220K, which is most ideal for people. Finally, one of the biggest attractions of Shackleton crater is the scientific potential of water and other resources in the crater [4]. Given the duration and unknowns with this water source, the potential of water in the Shackleton crater is not a dependency of the mission, but rather potential for extensibility.

In order to optimize the specific location of the base camp, simulations of the illumination conditions using topographical data were examined. A summary of the three simulations of the area near shackleton crater is shown in Table 3.2.

	Latitude (degrees)	**Longitude (degrees)**	**Max Avg Illumination (%)**	**Solar Visibility (%)**	**Max time in Shadow (hrs)**
Gläser and Oberst (2017)	−89.7849	203.97	81.0	85.5	221
Mazarico et al. (2011)	−89.78	204.27	86.7	90.5	–
Speyerer and Robinson (2013)	−89.740	201.2	71.6	–	145

Table 3.2: Simulations of Illumination Conditions Shackleton Crater [5].

While all three were fairly similar, the most reliable was the most recent simulation which modeled illumination conditions for twenty years beginning in January 2017 [5]. It showed a maximum average illumination of 81%, solar visibility of 85.5%, and a maximum time in shadow of only 221 hrs. This simulation was pivotal in selecting the specific coordinates of the landing site, which is 89° 47′ 5.64″ S, 203° 58′ 12″ E. This area is shown in Figure 3.3 as the black box labeled “S”. The areas labeled C1 and C2 are other regions of high illuminations included in the study referenced, but not selected for this paper.

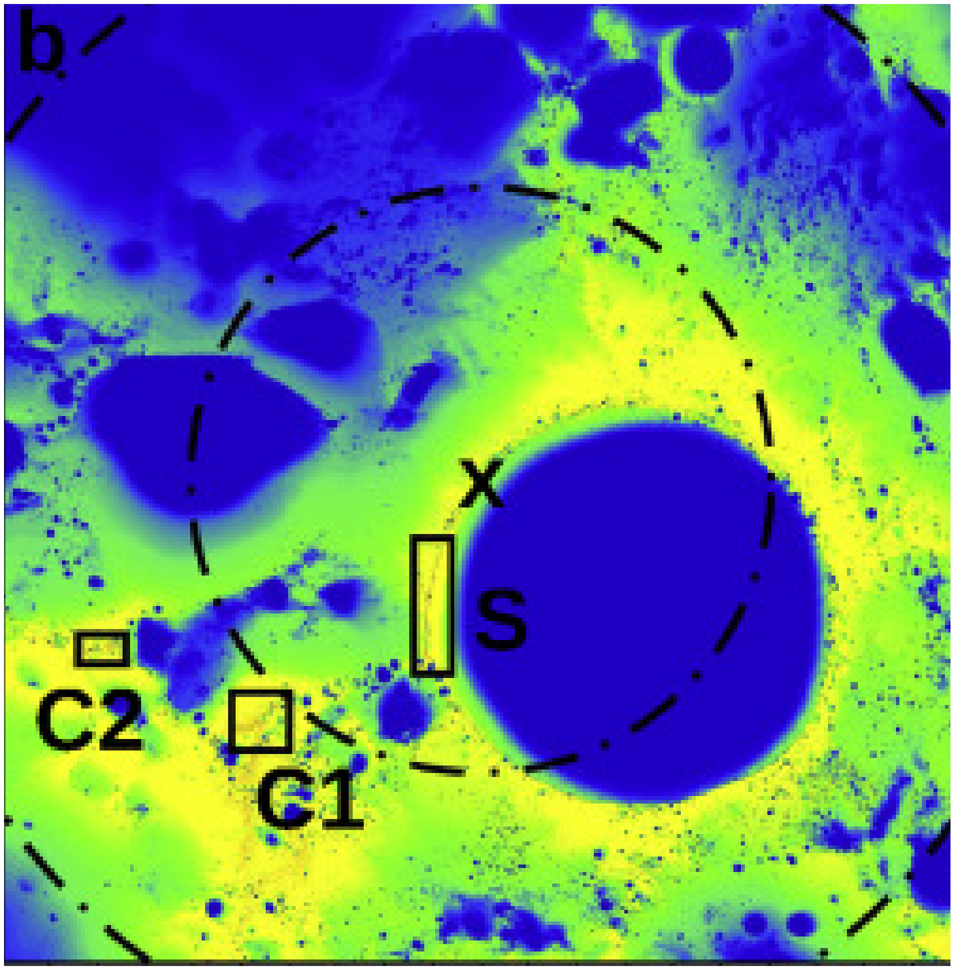


Fig 3.3: Regions of Highest Illumination near Shackleton Crater [5].

There are a few risk factors that tie into this location and the lunar environment in general. First, precise landing is critical. Solar panels and communication systems cannot be obstructed by steep slopes or large boulders. Additionally, Apollo landed near the equator, allowing it a free-return trajectory. Returns from the south pole do not share this benefit. If there are any complications, extra burn maneuvers and trajectory planning will be necessary for return to Earth.

Finally, as mentioned previously, lunar regolith is a non-trivial issue one can encounter anywhere on the moon. Eugene Cernan, commander of Apollo 17, stated that "… one of the most aggravating, restricting facets of lunar surface exploration is the dust and its adherence to everything no matter what kind of material, whether it be skin, suit material, metal, no matter what it be and it's restrictive friction-like action to everything it gets on" [6]. There are two types of adhesion: mechanical and electrostatic. The barbed shape of many dust grains causes them to actually rub deeper into garments rather than brush off [7]. Regolith has extremely low electrical conductivity meaning it is chargeable and remains charged causing it to levitate and coat instrumentation, particularly radiators and solar panels, decreasing power system performance [4]. These particles become charged by solar wind plasma, photoionization, and triboelectric charging.

In addition to these reasons, it's important to have mitigation methods for extensibility because Mars has the potential to be even worse, given the composition of its soil. There has been quite a lot of research into mitigation methods, including pressurized gas and electrostatic techniques for shaking. The mitigation method selected for this mission is a coating technology that would remove the build up of electrical charges. It involves coating super thin films of indium tin oxide on dry pigments, mixing those pigments to make paint, then coating the external hardware. For fabrics, methods of atomic layer deposition to treat fibers in spacesuit material will be researched and potentially utilized [8].

3.3 Scientific Operations

Location informed many of our decisions, specifically the scientific return. The LRO returned data that indicate ice may make up as much as 22% of the surface material in the crater. Laser sensing on the crater has been performed from lunar orbiters, which return brighter areas on the floor of the crater to indicate ice and water [9]. Interestingly, while the floor is bright, the walls are even brighter which indicates more volatiles. As mentioned earlier, cryogenic RFC power storage is highly efficient and ideal for the permanently shadowed regions. Furthermore, these permanently shadowed regions have been virtually untouched since their creation two or three billion years ago, so any sort of data or samples collected will yield much insight into the history of the Solar System. However, because this is a flagship mission, it is not prudent to venture into the crater during this first mission, so all experiments concerning the crater will be performed from the base camp, utilizing a neutron spectrometer for the potential volatiles. Although no adventures will be made into the crater, the extensibility opportunities are endless and nontrivial.

Scientific operations will also exist outside the crater. First, this mission provides a new environment for biometrics [10]. Similar to the International Space Station, it is important to study how the human body reacts to the lunar environment over the 45 day mission. This would come in the form of Actiwatch like on the ISS or a more advanced Apple Watch or FitBit that is constantly taking data on the astronauts. Next, there are several opportunities in regolith testing. This includes testing the effects of regolith on radiation protection, sintering, which could be used to make regolith into viable structures, and experimentation with dust plasma physics which studies the interaction of radiation, illumination, plasma, and dust. Lastly, because this is the flagship mission as far as base camps are concerned, resources will also be allocated to the Technology Readiness Level (TRL) development of new technology that did not necessarily meet the desired qualifications for the first generation. This includes an Oxygen Production Pilot Plant, Gas-Solid Flow Unit, and new habitat technology like inflatable tufts.

The table below depicts the mass, power, volume estimates for the scientific operations. Some of these were pulled from ISS heritage, but most were pulled from preexisting packages in NASA’s catalogue of potential experiments for the Moon and Mars [11]. This equipment will allow for plenty of scientific return regarding biology, regolith, volatiles, astronomy, and extensibility.

Type	**Operation**	**Mass (kg)**	**Volume (m^3)**	**Power (W)**
Extensibility	Tuft Pillow Design	195	1.67	40
	In-Situ Resource Utilization Demonstration Package (Oxygen Production Pilot Plant, Gas-Solid Flow Unit, Brick-Making Experiment)	750	0.6	2900
General Science	Lunar Geologic Field Equipment Package	336	1.8	500
	Lunar Geophysical Monitoring Package	216	0.5	96
	Neutron Spectrometer (WATER)	38.5	0	14
	SW UV Astronomical/Atmospheric Telescope	40	0.2	40
	Soft X-Ray Fluorescence Imager	3	0	2
	Small Research Telescope	200	2.5	500
Miscellaneous	Centrifuges, Incubators, Freezers, Microscopes, etc...	2500	75	97
Raw Total		4310.5	85.27	4189
20% Margin		862.1	17.054	837.8
Total Allocated		**5172.6**	**102.324**	**5026.8**

Table 3.3: Mass-Power-Volume Estimates for Scientific Operations [11] [12] [13].

4. Habitat

The largest obstacle to designing a lunar base camp habitat is a lack of heritage. Never before has a permanent settlement been established on the moon, and no habitat module that has visited was designed for more than a few days. Long-term habitats for spaceflight exist, like ISS habitation modules and detailed plans for Lunar Gateway modules. The radiation shielding, temperature regulation, and Micrometeoroid Orbital Debris (MMOD) threat mitigation that ISS and Lunar Gateway use in their habitats are crucial for developing a lunar habitat.

The construction of a lunar habitat will occur in three "generations" [14], The first, prefabricated and pre-outfitted hard shell modules, will be followed by the second, an assembly of components fabricated on Earth with some assembly required. The third generation will consist of large-scale structures built from indigenous materials.

These generations are useful tools to help understand how lunar construction will develop over time. Second generation habitat modules exist in the form of inflatables, built-up structures made from hard-shell materials assembled on site, or underground construction, among other things. There is extensive research available for these second-generation habitats, but despite the demand for easily modular, light, inflatable habitats, the difficulty of deployment of such a habitat without a crew available to aid in its construction is problematic. These low TRL designs would require a fully operational habitat for a crew to stay in in the event of a failure. Many designs also require leveling for foundation, minor to major excavation efforts, and a regolith shield to aid in radiation mitigation [14]. Regolith piling is particularly problematic. Leaving aside the process of moving the regolith itself, doorways for Extravehicular Activities (EVAs) would be very difficult to access without regolith contamination, and when further extensibility is desired, large portions of the habitat would first need to be excavated. The potential for extensibility of the habitat, however, motivates an interest in these second-generation habitats, not as a primary module, but as add-ons for additional workspace and living space.

Necessarily, a first-generation habitat must be the primary module for habitation. This means a self-contained module that is pre-outfitted with life-support systems, radiation shielding, among other necessary systems. As mentioned, a second-generation habitat would require piling a significant amount of regolith on top to gain the same benefits that can instead be installed directly into the structure of this first-generation module, at the sacrifice of added mass and increased complexity of the system.

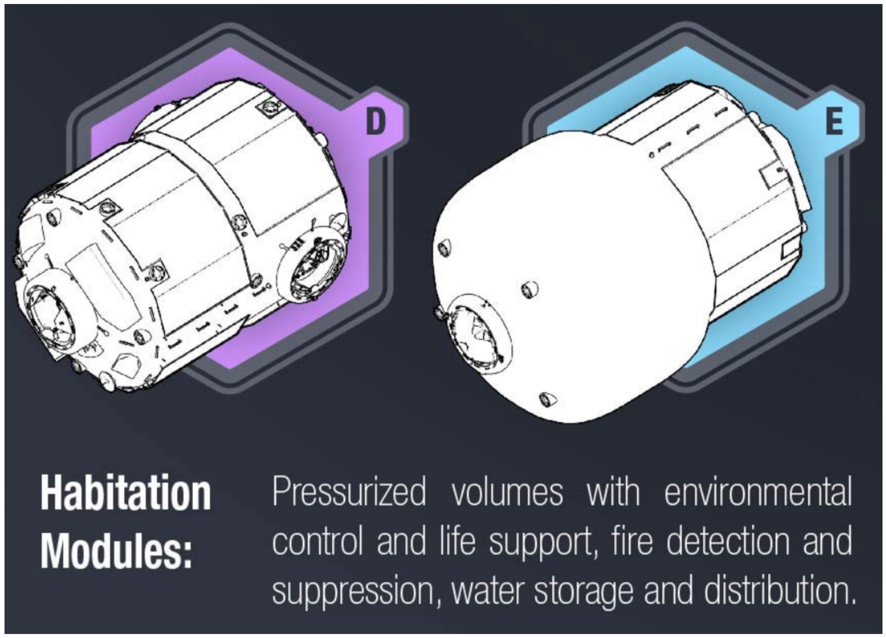


Fig. 4.1: Diagram of the habitation modules from Lunar Gateway [15].

The design of the primary module is derived from the Lunar Gateway habitation modules, shown in Figure 4.1, and modified to better fit the purposes of this mission.

Figure 4.2 shows a rendering of the primary module. The design of the module is shaped to maximize the habitable volume; the tapered end is to accommodate the size and shape of the Falcon Heavy payload fairing, the dimensions of which are shown in Figure 4.3. There are three ports on the habitat, all sized to International Docking Adapter (IDA) standards. These will be used for docking with NASA's Multi-Mission Space Exploration Vehicle (MMSEV) rover and for habitat extensibility. These ports have the ability to attach themselves to any secondary module that needs to be permanently deployed. The front of the habitat near the tapered end of the habitat has two suit ports to allow quick ingress and egress, for which the crew will have compatible suits. The front of the nose is outfitted with an equipment airlock for moving science equipment and consumables inside the habitat.

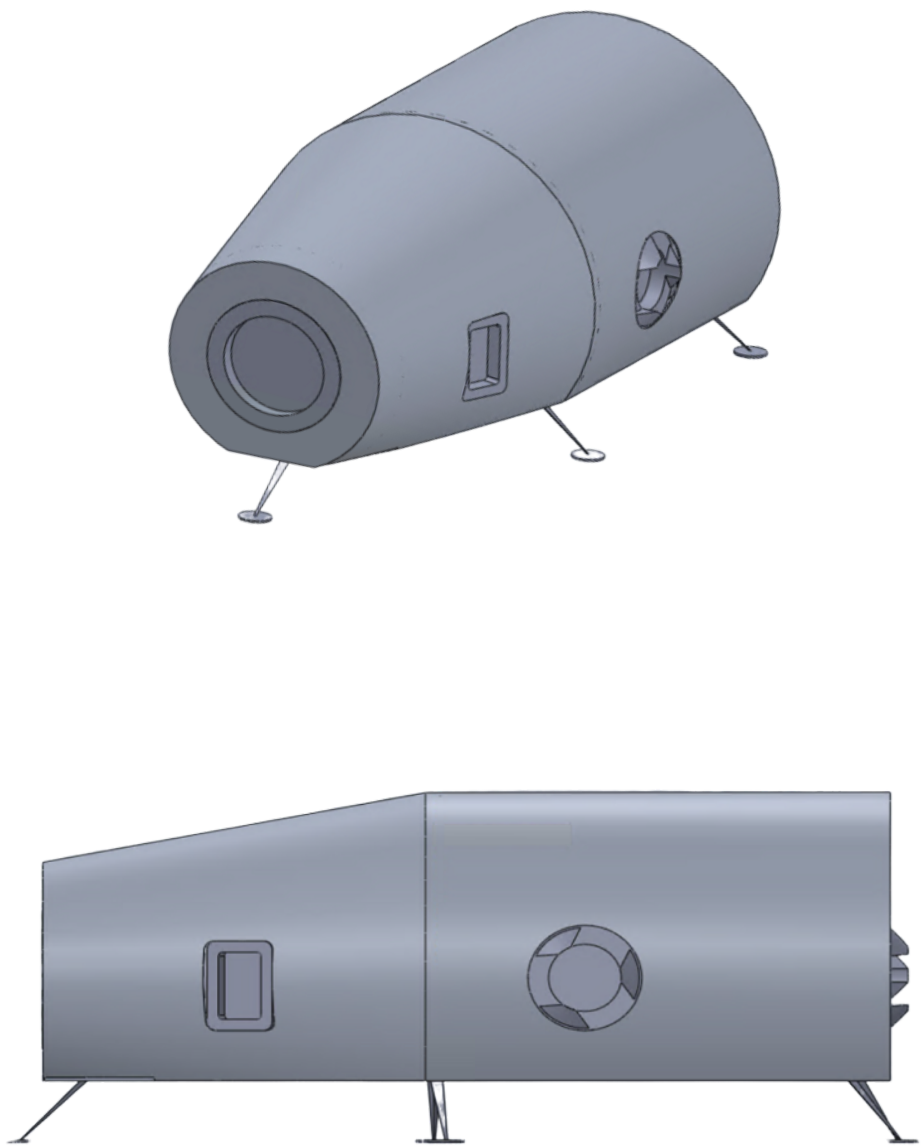


Fig. 4.2: Design of the primary habitation module.

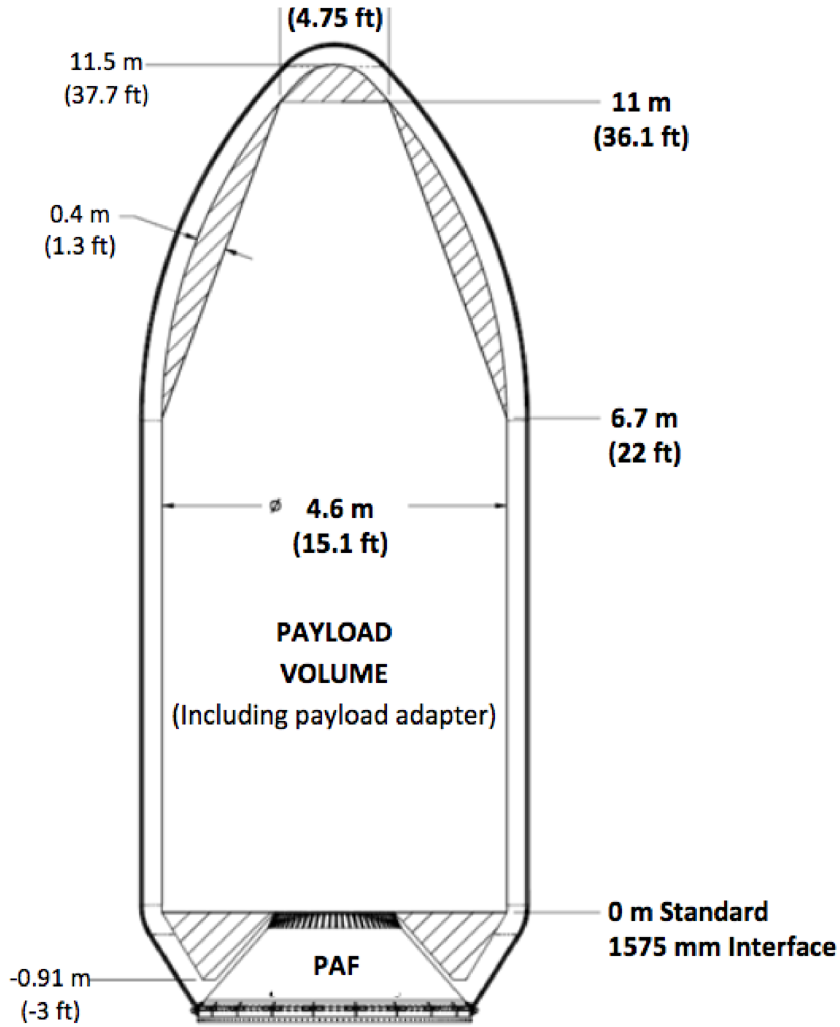


Fig. 4.3: Falcon Heavy payload fairing with dimensions [16].

Concept	Transportation	Construction	Experience	Foundation	Excavation	Sum
Spherical inflatable	5	3	1	3	2	14
Tuft pillow	6	3	1	5	6	21
Lunar crater base	5	2	4	2	6	19
Three-hinged arch	3	4	6	4	6	23
Underground construction	6	2	1	4	4	17

Table 4.1: Trade study results from a number of second-generation habitat designs [14].

Considering extensibility, there exists several types of second-generation habitats for consideration. A trade study published by the American Society of Civil Engineers outlines the pros and cons of a variety of these options, showing that a tuft-pillow inflatable design and a rigid 3-hinged arch are the best overall options (Table 4.1). The tuft pillow design (Figure 4.4) offers ~89 m^3 of habitable volume for just ~300 kg of material [14]. The walls consist of a thin Kevlar-49 material containing an airtight bladder [14]. This design, in addition to being extremely light, has a relatively simple deployment compared to other options. Minimal excavation and foundation requirements make it extremely desirable [14]

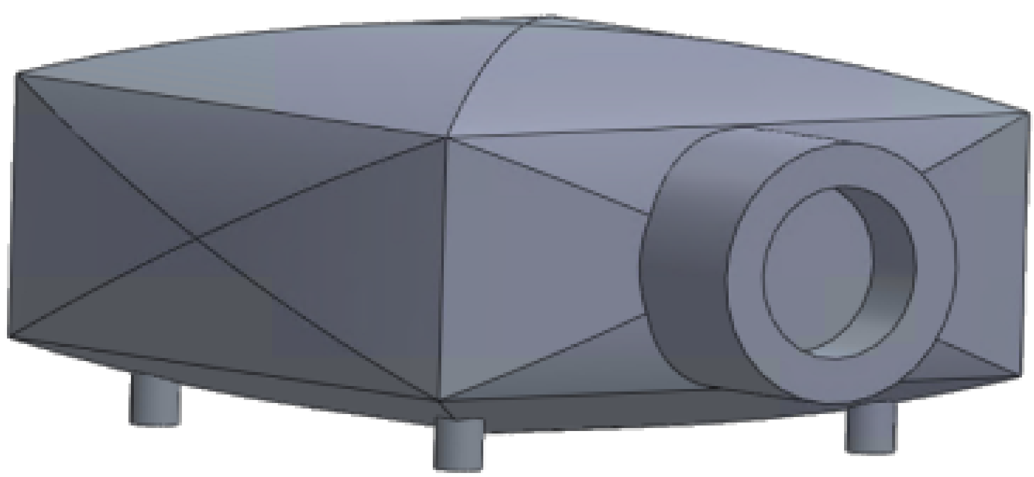


Fig. 4.4: Model of a tuft pillow design.

The use of inflatables as planetary habitats is relatively untested, with few deployments tests in relative environments, such as ISS Bigelow. As such, the TRL level for an inflatable design is low and needs to be improved before the benefits of inflatable habitats could be used as an exclusive design choice on future lunar missions or martian missions. Choosing to use the tuft-pillow design as a secondary habitat expansion module for Omond House would allow for the technology to be verified to a higher level, which in itself contributes to extensibility for future crewed space exploration, as discussed in the scientific operations section.

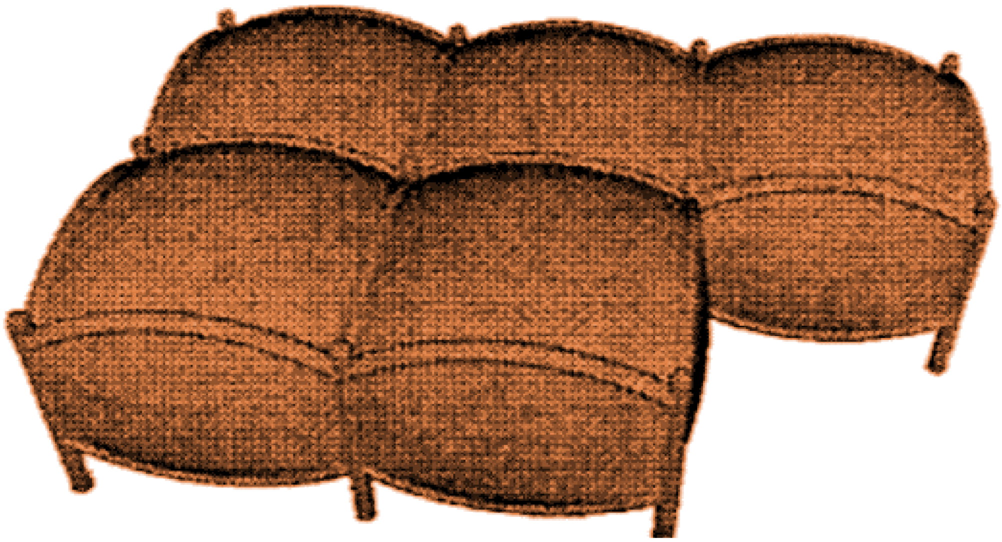


Fig. 4.5: Diagram of a cluster of inflatable tuft-pillow habitats [14].

This design presents issues when considering extensibility, since the walls are made of a Kevlar fabric with an internal bladder, altering them on the lunar surface to allow for the addition of another inflatable habitat may be difficult or impossible. Altered habitat testing on the moon could potentially waste a significant volume of air in the event of a failure. Likely, any tuft-pillow habitats would need to be prefabricated in their final configuration. If a cluster of five tuft-pillows, as shown in Figure 4.5, were sufficient to meet the desired habitable volume expansion, that cluster would need to be shipped to the lunar surface already preconfigured. Though undesirable in the long-term because it lacks modularity, the ability to quickly add lightweight and inexpensive volume to the base may prove to be invaluable.

The three-hinged arch design shown in Figure 4.6 has minimal foundation and excavation requirements, but its rigid structure, made primarily of a high-strength aluminum alloy, means that it has a considerably higher mass [14]. A similar habitable volume of ~120 m^3 requires ~30,000 kg of additional mass [14].

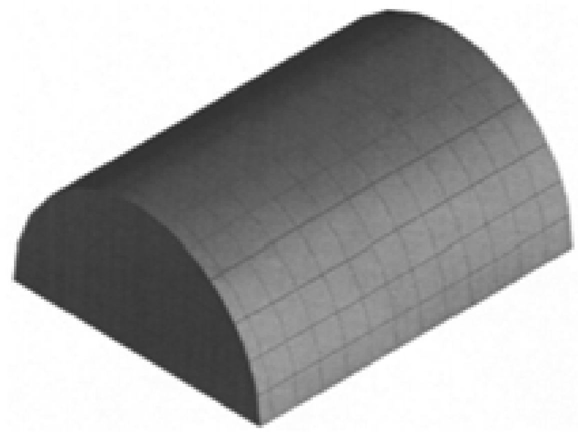


Fig. 4.6: Diagram of a three-hinged arch habitat [14].

The technology of rigid structures is much better understood than inflatables and for this reason is a safer option for the addition of crew-ready workspace. The design of a rigid aluminum structure would be simple compared to a flexible inflatable Kevlar structure. The modular capabilities of a 3-hinged arch could be simplified, as each end-wall could be outfitted with an International Docking Adaptor (IDA) port with docking capability with other modules or a common hub such as the primary first-generation module (Figure 4.7).

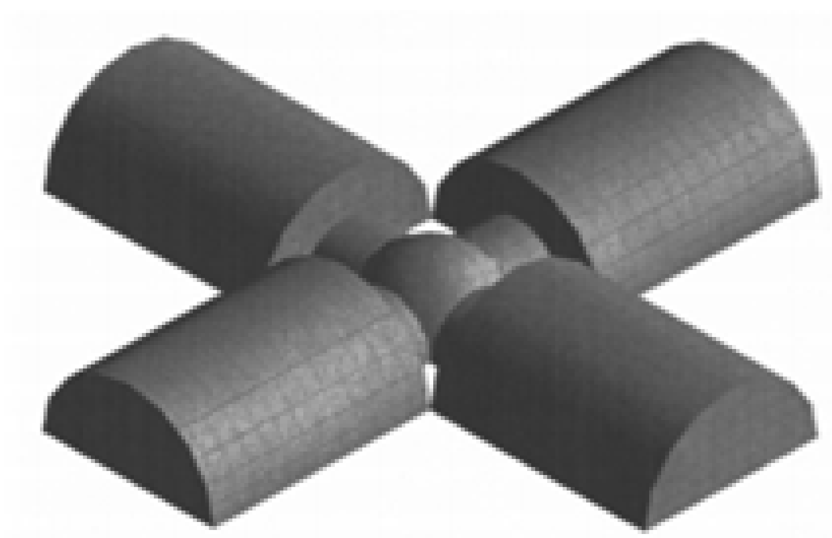


Fig. 4.7: Diagram of a cluster of three-hinged arch habitats attached by a common central node [14].

From a scientific operations standpoint, improving the TRL of a tuft pillow design would prove to be a more interesting option. Further investigating hard-shell modules like the three-hinged arch design would likely not provide a significant benefit to the accessibility of future lunar or martian missions. On the contrary, the tuft pillow design very well could. Exploring a light-weight, easily deployed habitat option may aid in driving down lauch volume and mass requirements for future missions, making the extensibility of lunar habitation more accessible. Figure 4.8 shows a possible outline of what an extended habitat may look like by the end of the flagship mission.

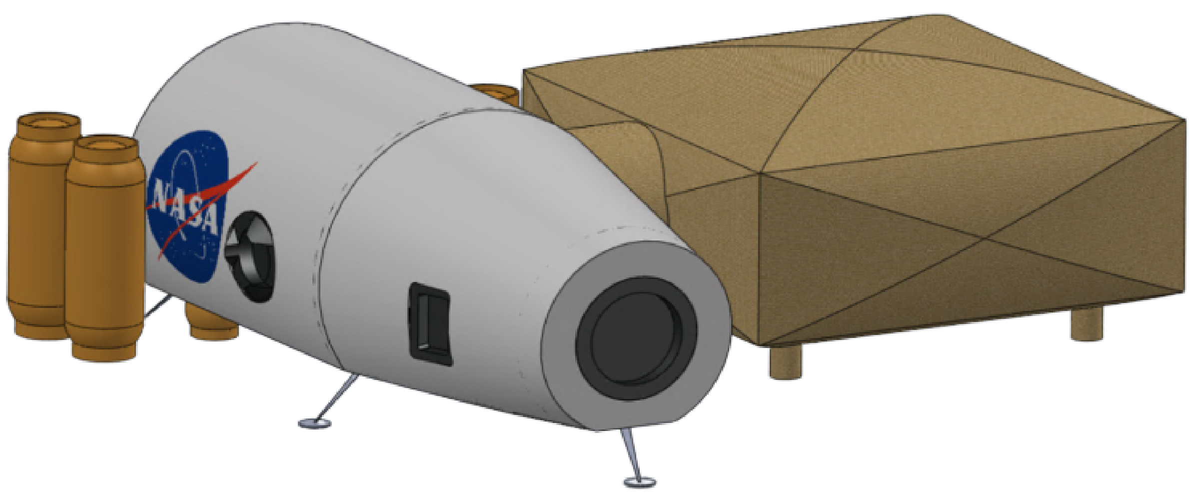


Fig. 4.8: Diagram of the primary module with attached life storage tanks and tuft-pillow module.

The primary module's multiple IDA ports act as attachment points to give access to the secondary tuft-pillow. The same ports are used for docking with the MMSEV. The primary module would have its radiation shielding built in, and that radiation shielding would also yield some benefits to temperature regulation and MMOD threat mitigation. The secondary tuft pillow would require regolith shielding to be used as crew-rated work space. Non-radiation protected space could be used for additional storage, always leaving the option open to add a protective regolith layer radiation protection if additional crew-rated workspace is needed. Regolith, however, is difficult to move in the lunar environment, so it is necessary to understand how much regolith would be required for adequate threat mitigation of these various risk factors. Additionally, the steps necessary for providing adequate radiation shielding the primary habitat must also be investigated (see section 5.1).

Components	Mass [kg]	Volume [m^3]
Structure	10000	132.58
IDA ports	1578	2.1
TOTAL	11578	134.68

Table 4.2: Mass and Volume budget for the primary habitat.

Table 4.2 shows a mass and volume breakdown for some of the components of the habitat. The CAD model for the habitat was altered with various material thicknesses and types. It has been determined that with a combination of aluminum and composite materials of varying thicknesses plus a mass allocation for built-in radiation shielding and other structural components, a reasonable estimate for the mass of the habitat structure is on the order of 10,000 kg.

5. Life Support

5.1 Radiation

There are two main types of radiation that are concerning on the lunar surface. The first, Galactic Cosmic Radiation (GCR), consists of ionized atoms that originate from outside of the solar system [17]. They travel very nearly the speed of light and can produce intense ionization as they pass through objects since they can often consist of heavier elements like iron [17]. Inside the Earth's magnetic field, astronauts are largely protected from this type of radiation, however, this is not the case on the lunar surface, and therefore the effects of GCR need to be accounted for. This type of radiation is the primary threat due to its constant presence. The intensity of GCR varies over the 11-year solar cycle, where the maximum dose occurs at minimum solar cycle, and the minimum dose occurs at maximum solar cycle [18].

The second type, Solar Particle Events (SPE), involve similar particles that are launched into space preceding coronal mass ejections (CME) that occur at solar flare sites [17]. The frequency and severity of SPEs depend on the solar cycle and vary drastically. If astronauts happen to be in the path of particles expelled by a SPE or CME without sufficient radiation shielding, the absorbed radiation dose could be problematic. Some of the largest recorded SPEs would have caused astronauts outside Earth's magnetosphere to absorb lethal doses within 10 hours of the start of the event [17]. Without warning, SPE exposure can cause whole-body doses of over 50 rem within a few hours, which is greater than NASA's annual allotted exposure and likely lethal when absorbed in that short of a time span [19]. Most of the time that astronauts are away from radiation shielding, however, they will have little to no absorbed radiation from SPE exposure, only from GCR [19]. Because of the variance in occurrence and severity of these events, it is important that a long-term base on the moon provides sufficient radiation shielding for both the constant threat of GCR and the possibility of encountering threats from SPEs.

The typical radiation dose for a person on earth is about 0.36 rem/year. International standards allow for as much as 5 rem/year for those whose occupations involve handling radioactive material [17]. Standard limits for spaceflight are much higher with NASA limiting their low earth orbit (LEO) astronauts to 50 rem/year, shown in Figure 5.1 [17]. Many adverse health effects and long-term risks exist when considering increased exposure to radiation, including nausea, vomiting, or long-term effects like central nervous system damage, cataracts, or even death[17]. Ultimately, an increase in cancer risk is the primary concern regarding high-level dosage of ionizing radiation to astronauts[17].

Organ Specific Exposure Limits for Astronauts

Exposure Interval	Blood Forming Organs	Eye	Skin
30 Days	25 rem	100 rem	150 rem
Annual	50 rem	200 rem	300 rem
Career	150 - 400 rem [200 + 7.5(age - 30) for men] 100 - 300 rem [200 + 7.5(age - 38) for women]	400 rem	600 rem

Fig. 5.1: Chart of NASA limits for radiation exposure for different limiting organs [17].

Career dose limits are based on a maximum 3% lifetime excess risk of cancer mortality. This dose is a function of the age and gender of the individual [14]. The sensitivity of the human body to radiation is related to the sensitivity of the cells that compose it. Blood-forming cells have relatively rapid regeneration, and since radiation can affect the regeneration of cells adversely, these organs are the most likely to increase the risk of cancer if the radiation dose is too high. As such, many organizations investigating human radiation sensitivity (including NASA) have chosen to impose limits on radiation exposure based on the dose incurred by these blood forming organs (BFO) [20].

Since GCR is a constant threat and SPE are sporadic and unpredictable, the goal of the radiation shielding will be to minimize the dose incurred by crew members on the lunar surface to allow for repeated trips to the lunar base and remain under the career dose limits by analyzing the GCR threat alone. If the shielding is enough to guard from high-energy GCR particles, the same particles from SPE can also be shielded. Note that the density of high energy particles per cubic meter in SPE can be much greater than in GCR. A thick enough shielding would be able to stop a significant amount of these particles in any amount, however.

GCR at solar minimum (maximum GCR dosage) can be up to 60 rem/year on the lunar surface [18]. This is the maximum expected BFO dose that an individual would be expected to endure without shielding. Since the effect of the minimum solar cycle is known to roughly double the influence of GCR, consider the minimum expected dose to be about 30 rem/year [18].

Data from Appendix A can be utilized to derive the formula that models the reduction in incurred dose behind a given shield depth of lunar regolith. This formula is displayed in Equation 1 below.

$$(1 - \delta D_n \rho)^d \quad (1)$$

Where δD_n is the change in percentage of radiation dose divided by the areal density in g/cm^2, ρ is density in g/cm^3 and d is depth in cm. The output of the formula can be multiplied by the expected dose to yield a new reduced dose that would be experienced under a particular depth of regolith.

The dose that an individual would expect to encounter can be modeled by a gaussian distribution with a mean of 45 rem/year and a standard deviation of 7.5 rem/year. This is so two standard deviations away from the mean in either direction is the expected minimum and maximum and all values contained between make up 95.4% of the data. Two standard deviations is chosen to be the expected minimum and maximum since the low and high estimates can vary between solar cycles. The expectation is that some solar minimums may see dosage higher than 60 rem/year and some maximums lower than 30 rem/year.

An Excel addon called @Risk was used to perform a Monte Carlo analysis on the data. The function derived for the reduction in radiation due to shielding was multiplied by the normal distribution of expected BFO dose equivalent radiation defined above, 30 to 60 rem/year. That result was plotted below with the mean and distribution of expected results at 1 and 2 standard deviations away from the mean.

Recall that the annual limit of BFO dose equivalent radiation allowed by NASA is 50 rem/year. Considering long-term extensibility of this lunar base, the shielding should be sufficient to safely house an astronaut with less than 1/10 of the annual limit over the course of a year or 5 rem/year for GCR alone. This limit is already quite conservative compared to the 50 rem/year limit imposed by NASA. This limit only considers GCR radiation and doesn't take into account any effects from SPE radiation, but the conservative limits imposed on the shielding allows for a significant amount of leeway concerning unexpected SPEs. This means in the event of particularly harmful SPEs, astronauts on base can remain safe by staying indoors and or within the protective shielding of the lunar regolith. The results shown in Figure 5.2 show that a shield of lunar regolith with a depth of 2.25 m would keep an astronaut below this limit with 95.4% confidence.

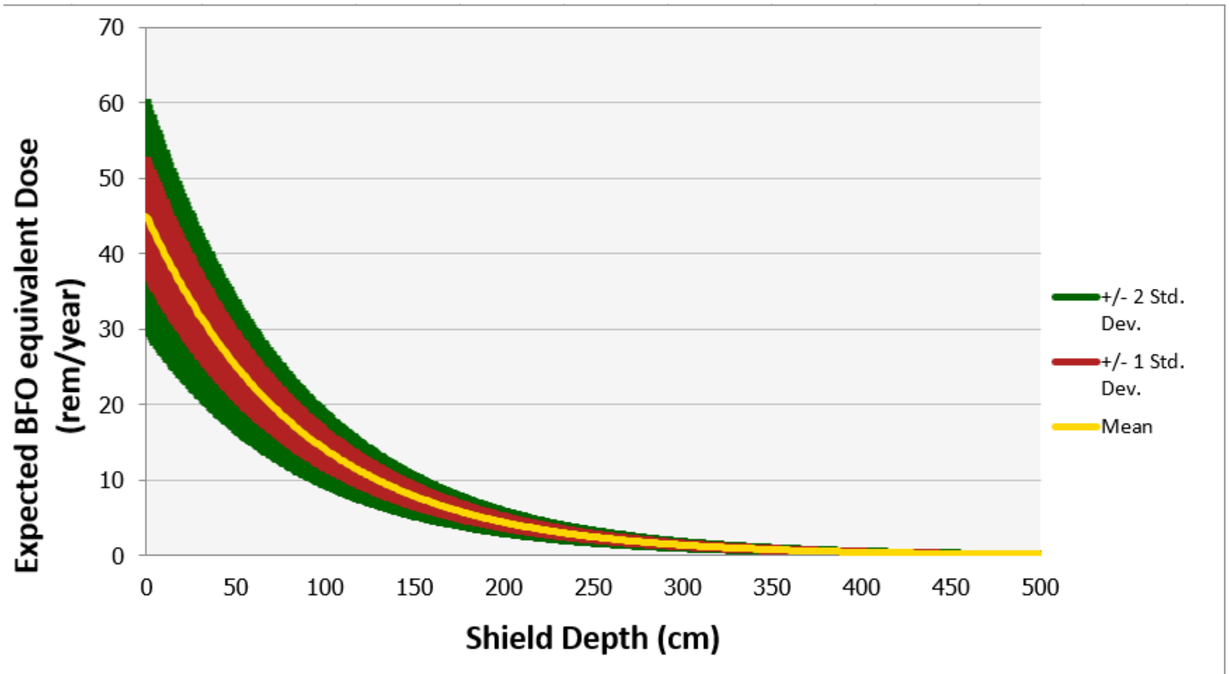


Fig. 5.2: Plot of mean and ± 1 and 2 standard deviations of the expected incurred BFO dose equivalent behind a given shield depth of lunar regolith.

2.25 m of regolith is not a trivial amount of regolith to move. This remains one the major hurdles of using one of the second-generation habitat options as a primary living space. This regolith shield would need to be deployed prior to crew arrival if it was meant to be their primary habitat in order to keep the astronauts under the required radiation exposure limits. This is why a habitat that is pre-outfitted with all the necessary radiation shielding is required for a flagship mission such as this one; radiation exposure cannot be overlooked. When choosing which materials will be used for the built-in radiation shielding of this pre-outfitted module, there is an important balance of mass and volume calculations that must be made since it can no longer rely on in situ materials. One suggestion for a shielding material that is popular amongst lunar habitat design is a shield of water.

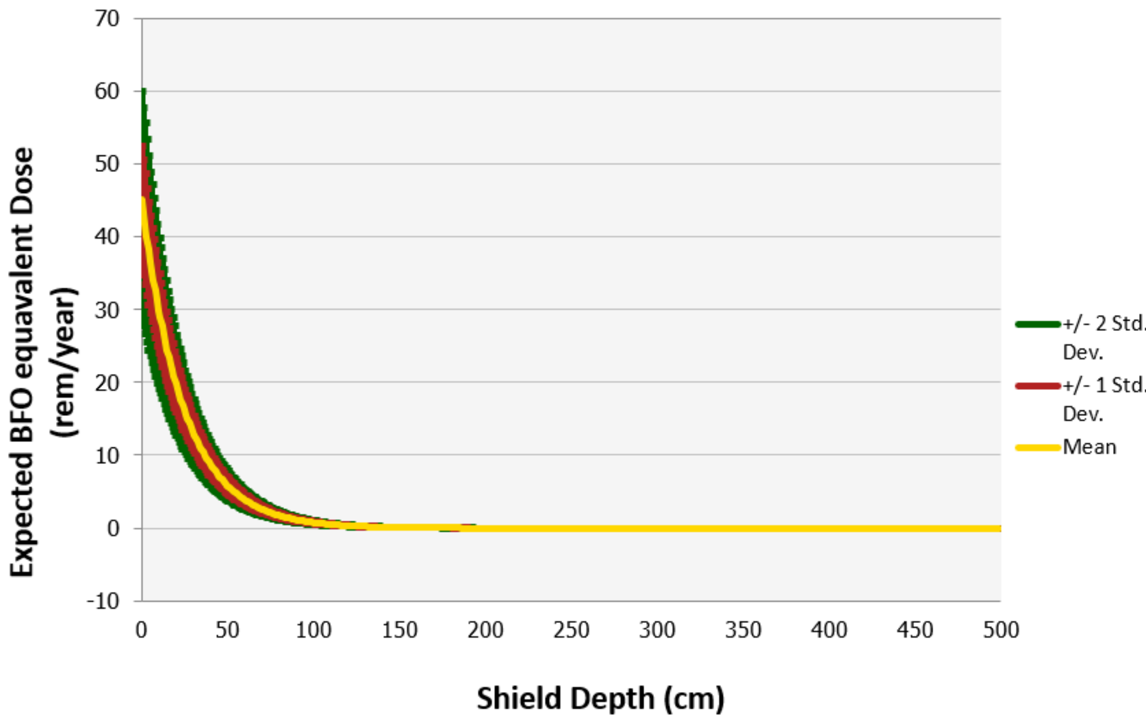


Fig. 5.3: Plot of mean and ± 1 and 2 standard deviations of the expected incurred BFO dose equivalent behind a given shield depth of water.

The same Monte Carlo analysis can be run using data for water, shown in Figure 5.3, and it is found that the same level of radiation shielding, keeping the crew under 5 rem/year of exposure, is possible with a water shield of 0.6 m (95.4% confidence). Though promising, a cursory estimation of the mass of a shield of this thickness has a mass of over 10,000 kg. Instead, this 0.6 m shield depth will be used as an estimate for the thickness of radiation shielding that would be required for a more purpose-built radiation shielding material. The ISS does not struggle with the same radiation problems that a lunar mission would because it exists within the Earth's magnetosphere, and Lunar Gateway does not have any published description of its habitat module's radiation shielding. Historically, NASA has researched polyethylene for radiation mitigation, and there is ongoing research for materials like a 2% boron nitride/polyethylene composite that suggests that it, or something similar, may act as an effective wall-filler material for radiation shielding [21]. This is one among many examples of composites for which research is ongoing about radiation mitigation. For now, the design of the Omond House primary habitat allocates this 0.6 m shell in which some material can be selected for radiation mitigation pending further research in the field of materials science.

Regardless, a significant amount of mass of the habitat will have to be allocated to this built-in radiation protection. It is perhaps advantageous to provide heavy shielding in areas of the habitat in which a lot of the crew's time will be spent and remove some of the radiation shielding in areas with lower foot traffic. For instance, higher levels of shielding may be provided over the beds and workspace of the crew, where much of their time will be spent, with lower shielding allocated near the suit ports and equipment ports, where the crew will spend little of their time. This is an optimization problem that may significantly reduce the mass of the radiation shielding required for the habitat while having little impact on the incurred radiation exposure by the crew.

5.2 Regenerative Life Support

Omond House will implement an open-loop regenerative life support system to provide the crew with water and air and to remove crew waste. The lunar base camp will reuse waste products, reducing mass requirements for future missions and enabling the testing of candidate technologies for future use in deep-space exploration. An open-loop system allows the life-support to implement current, high-readiness, and highly-reliable technologies.

Figure 5.4 depicts a block diagram of this life support system. As shown in the key, orange arrows represent waste flow, blue arrows represent water flow, and green arrows represent air and gas flow. Grey boxes denote machinery and procedural steps. Blue boxes represent tankage, and dark blue boxes highlight the methane vent port and the solid-waste storage tank as these represent the open ends of the system.

Promising research exists for utilizing methane as a fuel source, and produced methane could prove useful in future missions. Additionally, agricultural alternatives to human waste utilization and carbon dioxide reduction may prove possible upon returning missions to the base camp. The following sections will break down the components of this model.

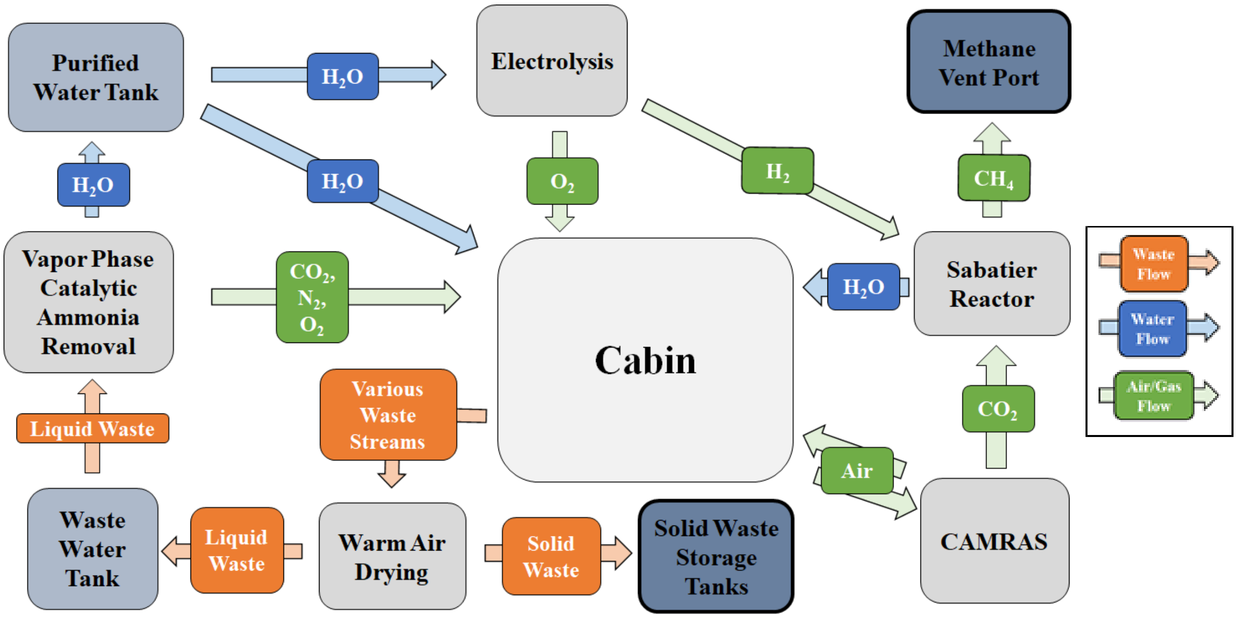


Fig. 5.4: Conceptual block diagram for an open-loop regenerative life support system.

5.3 Waste Management System

The waste management system (WMS) serves to collect waste streams from crew outputs and separate these into liquids that can be recovered and solids that must be stabilized and stored [22]. Figure 5.5 isolates the waste management system from the block diagram..

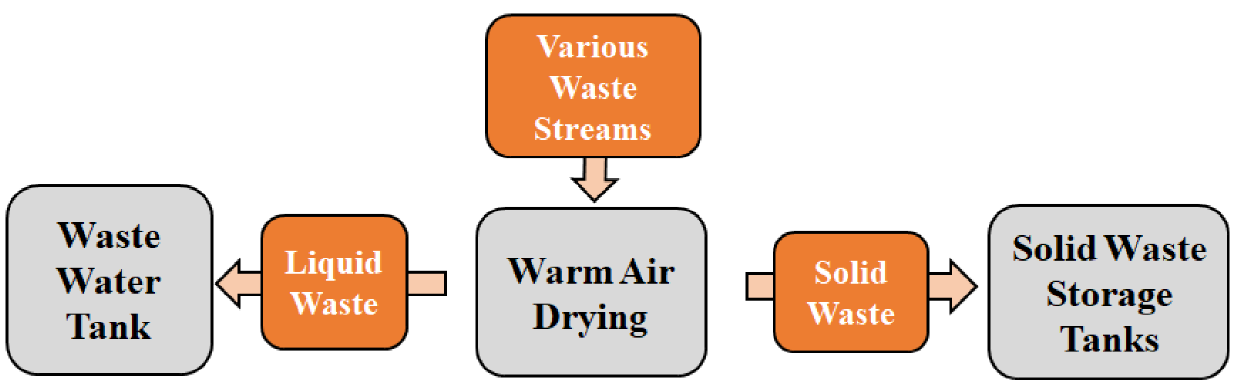


Fig. 5.5: Block diagram for the waste management system.

Streams that enter the WMS include urine and fecal waste, food scraps, hygiene water and air-moisture. In order to collect excretory waste, the base camp will implement a Universal Waste Management System (UWMS), shown in Figure 5.6. This technology, developed by UTC Aerospace Systems, improves upon mass, power, and volume requirements for current ISS technology [23].

Fig. 5.6: Universal Waste Management System [23].

Additionally, the UWMS incorporates improvements based on ISS crew-feedback [23]. Ridges are designed to help astronauts position themselves over the toilet and an updated seat position and angle facilitates placement of the urine collection system for female crew members. Simplified restraints allow crew members to maintain their position over the toilet with relative ease.

Excretory waste will be combined with other waste streams and passed into a warm air drying chamber [22]. Here, liquids will be separated from solids, passing solid waste into a storage tank and passing liquid waste onto the water recovery system.

In total, this system weighs 424.63 kg, requires 562.61 W of power, and occupies 3.18m^3. The mass breakdown can be seen in Table 5.1

Component	Function	Mass [kg]	Power [W]	Volume [m^3]
UWMS	Waste Collection	120.85	274.00	0.66
Warm-Air Drying Tank	Waste Treatment/Storage	303.78	288.61	2.52
TOTAL		**424.63**	**562.61**	**3.18**

Table 5.1: Mass power and volume breakdown for the waste management system.

5.4 Water Recovery System

The water recovery system (WRS) takes liquid wastes from the waste water tank and converts them into purified drinking water. Figure 5.7 shows a block model for the WRS.

Omond House will use a process known as Vapor Phase Catalytic Ammonia Removal (VPCAR) in order to achieve this. An experimental unit can be seen in Figure 5.8. VPCAR incorporates a wiped-film rotating disk (WFRD) with an evaporating chamber and a condensing chamber [22]. Liquid first passes into the evaporative chamber where inorganic salts, heavy organic compounds, and other impurities that do not evaporate are separated from the vapor. The resulting vapor is compressed and passed into an oxidation chamber. Here, volatile organics and ammonia are converted into carbon dioxide, nitrogen, oxygen, and nitrous oxide. The vapor mixture containing water and these gases is passed through the condensing chamber of the WFRD where the carbon dioxide, nitrogen, oxygen and nitrous oxide can be separated from condensed water.. Resulting water is then checked for purity before passing through to the pure water storage tank [22,24].

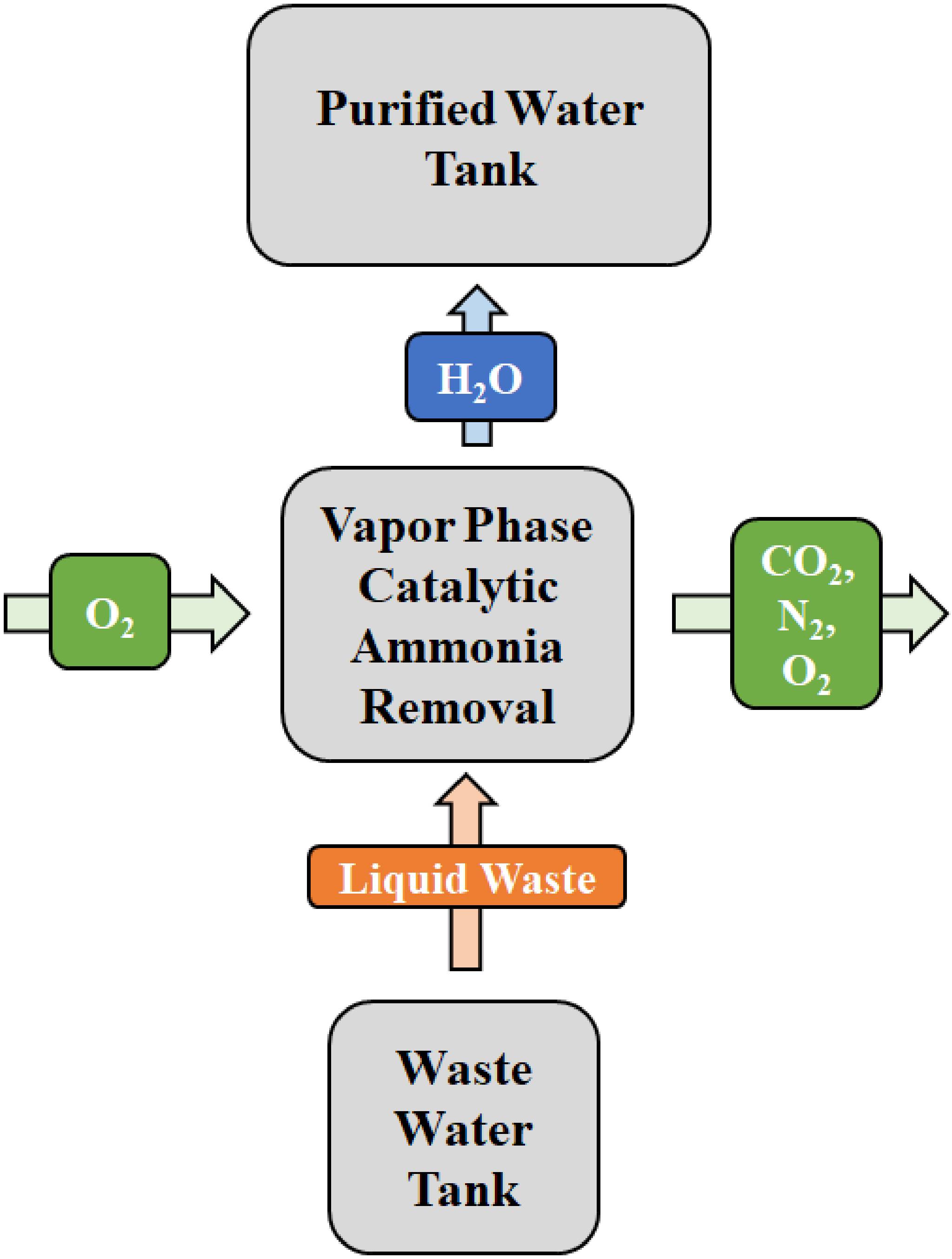


Fig. 5.7: Water Recovery System block diagram for the lunar base camp.

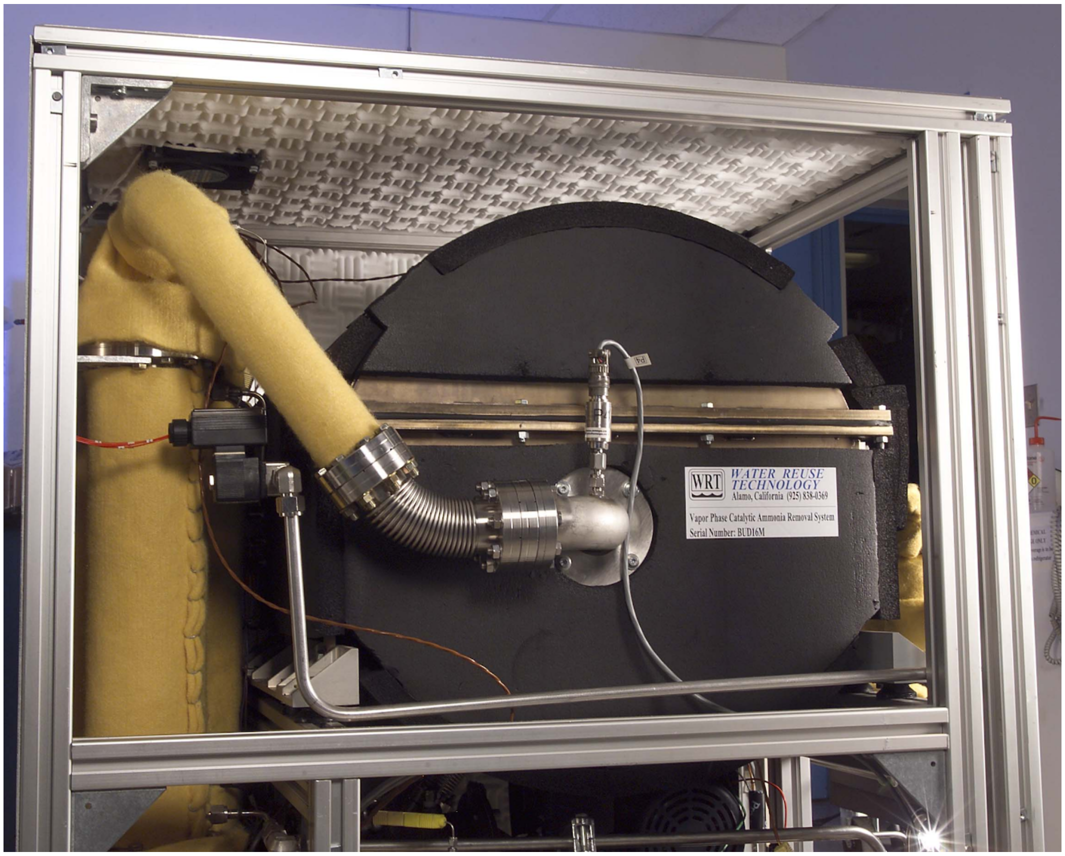


Fig. 5.8: Experimental VPCAR unit [25].

VPCAR has an equivalent system's mass—summarizing power, mass and volume requirements—five times less than that of current space station technology [26, 27]. Additionally, VPCAR procedures have been tested rigorously on earth and in reduced-gravity flight tests [27]. With a TRL of 7 and pathways set out to achieve TRL 9 before launch, VPCAR represents a high-performing, reliable technology that can reduce cost aboard Omond House.

Table 5.2 lists the mass, power, and volume requirements for the WRS.

Component	Function	Mass [kg]	Power [W]	Volume [m³]
VPCAR	Water Treatment	560.10	491.98	2.57
VPCAR	Treatment Tankage	91.13	9.96	0.23
ISS	Microbial Check Valve	0.63	0.00	0.00
VPCAR	Controller	36.91	156.18	0.08
ISS	Quality Monitor	8.64	4.72	0.04
ISS	Water Delivery	26.13	1.93	0.06
Spherical	Potable Water Tank	277.29	11.25	0.29
TOTAL		**1000.83**	**676.02**	**3.27**

Table 5.2: Mass power and volume breakdown for the Water Recovery System [22].

5.5 Air Revitalization System

The air revitalization system is the most complex of all the life support systems [28] and all systems in the Omond House. Figure 5.9 shows the air-revitalization system components and their relationships with each other.

The air-revitalization system consists of three main machines. First, the CO_2 And Moisture Removing Amine Swingbed (CAMRAS) filters carbon dioxide from the cabin. It achieves this by passing air through amine filter beds that collect carbon dioxide and moisture. These beds then rotate and expel carbon dioxide and moisture into a vacuum chamber [29]. Figure 5.10 shows a sample unit of CAMRAS.

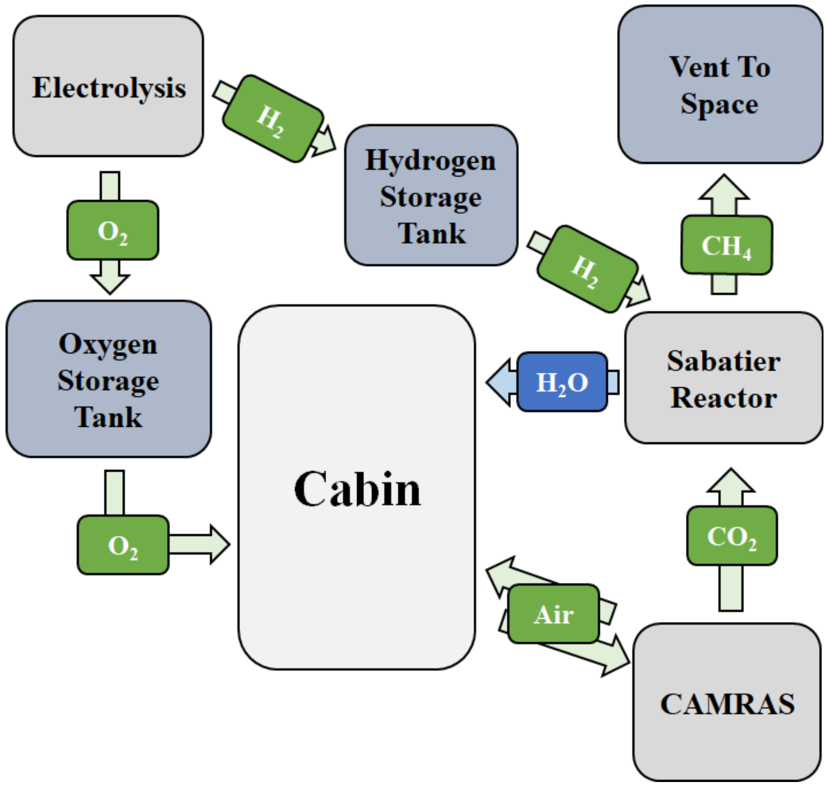


Fig. 5.9: Air revitalization system.

Fig. 5.10: CAMRAS sample unit [30].

CAMRAS is currently used on the ISS to supplement carbon dioxide removal, where it currently outperforms the 4-bed molecular sieves [31]. Additionally, CAMRAS is set for use on the Orion capsule, and will be a TRL 9 technology by the time it is used in Omond House [29].

Rather than venting CO_2 to space, carbon dioxide collected by CAMRAS will be fed to the Sabatier reactor where excess hydrogen will be used in a reduction reaction, shown in Equation 2 [32].

$$CO_2 + 4H_2 \rightarrow CH_4 + H_2O \tag{2}$$

A more idealized Bosch reactor produces pure carbon outputs, reclaiming a greater amount of water, but implementation of a Bosch reactor remains relatively untested and currently requires large amounts of power. Additionally, carbon accumulation can damage the reactor [32].

Oxygen and hydrogen will be produced through Electrolysis, a TRL 9 method currently in use on the ISS. By running an electrical current through water, electrons combine with water to form hydrogen gas and hydroxide ions at the cathode. At the anode, electrons are removed from water, creating oxygen gas and hydrogen ions. Oxygen will be fed to an oxygen storage tank and hydrogen will be fed to a hydrogen storage tank. A MPV breakdown is shown in Table 5.3.

Component	Function	Mass [kg]	Power [W]	Volume [m^3]
4BMS	CO_2 Removal	415.05	701.87	0.89
CAMRAS	CO_2 Removal Backup	338.36	160.08	0.00
Sabatier	CO_2 Reduction	129.06	134.54	0.16
ISS	Pressure Ctrl	127.2	23.5	0.26
SFSPE	O_2 Generation	241.45	1316.07	0.64
ISS	TCCS	53.34	141.68	0.57
ISS	ACMA	162.90	103.5	0.27
ISS	Sample Delivery	105.33	0.00	0.12
ISS	Airlock CO_2 Rem	543.9	397.00	0.68
High Pressure	N_2 Storage	68.05	0.00	0.13
High Pressure	O_2 Storage	115.11	0.00	0.26
Cryogenic	H_2 Storage	180	0.00	0.4
ISS	Fire Detection	4.5	1.48	0.01
ISS	Fire Suppression	20.40	0.00	0.12
TOTAL		**2504.65**	**2979.72**	**4.51**

Table 5.3: Mass power and volume breakdown for the air revitalization system [22].

5.6 Life Support Mass Flow Rates

Understanding the mass flow rates of critical commodities is critical for the design of a safe life-support system. Table 5.4 depicts the inputs and outputs of the aforementioned life-support components and the impacts these have on the mass-balance of carbon dioxide, oxygen, water, hydrogen, and methane.

Component	CO_2 [kg/day]	O_2 [kg/day]	H_2O [kg/day]	H_2 [kg/day]	CH_4 [kg/day]
VPCAR	-	-	20.72	-	-
CAMRAS	-4.06	-	-	-	-
Electrolysis	-	3.05	-3.43	0.38	-
Sabatier	*[-3.74]*	-	3.06	-0.69	*[-1.36]*
Crew	4.00	-3.36	-20.68	-	-
Total	**-0.006**	**-0.31**	**-0.33**	**-0.17**	***[-1.36]***

Table 5.4: Mass balance within the regenerative life-support system [22].

The first column in this table represents the mass-balance for carbon dioxide. CAMRAS has the ability to remove 4.06 kg of CO_2 from the atmosphere each day, while the crew will produce approximately 4 kg each day, giving a net mass flow rate of -0.006 kg/day. The reduction performed by the Sabatier occurs in series with CAMRAS removal and therefore is excluded from the mass-balance within the cabin. As demonstrated, CAMRAS can operate at high enough rates to remove sufficient CO_2 from the cabin; however, some amount of CO_2 will be vented into space due to restraints on the reduction rate.

The next two columns detail oxygen and hydrogen mass balances. These two commodities are linked to one another by means of the electrolysis rate. Oxygen can be generated at up to 4.12 kg/day, at which point the oxygen balance will turn positive. Additionally, oxygen production can be slowed to turn the water balance positive. The optimal electrolysis rate will depend greatly on cabin conditions and crew activity levels, and the ability to adjust will help maintain equilibrium.

In either case, however, the hydrogen mass balance remains negative due to high demands from the Sabatier reactor. Additionally, net losses in both water and oxygen levels will occur over the 45-day stay. High methane production rates, shown in the final column, make methane storage impractical.

Due to the open-loop nature of the regenerative life-support system, mass losses are inevitable. In order to account for this, consumable tanks will be brought to the lunar surface along with the habitat. Table 5.5 details the accumulated mass losses over 45 days as well as the required consumable mass and volume.

Commodity	O_2	H_2O	H_2
45-Day Losses [kg]	13.64	14.58	13.25
Consumable Amt [kg]	30	40	20
Tank Volume [m^3]	3.2	0.29	0.40
Tank Mass [kg]	115.11	277.29	180

Table 5.5: Consumable tankage requirements [22].

These tanks will attach to the sides and belly of the habitat after arrival as shown in Figure 5.11.

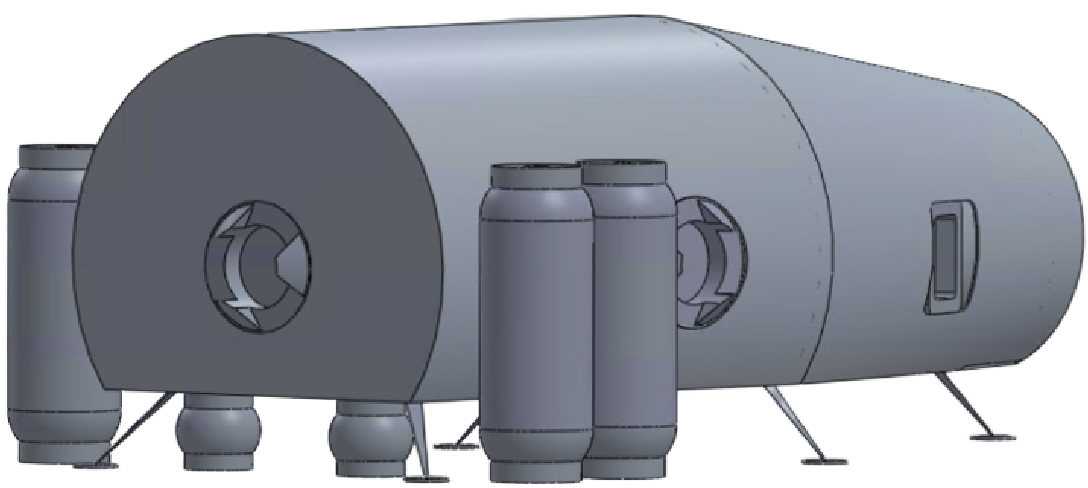


Fig. 5.11: Consumable tankage.

Large tanks required for solid waste storage, consumable oxygen, and consumable nitrogen will attach to the sides of the habitat. Smaller tanks for consumable pure water and consumable hydrogen will be placed beneath the habitat. Requirements for the nitrogen tankage will be discussed in the next section alongside the habitat atmospheric controls

5.7 Atmospheric Controls

The artificial atmosphere is the atmosphere inside the base camp that is experienced by the crew. Each crewed spacecraft has an artificial atmosphere that can vary in overall pressure and molecular composition. The pressurization procedure for Omond House's artificial atmosphere is based on the ISS mission heritage. Continuous measurements of the atmosphere's qualities, i.e pressure, oxygen content, nitrogen content, will be taken by the system. Consumable tanks of oxygen and nitrogen integrated into the life support system will pump gasses into the cabin pressurize the system as well as keep oxygen and nitrogen gasses at desired levels. Table 5.6 shows the different artificial atmospheres designed for different missions.

Mass Allocation for Pressuriziation								
Modeled Enviornment	Oxygen %	Nitrogen %	Operating Pressure (kPa)	O2 Total (kg)	O2 Storage Mass (kg)	N2 Total (kg)	N2 Storage Mass (kg)	Total Mass for Pressurization
ISS	21.1	78	101.3	12.64	17.24	46.94	71.54	88.78
Apollo	100	0	34.47	20.48	27.93	0.00	0.00	27.93
Skylab	76	24	34.47	15.15	20.67	5.32	8.11	28.79
Ideal	34	66	57	11.51	15.71	22.35	34.06	49.77

Table 5.6: Calculated mass values for multiple artificial atmospheres.

While Omond House is based on ISS heritage for pressurization, the atmospheric content will be based on the "Ideal" case, the chosen case for this base camp described in *Integrated Extravehicular Activity Human Research & Testing Plan: 2019* [33]. The chosen case represents an atmosphere of 34% Oxygen which is the highest oxygen a spacecraft can have while the remaining atmosphere will be 66% Nitrogen. As the partial pressure of oxygen is higher than the Earth's atmosphere, the pressure of the Omond House cabin can be lowered from 101.3 kPa to 57 kPa [33].

The chosen atmosphere has two main benefits: lower mass and shortening prebreathe procedures. The chosen atmosphere saves mass because the overall pressure of the atmosphere is lower. Per the ideal gas law, pressure is directly related to the number of moles of gas. For a fixed volume and temperature, the lower pressure of the Omond House cabin means a lower amount of moles is needed to pressurize the cabin. Small reductions in mass save large amounts of energy and reduce costs. The chosen case also significantly shortens prebreathe procedures. Before EVA, astronauts must flush the nitrogen from their tissues to prevent decompression sickness. Decompression sickness arises because the pressure of the spacesuit used during EVA is lower than the pressure of the cabin in the ISS. This causes nitrogen bubbles to form inside the human body, which can move around the body. Prebreate procedures flush nitrogen from the human body, and are necessary before every space walk On the ISS this is accomplished by having the astronauts breathe pure oxygen for one hour prior to EVA, including breathing pure oxygen during an initial ten minutes of exercise at the start of the prebreathe. Then pressure in the airlock is lowered to 70.3 kPa and astronauts breathe pure oxygen for an additional thirty minutes before putting on spacesuits and breathing pure oxygen for another additional hour. The astronauts are then ready for EVA after two and a half hours of prebreathe procedures at minimum [34]. However, these procedures can be shortened by lowering the cabin pressure initially to better match the space suit pressure, and by increasing the oxygen content of the cabin. For the chosen atmosphere, the cabin pressure does not need to be lowered before EVA. Additionally, astronauts only need to breathe oxygen for fifteen minutes prior to EVA [33]. Many scientific operations and base camp improvements take place on the lunar surface, necessitating frequent EVAs. By cutting down prebreathe procedure times from over 180 minutes to fifteen minutes, EVAs are more flexible and not as time consuming. Both qualities significantly increase the time the crew is able to access the lunar surface, leading to greater scientific return and extensibility modifications.

Similar to the ISS, the habitat module experiences leakage that occurs daily. Sources of leakage occur during EVA, when gasses are vented from the system, and during airlock depressurization. The leakage rate for the ISS is -0.227 kg/day of air [35] As the ISS has a habitable volume of 899m^3 [35], which is significantly larger than the Omond House habitable volume of approximately 48m^3 passive leakage rates are much larger on the ISS. Even though EVAs will be more frequent on Omond House than ISS, the use of suitports reduces the air lost due to EVA because they are used instead of airlocks, which vent 1.6 kg of air per EVA [35]. As Omond House is pressurized based on ISS mission heritage and environmental controls and life support systems (ECLSS) is used, the passive leakage rate is assumed to be the same and the total leakage rate can be adjusted for the volume difference. The leakage rate for Omond House is -0.012 kg/day, which can be resupplied via consumables.

5.8 Thermal Controls

Located along Shackleton Crater at the South Pole, Omond House exists in a cold environment that fluctuates with sunlight. In order to ensure crew safety and comfort, the habitat will be maintained at temperatures between 65 and 80°F, using a combination of active and passive thermal control.

Active thermal controls will consist of a water-filled coolant loop running through the habitat walls as well as resistive patch heaters. In hot-biased regions of the habitat and during the lunar day, this coolant loop will remove excess heat and exchange it with the cooler/shaded regions of the habitat. During the lunar night and in permanently shaded regions of the habitat, resistive patch heaters will assist in heating the habitat air and surfaces. These heaters will ensure that air within the cabin remains above the dew point, or that water will not be able to condense on any habitat surfaces.

This system will weigh 397.75 kg, require 3.15 kW of power, and take up 0.9 m^3. The mass power and volume breakdown can be seen in Table 5.7 below.

Component	Function	Mass [kg]	Power [W]	Volume [m^3]
Internal Thermal Control System	Thermal Controls System	211.83	2585.10	0.36
Common Cabin Air Assembly	Air Conditioning	60.43	335.59	0.22
Avionics Air Assembly	Payload Cooling	37.20	175.00	0.10
Atmosphere Circulation	Air Flow	29.61	61.00	0.06
Microbial Contaminants Control	Airborne Particulate Removal	309.66	0.00	0.81
TOTAL		**648.73**	**3156.69**	**1.55**

Table 5.7: Mass power and volume breakdown for the thermal control systems [22].

5.9 Food

All food and nutrition required by the astronauts will be consumables that are not replaced by the semi-closed-loop system. The food required by the crew is estimated by the Estimated Energy Requirements (EER) Equations (3)(4) shown below [28].

$$Men: \ EER = 622 - 9.53\ Age\,[y] + 1.25\,(15.9\ Mass\,[kg] + 539.6\ Height\,[m]) \qquad (3)$$
$$Women: \ EER = 354 - 6.91\ Age\,[y] + 1.25\,(9.36\ Mass\,[kg] + 726\ Height\,[m]) \qquad (4)$$

Additional provisions are required for EVA and exercise. 200 kcal per hour of EVA and 300 kcal per hour of exercise must be added to the daily EER formula [28]. The mass of the food required by the crew is shown in Table 5.1 below. Many ISS foodstuffs exist in forms that are tolerable for a zero gravity environment. Food that crumbles is exchanged for foods that do not, i.e tortillas instead of bread. Many condiments and ingredients also exist as gels or are not used in general. As Omond House exists in a non-zero gravity environment, foods like bread and salt can be used in their natural forms. This allows the menu to be expanded from what astronauts typically enjoy on the ISS.

Packaging requirements must also be considered. Each crew member requires 1.7 kg of food per day, which includes the weight of packaging per the EER, EVA, and exercise requirements [28]. Foods are classified into four categories based on how they are packaged. Rehydratable foods have water removed before launch to conserve mass, and are rehydrated by water from the habitat module or in the case of the Space Shuttle, rehydrated by using water produced by fuel cells [36]. Thermostabilized foods are heated to remove bacteria and are then canned. Intermediate moisture foods are foods that have some, but not all, of the water removed from them to increase shelf life [36]. Natural form foods are unprocessed foods like nuts, trail mix, oats and granola [36].

5.10 Medical

The medical system is a crucial component of Omond House. Long-term operations on the lunar surface are inherently risky, and proper equipment, facilities, and trained personnel are needed to ensure that sickness and injury is not just preventable, but treatable. The main requirements for the medical system are listed below [28].

1. Two crew members shall be certified and trained EMTs such that they are able to provide emergency care.
2. All crew members shall be recieve CPR, First Aid, and AED trainings prior to landing on the lunar surface
3. An EMT trained crew member shall stay inside the habitat module at all times

4. The habitat module shall have a designated space to perform medical procedures.

These requirements ensure that the crew is able to be cared for by at least one EMT trained crew member. If a trained crew member requires treatment, an EMT trained crew member will be ready and available, even if the other two crew members are performing EVA. Additionally, if one EMT trained crew member is incapacitated in any form, the second EMT trained crew member will be available to assisst them and the other crew members.

Frequent exercise is necessary to maintain healthy muscle and bone mass. Bone density will decrease and muscles will begin to atrophy as the gravitational force that usually acts on the human body will be significantly reduced. The Advanced Resistive Exercise Device (ARED) is currently used on the ISS and provides up to 600 lbs of resistance [37]. ARED works by using vacuum cylinders to provide a resistive force. The user inputs force against the vacuum cylinder, simulating free weight exercise [37] The ARED is a robust system, operable in zero gravity and on Earth and can be used for 15 years or up to 11 million cycles. Already used on the ISS, the ARED will be familiar to the crew on Omond House.

In Table 5.8 the mass and volume budgets for the medical system are shown. The medical system includes exercise equipment, medical supplies, and medical system devices such as cots, biomonitoring equipment, and tools.

Item	**Mass (kg)**	**Volume (m^3)**
Aerobic Exercise Device	34	3.1
Resistive Exercise Device	56.7	5.7
Exercise Equipment	2.3	.003
Medical Kit	4.5	0.007
Contingency Kit	2.7	0.010
EVA Response Kit	0.23	0.036
Environmental Health Kit	2.3	0.007
Medical System Devices	136	1.50
Total	223.43	10.363

Table 5.8: Mass budget of the medical system [28].

5.11 Psychology

The mental health of the crew also needs to be monitored and designed for. If the crew is in a poor mental state, then their efficiency is decreased. In extreme cases, as seen in Skylab 4, the crew can refuse to perform their duties all together. Because time on the lunar surface is valuable, and the health of the astronauts is important, proper considerations must be taken when accounting for the crew's psychology. Keeping the astronauts on a consistent schedule with frequent personal time is critical to mission success [28]. Table 5.9 shows the work schedule astronauts on the ISS follow.

Activity	Weekday Schedule (GMT)
Post Sleep	0600 - 0650
Breakfast	0650 - 0810
Work Preparation	0810 - 0820
Scheduled Assembly, Systems, Utilization Operations	0820 - 1305
Lunch	1305 - 1400
Scheduled Assembly, Systems, Utilization Operations	1400 - 1530
Exercise	1530 - 1700
Scheduled Assembly, Systems, Utilization Operations	1700 - 1850
Evening Work Prep	1850 - 1930
Presleep	1930 - 2130
Sleep	2130 - 0600

Table 5.9: Work schedule for ISS astronauts [28].

The crew is allowed adequate personal time on weekends and are not expected to work. While the crew are only on the lunar surface for 45 days, having personal time and weekends off will allow the crew to be more productive overall. Additional methods for improving the psychology of the crew include offering fresh food options, frequent exercise, and sufficient habitable volume.

Habitable volume is defined as non-used and unobstructed volume. It represents the space that the crew can freely move and perform activities in As Omond House operates on the lunar surface under the influence of gravity, habitable floor area must be maximized rather than habitable volume Figure 5.12 shows the habitable floor area for non-zero gravity environments for a crew of four for multiple undersea missions. The relationship between habitable floor area and mission duration follows a logarithmic trend. This trend is dictated by Equation 5 below

$$Habitable\ Floor\ Area\ /\ Crew\ Member\ = 2.27\ *\ ln(duration\ in\ days)\ - 1.83 \quad (5)$$

With a duration of 45 days, the habitable floor area from the trend is 6.81 m^2.

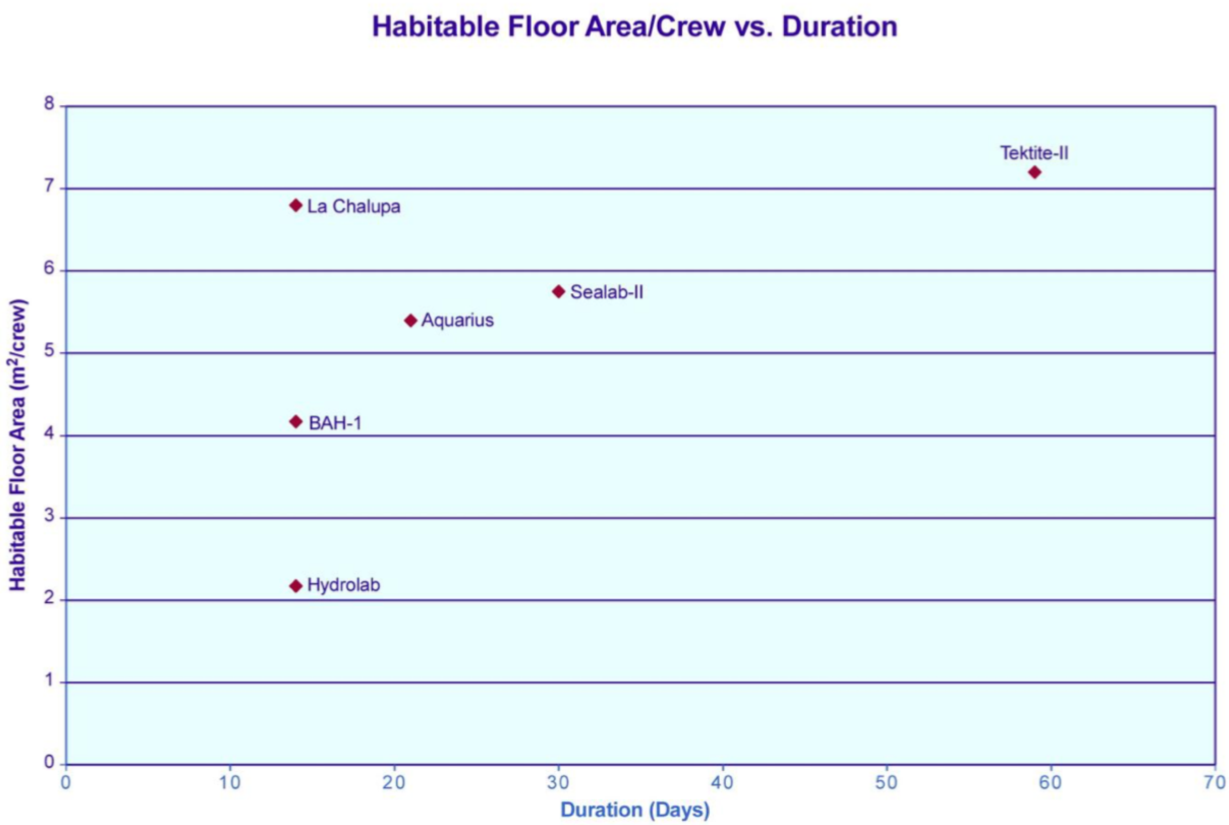
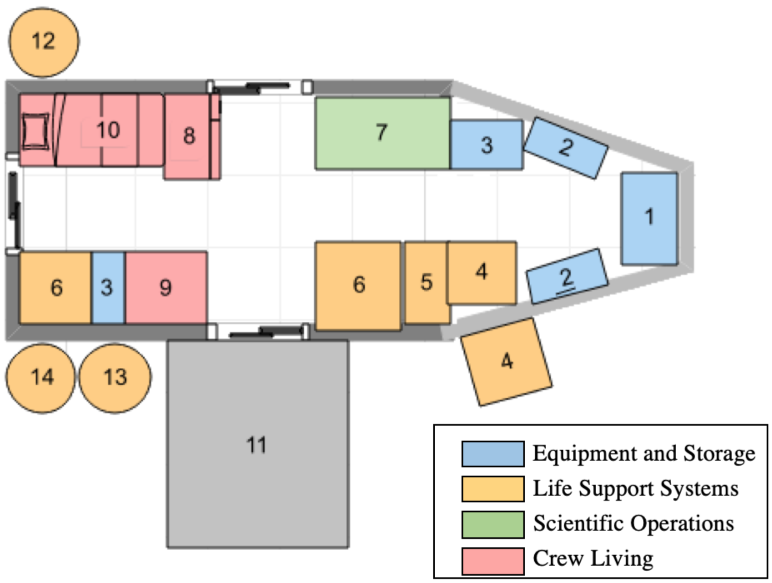


Fig. 5.12: Habitable volume vs. floor area for a crew of four [28].

The interior floor plan and corresponding legend is shown in Figure 5.13. The equipment hatch and suit ports are placed at the tapered end of the habitat module.



Legend	
1	Equipment Hatch
2	Suit Ports
3	Extra Storage Space
4	Power Controls and Storage
5	Thermal Controls
6	ECLSS
7	Science Operations and Storage
8	Food Preparation and Storage
9	ARED
10	Beds
11	MMSEV Docking Area
12	Waste Tank
13	Nitrogen Tank
14	Oxygen Tank

Fig. 5.13: Interior floor plan of habitat module.

The equipment hatch is the only airlock on the habitat module, and will be used for transferring equipment from the lunar service to the interior of the module and vice-versa. The life support systems are placed throughout the module, with tanks and power storage on the exterior of the habitat module. The thermal controls are placed in-between ECLSS and the power controls. ECLSS is split in two parts to maximize space. The waste collection portion of ECLSS is on the left side of the module next to the crew living accommodations while the remainder of the system is next to the thermal controls. Science operations will be conducted and stored in the center of the habitat module. Located near the suit ports and equipment hatch, lunar samples and science equipment will be easily transferable to and from the lunar surface. The crew living accommodations are on the right side of the module. This includes the ARED, food preparation and storage, and the beds. The beds are stacked to save space, and are collapsible and able to be stored in the extra storage space provided or in the floor or ceiling. This provides an additional 2m^2 of space that can be used for exercise, recreation, work, or for medical purposes.

The habitat module has a total floor area of 23.9m^2, and a habitable floor area of 12.8m^2. The habitable floor area per crew member is 3.2m^2, less than half of the number obtained from the trend. While not a requirement, maximizing the habitable floor volume for each crew member will improve crew comfort and therefore, productivity. However, based on constraints imposed by the payload fairing of the launch vehicle and the deployment of the base, the habitat module is as large as possible.

While the crew will be in smaller quarters than desirable, by establishing a permanent module that can be expanded in future missions, this is only an issue for the first crew. Second generation structures currently being tested in this mission will be TRL ready technologies ready to be implemented fully in follow up missions.

6. Power

The power generation, storage, and distribution system created for Omond House is an extremely important design consideration to ensure both mission success and astronaut safety during their time on the lunar surface. Power must be continuously distributed to all necessary systems, especially critical systems such as life support systems, communications systems, habitat lighting, and any other systems that directly contribute to ensuring the well being of the astronauts inhabiting the settlement. Redundancies and reserve power storage systems are to be put in place to ensure that power is distributed to all critical systems if system faults or failures occur.

6.1 Power Requirements

The first step in designing the power system for Omond House is determining how much power would be required by various systems and subsystems during different operational modes for the fully operational habitat design. Because power requirements change for different stages of the development process and mission timeline, research and analysis must be performed to determine the magnitude and difference in power requirements for various operational modes. Completing this analysis is necessary to obtain an accurate value of power required for all stages of the settlement's life cycle. Operational modes considered during this research and analysis process include the following: nominal operations while astronauts are awake, nominal operations while astronauts are asleep, initial construction of the habitat, maintenance activities completed on the habitat, lunar exploration activities, emergency situations, and scientific operations. The resulting system power requirements analytically determined for each operational mode are displayed in Figure 6.1. It can be seen that, including contingency and margin to account for any design changes or additions, the overall power required by Omond House is estimated to be approximately 25 ± 2 kW.

This analytical result matches theoretical results obtained using heritage metrics and values from the International Space Station scaled down to the size of Omond House. Through the comparison of the habitable volume and respective power requirement of the ISS to the habitable volume of Omond House, a theoretical estimate for its power requirement can be obtained. The power required by the ISS is between 75 and 90 kW depending on the operational mode for the station. The hypothetical power required is approximately 20 - 30 kW, confirming the results obtained in the analytical study [38].

As Omond House expands for future missions, the power requirement will steadily increase. Also, as the base begins to expand over the first few missions soon after the initial establishment of the habitat, the power required by the settlement will increase to approximately 30 kW [39]. Therefore, extensibility and an easily expandable design for the power system has been considered. Note that the power required for critical systems such as life support, communications, lighting, etc. that ensure astronaut safety during the mission is approximately 11 kW for all operational modes. This is the amount of power that must be generated and distributed to critical systems during every phase of the mission.

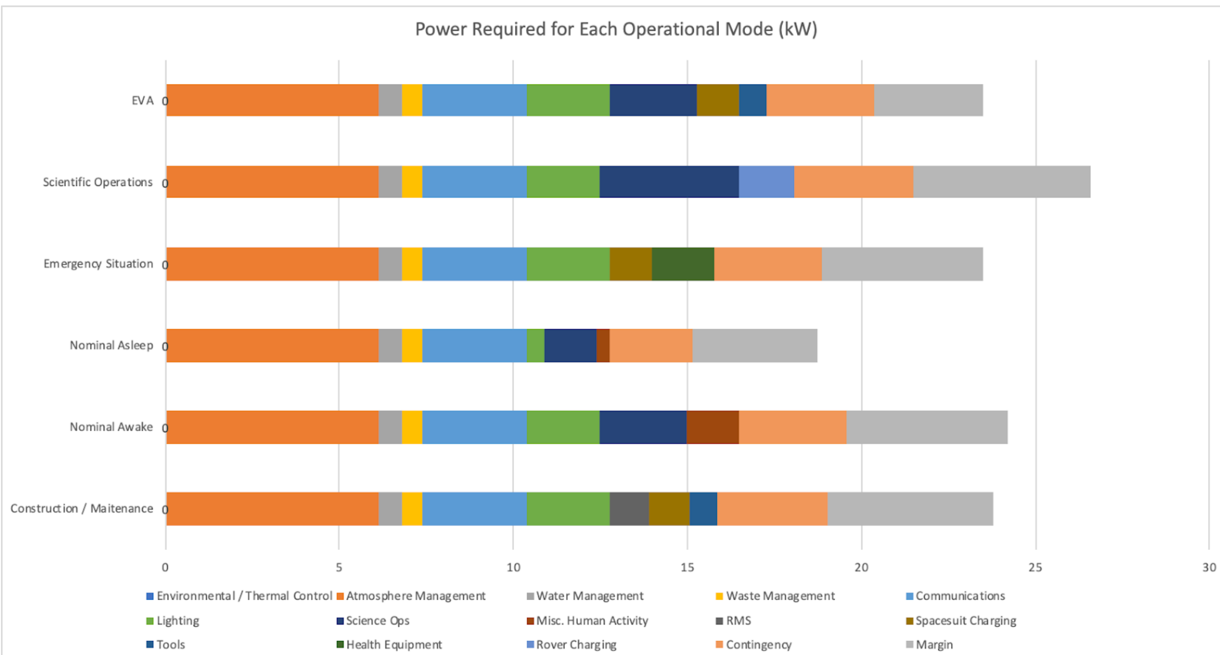


Fig. 6.1: Estimate system power requirements for different operational modes [38].

6.2 Trade Studies and Decision Matrices

Once an approximated value for how much power must be generated to nominally operate all Omond House systems has been determined, the method of power generation and power system design is now considered. Trade studies and decision matrices were completed to determine the prefered method of power generation for

Omond House given its location on the lunar surface, arising technologies in the 2020s, past heritage, and other important design factors.

A trade study was completed between using photovoltaic power (solar arrays), radioisotope thermoelectric generators, and arising nuclear fission reactor technology. Solar panels and RTGs are the two most common power generation systems used in the past and both have inherent advantages and disadvantages. Solar panels convert energy and light from the sun's rays to electric power, while RTGs convert the heat generated by a radioactive material, like plutonium, into electricity using thermocouples. Nuclear fission reactors harness the energy released by the splitting of uranium atoms and convert that energy into electrical power. The results of the trade studies, displayed in Figure 6.2a, show that nuclear and photovoltaic power are the best options to be used for the Omond House power generation system.

Based on the results from this trade study, a combined approach to power generation was selected. Both nuclear energy and photovoltaic power were chosen to be used for the power system. RTGs were not considered because, in comparison to the other two methods analyzed, RTGs do not generate nearly enough power to provide enough energy to a fully operational lunar habitat [40]. Nuclear power was selected as the best option due to its high power density per kilogram along with the fact that a nuclear reactor generates power continuously regardless of the moon's illumination conditions [41]. In other words, using nuclear power eliminates the need for immense power storage requirements that would be needed during the lunar night if the power system relied only on solar panels. Because the nuclear power system would be brought to the lunar surface prior to the astronauts arrival, there is little to no risk of astronaut exposure to radioactive materials. The Kilopower nuclear reactors selected for this mission are to be sufficiently shielded so that they are safe for astronauts to interact with. A combined approach to power generation was chosen primarily to add factors of redundancy and robustness into the power system. By using two different power generation methods, power being generated and distributed to Omond House is not completely reliant on one source of power. That way, if something happens to one of the systems, the other will still be able to provide adequate power to Omond House and astronauts wouldn't be left without power. Solar panels were also used to maximize the location of Omond House at the Shackleton Crater. Because there is near constant sunlight through much of the year on the rim of the crater, solar power is ideal at this location.

(a)	Cost (2x)	Complexity (1x)	Need for Power Storage (4x)	Weight / Size (1.5x)	Power Generated (3x)	Weighted Total
Photovoltaic (Solar Arrays)	U: 7 W: 14	U: 7 W: 7	U: 5 W: 20	U: 5 W: 7.5	U: 8 W: 24	**72.5**
Radioisotope Thermoelectric Generator (RTG)	U: 6 W: 12	U: 6 W: 6	U: 1 W: 4	U: 9 W: 13.5	U: 1 W: 3	38.5
Nuclear Fission	U: 2 W: 4	U: 5 W: 5	U: 10 W: 40	U: 6 W: 9	U: 9 W: 27	**85**

(b)	Cost (3x)	Weight (2x)	Reliability (2x)	Availability (1x)	Power Generated (4x)	Weighted Total
Silicon Solar Cells	U: 9 W: 27	U: 5 W: 10	U: 4 W: 8	U: 9 W: 9	U: 3 W:12	66
Gallium Arsenide Solar Cells	U: 1 W: 3	U: 7 W: 14	U: 8 W: 16	U: 2 W: 2	U: 9 W: 36	**71**

Fig. 6.2: (a) Power generation method decision matrix. (b) Solar cell material decision matrix [40,41,42].

The next decision to be made was what material to use in the manufacturing of the solar cells to be used for the solar arrays. The two materials analyzed and compared are Silicon and Gallium Arsenide. Results of this trade study are displayed in Figure 6.2b. Silicon is a much more available and common resource in comparison to Gallium Arsenide, which is why it is much more commonly used in the energy and space industries. Because it is so much more common, Silicon solar cells cost almost a thousand times less than Gallium Arsenide cells to manufacture, which is an important advantage of using Silicon cells for most applications. However, electrons are able to move through Gallium Arsenide much quicker than they can through Silicon meaning Gallium Arsenide cells have a much higher power density, can generate more power for a given area of cells, and are more efficient than Silicon solar cells. Gallium Arsenide also has a natural resistance to moisture, radiation, and UV light making it a great choice for space and lunar power applications [42]. Although they cost orders of magnitude more than Silicon cells, the efficiency and power output increase from using Gallium Arsenide solar cells outweigh the significant increase in cost.

6.3 Power System Design

Based on the calculated estimate power requirement and trade studies completed, an initial design for the Omond House power system was determined. The power system is to be deployed in two phases:

1. A gimballed Gallium Arsenide solar array attached directly to the primary habitat module to generate initial power to critical systems and reserve power.
2. Two Kilopower nuclear fission reactors used to generate primary power for Omond House.

The primary purpose of the phase one power system is to generate sufficient power to run critical systems the moment astronauts land on the lunar surface and support them while they complete tasks over their first 72 hours on the lunar surface. Assembling and turning on the phase two power system is the primary objective for the astronauts once they land on the moon. The phase one power system ensures that the astronauts have immediate access to life support and other critical systems. The system itself is made up of one deployable solar array made out of Gallium Arsenide solar cells similar to those used on the Orion service module. Instead of the X-wing design used for Orion (Figure 6.3), the phase one power system incorporates the area of the four solar panels on Orion into one large solar array. An illustration of the deployed phase one power system can be seen in Figure 6.4. The solar array will have gimballing capability to ensure the maximum angle of incidence of sunlight impacts the solar arrays regardless of the sun's position in the sky or habitat landing position. The power generated by the phase one power system is approximately 11.2 kW, which is enough to continuously provide power to critical systems until the phase two power system is established [43]. The solar array will be deployed remotely prior to the crewed mission to the habitat to ensure life support systems are up and running, and Omond House is habitable when the astronauts arrive.

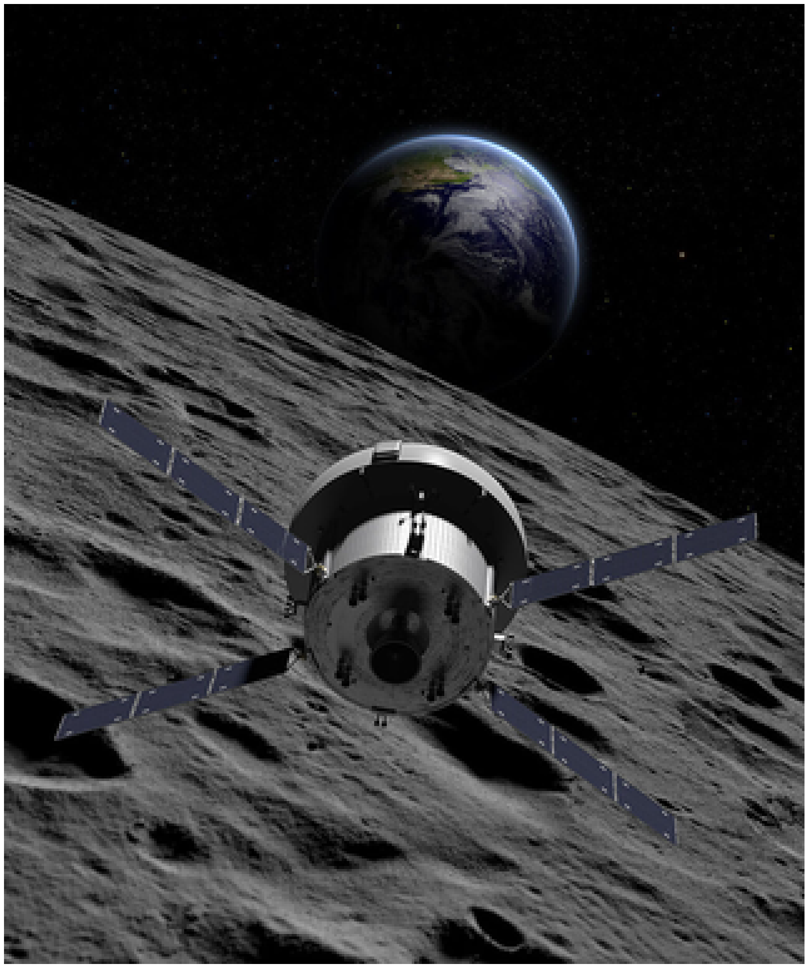


Fig. 6.3: X-wing solar array design used on the Orion spacecraft [44].

If the phase one power system is deemed completely unusable and cannot be repaired the astronauts have two options. They must either assemble the phase two power system within the first 72 hours of the mission or return to Earth. The former option is riskier. If the system runs nominally, the astronauts are provided with enough power to inhabit Omond House even without the phase two power system ensuring astronaut safety. The phase two power system provides the total power required to run both critical and non-critical systems needed to complete mission objectives and establish a permanent lunar settlement.

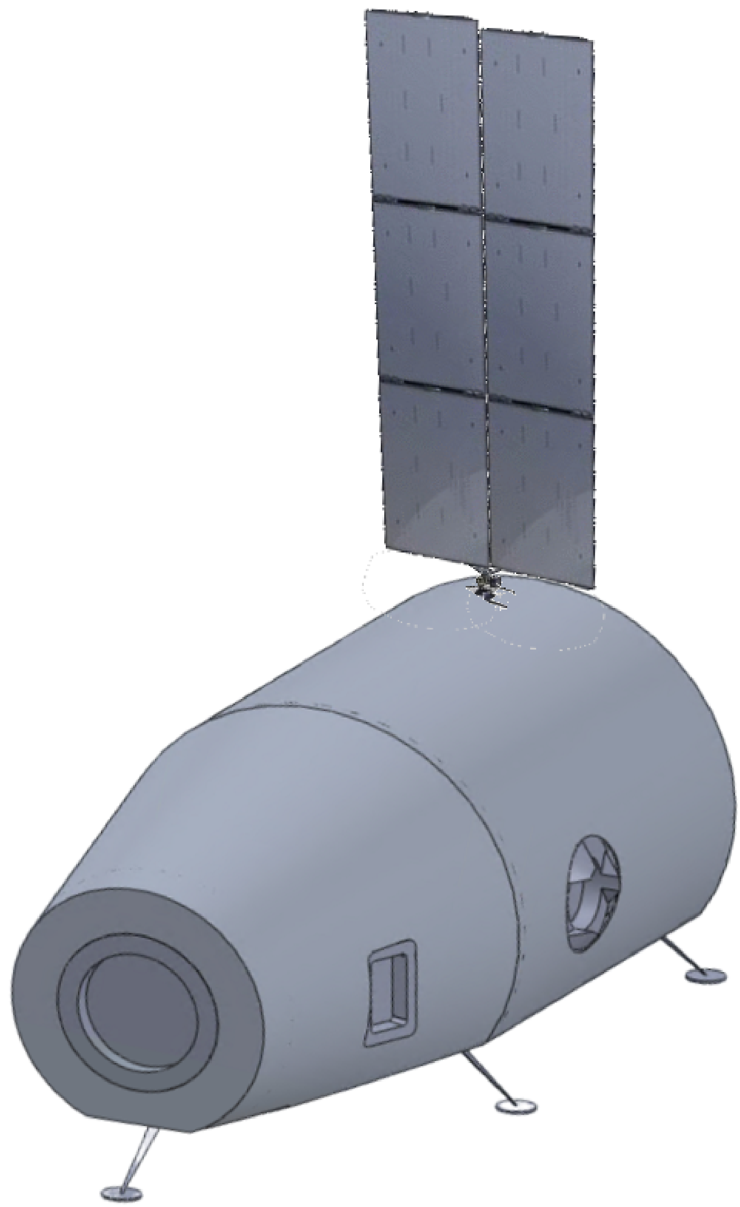


Fig. 6.4: Phase one power generation system.

Once phase one power is being provided to Omond House, the astronauts can focus on turning on phase two power, two Kilopower nuclear reactors. Figure 6.5 displays the design for a 10 kW Kilopower nuclear reactor currently being developed by NASA. Currently the technology is in TRL 5 and testing is being completed through the KRUSTY experiment [45]. Each Kilopower reactor is made up of a Uranium core, a stirling power conversion unit, heat pipes and a radiator for reactor cooling, radiation shielding, and a boron neutron absorber control rod. A schematic for the Kilopower reactor is shown in Figure 6.6. Once turned on, the power generated by phase two is able to deliver 20 kW plus the 11.2 kW from phase one power to the Omond House systems. The total power provided by the power system is approximately 31.2 kW, which is more than enough to run all systems that require a total of 25 kW. On astronaut arrival to the lunar surface, the two Kilopower reactors have already been deployed from the lander to the lunar surface about 50-100 meters away from Omond House. With the aid of the MMSEV, the astronauts must deploy cable and connect the reactors to the habitat. Once the reactors are wired and ready to be turned on, astronauts must remove the boron rod that has been suppressing the fission reaction. On removal, the uranium atoms will begin to split, and the reaction will begin [45]. At this point, phase two power will be generated by the fission reaction and this power is transmitted to Omond House via the cable hook up. Once phase two power is operational, non-critical systems can be turned on and other mission and scientific operations may begin.

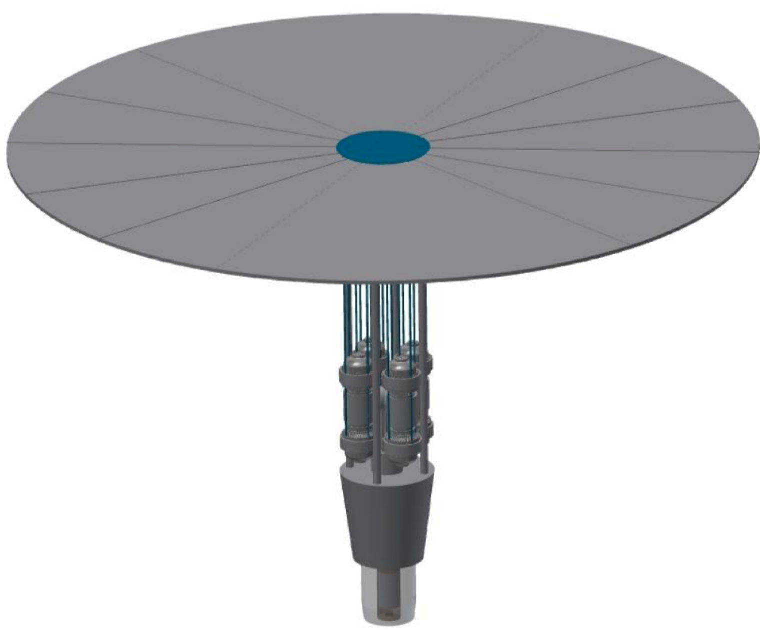


Fig. 6.5: 10 kW Kilopower nuclear fission reactor [41].

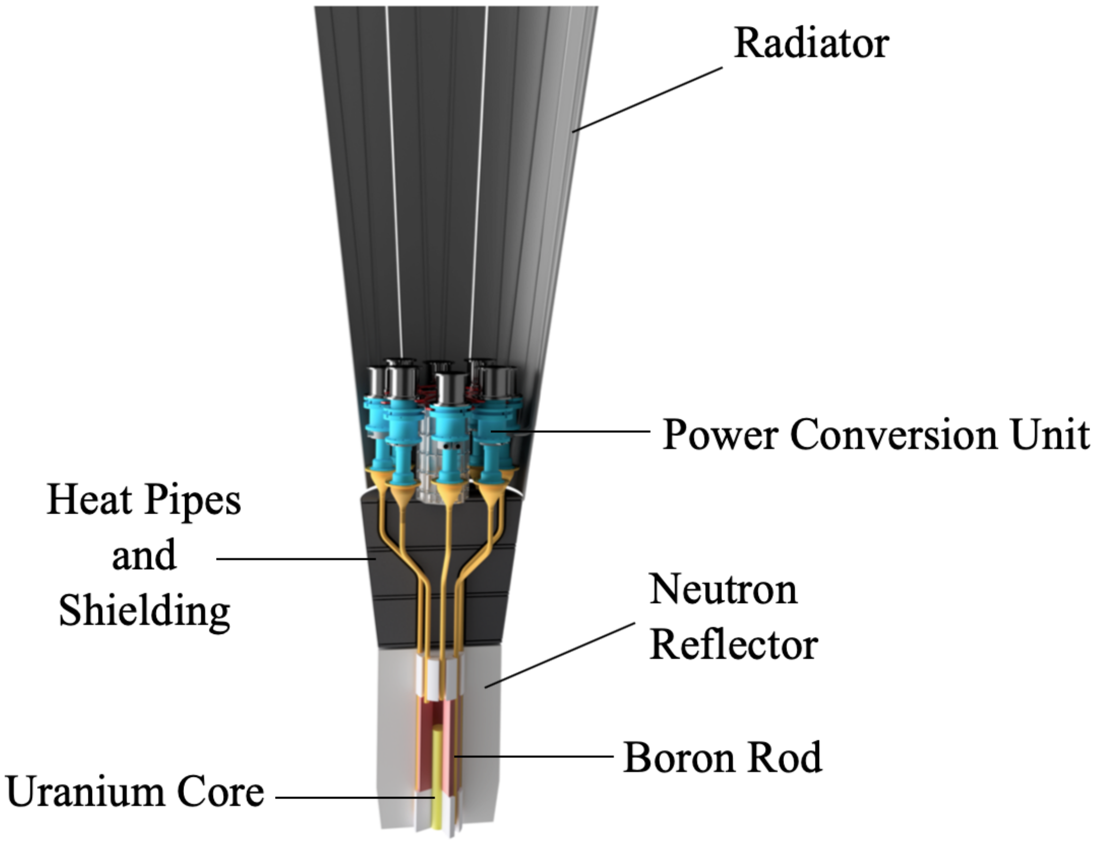


Fig. 6.6: Kilopower reactor schematic [46].

The most challenging aspect of the Omond House power system design is the power storage system. Even though Omond House will be in near constant sunlight for much of the year, there are still periods of darkness. The max time Omond House will spend in darkness is still 221 hours, which is a long period of time in terms of power storage needs [47]. This means that without any other power sources, the power storage system would have to support the critical systems of the habitat for 221 consecutive hours, which is not feasible without either a large amount of batteries or regenerative fuel cells. Using Kilopower reactors decreases the need for massive amounts of stored power. Power storage cannot be ignored though, even with the aid of the Kilopower reactors. The power storage system designed for Omond House is made up of 48 120V Lithium Ion batteries that have been scaled from Orion spacecraft heritage. The Lithium Ion battery used is illustrated in Figure 6.7. The total energy storage capacity of these batteries is 172.8 kWh [48]. More research into power storage systems like cryogenic regenerative fuel cells should be completed for future base expansions so that there is not such a large dependence on the Kilopower nuclear reactors to ensure adequate power to the base's critical systems during periods of darkness. An illustration of the operational Omond House power system including the power generation systems, power management and distribution systems (PMAD), and MMSEV is displayed in Figure 6.8.

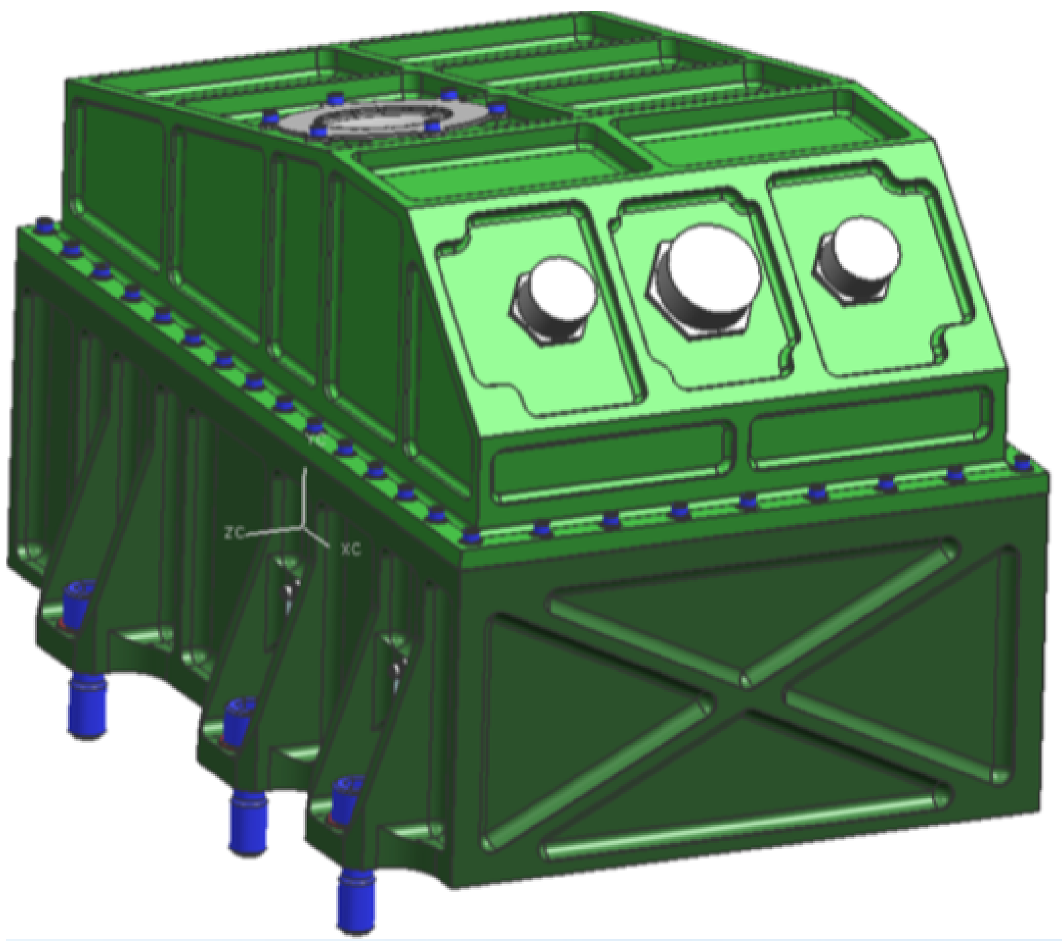


Fig. 6.7: 120 V Lithium Ion Battery - scaled from Orion [49].

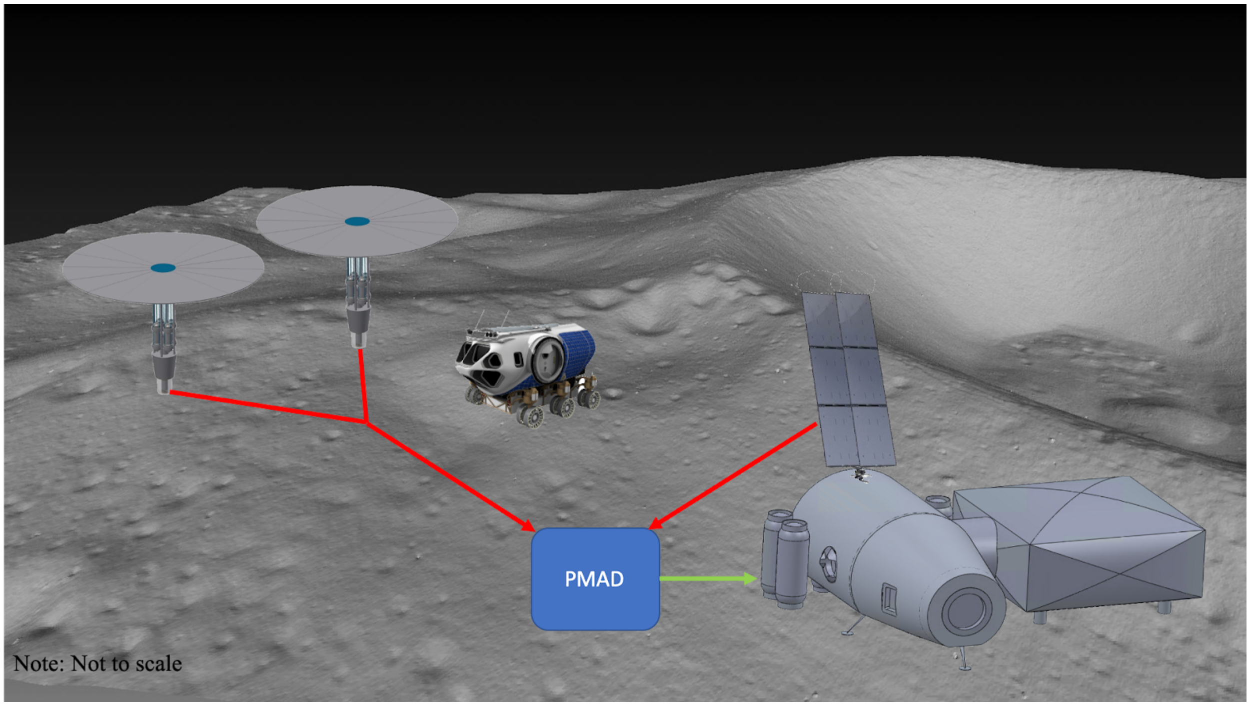


Fig. 6.8: Omond House power system illustration [46, 50].

A simplified block diagram schematic for the phase two power system is illustrated Figure 6.9. The solar arrays capture sunlight and convert the solar energy into electrical power. The Kilopower reactors convert the nuclear energy from the fission reaction to electrical energy and transfer it to the PMAD systems. The power from the solar arrays and Kilopower reactors is combined in a voltage converter. If batteries are not fully charged, power flows through a charge controller and charges the batteries. When the batteries are fully charged, power flows directly from the voltage convertor to the Main Bus Switching Unit (MBSU). The MBSU is essentially a main junction for the power system where electrical energy is segmented and distributed to different loads. Power flows from the MBSU to different DC-to-DC Conversion Units (DDCU) that convert the electrical signal to proper voltage magnitudes required by each load.

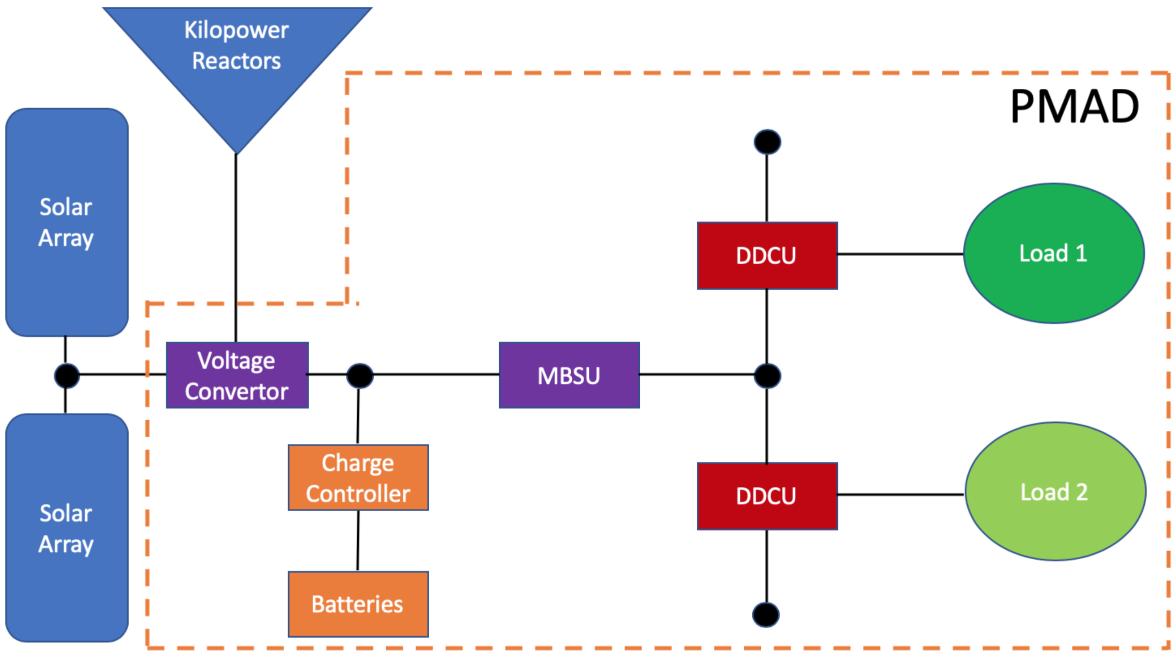


Fig. 6.9: Power system simplified block diagram [50].

6.4 Extensibility

The most important factor for extensibility will be power storage capabilities. More research should be put into using cryogenic regenerative fuel cells (RFCs) in addition to Lithium Ion batteries. RFCs are made up of an electrolyzer and a fuel cell that can convert electrical energy from the solar arrays and Kilopower reactors into chemical energy for storage and then back when needed. A schematic of a cryogenic RFC is displayed in Figure 6.10. Cryogenic RFCs are the best permanent lunar settlement power storage device because they have the highest power density and decays by a much smaller amount over time compared to batteries. Cryogenic RFCs are preferred over non-cryogenic RFCs because non-cryogenic RFCs require that the gases within them are kept at extremely high pressures. This leads to needing extremely heavy tanks, increasing the mass requirement of the power system. Minimizing the mass needed is an important consideration, especially for launches where payload is limited. Instead of keeping the gases at high pressures, cryogenic RFCs work by keeping its components at extremely cold temperatures. The main issue with using cryogenic RFCs is deployment. Because cryogenic RFCs can only operate at an extremely cold temperature, they must be placed within the Shackleton Crater. The complexity of having to figure out how to place them in the crater is the main issue of implementation [51].

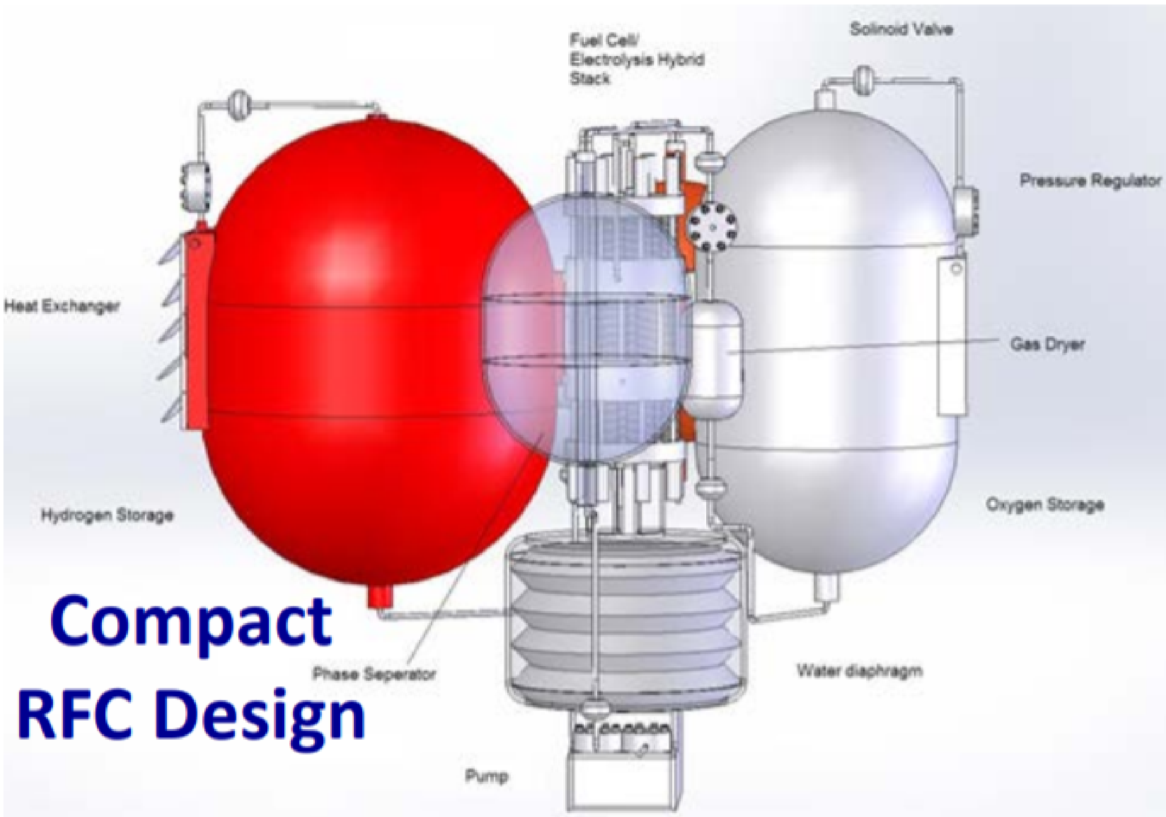


Fig. 6.10: Cryogenic Regenerative Fuel Cell Schematic [52].

6.5 Mass, Volume, Area, and Lifetime Estimates

Initial mass, volume, area, and lifetime values can be calculated for the power system. These totals include the solar array, Kilopower reactors, batteries, PMAD system, two ATHLETE rovers, and associated power system hardware. Estimated totals are displayed in Table 6.1. The calculated totals for mass and volume fit within launch requirements with room for margin.

Total Mass of Power System	7420.44 kg
Total Volume of Power System	36.45 m^3
Total Area of Solar Arrays	28.32 m^2
Designed Lifetime of Kilopower Reactors	12 years
Lifetime of Arrays on Lunar Surface	2-3 % efficiency decrease / year of operation

Table 6.1: Solar array cost, mass, area, volume, and efficiency estimates [41, 43, 48, 53, 54, 55].

7. Communications

A robust communications network is essential to supporting the well-being of the crew throughout their missions. Additionally, operating a Lunar base creates an important opportunity for the testing and demonstration of new and improved technology. The system will be responsible for communicating audio, video, life support, science, and equipment commands and health data to and from Omond House while crewed. Additionally it will need to communicate trajectory, descent and landing data to help get the habitat and cargo safely to the Lunar surface.

The Omond House communications network will incorporate both S-band radio communications and laser communications. S-band was selected for the primary communications network to provide robust and continuous communication with Earth. The laser communications terminal provides the capability to achieve high data rates at relatively low power cost. Having the capability to transmit and receive at high data rates allows for the transfer of high resolution images and scientific files to be sent, in full, back to Earth.

7.1 Communications Relay Satellite

Due to the 1.5° declination in the Moon's orbit, the south pole of the moon will experience Earth rises and sets. These events will likely occur at about the ascending and descending nodes of the Lunar orbit respectively. Earth will only be visible from our landing site at Shackleton Crater for about two weeks of the four week period of the Lunar orbit. Since ground stations on Earth will not be continuously visible from Omond House on the rim of the Shackleton Crater, a communications relay is necessary in order to prevent a two-week communications blackout between Earth and Omond House. A communications relay satellite will be used to close this two-week gap.

The relay satellite will be equipped to relay communications using both S-Band and laser communications systems. The orbit for the relay was selected based on a proposed orbit for the lunar gateway. This orbit was chosen to both maximize the time spent south of the moon and to entertain the possibility that the lunar gateway could fill this role. The relay satellite will be put into a southern near rectilinear halo orbit (NRHO) around the Earth-Moon Lagrange Point #2 (EML2). This orbit is shown in blue in Figure 7.1 below.

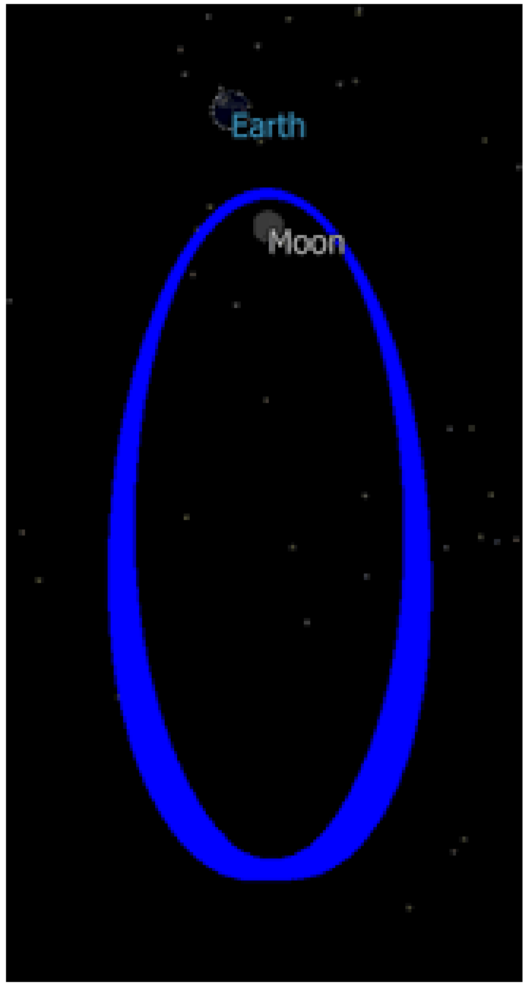


Fig.7.1: Desired Relay Satellite Orbit [56].

The satellite orbit will take it as close as 1,600 km from the lunar surface (when it passes North of the moon) and over 68,000 km away from the lunar surface (when it passes South of the moon) [57]. This highly eccentric orbit maximizes the time the spacecraft spends south of the moon, where it can create a connection between Earth and Omond House. The pass around the north side of the moon will take a few hours and communication will be lost during this time. For human expeditions to space constant communication with the crew is desirable to ensure their safety. To prevent any gaps in communication, a second relay satellite will be used. The two satellites will use the same orbit, but will be offset so that they are never both on the North side of the Moon at the same time.

7.2 Laser Communication Equipment

The laser communications network will include a single terminal at the lunar base and a double terminal on each of the relay satellites. The double terminal would simply mount two optical modules so one can be constantly receiving and the other can be constantly transmitting in a different direction. The Lunar Lasercom Space Terminal (LLST) is composed of three modules: optical, modem, and control. The optical module is composed primarily of a telescope, and a gimballing system allowing it to change direction. The modem module takes care of power amplification and the control module handles the modulation and demodulation of the signal. The LLST has been flight tested on the LRO and the Lunar Atmosphere and Dust Environment Explorer (LADEE). The configuration is shown in Figure 7.2. Each of these modules weighs about 30kg and operates at about 90W of power [58].

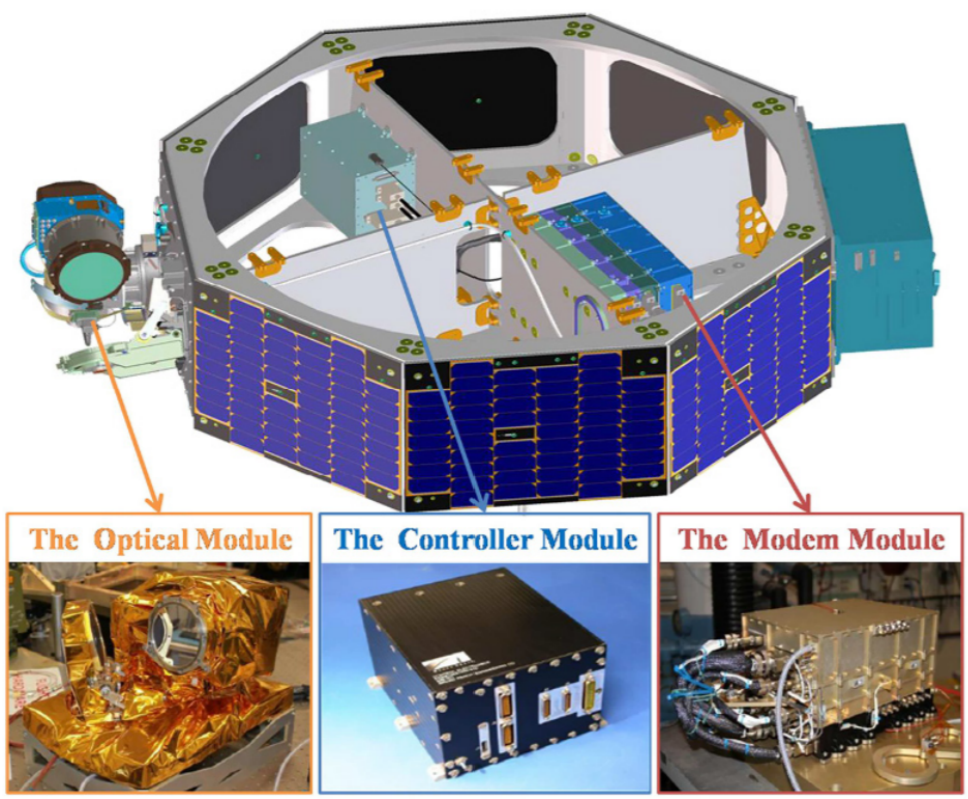


Fig. 7.2: Lunar Lasercom Space Terminal Configuration [58].

The optical module is gimbaled for accurate pointing and tracking of the uplink signal. The maximum uplink and downlink rates achieved by the lunar orbiters are 20Mbps and 620 Mbps respectively [58]. The laser communications equipment on the relay satellite and in the habitat of Omond House will be nearly identical to the equipment displayed in Figure 7.1 above. Therefore we expect the maximum data rates previously achieved to be our maximum data rates as well.

There are a limited number of ground stations with the capabilities for laser communications. These ground stations are located in California, New Mexico, and the Canary Islands. They are controlled by the Lunar Lasercoms Operations Center (LLOC) which is located at the MIT Lincoln Laboratory in Lexington. We hope the next decade will bring expanded laser communications ground systems, but will not make assumptions about the geography or capabilities.

7.3 S-Band Communication Equipment

The Unified S-band network will serve as the primary communications network for Omond House. The necessary equipment will be present on both the habitat and the communications relay and may vary depending on the choice of the relay. It will include a pair of low, medium, and high gain antennas to account for all necessary communication modes and redundancies. The equipment on the relay satellites will be doubled to enable the satellites to transmit and receive the full amount of information in different directions. These modes include communication with Earth, EVA communication, large data uploads and downloads, and emergency communications.

NASA's Near Earth Network (NEN) was selected for the communications ground network. The NEN includes over 25 antennas at ground stations across all seven continents from Alaska to Antarctica [59]. This abundance of ground system support is the most important reason for choosing the NEN. This will support the continuous communication between Earth and Omond House [59].

7.4 Extensibility

The ideal communications scenario is a relay that creates a permanent connection between Earth and Omond House. This is possible, due to the unique characteristics of Malapert Mountain. Malapert Mountain refers to a region of the rim of Malapert Crater which is highlighted in Figure 7.3 below. It has the unique feature of maintaining a constant line of sight with both the rim of Shackleton Crater and Earth, making it the ideal landing spot for a permanent communications relay.

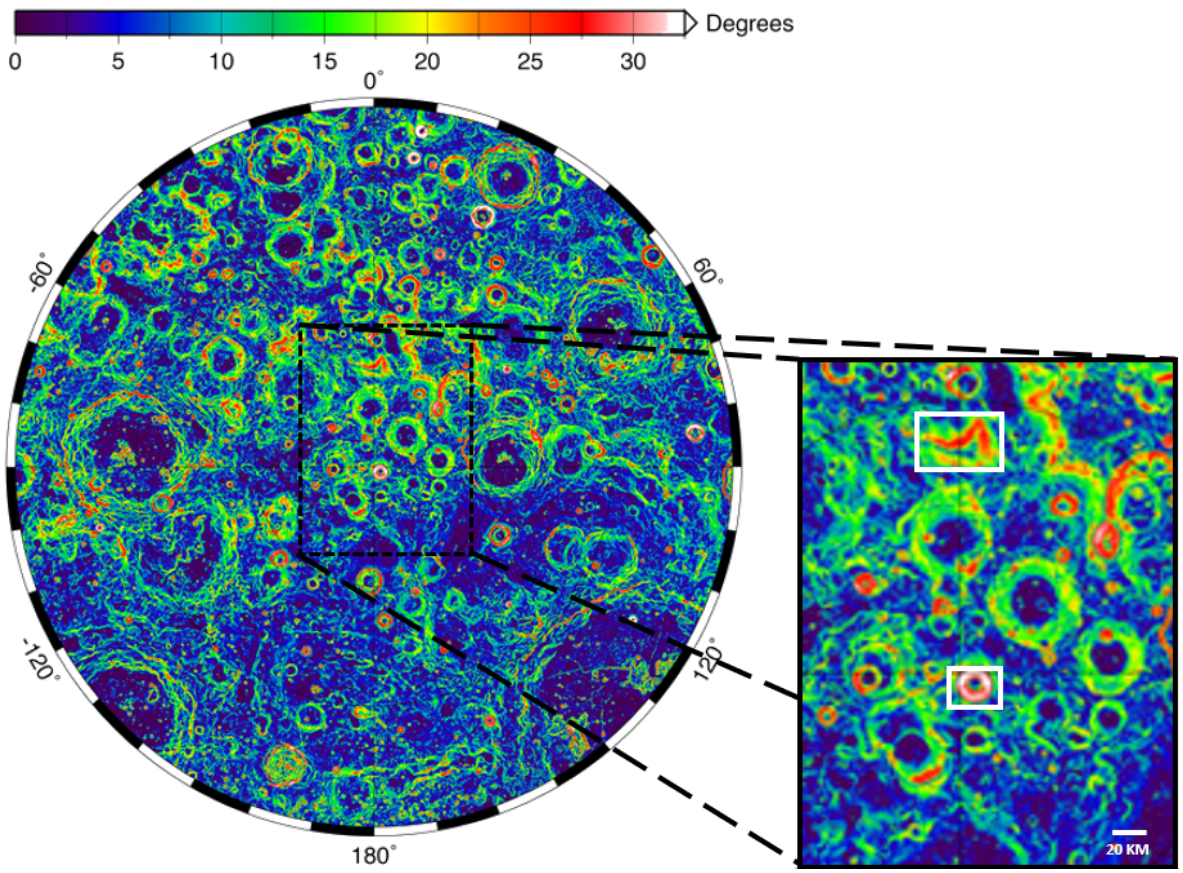


Fig. 7.3: Topography of Lunar South Pole Region - Malapert Mountain & Shackleton Crater [60].

Considerations for a relay at Malapert Mountain were made, but there is not enough room in the budget for an additional moon landing, and the treacherous terrain between Shackleton Crater and Malapert Mountain, shown in Figure 7.2 above, is too risky to send a rover that would function as a relay. Although the first generation of Omond House will not establish a relay here, it's an important feature for the extensibility of the lunar base camp.

7.5 In-Transit Communication

The primary habitat lander will include a basic S-Band communications system for orbit maneuvers and landing. Additions to the S-Band network and the laser communications equipment will be transported to the lunar surface in the cargo launches. The cargo launches will rely on the communications networks of the commercial landers contracted to deliver the payload to the Lunar surface.

8. Command & Data Handling (C&DH)

The C&DH system of Omond House is essential to the success of the mission. The system in the habitat will focus on extensibility and modularity. This will allow crews and science operations to come and go during the lifespan of the habitat, and new pieces to be added to the habitat without much difficulty connecting. A Wifi network will be used to connect essential subsystems in the habitat and allow easy connection of science operations and computer terminals. The wifi network helps to maximize the extensibility of the habitat, allowing data to be accessed at any connected computer and the number of connected computers will not be limited by available ports. The scientific operations to be conducted at Omond House will likely output large data files. To maximize the capacity for these operations, it's important to have an abundance of storage for these files. The habitat will be equipped with an abundance of solid state storage, to make sure data storage never inhibits our scientific progress. This plan for the habitat's C&DH network is displayed in Figure 8.1 below.

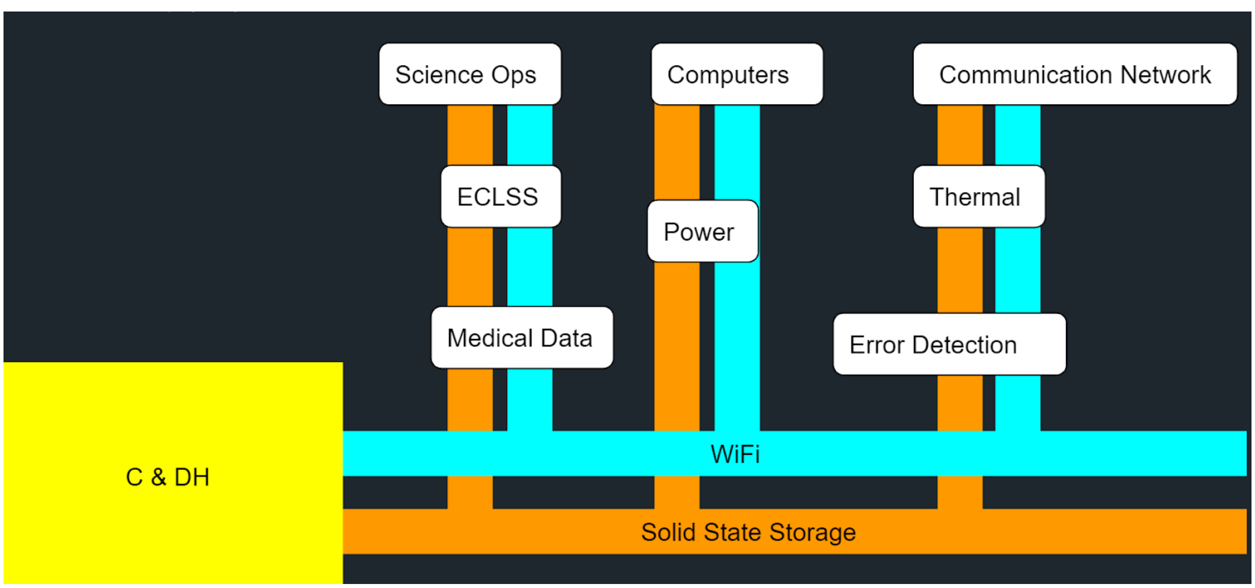


Fig. 8.1: C&DH Network Plan

9. Launch Vehicles

9.1 Launch & Trajectory Overview

The ideal trajectory to transport the Omond House payloads to the Moon is one that minimizes fuel cost and can allow for a precise and accurate descent to the Shackleton Crater landing site at the lunar south pole. Fortunately, the heritage on lunar trajectories is extensive, due to both manned and probing missions that have been taking place since the late 1950's, most notably the Apollo and GRACE missions. Because this segment of the Omond House mission is uncrewed, this trajectory is not constrained by the psychological and physiological needs of astronauts, or by the safety factors necessary to mitigate the potential loss of crew life. For these reasons, the time of flight (TOF) and abort capabilities of the transfer are not weighted in the decision matrix of the trajectory trade study, seen below in Table 9.1.

A Hybrid trajectory (Elliptical Free-Return + Hohmann-esque Transfer with an elliptical initial orbit) allows the payload to ballistically return to Earth should flight deployment systems fail. However, this trajectory requires a TLI burn near the perigee of the free return elliptical orbit. Due to the Oberth effect, this trajectory requires more ΔV than a Hohmann transfer, in which the TLI burn occurs in Low Earth Orbit (LEO), making the Hohmann transfer more desirable in this category. Hohman transfers have some abort capability, as burns can be performed in order for the payload to slingshot around the Moon and return to Earth. A Low-Energy Trajectory requires less ΔV than any other trajectory in this trade study, requiring about 130 m/s less than a Hohmann transfer [61]. In addition, low-energy trajectories have a TOF of two to three months, significantly longer than the two to three-day TOF of Hohmann and Hybrid Transfers. This allows the burns to be scheduled during times in which the spacecraft can communicate with both the Madrid and madrigal Deep Space Network (DSN) stations, allowing dual complex coverage of mission critical events [61]. The long transfer time, as well as the dual coverage from DSN allow for a comfortable operating environment in which small-specific impulse burns can be performed over a large period of time for high trajectory precision. Low Energy transfers also have long launch windows (~ 21 days), whereas Hohmann and Hybrid transfers usually do not have more than three consecutive dates in their Launch windows [61, 62]. This creates a high margin for error in case of weather conditions or errors discovered in a flight readiness review delay launch. For these reasons, a low-energy trajectory is the clear choice.

DECISION MATRIX	ΔV		TOF		Abort Capability		Transfer Window		Weighted Total
	Wt	4	Wt	1	Wt	1	Wt	3	
	U	W	U	W	U	W	U	W	
Hohmann Transfer	4	16	7	7	6	6	4	12	41
Low-Energy Transfer	9	36	3	3	3	3	9	27	69
Hybrid Trajectory	3	12	6	6	8	8	4	12	38

Table 9.1: Trajectory Decision Matrix.

A Bat Chart showing the current launch and landing plan can be seen below in Figure 9.1. Five Falcon Heavy launches will be performed in the summer and autumn of 2030 at Cape Canaveral Air Force Station in Florida.

The first launch payload will contain the MMSEV rover, the communications relay satellites, and a Blue Moon lander. The second launch will contain the habitat lander, which will remain in an LEO parking orbit until the ascension of the third launch, which will be carrying the habitat module. In LEO, the habitat module and lander will rendezvous, dock, and then perform a joint TLI burn. The fourth launch will deliver power systems , which consists of two Kilopower reactors, power storage, and PMAD. It will also contain two ATHLETE rovers, and a Blue Moon lander. The fifth and final launch will carry science operations systems, namely the tuft-pillow module & other general science equipment, as well as life support consumables (waste, nitrogen, and oxygen tanks, as well as food) and a Blue Moon lander.

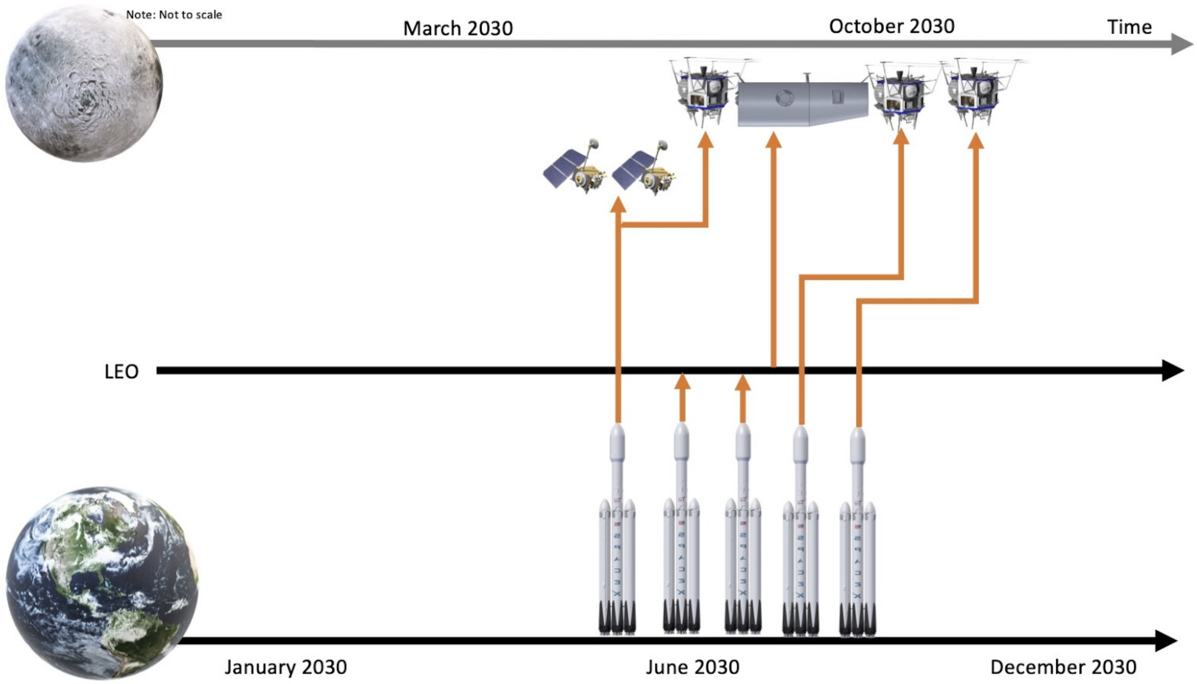


Fig. 9.1: Bat Chart for all Omond House Launches [63, 64, 65].

After launch, the spacecraft will utilize a Low Energy Trajectory to reach the Moon. This trajectory can be seen in Figure 9.2.

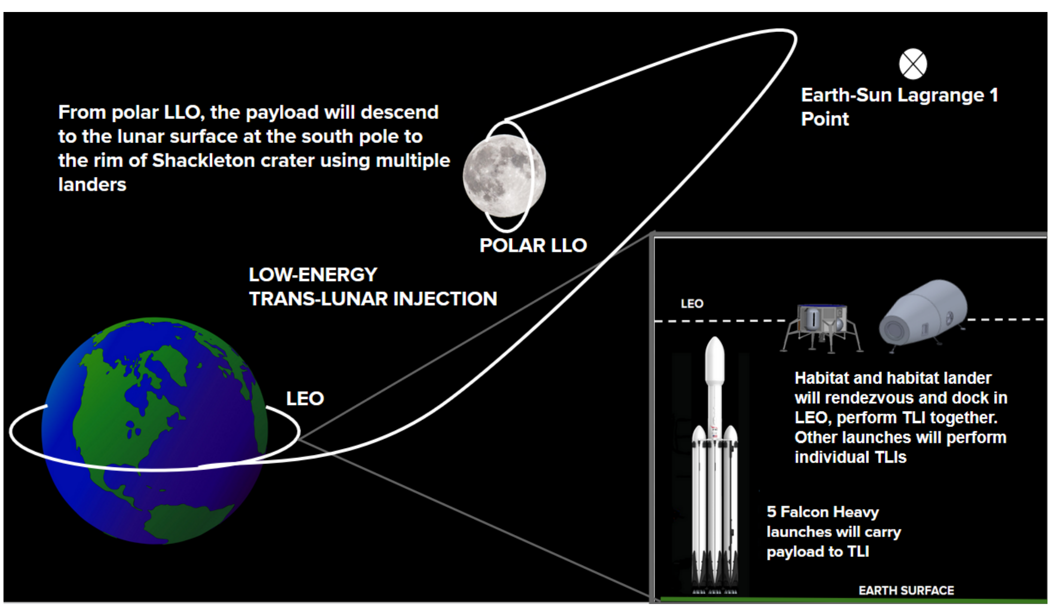


Fig. 9.2: Launch Trajectory ConOps.

In LEO, a TLI burn will be performed by the spacecraft to raise their apogee to 1.5 million kilometers from Earth [66] into the manifold of the first Earth-Sun Lagrange point (EL1). The EL1 manifold is a chaotic region in which small perturbations create large differences in the following trajectory. Here, the spacecraft will perform a small burn to adjust the trajectory in order to intercept the Moon. Once at the desired altitude above the lunar surface, the spacecraft will perform another burn to be captured into a 100 km polar low lunar orbit (LLO). From here, the communications relay satellites will separate from the rest of the payload from the first launch, and insert themselves into NRHO. From LLO, spacecraft will execute deorbit burns to begin the descent to the lunar south pole. As the landers approach the surface, a braking burn will slow each lander to a stop. The ΔV for each burn can is tabulated below in Table 9.2.

Maneuver	ΔV [m/s]
TLI Burn	3180
EL1 Burn	9
LOI Burn	400
Deorbit Burn	315
Braking burn	1700

Table 9.2: ΔV for all maneuvers [67].

9.2 Launch Vehicle Selection

The Falcon Heavy is currently the selected vehicle, but many were considered. Table 9.3, below, shows the trade study that was completed analyzing the current and planned heavy launch vehicles. Technology readiness had the highest weighting due to the RFP's focus on using existing technology wherever possible. The cost per kilogram was weighed next, and this is to emphasize the cost efficiency of the vehicle. Following is the payload capacity to TLI, then fairing diameter, and finally cost per launch.

DECISION MATRIX	Cost/Launch		Cost/Kg		Payload to TLI (kg)		Fairing Diameter (m)		Technology Readiness		Weighted Total
	Wt:	1	Wt:	4	Wt.	3	Wt:	2	Wt:	5	
	U	W	U	W	U	W	U	W	U	W	
SLS	1	**1**	1	**4**	9	**27**	10	**20**	1	**5**	**57**
Falcon Heavy	8	**8**	8	**32**	8	**24**	7	**14**	10	**50**	**128**
Starship	10	**10**	10	**40**	10	**30**	9	**18**	1	**5**	**103**
Vulcan	9	**9**	9	**36**	3	**9**	8	**16**	5	**25**	**95**
New Glenn	7	**7**	7	**28**	5	**15**	7	**14**	3	**15**	**79**

Table 9.3: Trade Study of launch vehicles [68, 69, 70].

The Space Launch System (SLS) Block II was the first vehicle analyzed. This vehicle suffered mostly in the technology readiness category, due to the number of budget and schedule slips the program has dealt with. There is also a question about whether enough SLSs will be produced in order to procure one outside of their already planned manifest. The SpaceX Falcon Heavy was the second vehicle analyzed, and the winning vehicle. Because it was the only flight-proven vehicle analyzed, it took the highest ranking in the technology readiness category. SpaceX is also responsible for the third vehicle analyzed, the Starship. This scored the same in the technology readiness category as SLS due to the groundbreaking work that is required to get the rocket flying. It is, however, the heaviest lift vehicle analyzed and, if it performs and is costed like promised, would be a legitimate launch option. The United Launch Alliance (ULA) Vulcan was the lightest lift vehicle considered, and its performance impacted because of it. Finally, the Blue Origin New Glenn was the final vehicle looked at in depth. It is still a lighter-lift rocket and still suffering in the technology readiness category as Blue Origin has not regularly been completing orbital launches like the other companies involved. Other vehicles looked at but not considered in the final trade study were Ariane 6, due to the logistical issues involved with transporting payloads from the US to their launch sites, Atlas V, due to the Vulcan being the newer development of it, and the other versions of the SLS, due to availability concerns.

Official numbers have not been released for what the Falcon Heavy could bring to TLI but referencing expert opinions and interpolating with other published payload numbers, the estimated range is between 20-22 tons [71, 72]. This number will be further refined as the delta-V budget is finalized. Also, the published $150 million per launch value was used for costing 73]. The faring is 5.2m in diameter and 13.9m in length [74]. Five launches were required to fit the volume requirements for the payloads. Selecting a launch vehicle 10 years in advance is difficult, and this trade study demonstrates that the market should have multiple healthy options that are capable of transporting all of the cargo to the surface. The team recognizes that the launch market may significantly change over the next decade, but it will likely evolve to include more options and not less. A mixed fleet may be required.

9.3 Lander Selection

The habitat module landing will be the second landing. Design considerations for this habitat module include emphasizing compatibility with the selected launch vehicle and minimizing deployment work required. It was specifically inspired by ULA's "Dual Thrust Axis lander" and Masten Space Systems' "Xues" lunar lander. The only deployment work required will be setup of the power grid to support the habitat module and surrounding base camp. Minimal debris cleaning from around the airlocks may also be necessary to allow for easiest ingress and egress but is not expected to be significant.

The other three landings will be commercial landers. The NASA Commercial Lunar Payload Services (CLPS) program has 14 companies currently involved in producing landers, with the NASA current stated goal being landing 300kg on the lunar surface [75]. This is far from the scale required for the lunar base camp. However, two companies involved in CLPS are already working on 4-5 ton landers: Blue Origin's Blue Moon and Lockheed Martin's McCandless Lander [73, 75]. Lockheed Martin has already stated an interest in developing further iterations of McCandless that can handle heavier payloads [76]. Other promising commercial lander developments include Blue Origin stating that the Blue Moon lander will be able to land with 75 ft accuracy on the lunar surface and includes a crane to transport payloads to the surface [77]. There are also many human-rated landers being developed, but little information is publicly available about them. Boeing has promised a lander focused on the “fewest steps to the Moon,” not relying on Gateway [78]. The other main contender currently seems to be the “National Team” lander, with components coming from Blue Origin, Lockheed Martin, Northrop Grumman, and Draper Space Systems [79]. More information on these landers, specifically with regards to their developments in the Artemis program, will be released in the upcoming weeks.

Since the commercial lander market is developing rapidly, it is expected that landers with the payload capacity necessary for this kind of mission will be developed in 5-7 years: in time for the lunar base camp mission. For the current estimates, a combination of Apollo technology and lander projections were used to determine payload manifests and sizing information.

9.4 Landing and Deployment

Following the first landing, the MMSEV will deploy and attempt to communicate with Earth via the communications relay satellite. After successfully establishing communications, MMSEV will be utilized by operators on Earth to survey the area in order to find an optimal landing location for the Habitat. This will be performed in the six weeks between the first landing, containing the MMSEV, and the second, which will deploy the habitat. Afterwards, the MMSEV will begin transporting the other payloads to the habitat module landing site, as seen in Figure 9.3.

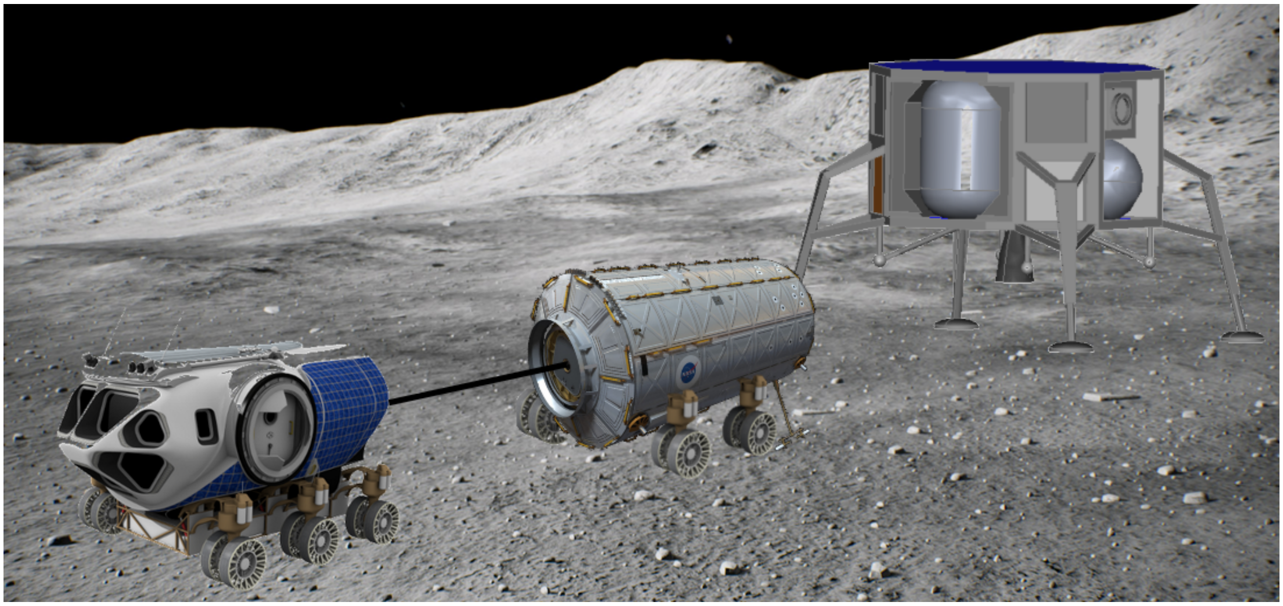


Fig. 9.3: MMSEV towing payloads toward the habitat.

Subsequent to the second landing, the habitat will be lowered to the Lunar surface via the HL crane. It will then autonomously deploy the first phase power system in order to power critical systems and initialize communications with Earth.

The third landing, corresponding to the payload of the fourth launch, will be towed to the habitat lander site by the MMSEV. Here, the ATHLETE rovers will deploy and begin the installment of the two Kilopower reactors, power storage, and PMAD systems necessary for the second power phase. Figure 9.4 below evidences the dexterous capabilities of the ATHLETE rover.

Fig. 9.4: ATHLETE lowering a payload from a lander [80]

The fourth and final landing, containing science operation equipment and life support consumables, will be towed to the habitat module site by the MMSEV. Once there, the ATHLETE rovers will transport the oxygen, nitrogen, and waste tanks to their desired location. Figure 9.5 summarizes the deployment timeline before crew arrival. In this figure, "L" denotes the time of landing. Both the MMSEV and ATHLETE rovers are designed specifically to operate in the Lunar environment. Therefore, there are no concerns with regolith, radiation, or other environmental factors affecting their operational capabilities.

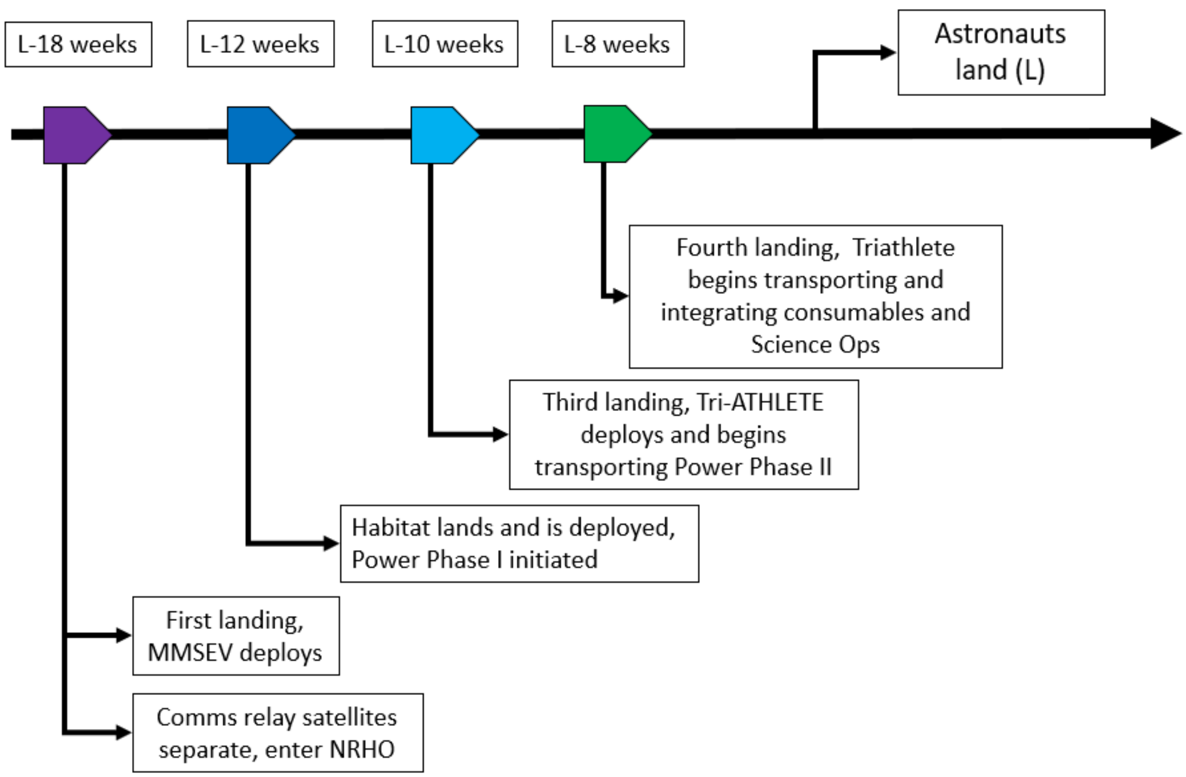


Fig. 9.5: Timeline of pre-crewed deployment.

Once the crew arrives, they will have 72 hours to finalize integration and deployment. An hour-by-hour time budget of the first 48 hours can be seen below in Table 9.4 of the schedule subsection. After these tasks are complete, the habitat module and it's life support systems will be completely set up, and science operations can begin, giving a 24 hour margin in case of unforeseen deployment issues.

Time, hours (initial, final)	Day	Activity
L L+2	1	Astronauts shuttle to habitat using the MMSEV
L+2 L+7	1	Astronauts connect oxygen, nitrogen, and waste lines to their respective external tanks, finishing their integration.
L+7 L+18	1	Astronauts return, eat dinner and rest.
L+18 L+20	2	Astronauts eat breakfast and prepare for EVA.
L+20 L+27	2	Astronauts split into two groups of two. Group one begins setup of the second power phase, wiring the Kilopower reactors to PMAD and the habitat using the MMSEV, while the second group uses the ATHLETE rovers to bring in consumables from the 5th launch.
L+27 L+38	2	Astronauts return, eat dinner and rest.
L+38 L+40	3	Astronauts eat breakfast and prepare for EVA.
L+40 L+48	3	Astronauts again split into two groups in order to finish the work of the previous day's EVA.

Table 9.4: Timeline of crewed deployment (first 72 hours after crew landing).

10. Schedule

Table 10.1 Details the Launches and Landings of Omond House's components.

Launch #	Launch Date	Landing Date	Components Included
1	May 2030	August 2030	MMSEV & Communications Satellites
2	July 2030	October 2030	Habitat Module
3	July 2030	October 2030	Habitat Lander
4	August 2030	October 2030	Science Operations Equipment and Life Support Equipment
5	August 2030	November 2030	Consumables and Storage Tanks

Table 10.1: Launches and Landings of Omond House's components

11. Costing

Costing was done with a few constraints from the RFP. The $12 billion budget is in FY2019 dollars, no human spaceflight needs to be included, and usage of commercial off the shelf (COTS) and existing architecture is "strongly encouraged." All new technology developments were costed with additional margins. Four different methods of costing were utilized.

The first costing method was simply using COTS numbers and publicly available costing data. This was primarily used for the cost of the Falcon Heavy launches and some initial lander estimates. The second costing method was the NASA Advanced Mission Cost Model (AMCM). This is an equation-based costing method with the dry mass of components being the major driving factor of the cost. This method was used for the habitat, and initial rover and lander iterations. The third costing method was using cost-estimating relationships (CER). The primary document used to provide these relationships was the NASA Cost Analysis of Life Support Systems. This is a 1973, Apollo-era document that was mainly used to fill in some of the costing gaps left by the previous two methods. It is recognized that the technology this document is based off of is significantly outdated, and that's why it was used only as a beginning reference point. The final costing method was the NASA Project Cost Estimating Capability (PCEC). PCEC is based off of the NASA Air Force Cost Model (NAFCOM) heritage but updated to be the best tool currently available. NAFCOM tools have traditionally had problems costing developing and new technologies, especially things like additive manufacturing, 3D printing, and composites. This is primarily due to the fact that the CERs in the model are developed using costing data from all NASA missions, including Apollo, Shuttle, ISS, New Horizons, Cassini, and the Mars rovers. The PCEC model also had NASA CADRe-based WBS built in, so a major upgrade to our WBS was completed. This also contributed to the significant increase in fidelity of our costing model.

The current best estimate of the cost is $11.85 billion dollars, or 98.73% of the allocated budget. This is detailed in the current work-breakdown structure (WBS) shown in Table 11.1, below. A 15% reserve cost is already included. This estimate increased by approximately 15% when the PCEC model was implemented, however, an additional launch was also added in. The most significant change when adding the PCEC model was having a better understanding of the personnel and management costs associated with a project of this scale. The previous costing methods lacked applicable CERs, which led to the reserve cost being decreased from 20% to 15%.

OMOND HOUSE	
1. Project Management	202,501,668
2. Systems Engineering	642,456,623
3. Safety & Mission Assurance	199,174,733
4. Science/Technology	325,000,000
5. Payloads	5,519,615,536
5.1 Payload Management	39,778,416
5.2 Payload Systems Engineering	81,341,175
5.3 Payloads	5,166,024,828
5.3.1 MMSEV + ATHLETE	700,000,000
5.3.2 Comms Relay	583,000,000
5.3.3 Habitat Lander	264,000,000
5.3.4 Habitat	2,671,895,307
5.3.5 Power Systems	94,624,636
5.3.6 Science Ops	715,000,000
5.3.7 Life Support	137,504,885
5.4 Payload I&T	232,471,117
6. Flight System	1,406,253,205
6.1 Flight System Project Management	74,782,975
6.2 Flight System Systems Engineering	86,470,230
6.3 Falcon Heavy	750,000,000
6.4 Commercial Lander	495,000,000
7. Mission Operations System	726,818,617
7.1 MOS Management	239,850,144
7.2 MOS Systems Engineering	414,286,612
7.3 Mission Operations Center	72,681,862
8. Ground Data System	370,424,063
9. System Assembly, Integration, Test	655,799,751
10. Reserves	1,800,000,000
TOTAL	11,848,044,196

Table 11.1: High level WBS and costing values.

Figure 11.1, below, shows the budget broken down as a percentage of the total budget. Payloads and payload engineering takes up the largest part of the budget, which is also where the most technology and hardware development will be required.

Figure 11.2, below, shows a comparison between the initial costing methods and the more accurate PCEC estimates. Some categories for the AMCM + CERs appear to have a $0 budget allocation, but that is due to further detailing out the WBS. Project management appears to have a much higher budget with the old method of costing, however, the new WBS means that sections 1 and 2 are program-level project management and systems engineering, while 5, 6, and 7 each have additional budget line items for management and systems engineering.

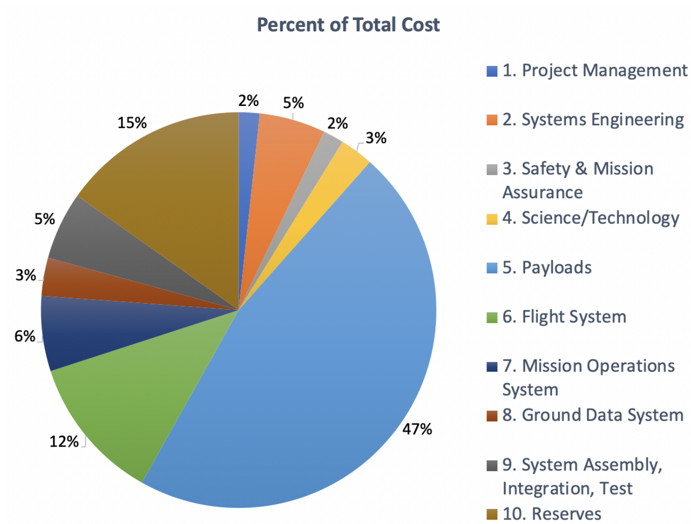


Fig. 11.1: Costing by percentage breakdown.

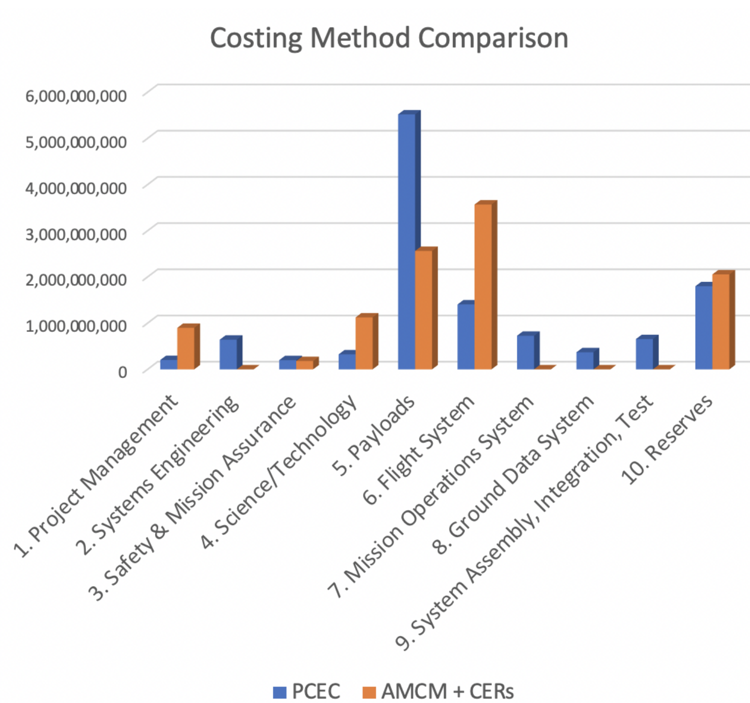


Fig. 11.2: Comparison between the two major costing methods used.

12. Compliance Matrix

<table>
<tr><th>Req. #</th><th>Requirement</th><th>Accordance</th><th>Pg. #</th></tr>
<tr><td colspan="4">Accordance Summary</td></tr>
<tr><td>1</td><td>The initial cost for the lunar base camp shall not exceed 12 Billion US Dollars from the start of the program through the human expedition.</td><td>YES</td><td>89-91</td></tr>
<tr><td colspan="4">With a 15% reserve, Omond House will cost 98.73% of the allocated $12 billion, or $11.85 billion.</td></tr>
<tr><td>2</td><td>The base camp shall allow for future expansions to accommodate more crew for longer duration in future missions.</td><td>YES</td><td>24-25, 27</td></tr>
<tr><td colspan="4">The habitat module is outfitted with three IDA ports for the addition of future modules. Experimental modules (tuft pillows) are also tested on this mission.</td></tr>
<tr><td>3</td><td>The launch manifest selected shall have base camp components delivered to the landing site on or before December 31, 2030.</td><td>YES</td><td>88</td></tr>
<tr><td colspan="4">All components will land in the summer of 2030, and will be towed to the habitat by the MMSEV in the autumn of the same year.</td></tr>
<tr><td>4</td><td>The base camp shall operate fully and support a crew of four people within 72 hours of their arrival on the lunar surface</td><td>YES</td><td>61-68, 87</td></tr>
<tr><td colspan="4">Using the first-phase power system, the crew will be able to immediately inhabit the habitat module. The second-phase power system and life-support consumables will be deployed and integrated by the crew in 48 hours, giving a 24 hour margin.</td></tr>
<tr><td>5</td><td>The astronaut habitat of the lunar base camp shall have structures and systems in place to limit radiation exposure to a maximum of 5 rem.</td><td>YES</td><td>32-37</td></tr>
<tr><td colspan="4">.6 m of polyethylene composite (or suitable stand-in, pending futher research) will shield the habitat module.</td></tr>
<tr><td>6</td><td>The power supply of the lunar base camp shall provide power to the base camp and its functions for 90 days.</td><td>YES</td><td>61-68</td></tr>
<tr><td colspan="4">Omond House will be powered by two Kilopower reactors and two gimballed gallium arsenide solar arrays.</td></tr>
<tr><td>7</td><td>The lunar base camp shall have a contained laboratory environment with necessary equipment to maximize scientific return.</td><td>YES</td><td>20-21, 55</td></tr>
<tr><td colspan="4">The habitat module will have dedicated scientific operation and storage space. In addition, experimental technologies will be tested external to the habitat, on the lunar surface.</td></tr>
<tr><td>8</td><td>The crew shall be supplied with minimum basal energy expenditure calorie rations per day per the National Research Council’s definition.</td><td>YES</td><td>51</td></tr>
<tr><td colspan="4">1.7 kg of food will be allotted per crew member per day in order to meet estimated energy requirements.</td></tr>
<tr><td>9</td><td>The base camp shall supply each crew member with a minimum of 0.65 gallons of water per day.</td><td>YES</td><td>40-42</td></tr>
<tr><td colspan="4">The semi-closed loop water system will output .65 gallons of water for each crew member every day.</td></tr>
</table>

<table>
<tr><td>10</td><td>Wastewater shall be filtered and recycled for reuse by the crew.</td><td>YES</td><td>40-43</td></tr>
<tr><td colspan="4">Wastewater will be purified through vapor phase catalytic ammonia removal.</td></tr>
<tr><td>11</td><td>The base camp shall provide sufficient breathable air to each crew member.</td><td>YES</td><td>43-49</td></tr>
<tr><td colspan="4">A semi-closed loop system that utilizes a sabatier reactor, electrolysis, and the CAMRAS system, the habitat module will supply the crew with sufficient oxygen and atmospheric pressure.</td></tr>
<tr><td>12</td><td>The base camp shall include a regenerative biological waste management system.</td><td>YES</td><td>38-39, 40-43</td></tr>
<tr><td colspan="4">Solid waste will undergo warm air drying and be stored. Liquid waste will be purified by undergoing vapor phase catalytic ammonia removal and be reused.</td></tr>
<tr><td>13</td><td>The base camp shall include an airlock which shall allow the crew to ingress/egress whilst maintaining pressurisation.</td><td>YES</td><td>24-25</td></tr>
<tr><td colspan="4">Crew ingress/egress will be possible via two suitports on the habitat module and two suitports on the MMSEV.</td></tr>
<tr><td>14</td><td>The base camp shall maintain air temperature between 65 and 80 degrees Fahrenheit.</td><td>YES</td><td>50</td></tr>
<tr><td colspan="4">Omond House will maintain a temperature between 65 and 80 degrees Fahrenheit using water filled coolant loops and resistive patch heaters.</td></tr>
<tr><td>15</td><td>Robotic rovers performing mission tasks on the surface of the moon shall operate nominally while being exposed up to at least 380 mSv of ionizing radiation.</td><td>YES</td><td>84-86</td></tr>
<tr><td colspan="4">The MMSEV and ATHLETE platforms are designed to operate effectively in Lunar radiation environments.</td></tr>
</table>

Table 12.1: Compliance Matrix.

13. Conclusion

The first principles used when designing Omond House attempted to mitigate risk while also being a robust, detailed design of a base camp capable of supporting a crew of four for 45 days. One of the largest risks associated with the current baselined design is the deployment of the habitat. If the habitat is not able to successfully disembark from the lander, additional unplanned launches will have to occur to fix this issue. Also, if any of the launches land far from the landing site, this would be detrimental since it would not be able to be relocated to the proper location. However, these risks have been minimized in our choices of deployment methods, and the base camp was also designed to increase mission reliability by making systems completely independent and redundant. Furthermore, Omond House is highly modular, which would serve to be highly extensible to future deep space missions. To recap, the detailed design of Shackleton Base Camp Omond House comes in on budget, on schedule, uses almost entirely TRL 9 level technologies, and considers all necessary subsystems for a successful mission by December 31st, 2030.

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15. Appendices

Appendix A: Regolith density figures [app1]

Target	Depth (g/cm^2)	δD	δD_n $(g/cm^2)^{-1}$	
Apollo 16, 61501	*7.54*	*0.071*	*0.009*	
Apollo 16, 62241	*7.52*	*0.066*	*0.009*	
Apollo 16, 64501	*5.97*	*0.044*	*0.007*	
Apollo 16, 61141	*12.33*	*0.103*	*0.008*	
Apollo 11, 10084	*6.67*	*0.056*	*0.008*	
Apollo 17, 70051	*11.68*	*0.111*	*0.01*	
Simulant JSC-1A	*12.89*	*0.116*	*0.009*	
Simulant JSC-1AF	*12.65*	*0.115*	*0.009*	
Simulant MLS-1A	*12.37*	*0.11*	*0.009*	
Simulant MLS-2	*12.37*	*0.121*	*0.01*	
Simulant "Claudia"	*12.53*	*0.122*	*0.01*	
Simulant "Hap"	*12.48*	*0.114*	*0.009*	
Synthetic 67461	*12.01*	*0.103*	*0.009*	
Synthetic 15041	*12.54*	*0.106*	*0.008*	
Synthetic 70051	*12.49*	*0.108*	*0.009*	
Mean Lunar Regolith			0.008828506	0.882851 %
Aluminum	5.4	0.054	0.01	1 %
Graphite	7.2	0.111	0.015	1.5 %
Water	5	0.2	0.04	4 %

	min (g/cm^3)	**Max (g/cm^3)**	**Mean (g/cm^3)**	**cm/%**
Typical regolith density	0.8	2.15	1.311487705	**0.863671**
Typical Aluminum density			2.7	**0.37037**