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Practical Lunar Surface Site Selection Criteria to Optimize Habitat Environmental Control

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Site selection criteria for a lunar habitat requires the consideration of a variety of factors ranging from view of the sun to proximity to spacecraft landing sites. All of these driving factors are traded against each other to arrive at candidate landing sites, as recently highlighted in NASA's site selection for the Artemis III mission. Selecting sites amongst the desolate, diverse and shadowy terrain of the south pole is a challenge likely not seen since the placement of McMurdo Base in the Antarctic or the placement of homesteads in the days of the western expansion in the United States. While not obvious, one class of considerations for site selection criteria has to do with reducing habitat environmental risks. Specifically considering thermal control, radiation mitigation and dust mitigation as hazards and systems design challenges, we strive to find solutions that minimize cost, mass and complexity. Surface construction and regolith moving, shielding and environmental systems are candidate solutions we target for developing efficiencies. To that end, we also looked at how topographic features on the lunar south pole can be used to optimize habitat environmental control by minimizing the need for heavy machinery or complex systems. While these are ultimately traded against other priorities, it is important to consider them and their relative importance and practicability. The candidate site selection criteria resulting from this assessment are discussed in this paper.

Nomenclature

GCR	=	Galactic Cosmic Radiation
LROC	=	Lunar Reconnaissance Orbiter Camera
PSI	=	Plume Surface Interactions
PSR	=	Permanently Shadowed Regions
SEP	=	Solar Energetic Particles

I. Introduction

WE can all appreciate that putting in place a sustained and sustainable lunar habitation capability on the Moon is a very difficult mountain to climb. The characteristics of the lunar surface seek to make creating a safe and comfortable environment for people a difficult endeavor. Investigators have explored a variety of concepts for lunar habitats and bases for over 50 years. Every one of them seeks to find solutions for how to live in the extreme thermal, radiation and dust environments of the lunar surface either by design or operation. In this paper we take a step back and look at how history may provide additional perspectives on solving these hazards. We first remind ourselves how early explorers, settlers and colonists established residence in North America. We briefly look at how they solved the hazards faced in their time to gain a foot hold in what to them was also a hostile and challenging environment. We then look towards the lunar landscape for ways we might adjust our strategy for establishing a lunar base. We seek to add to our toolbox of methods for how it can be done safely and successfully. In this process we will find that the lunar topography, in at least a few ways, can make our challenge easier. This approach can show us, in addition to living "off" the land, how living "in" the land, meaning to fit within the lunar topography, can be an improvement over simply living "on" it.

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II. Historical Analogs to Lunar Habitation

If the lunar surface is considered a New Frontier then it stands to reason to consider lessons learned from earlier frontiers. Afterall, this is not the first time that humans have ventured into new territories with the intent to stay. The natives crossing over the bearing straight into North America didn't visit and go home. The Europeans didn't visit North America and return to Europe. Early settlers during the westward expansion towards the Pacific Ocean didn't visit and return to the comfort of their east coast towns. They all went to stay. They all went not fully understanding the challenges they would face, the environment they would endure or the land they would live on. They went anyway and they brought with them practical understanding of what it would take to figure out how to make a home in the wilds of new territory.

Similar to how we plan to use in-situ resources to live off the land, our ancestors did the same. Using tree branches and tree trunks, sod, clay, dirt and rocks, native American and European explorers from the arctic to central America built shelters to protect themselves from the elements. Teepees were used by native Americans and igloos were used in arctic regions, but for American settlers simple one-room sod houses, or "soddies", and one room log cabins were used before frame houses were possible.[13] The question more germane to our discussion here, however, is what strategies did they employ for knowing what design to build and where to build them? What strategies did they employ to make the process easier or increase potential for a successful result? Picture, for example, a settler on a newly acquired homestead in the foothills of Colorado where, in order to keep the land, they were required to build a home and keep livestock.[18] How would they go about choosing the building site and designing the layout of the home? In another example, consider how a colonist in coastal South Carolina might decide which direction their house should face and how to design it? These examples are analogs to establishing habitation on the Moon.

Figure 1. – Early North American shelters and homes. *Left to Right: Mesa Verde Cliff Dwelling [18], log cabin [8], sod house[13], and colonial home[9].*

Demonstrations of human ingenuity to build shelters and homes are abundant throughout our history with a few examples shown in Figure 1, but many more can be found across north America and the world. Ranging from pueblo style cliff dwellings, sod and log houses, they all used natural materials combined with manufactured or natural earthen features to create a shelter. However, all these types of homes were at risk of damage by natural causes such as rains, winds and floods.[4,23] Sturdy frame houses followed to provide more robust housing solution, such as the example in Figure 1. As civilization developed our expectations of durability and safety also increased and was reflected in how we build our homes.[9]

Using some examples we can identify the strategies used by settlers and colonists to locate and design their dwellings. As mentioned earlier, during the age of westward expansion in the United States, deeded plots of land were awarded to people who demonstrated the ability to live and farm on them. In order to be successful the homesteader had to first create a layout of how they planned to use the land.[4] Many of these same strategies continued in establishing colonial frame houses.

They had to take into account access to the plot – how to approach the location by foot, horse and carriage. Perhaps there was an existing trail that only needed to be widened. The access route also had to be solid enough to not erode away and stable enough to not be hazardous. The termination point had to be mapped out so that adequate space was provided for carts to approach close to the home but leaving room to turn around, and perhaps room allocated for more than one cart at a time.

Access to water had to be planned. Locating a source of water and a route to get there had to be identified.[23] Perhaps a new trail had to be created, and steps built from stone to make hill climbing easier while carrying buckets of water. If a well could be built, a location had to be allocated for it in the site plan.

Vantage points for threats had to be factored into a site plan. Weaknesses of sneak attack by animals or other foes had to be identified.[12] This might mean that the lodging location had to be at the highest point on the land even if it made access to water and access by carriage more challenging.

In establishing the actual home on the land the homesteader had several more factors to consider. They had to assess the quantity and type of materials available. This would determine, for example, if a log cabin or a sod house were to be built. A log cabin needed trees and material for chinking between the logs. A lot of trees would be needed for a sizable home and those trees had to be cut down, stripped, notched and stacked.[12] A certain tool set was needed for this job. In contrast, a sod house needed tough, flat areas of grass. The sod house used blocks cut from the densely packed roots formed by the grass. The roots held tightly together what would otherwise be a block of dirt that could dry and crumble.[19] They need animals to help strip the sod from the ground and cutting tools to shape the blocks.[13] Quite a different tool set than those used for the log cabin.

The homesteader also looked at natural features on their land that might help. A grassy hill made of dirt instead of rock could be dug into. A deep hollow dug into the hillside could potentially serve as the back and side walls to a home. Only a roof and front wall would need to be built.[23] Care had to be taken however to understand drainage of water off the hill and the stability of the dirt or the home could flood or collapse.[4] Other features could be a large boulder or rocky cliff. These could be incorporated into the house as a wall or a windbreak. All of these strategies served to reduce the amount of effort and supplies needed to build the shelter and improve its safety and comfort.

Finally, the effect of the elements had to be observed, predicted and accounted for. Direction of the passage of the sun was an important one of these.[12] Anyone who lives in an area where snow falls knows that a south facing home will have the benefit of the sun melting snow off their driveway and entrance and warming the home. Additionally, placing windows in the direction of the passing sun provided natural light inside the home. The importance of the sun's direction cannot be understated when it comes to site layout.

Wind direction was another important weather element to consider when designing and placing a home.[12] The settler had to predict if snow would be driven into the front of a house and create dangerous drifts. Wind could also be a structural hazard if the home was too exposed to its direct force. However, it was also advantageous to have windows or doors facing the wind so that they could be opened during summer months to allow a breeze to cool a home or keep it fresh and dry. Colonists along warm coastal areas sought this strategy, harnessing fresh breezes coming off the ocean. As mentioned before, natural topography was also incorporated into a strategy to block or expose the home to wind as needed. Nearby hill, valley and canyon features were monitored to understand the behavior of winds flowing down or around them before deciding how and where to place a home.[23]

All of these factors also drove the design of the house being built. The geometry of the home had to work with the land and elements.[12] The home may have had to be long and narrow. It might have had to have a loft or second story because of limited flat, level land. Windows had to go in specific locations to capture the breeze. The sun facing side of the house may be made bigger to capture more warmth from the sun. This variety of factors would have to be considered when laying out the footprint and design of the shelter.

Compromises were required in balancing all the strategy options at hand. Like a toolbox of options, the settler, homesteader or colonist had to choose wisely from what was available to them. Windows exposed to westerly or easterly ocean breezes would also be susceptible to wind damage if a hurricane approached. On the other hand protection from the wind could result in a poorly ventilated home that might also stay damp and grow mold. A good view of the sun would help in the winter but possibly make the interior of the home unbearably hot in the summer. Use of a hillside or rocky cliff for making the construction process easier can present hazards of subsurface water, land slumping or rock falls. All efforts for site selection and shelter construction involved compromises between feasibility, effort, safety and comfort. Establishing a sustained habitatable infrastructure on the Moon will not be any different.

III. A Different World

In more modern times we bring with us a different mentality when establishing habitation on a plot of land. On Earth we no longer agonize over the same challenges and compromises that our ancestors did. We modify the terrain with giant earth moving machines instead of dealing with its natural state. We consider ourselves lucky if our northern home faces south when it snows, but we don't require it. Air conditioning systems render the need for strategic placement of windows unnecessary. Sump pumps keep water out of our homes. Building codes and sturdy materials and construction methods enable us to be less worried about most winds. We are able to divorce the environment and topography from our choice of location and home design. In effect we've learned to live on the land instead in (and off) it.

Living on the land, being able to inhabit a location nearly irrespective of its original topography, geology or natural elements is a great thing when infinite materials, people and machinery can easily be brought to bear. It has enabled population explosions in areas on Earth where habitation wasn't possible. But the question now at hand is how do we go about inhabiting the Moon, and, by extension, Mars? In this new frontier we are people, time and resource limited. In grafting our current methods over to this new world, most concepts simply deliver prefabricated habitat modules on the lunar surface and then try to employ more elaborate technologies or regolith movers, to modify the land or maintain a habitable environment. As a hypothetical exercise, however, let's put ourselves in the minds of the native American, settler, homesteader or colonist and change the location to the Moon. What options or new approaches might we develop using their perspective on the challenge?

The Land Before Us

As during historical accounts, a survey of the land before us is a good place to start. The topography and environment of the lunar South Pole, shown in Figure 2, is extraordinarily varied. Ancient bombardment and volcanic activity resulted in overlapping craters, valleys, steep slopes, and areas of permanent darkness as well as almost permanent light. At a macro level it seems daunting to imagine living on this chaotic terrain. However, one can propose that the Earth would also have this impression when viewed from high above. Zooming in closer however we find that on the scale appropriate for human activity we start to get a different perspective. The humans of history had the benefit of seeing this ground-level view first and so were not deterred by intimidating orbital images. There are benefits from getting a similar perspective.

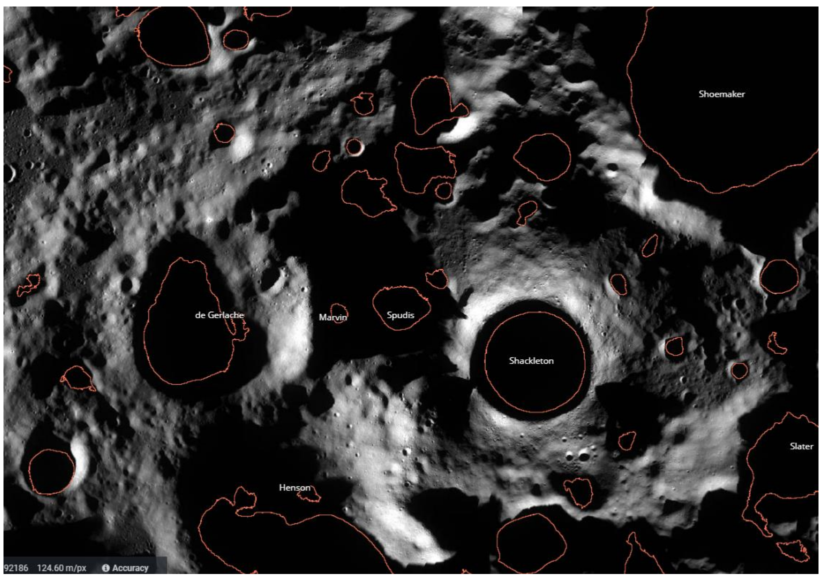

Figure 2. – Lunar South Pole. *Permanently Shadowed Regions (PSR) outlined in red. (Image from quickmap.lroc.asu.edu)*

Major landmarks on the south polar region such as Shackleton crater, de Gerlache crater, and Shoemaker Crater are like giant lakes on the Earth's surface – full of potential benefits to sustaining life but also treacherous to navigate. As a result, we focus on the surrounding topography. A very popular region of interest is the Connecting Ridge between Shackleton and de Gerlache. [21] This region is high, fairly flat, and exposed to nearly year-round sun.

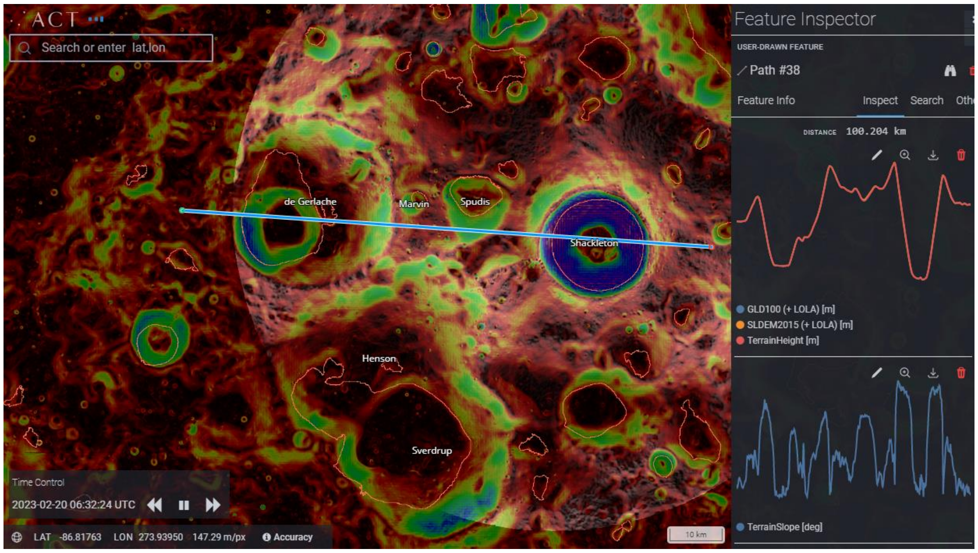

Figure 3. Lunar South Pole Dynamic Topography. *Elevation and slope profiles shown for the cross section indicated with the blue line (LROC QuickMap).*

Figure 3 presents an example of the steep slopes and long distances created by the major craters Shackleton and de Gerlache as extracted using the LROC QuickMaps website tool. Between them is the Connecting Ridge. The lower right box gives the slope over the course of the blue line. As expected there are spans of sustained high slope gradients in this region.

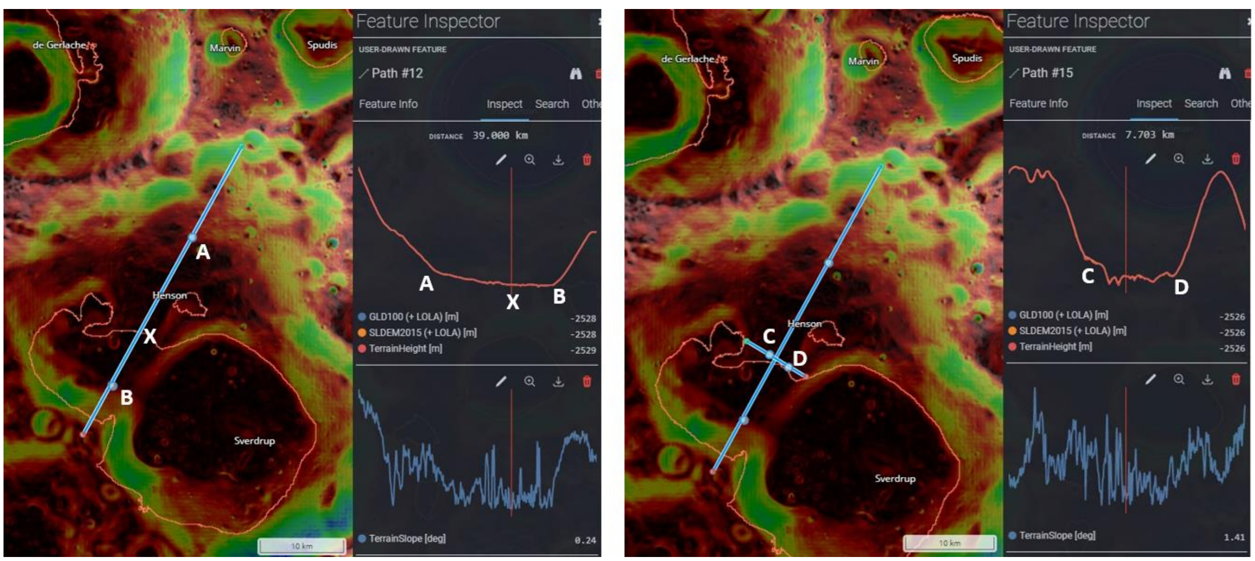

Figure 4. A Long Gentle Valley Leading into the Henson PSR. *The left-side image presents a cross section from the flank of the Shackleton-de Gerlache Ridge extending across the Henson PSR. Along this cross section, the gentle valley floor stretching from location A to location B is approximately 20 km long. The right-side image presents a cross-section transverse to the A-B direction and just outside the Henson PSR. The distance from location C to location D is approximately 2.5km (LROC QuickMap).*

Outside of the major landmarks we find less extreme features, also studied using the LROC QuickMap website tool. Figure 4 gives an example of more gentle slopes, plains, and valleys also found in the south pole region. Here we find a stretch land with more agreeable shape. The two blue lines intersect gentle sloping plane about 2.5km by 20 km and crosses into the Henson PSR without extreme, sustained slopes. The lower right corner does capture slope variability that still cause concern. These would need to be investigated further by mobile assets to fully characterize.

Figures 3 and 4 highlight the spectrum of varied topography in this region with remaining areas falling between the extremes. As we continue to explore at the ground level many other features will take shape. Here is where our hypothetical settler perspective can get creative.

Some researchers have explored concepts that make forays into incorporating natural features into habitat architecture. Eichold (Ref 10) proposed a concept where a crater is incorporated into the habitat design. One can imagine variations on this theme if the right size crater can be found for constructing a habitat using its rim for mounting structure. The result is a habitat already partially underground which, as we'll talk more about later, can be helpful. Boldoghy, et al, (Ref 3) proposed a concept that used a natural rile or steep-walled valley feature. This also gives a good starting place for further covering the habitat with regolith for radiation protection. Most recently a team from ESA (Ref 11) proposed the use of a crater for a similar purpose. In their concept the habitat was built vertically one element at a time, only installing the next after the preceding module was buried. The result was a filled in crater with an entrance at ground level.

In each of these works certain construction benefit was sought by using a natural topographical feature. Mostly to the point of needing less excavation and site preparation, but also less materials. These are helpful, but we want to follow this line of thinking in search of additional benefits. Drawing on our earthly homesteader relatives, we further capitalize on topography to find ways to improve the internal environment of our lunar surface habitats.

IV. Opportunities to Benefit the Habitat Environment

Before putting blinders on and delving headlong into site selection for a permanent habitat based on benefits to environmental control, we acknowledge that other factors are also at play. We acknowledge that in wholistic development of site selection criteria a compromise will be required to balance these drivers. There are factors like proximity to placement of solar panels, proximity to scientific places of interest, proximity to recoverable materials for in-situ resource utilization and a certain amount of flat area for landing pads that must also be considered, among others. With that said, for the purposes of this discussion we ask the question - what site selection criteria would benefit environmental control? Along with this question, we will want to capture other factors we care about such as the amount of energy required to operate in a location, the amount of site preparation required before habitation can occur and the ability to stay on the surface permanently.

Equipped with a historical perspective and a survey of the new lunar frontier of the south pole, we look at the Moon with a new lens. As with the settler who faced the dangers of his new frontier, we face major challenges on the Moon for proving a safe environment for enabling permanent habitation. Among these challenges are dust exposure, thermal control and radiation exposure.

A. Dust exposure

The rationale and proof for why dust is a major hazard does not need to be replicated here (see Ref 5 and 27). How to mitigate and control dust in the cabin is a subject of ongoing modeling and systems design (see Ref 17). However, these systems often depend on a known entrance quantity and rate of introduction in the cabin. Estimating these values is a challenge. We must control the dust contamination on suits, equipment and free space as much as possible to help ensure the habitat systems are not overloaded.

Mechanisms for dust deposition on hardware and suits stem from lofted dust that resettles. Dust can be lofted by walking in dusty areas, rover wheels, launch/landing of visiting vehicles, and electrostatic dust levitation occurring during passage of the sun's terminator.[7] If sintered or paved roads are eventually developed the first two mechanisms can be reduced in contribution. The other two could benefit from strategic site selection.

The danger of dust lofting by visiting launch vehicles is not new and researchers have proposed the construction of shields around landing pads and some have proposed construction of berms.[20] However, a site which provides a natural barrier – a ridge or hill for example – could mitigate the problem by placing landing pads on one side and the habitat system on the other. The steeper the incline the better so that the hill doesn't act like a ramp to loft the dust on top of the habitat. Understanding the effect of Plume-Surface Interactions (PSIs) on surface infrastructure is a key are of additional study.[26]

A newer concern is the phenomenon of electrostatic dust levitation occurring when the night-day terminator passes over a dusty area. The dust is electrostatically levitated into free space where it briefly resides until it settles again.[7] The phenomenon can result in repeated dust coating onto equipment and rovers and crew. It could even make its way directly into airlocks where hatches are left open as a safety precaution. Our homesteader might take the pragmatic approach and suggest that the habitat and rovers not be kept in a location where the sun's terminator may pass! This leaves two options – a location always in full sun or a location always in dark, two natural ways that this can be achieved. In doing such a trade we'll need to consider the effects full sun can have on hardware – both for degradation and thermal reasons. Full darkness on the other hand will come with the challenge of getting very cold.

Considering the two natural mitigation options for mitigating dust intrusion into a habitat – a natural hill or ridge to block launch vehicle-lofted dust and a continual dark or lit location – begs the question: Are they mutually exclusive? Can you have both? This would be the challenge of locating candidate sites that meet our criteria and not the goal in this paper. For now, we only identify candidate site criteria and leave the candidate location and subsequent compromise promise for another discussion.

B. Thermal Control

Thermal control of lunar habitat, or any lunar surface spacecraft, is a recognized challenge by designers.[25] In polar regions the sun will pass over head and thus continually heat the habitat as well as the regolith around it. As a result, having a cold sink to reject heat is problematic in these locations. At the south pole the sun moves all around the habitat and thus can have a different incidence angle every day. Another challenge is the cyclically heating and cooling of materials. This can cause degradation and structural fatigue over time.[6]

There are candidate habitat site selection criteria that could mitigate this development challenge. All have to do with the use of permanently shadowed areas. These regions provide a stable, cold place as a starting point. However, the extreme cold is itself also a challenge. This will be another trade when balancing pros and cons of site selection.

One approach is to use a PSR as a heat sink for habitat cooling systems. This approach presents design challenges for fluid pumps and plumbing but still an option to explore. In this approach the habitat could be placed inside the temperature stable PSR.[21] This might sound extreme but if the negatives of this approach are addressed the benefits can be exploited. For example, if the habitat were placed near the end of the PSR a nearby sunlit area radiated a low level of heat and reflected some light into the PSR, the extreme temperatures and darkness may not be as low. Additionally, a robust power grid could operate a strategically place heater system to provide the amount of heat in the right locations. Thermal models may be simplified where varied sun exposure is eliminated. Alternatively, reflectors could be added outside of the PSR to reflect sunlight into the PSR, the environment could also be controlled. This concept has been proposed as a method of extracting water from PSRs.[24] In effect, the PSR serves as a constant low point from which a custom thermal environment could be created to the benefit of thermal control systems and lighting.

Managing cabin temperature is a tightrope between the heat that must be collected and the ability to reject it. If the ability to reject the heat is robust and constant then internal heat generation can be afforded more flexibility. Additionally, off-nominal conditions can be less dire if we have large margins for heat rejection. In summary, the nature of the site we choose could enable to walk the tightrope with more confidence.

C. Radiation Exposure

Radiation exposure is a leading hazard in preventing a sustained long-term presence on the Moon. The two components of Galactic Cosmic Radiation (GCR) and Solar Energetic Particles (SEP) must be addressed to keep exposure rates to acceptable levels.[15] Many researchers have proposed concepts of burying habitats with up to five meters of regolith.[8,22] Others have proposed methods for filling a structure with regolith that overlies the habitat.[2] The effectiveness of this approach has been analyzed and theoretically shown to mitigate the hazard.[14] However, most of these share a common feasibility challenge. These approaches require sizable machinery to accomplish the design goals. The developing, landing and operating this heavy machinery in terms of cost and time is not well understood, neither are the structural designs or the long terms effects of the habitat that would be buried. We need to consider other ways that this challenge can be chipped away.

The first approach is to address the two radiational sources separately. SEPs are depended on a few of the sun. For example, if you are on the dark side of the Moon, solar radiation is blocked by the Moon itself.[16,22] Simply put, if the habitat never faces the sun then it is not exposed to solar radiation. Next, since GCR exposure depends on the view to open space, on an open plain such as the lunar lowlands, this is roughly a hemispherical zone of exposure with the habitat at its center. If we can reduce this view of deep space then we reduce our exposure to GCR. This effect is illustrated in the simple diagram shown in Figure 8.

One way of meeting both of these criteria without burying the habitat, or covering it completely with regolith, is to place it in a lava tube. In this concept the habitat is shielding by the thick ceiling of the lava tube. This option comes with its own challenges at pointed out by Billings, Et al. (Ref 1). There will be a lot unknowns concerning the stability of the entrance to the lava tube as well as its interior. However, another option may partially make use of a similar strategy.

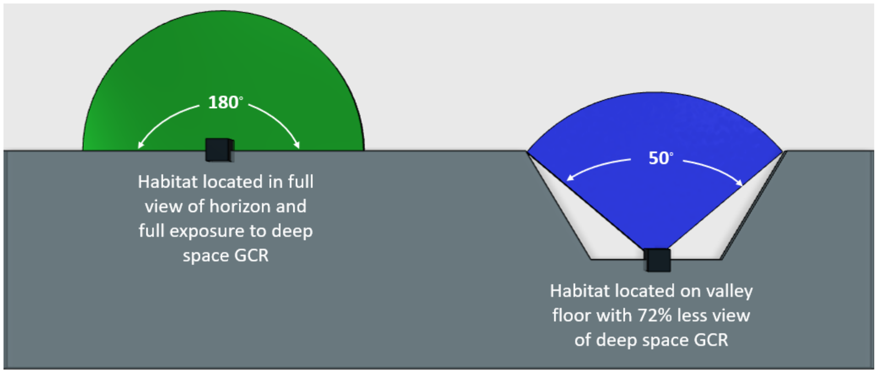

Figure 8. GCR Exposure Reduced by Natural Topography. *The top surface installed habitat is exposed to GCR radiation from all directions – 180 degrees across the sky. In contrast, the habitat located at the bottom of hypothetical valley has a much less view of deep space, resulting in less exposure.*

A habitat in a PSR is by definition never in direct sunlight. This characteristic mitigates solar radiation exposure. Second, a PSR is likely a depression or at least a location surround by higher terrain. By placing a habitat in a location surrounded by higher elevations, the hemisphere of exposure is reduced. The higher the elevation difference and closer the slope is the habitat, the smaller the window of exposure becomes. In effect we would be looking for a box canyon or deep valley. If the valley also ends in a steep wall, or is effectively a cul-de-sac shape, then the habitat can shielded on three sides. This feature could also be a crazy where one section of the rim has been demolished by another impact or collapse. While not completely a solution to GCR exposure, it helps. Other engineering approaches can be used to supplement and close the window of exposure completely. In summary, we make use of natural topography to do part of the job for us, thereby reducing it to a more manageable and feasible task.

V.   Results

In the above discussion we have spanned both space and time to make initial use of a historical perspective on how humans establish residence on new lands. We applied that perspective to three areas that affect the environment within a lunar habitat: thermal, dust and radiation. The outcome of this exercise produced a short list of candidate site selection criteria. Each of them comes with their own challenges, pros and cons that would be included in site selection trade studies. The list generated here can be summarized in five criteria:

1) Natural topographical barrier between the habitat and the visiting vehicle landing pads
2) Full sun all the time or in full shade all the time.
3) Very close proximity to or directly inside a PSR
4) Bottom of a steep walled valley or cul-de-sac-shaped ridge with one entrance.

These criteria are only a small subset of what would be a long list of candidates that would need to be traded in the site selection process and should not be interpreted as the only criteria used. They represent only those that might aid with the three cabin environment characteristics discussed. It is interesting to note that in order to help with radiation, dust and thermal control the site criteria favor placing a habitat in a depression or valley, close to or in a PSR. These types of locations can present other operational and technical challenges that would need to be addressed, not the least of which is the extreme cold temperatures that can be found in a PSR.

The topography at the Henson PSR shown in Figure 4 is an example of one location that could be further evaluated against the criteria developed here. The data provide by the Lunar Reconnaissance Orbiter Camera (LROC) Quickmap tool indicates a gentle terrain leading into the Henson PSR. Steep slopes abound in all directions surrounding the strip of land indicated. This example may support the criteria here, but it would take a closer, ground level inspection to determine if a suitable level place can be found that also provides a natural barrier to visiting vehicle lofted dust.

VI. Conclusion

We have extracted a useful perspective on establishing habitation on the new frontier of the Moon by looking at historical "new frontiers" settled by newcomers to North America. This perspective, to live in the land and not just on it, can help us break apart and overcome the challenge of establishing a permanent presence on the Moon. The cursory approach taken here has produced a short list of candidate site selection criteria for consideration. These criteria seek to find locations that can aid us in the management of the thermal, radiation and dust environment of the lunar habitat cabin. It takes a ground level view of the topography, and a willingness to merge into it, to aid us in developing site selection criteria. However, it is acknowledged that these are not the only criteria that have to be considered. Compromises and partial solutions will fit together to ultimately be successful. Just like the settlers and colonists, we will innovate, and we will find a way to gain a secure footing in this new world!

References

[1]Billings, T.L, Walden, B., York, C.L. "Lunar Lavatube Base Construction", *Space2000*, edited by K.M. Chua et al., American Society of Civil Engineers, Albuquerque, New Mexico, 2000, pp. 631-637.

[2]Boeing (1990) Robotic Lunar Surface Operations, Boeing, Huntsville, AL

[3]Boldoghy, B., Kummert, J. Szilagyi, I, Varga, T., & Berczi, S., "Construction of a Lunar Architectural Environment with Joint Constraints of Thermal Balance, Economic Technologies, Local Material Using: Strategy, Design and on Site Assembly", Lunar and Planetary Science XXXVII, 2006.

[4]Bradsher, G., "How the west was settled: the 150-year-old homestead act lured Americans looking for a new life and new opportunities." Prologue, vol. 44, no. 4, winter 2012, pp. 26-35. Gale Academic OneFile, link.gale.com/apps/doc/A330714996/AONE?u=googlescholar&sid=bookmark-AONE&xid=abcbdfc0. Cited 20 Feb. 2023.

[5]Cain, J., "Lunar Dust: The Hazard and Astronaut Exposure Risks", *Earth, Moon, and Planets*, Volume 107, Issue 1, 2010, pp.107-125.

[6]Cohen, M., & Benaroya, H., "Lunar- Base Structures", *Out of this World: A New Field of Space Architecture*, Edited by Scott Howe and Brent Sherwood, 2009.

[7]Colwell, J., Robertson, S., Horanyi, M., Wang, X., Poppe, A., Wheeler, P., "Lust Dust Levitation", *Journal of Aerospace Engineering*, January 2009.

[8]Connolly J., (1992) Regolith Shielding Methods, NASA, Johnson Space Center, Houston, TX

[9]Craven, J., "About New England Colonial Architecture", https://www.thoughtco.com/colonial-houses-in-new-england-178009, July 1, 2019, Cited 20 Feb 2023.

[10]Eichold, A., "Conceptual Design of a Crater Lunar Base", *Proceedings of the Return to the Moon II*, AIAA, Reston, VA, 2000, pp. 126-136.

[11]ESA, "Imagining a Moonbase", https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Imagining_a_Moon_base, 2019, Cited 19 Feb 2023.

[12]Hufford, D., "How Log Cabins Were Built", https://www.notesfromthefrontier.com/post/how-log-cabins-were-built, November 23, 2019, Cited 20 Feb 2023.

[13]Hufford, D., "Sod Houses – Humble Homes of the Prairie", https://www.notesfromthefrontier.com/post/sod-houses-humble-homes-of-the-prairie, March 11, 2020, Cited 20 Feb 2023.

[14]Jia, T., and Lin, Z., The Radiation Environment on the Moon from Galactic Cosmic Rays in a Lunar Habitat, Radiation Research, Vo. 173, Feb 2010, pages 238-244.

[15]Letaw, J., "Radiation Biology", *Fundamentals of Space Life Sciences*, Volume 1, edited by Susanne Churchill, 1997, Published by Krieger Publishing Company

[16]Letaw, J.R., Silberberg, R., & Tsao, C.H., "Radiation Hazards on Space Missions Outside the Magnetosphere", *Adv. Space Res*. Vol. 9, No. 10, 1989, pp 285-291.

[17]Marandola, E & O'Hara, W., "Assessing Dust Migration Through Pressurized Habitable Volumes", *51st International Conference on Environmental Systems*, ICES-2022-328, July 2022.

[18]National Park Service, https://www.nps.gov/meve/learn/education/artifactgallery_cliffpalace.htm May 12, 2020, Cited 20 Feb 2023.

[19]Nebraska Studies, "Building a Sod House", http://www.nebraskastudies.org/en/1850-1874/the-challenges-of-the-plains/building-a-sod-house/#:~:text=Sod%20was%20laid%20around%20the,frames%2C%20held%20them%20in%20place., Cited 20 Feb 2023.

[20]Sherwood, B., 2009, "Lunar-Base Site Design", *Out of this World: A New Field of Space Architecture*, Edited by Scott Howe and Brent Sherwood, 2009.

[21]Simonsen, L., DeBarro, M., & Farmer, T., "Conceptual Design of a Lunar Base Thermal Control System", Proceedings of the Second Conference on Lunar Bases and Space Activities of the 21st Century, Edited by W. W. Mendell, Publication 3166, Volume 2 (Part 7), 1992, Pages 579 – 592.

[22]Simonsen, L., Schimmerling, W., Wilson, J.W., & Thibeault, S.A., "Construction Technologies for Lunar Base: Prefabricated Versus In Situ", *Proceedings of the Workshop on Shielding Strategies*, NASA, Langley Research Center, Hampton, 1996, VA, Pages 297-326.

[23]Smithsonian, "Our Story: American History Stories and Activities You can Do Together", https://amhistory.si.edu/ourstory/activities/sodhouse/more.html, Cited 20 Feb 2023.

[24]Sowers, G., & Dreyer, C., "Ice Mining in Lunar Permanently Shadowed Regions". *New Space*. Dec 2019.235-244.

[25]Sridhar, K., & Gottman, M., "Lunar Base Thermal Control Systems Using Heat Pumps", *Acta Astronautica*, Volume 39, Issue 5, September 1996, Pages 381-394.

[26]Swiney, G., & Hernandez, A., "Lunar Landing and Operations Policy", NASA Report ID 20220015973, 30 September 2022.

[27]Zakharov, A.V., Zelenyi, L.M. & Popel, S.I., "Lunar Dust: Properties and Potential Hazards", *Sol Syst Res*, 54, 2020, pp 455–476.

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