Development of a Lunar Regolith Thermal Energy Storage Model for a Lunar Outpost

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Last, but not least, I would like to thank my family for their constant support.

That’s no Moon. It’s a space station.

- Obi Wan Kenobi, Star Wars Episode IV: A New Hope
The Moon has always been an important milestone in space exploration. After the Apollo landings, it is logical to think that the next step should be a permanent habitation module, which would serve as a testing ground for more ambitious projects to Mars and beyond.

For a lunar base to come into realization, it is necessary to assess a number of technological challenges which are due to the harsh conditions that can be found on the Earth’s satellite. One of these tasks revolves around energy storage: During the day it is possible to use photovoltaic cells and convert the solar irradiance into electrical energy to power an outpost, however during the lunar night this source is not available.

Current investigations establish that the optimal landing site for a permanent mission would be on the rim of the Shackleton crater, near the South Pole. This would reduce the night duration from 14 days to 52 hours of the lunar cycle, which is 29.5 days. While this significantly decreases the exposure to the cold temperatures of the Moon when there is no sunlight, there is still a need for a system to provide energy to the lunar base over this period.

Therefore, this study pretends to serve as a possible solution for the aforementioned problem, by developing a system storing energy as thermal energy and then harvesting it as electricity using thermoelectrics.

First, a theoretical introduction is presented, where the problem statement is exposed, along with background information regarding the solar illumination and the lunar soil. At the same time, an insight on regolith sintering techniques is given. These techniques are important as a means to providing thermal energy storage during the night cycle.

After this, the core of the study is developed: The ideal system for energy storage is broken down into segments, and each of them is explained attending to the possible requirements of a lunar base, while providing supporting simulations when deemed appropriate. These are the solar concentrator, thermal mass, thermoelectric array, cold sink and, if necessary, a pipe network.

Following this chapter, a device is proposed. Based on the previously mentioned guidelines, an ideal thermal energy system is simulated and evaluated. Although it is not optimized for efficient energy harvesting, it serves as insight on the design and simulation constraints that appear when one wants to collect electrical energy from thermoelectrics with relatively low efficiency.

It was estimated that the prototype would output a mean power of 3.6 Watts over the whole duration of the lunar night. Although in its current state this technology would not present significant benefits over existing energy storage methods such as nickel-hydrogen batteries, this study also proposed several optimization methods which could vastly increase the performance of the device. These include adding more efficient thermoelectric patterns, or modifying the properties of the semiconductors by doping or using nanostructures, and present follow-on opportunities for further research.
Abstract - Française

La Lune a toujours bénéficié d’un statut particulier et privilégié dans l’exploration spatiale. Après les premières excursions lunaires lors des missions Apollo, l’installation d’habitats permanents à sa surface apparait comme une suite logique, permettant la préparation de projets plus ambitieux vers Mars et au-delà.

Pour que ce projet de base devienne réalité, de nombreux défis technologiques doivent être relevés afin de répondre aux conditions extrêmes de la surface lunaire. Un des points critiques est la question du stockage de l’énergie : si durant le jour l’usage de panneaux solaires permet de convertir une partie de la lumière incidente en électricité afin d’alimenter le module habité, cette source d’énergie n’est plus disponible une fois la nuit tombée.

Les recherches actuelles ont montré l’intérêt d’utiliser la crête du cratère Shackleton comme site d’installation d’un habitat permanent. Cet emplacement, situé près du pôle sud, réduit en effet la durée de la nuit de 14 jours à 52 heures. Bien que ce choix limite fortement la période d’obscurité et donc d’exposition aux très basses températures, il reste nécessaire d’utiliser un système pour fournir de l’énergie à la base durant la nuit.

Par conséquent, cette étude propose une solution possible au problème précédent en s’intéressant à la possibilité de stocker de l’énergie sous forme thermique puis de la restituer partiellement sous forme électrique par l’utilisation de modules thermoélectriques.

Dans un premier temps une introduction théorique est proposée, présentant la problématique du projet ainsi que des données sur l’éclairage et le sol lunaire. L’utilisation de techniques de frittage du régolithe lunaire pour la conception de certains composants est aussi abordée.

La seconde partie s’intéresse plus particulièrement à la solution envisagée en détaillant chaque sous-système. Le concentrateur solaire, la masse thermique, l’arrangement de modules thermoélectriques, la source froide et, lorsque nécessaire, le réseau de tuyauterie sont ainsi étudiés dans l’optique de répondre aux exigences de l’habitat et en utilisant des simulations lorsque jugées pertinentes.

Ayant détaillé les sous-parties, un concept est alors proposé. En s’appuyant sur les contraintes et définitions des parties précédentes, un système de stockage thermique d’énergie idéal est simulé et évalué. Bien qu’il ne soit pas optimisé pour collecter le plus efficacement possible l’énergie thermique, ce modèle donne un aperçu du design et des contraintes de simulation apparaissant lors de travaux se basant sur l’utilisation de semi-conducteurs thermoélectriques au rendement relativement faible.

Selon les simulations, le système prototype serait capable de fournir en moyenne une puissance de 3,6 W en sortie tout au long de la nuit lunaire. Bien que dans l’état actuel cette technologie ne présente pas d’avantages significatifs par rapport aux méthodes existantes de stockage de l’énergie comme les accumulateurs nickel-hydrogène, cette étude propose aussi plusieurs optimisations possibles avec potentiellement à la clé d’importants gains de performances pour le dispositif. Parmi celles-ci, on note la possibilité d’utiliser une disposition de modules thermoélectriques plus efficace ou de modifier les propriétés des semi-conducteurs que ce soit par dopage ou par l’utilisation de nanostructures, ouvrant la voie à d’autres opportunités de recherches.
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1. Introduction

During the 32nd Space Symposium held in Colorado during the spring of 2016, Johann-Dietrich Woerner, director general of the European Space Agency, stated that the plans for ESA for the next ten to twenty years included developing a so called Moon Village.

Although not a village in the strict sense, it would consist of structures for astronauts to live in and perform scientific experiments, business, mining, and even tourism, and is generally seen as the next step of semi-permanent habitation beyond low earth orbit [1]. It was addressed as a needed joint effort from the international community, with the idea of establishing a global exploration activity from which every country can benefit [2].

From a feasibility point of view, this program raises a fair number of questions which need to be addressed in order to ensure a successful mission. For instance, what are the most desirable locations on the Moon’s surface for habitation attending to solar illumination and communication systems, what effects the reduced gravity of the Moon might have on astronauts when compared to the International Space Station or Earth, what requirements are needed for habitation, or which energy systems will be employed.

The current investigations for habitat design for this lunar base focus on an inflatable dome, where the hosts would live. This dome is covered by lunar regolith\(^1\) using 3D printing techniques which employ manned robots. By using local materials such as regolith, ESA expects to vastly reduce the cost of the mission by avoiding sending construction supplies. The next picture, courtesy of Foster + Partners, illustrates this concept (Figure 1) [3]:

![Moon Village concept by ESA in collaboration with Foster + Partners](image)

In the same sense as habitat design, energy storage could also benefit from in-situ resource utilization. It is widely accepted that a reliable and space-proven method for energy generation in space is the use of solar panels. They have no moving parts, have generally a long life, and require little to no maintenance, while at the same time providing considerable amounts of energy. Despite this, they present a handicap in the context of space exploration: They require the presence of solar illumination to function. As it is widely known, the Moon presents its own day and night cycle, which lasts 29.5 Earth days. As it will be explored later, this cycle is a function of the latitude, and different parts of the Moon present different illumination patterns. For

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\(^1\) Lunar regolith is the name commonly given to the dust-like material found on the surface of the Moon
instance, one of the preferred locations by the European Space Agency, the Shackleton Crater, is located at the South Pole, and presents a maximum of 52 hours of total darkness per cycle [4]. Even if this period seems small when compared to the day cycle, it is enough to require an alternate energy system other than solar panels, as the demands from the lunar base with regards to heating and electricity will likely increase during the lunar night.

This work therefore explores the design and fundamental conception of a thermal energy storage system. It benefits from the almost constant sun incidence over the surface of the south pole of the Moon, as well as the thermal properties of sintered lunar regolith and native regolith. A description of the lunar environment is first presented, and serves as an extended introduction of the different physical processes happening on the Moon.

Later, a basic thermal energy storage system is introduced, where every block is described along with supporting simulations when needed. This chapter is intended to illustrate the theoretical working principle of the system, without taking into consideration feasibility concerns. An emphasis is placed around thermal storage and the interaction between sintered and native regolith.

After this, a more compact, physically viable option is explored, with simulations of the developed thermoelectric circuit. The objective of this is to present a system which could comply with the idea of a Moon Village: A lightweight, compressed, and modular device, that can easily adapt to an increase in electricity demand as the lunar outpost expands.

Finally, the conclusions are presented. In this chapter, the previously mentioned systems are analysed, while at the same time providing information regarding possible constraints and assumptions made during the development phase of the work. It also serves as comparison against other energy storage options which could also be employed to supply electricity to the lunar habitat, such as batteries.

2. Lunar Environment

When designing an energy storage system, one must take into account the environment in which the device is supposed to work, as its performances will vary greatly with regards to it. The harsh conditions on the Moon present a challenge, especially with respect to keeping a thermal mass relatively hot for a long period of time, with temperatures ranging from -233 to -18 °C on its surface during the night. On the other hand, the presence of vacuum cancels the convection effects of air which are typically found on Earth. It is therefore clear that a good analysis of the physical processes taking place in the surroundings will be critical to develop a system which benefits from them.

As a result, this chapter focuses on analysing the environment that is likely to be found on the lunar surface based on bibliographic research and educated assumptions. This includes analysis of the Sun incidence, of the lunar surface, as well as an introduction to sintering techniques for regolith, with the objective of enhancing the capabilities of the lunar rock to be used as a thermal mass.

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2 Sintering regolith consists in modifying its properties by physical processes. See 2.4.
2.1. Sun Incidence

Arguably, one can find three heat sources on the Moon. The first one is the Sun, which illuminates its surface in a stable pattern, although it presents day and night cycles. The other source is heat from the Moon mantle, which is located between 60 and 300 km below the surface [6]. Digging techniques are often complex, and the amount of energy that would be needed to simply access this area would surpass the energy that could be extracted from it, which poses a significant technological challenge even on Earth. The last one is thermal input from the Earth, but it can be regarded as negligible when compared to other radiation sources. As a result, the only source which can be used in an efficient manner with today’s technology is solar radiation.

Heating of the surface of the Moon will depend on the material absorptivity, as well as the solar radiation power, which is a function of the Moon’s location in its orbit. The solar radiation power, usually referred to as $G_s$, per unit area incident at the lunar surface varies from a maximum of 1450 W/m$^2$ to a minimum of 0 W/m$^2$, corresponding to the lunar day and night, respectively. [4] Equation 1 illustrates the received solar heating power as a function of the incident solar angle:

$$G_{s1} = G_{s,max} \cdot \cos(\beta_s) \quad (1)$$

$G_{s,max}$ represents the maximum solar radiation power, 1450 W/m$^2$, and $\beta_s$ is the solar angle of incidence, or the angle between the surface normal and the sun direction for incoming radiation [4]. As established by Malla and Brown, $G_s$ (the solar radiation power magnitude) can be expressed as shown in Equation 2:

$$G_{s2} = \begin{cases} G_{s,max} \cdot \sin\left(\frac{2\pi t}{t_c}\right), & \text{Day} \\ 0, & \text{Night} \end{cases} \quad (2)$$

Where $t_c$ is the time for a complete lunar phase cycle (29.5 days), and $t$ is the variable which controls the time during the lunar day. For the lunar night, it can be observed that the radiation power is set to zero. This function can be plotted for a clearer insight on the impact of the angle of incidence over time (Figure 2):

![Figure 2 - Solar radiation throughout the lunar cycle](image)

*Figure 2 - Solar radiation throughout the lunar cycle [3]*
In the previous picture, the fluctuations of the solar flux can be observed for the lunar equator. It illustrates an approximately even distribution of day and night cycles. By changing the latitude on the Moon surface, the night periods can be significantly reduced, although by doing so one would also be reducing the maximum received solar energy flux. This is due to the fact that, as the sun rays extend towards the poles, they become tangential to the surface.

With $G_s$ from Equation 2, one can also obtain the applied solar heating energy $q_s^\prime$, which reaches the lunar surface:

$$q_s^\prime = G_s A$$

Being $A$ the surface area receiving radiation. By multiplying the solar heating energy by the absorptivity of the material, one can obtain the radiation entering the system due to the Sun’s influence. From this, it is possible to obtain the temperature at the surface. There are several methods which can be employed to achieve this. First, it is needed to understand the thermodynamic processes happening on the moon, which are illustrated in Figure 3:

![Figure 3 – Thermal balance in the Lunar Surface [4]](image)

It can be seen that thermal inputs are direct solar radiation ($q_s^\prime$) and internal heat flow ($q_i^\prime$), whereas thermal outputs are lunar albedo ($q_r^\prime$) and non-blackbody radiation ($q_{nbb}^\prime$). The thermal input from the Earth has been neglected due to the aforementioned reasoning.

The heat flow through the lunar soil is therefore given by the following thermodynamic differential equation (Equation 4):

$$kV \frac{\partial^2 T(X,t)}{\partial X^2} - Mc \frac{\partial T(X,t)}{\partial t} = q_{out}(X,t) - q_{in}(X,t)$$

Being $k$ the thermal conductivity of the regolith, which will be explored in the next chapter, $V$ the volume of regolith, $t$ being time, $X$ the regolith depth, $T$ the temperature at time $t$ and depth $X$, $M$ is the mass of regolith, and $c$ is the specific heat capacity of regolith [4]. A number of simplifications can be made to the previous equation: considering a surface instead of a profile which varies with depth removes that component, as well as assuming a steady state scenario. This would simplify Equation 4 into:

$$q_s^\prime + q_i^\prime = q_{nbb}^\prime + q_r^\prime$$

To solve the previous equation, a numerical integration approximation is needed, such as a fourth-order Runge-Kutta procedure [4]. Alternatively, given that the temperature profile of the lunar regolith does not change after the first 30 centimetres [14], the internal heat flow can be
considered negligible. At the same time, neglecting the effects of outward radiation would vastly simplify the equation, leaving just direct solar radiation as the main source. Then, this problem could be solved by simply applying the Stefan-Boltzmann equation:

\[ j^* = \sigma T^4 \]  

(6)

Where \( j^* \) is the power radiated from a black body, \( T \) is the temperature, and \( \sigma \) is the constant of proportionality, defined as [7]:

\[ \sigma = \frac{2\pi^2k^4}{15c^2h^3} = 5.670373 \cdot 10^{-8}Wm^{-2}K^{-4} \]  

(7)

The temperatures obtained through this method were compared to the ones found by Malla and Brown (387.1 K) [4] as well as the work by Balasubramaniam (388 K) [8], and the results were deemed accurate: For a theoretical maximum of 1450 W/m² of solar radiation, a temperature of 399.8 K is obtained. This value deviates in 3% with the previously mentioned authors.

2.2. The Shackleton Crater

The rim of the Shackleton Crater, located at the south pole of the Moon, has been regarded as one of the ideal locations for a man-made permanent base when attending to solar illumination. In the work of Balasubramaniam [8], this emplacement is chosen due to its nearly constant sunlight [10]. Theoretically, it should be permanently illuminated by the Sun, but the small tilt of the Moon’s axis with respect to the ecliptic results in periods of darkness which can last up to 52 hours. The following picture shows the crater on a topographic map of the Moon (Figure 4):

![Shackleton Crater](image)

Figure 4 – The Shackleton crater. Image courtesy of NASA [11]

The rim of the crater is at a higher elevation than most geographical entities in its surroundings, which means that it is not shaded by them, contributing to its excellent illumination pattern. It
can be therefore assumed that it presents a spatially uniform solar flux incidence, which only varies with time. This solar radiation, however, is weaker than the theoretical maximum exposed in the previous sub-chapter. The reason for this is that the maximum is obtained when the sun rays are normal to the Moon surface, which only happens at the equator. For the South Pole, since the Sun rays are almost tangent to the surface, the heat received is in the order of 600 W/m² [8]. In the work of Balasubramaniam it is stated that it is possible to use a solar tracker to redirect the rays into a more desirable angle, effectively obtaining the maximum heat for the complete duration of the lunar day. Although one must take into account losses due to the general efficiency of the solar tracker, in this study they are considered negligible.

2.3. Lunar soil

As it can be observed in Figure 3, the lunar surface is formed of two layers that have different physical properties, which were determined during the Apollo 15 and 17 missions [9]. The top layer, 2 centimetres deep, consists of loose regolith. It consists of loose dust-like particles, and it has lower thermal conductivity than the rest of the lunar material. This property allows it to behave as a shield for incoming solar radiation, effectively creating a temperature difference along its vertical cross section of up to 25%. The other layer consists of compacted regolith, usually referred to in the literature as native regolith. Its thermal properties still allow for it to be categorized as a very good insulator, although its thermal conductivity is higher than the top layer.

This means that the penetration depth of the system is relatively low, with heat reaching not more than 20-30 centimetres below the surface of the Moon during the lunar day. Beyond this point, the temperature can be regarded as constant at 254.8 K [14].

During the Apollo missions, the general limit for excavation was established at around 50 centimetres. This is of course dependent on the location, and in some cases the bedrock will appear earlier, or later.

The following table (Table 1) collects the most important properties of native regolith, which will be used for this study. It also contains the properties of sintered regolith, which is described in the following sub-chapter (2.3. Modifying the properties of lunar soil).

<table>
<thead>
<tr>
<th>Properties</th>
<th>Native regolith</th>
<th>Sintered regolith (basalt rock)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thermal Diffusivity</strong></td>
<td>$6.6 \times 10^{-9}$ m²/s</td>
<td>$8.7 \times 10^{-7}$ m²/s</td>
</tr>
<tr>
<td><strong>Density</strong></td>
<td>1800 kg/m³</td>
<td>3000 kg/m³</td>
</tr>
<tr>
<td><strong>Specific heat</strong></td>
<td>840 J/(kg · K)</td>
<td>800 J/(kg · K)</td>
</tr>
<tr>
<td><strong>Thermal Conductivity</strong></td>
<td><strong>Top 2 cm</strong>: $1.5 \times 10^{-3}$ W/(m·K)</td>
<td>$2.1$ W/(m·K)</td>
</tr>
<tr>
<td></td>
<td><strong>Rest</strong>: $1.2 \times 10^{-2}$ W/(m·K)</td>
<td></td>
</tr>
<tr>
<td><strong>Surface Emissivity</strong></td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td><strong>Surface Absorptivity</strong></td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td><strong>Penetration depth</strong></td>
<td>0.2 - 0.3 m</td>
<td>2 m</td>
</tr>
</tbody>
</table>

*Table 1 – Properties of native and sintered lunar regolith*
2.4. Modifying the properties of lunar soil

Although the properties of native regolith are regarded as very poor when it comes to energy storing, it contains the elements needed to be converted into a reasonable thermal conductor. Experiments carried out by ESA in cooperation with DLR show that, provided that enough energy is applied to the regolith, its properties can be altered. The methods for achieving this are usually:

- **Compacting and sintering:** First, the regolith is heated by microwaves, which couple with the nanophase metallic iron unique to lunar regolith and magnetite, a ferrous material. This reduces the thermal contact resistance of the material, while at the same time increasing its bulk thermal diffusivity.
- **Melting regolith and solidifying it into a solid block:** This could be achieved by using solar energy, microwave energy, or heating by electrical resistance. As the previous case, this method also reduces the thermal contact resistance of the material.
- **Incorporating physical interfaces which increase its thermal capacity:** Such as heat pipes, thermal rods, or heat transfer fins.
- **Reducing regolith using thermochemical processes, yielding a metal-enriched material:** It could be a bypass product of processes which produce oxygen from lunar regolith [8].

Of special interest are the processes which increase the thermal conductivity of the material. As it will be explored later, this is a key parameter for an energy storage device which relies on thermal energy. The current work carried out by DLR explores sintering regolith in the same way in which 3D printers work, by producing a filament of material and depositing it on a flat surface. With this technique, it is expected that in the near future it will be possible to create blocks of different shapes made of sintered regolith, such as the ones who have been considered for this study.

3. Thermal energy storage system design

As mentioned earlier, the motivation of this work is to find a way to supply energy to a Lunar Base during the night period, which can be up to 52 hours on the rim of the Shackleton Crater.

Given that there is no usable energy source when this area is shaded, it becomes apparent that the only way to supply electricity to an outpost is by storing it first. Although storing it by using batteries connected to solar panels would be a viable solution, this study tries to emphasize on the in-situ resource utilization aspect of space habitation. By employing local materials, significant weight can be reduced from the mission, while at the same time allowing for more core systems to be shipped.

Therefore, the ideal solution would be a modular system that easily scales with the increasing electrical needs of an expanding Lunar Base, while at the same time benefitting from the properties of lunar regolith.

In a general sense, it has been established that the ideal operation of the model should be as follows: First the energy of the Sun is captured during the day, and stored into a thermal mass. This mass essentially acts as an accumulator, heating to a certain temperature before achieving
thermal equilibrium. Later, during the night, this heat is employed to power the hot side of a thermoelectric circuit. If the accumulator is carefully designed, it should be able to provide heat to the thermoelectrics during the 52 hour period of night without radiating its heat to the exterior. The thermoelectric module, in turn, will convert this thermal energy into electrical energy, which will be used to power the systems in the Lunar Base. The next figure (Figure 5) illustrates the working principle of the system:

As it was explained before, the Sun incidence on the South Pole of the Moon does not allow for it to produce significant heating. Therefore, the system first employs a Solar Concentrator. This consists of a Sun tracker, which reflects the Sun rays into a stable point with a desired incidence angle, and a Fresnel lens, which concentrates the solar radiation and serves as a way to increase the surface temperature of the illuminated areas. During the day, this solar concentrator heats an aforementioned thermal mass, or hot sink. The temperature of this hot sink will increase until it achieves thermal equilibrium, and will stay at this temperature for the remaining of the day period. At the other end of the system there is a cold sink, which does the opposite effect. It will draw heat from the cold side of the thermoelectric array, with the idea of maintaining a thermal gradient, which is needed for the thermoelectric system to produce electricity. Between the two sinks, there is a thermoelectric array. These devices are comprised of a hot connector, a cold connector, and a semiconductor between them, and will produce a voltage drop based on the temperature difference.

The next chapters serve as an in-depth explanation of each of the modules previously explained. Simulations of different environments are provided when needed, with the objective of supporting the design choices and giving an insight on the conditions which could be found on the Moon.
3.1. Solar Concentrator

As stated earlier, the solar flux received on the South Pole of the Moon is not powerful enough to serve as a heating source for the system. This is due to the fact that the Sun angle is always very oblique to horizontal surfaces. Therefore, a tracking solar reflector is essential. It has been demonstrated that the maximum surface temperature at the South Pole does not deviate from the temperatures which can be found at the surface of the Moon on the equatorial regions if such a system is employed. As a result, a constant 1450 W/m² can be assumed as output of the solar tracker, instead of a heat flux of 600 W/m², which is usually assumed at such latitudes [8].

The working principle of a solar tracker is simple: a mechanical device which changes the orientation of a plane, in which usually a solar panel or a reflector is mounted, to follow the Sun’s path to maximize energy capture. By doing this, it is possible to illuminate a specific area with a preferred angle of incidence, which is especially desirable for the case of concentrated solar systems. The following picture illustrates this concept (Figure 6).

As it can be seen, solar tracking with two degrees of freedom can be achieved by employing two stepper motors, which allow the system to orient itself towards the Sun. As it was stated, the Shackleton Crater provides a high ground that prevents the whole system to be shaded by the neighbouring geography. Therefore, a third degree of freedom which would allow the system to move vertically would not be needed.

Without taking into account the losses due to the reflector, by employing a solar tracker we would obtain a temperature on the incident surface of 390 – 400 K. Although this temperature is relatively high when compared to the average surface temperature on the Earth, it is not enough to power a system during the 52 hours of lunar night. In order to raise the surface temperature, a Fresnel lens should be used.

This kind of lens allows for a large aperture and a short focal length, without the mass and volume of material that would be required by lenses of conventional design, usually to the point of being a flat sheet. At the same time, the light it can capture from a source can be from a greater angle, making it ideal for this study case. Fresnel lenses can concentrate sunlight as much as 500 times. To calculate the amount of magnification needed for the system being studied, one must first establish the desired temperature at the surface. Although the reasoning will be elaborated with more detail later on, a desired surface temperature of 1000 K is to be obtained [13]. Therefore, from the Stefan-Boltzmann equation (Equation 6):

\[ j^* = \sigma (1000)^4 = 56703,743 \text{ W/m}^2 \]

This is the desired heat flux at the output of the Fresnel lens. It is known that the input is the theoretical maximum, 1450 W/m². The magnification ratio can thus be computed as:
\[ C = \frac{\text{Flux}_{\text{output}}}{\text{Flux}_{\text{input}}} = \frac{56703.73}{1450} \approx 40 \]

A Fresnel lens with a magnification ratio of 40 would theoretically output a surface temperature on the Moon of 1000 K, if the solar reflector is able to project 1450 W/m². Given that the needed solar concentration is one order of magnitude below the aforementioned current technological limit, it is reasonable to think that such a system can be conceived, even if it had to account for radiation and efficiency losses.

### 3.2. Thermal Mass

Arguably the most critical block in the system, the hot sink stores the thermal energy provided by the solar concentrator. It has to contain that energy and deliver it to the thermoelectric subsystem for an estimated time of 52 hours, while at the same time minimizing the thermal interaction with the environment. Radiation against space or other elements of the system would cause a rapid loss of heat, and thus the system would not be able work under the specified conditions. It therefore becomes apparent that the thermal mass should be shielded and properly sized for this task.

To assess this, a simulation environment in the software COMSOL Multiphysics was created. The objective was to replicate the conditions on the Moon attending to material properties and temperature profiles, to evaluate the heat development of different shapes and sizes of thermal masses. As stated by Wesselink [14]: “The change in heat content of an internal element of volume equals the net amount of heat energy conducted through its walls”. The governing equation for these simulations will thus be the equation of heat conduction:

\[ \rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T = \nabla \cdot (k \nabla T) + Q \quad (8) \]

For the first test, a cube of sintered regolith with 50 cm per side is surrounded by native lunar regolith and a top layer of loose regolith. The cube has a starting temperature of 1000 K. The picture below illustrates this environment (Figure 7):
The sizing of the surrounding native regolith was decided attending to the penetration depth of that material. By doing it this way, one can be certain that the loose regolith layer will not heat up and eventually radiate to space, essentially losing heat and reducing the system performance.

The heat flow was analysed for 52 hours, and the results can be seen in the figures below.

**Figure 8 - Loss of heat of a sintered cube over 52 hours**

**Figure 9 - Loss of temperature at the center of the cube**
Figure 8 illustrates how the thermal energy is being transferred to the surrounding media by conduction at the 52 hour mark. It can be observed that the core of the sintered cube is at 790 K at the end of the simulation, whereas the surrounding regolith is at around 500 K. This highlights the insulating properties of the native regolith, which is able to keep the hot sink at a high temperature for a relatively long amount of time. In Figure 9 this process can be quantified. The simulation starts with the inner block at 1000 K, and the loss of temperature over time can be observed: overall, the loss of temperature for the core of the cube is 220 K over a period of 52 hours (end of X axis).

Figure 10 represents a point located at 10 cm away from one of the edges of the cube, and the increase in temperature due to conduction over time is clear.

At the same time, a concept that was mentioned before can also be examined in the simulation: the penetration depth of native regolith is very low, and over a long period of time only the surroundings of the sintered cube, between 15 and 25 centimetres, are affected by the conduction processes. This complies with studies from the Apollo missions.

It is also worth mentioning that the starting temperature for the surrounding regolith was chosen to be the theoretical stable temperature after 30cm depth at the Moon, which is 254.8 K. This was to consider the more stringent case, in which thermal transfer would be maximum, given that the differential of temperature between native and sintered regolith would be greater.

The next picture (Figure 11) shows the temperature profiles at the core of the sintered block for different starting temperatures:
As it can be observed, the highest the starting temperature of the block is, the bigger the loss over time will be. For the lowest range, the temperature could be regarded as almost constant over the whole night period.

After a number of design iterations, it was decided that the ideal shape of the thermal mass should be a cylinder. By reducing the amount of edges, the conduction process is minimized, and the energy retained is greater, while keeping the volume relatively small. At the same time, it presents advantages when a thermoelectric array is incorporated around it, as it will be seen in the following subchapters.

### 3.3. Thermal mass heating

Another important factor that should be considered is how the thermal mass is going to reach the desired working temperature. A heat pipe network could be employed, in which part of the circuit could be exposed to the solar radiation. The heat would then be transported underground, where it would increase the temperature of the hot sink. This is further explored in section 3.5: Heat Rejection. For the proposed device, the heat sink is placed on the surface of the Moon, and is illuminated by the solar concentrator.

It is therefore necessary to assess the radiation and conduction processes which will distribute the heat inside the sintered regolith block. Specifically, the rate at which thermal equilibrium is obtained should be evaluated, while at the same time ensuring that there is no gradient of temperature along the length of the cylinder, which could decrease the performance of the thermoelectric block.

This simulation environment was created in COMSOL Multiphysics, and the results can be found below (Figure 12):
Figure 12- Temperature profile for a cut of the cylinder after 200 hours

In the picture above, the cylinder can be seen in the middle of the image. The incoming solar radiation is projected from the top over a period of 200 h. As expected, due to the different thermal conductivities, the sintered block has a much higher temperature in its entire length, whereas the native regolith is only heated over the first 15-25cm, while the rest is kept at a very low temperature. This is in line with the observations from the Apollo missions, as well as the studies conducted by Wesselink [14]. The next image (Figure 13) shows the heating graph of the bottom of the cylinder:

Figure 13– Temperature graph over time for the bottom of the cylinder (depth of 0.5m)
It can be seen that the temperature for the bottom of the cylinder starts at the previously mentioned 254.8 K, and quickly increases until a point in which it starts to stabilize, around 950 K. After 200 hours, when the temperature was considered mostly stable, the heat input was switched off. The motivation behind this was to simulate the loss of temperature of the sintered cylinder due to radiation to space over a period of 52 hours. In Figure 13 it can be seen that, although the temperature is not back to the initial condition of 254.8 K, radiation towards space without an insulating shield would not allow the system to extract any energy. Therefore, a servo-actuated lid should be employed, which would close at the end of the day period, protecting the hot sink of the system from temperature loss.

### 3.4. Cold Sink

The objective of a cold sink is to serve as a heat dump for the thermoelectric block. As the hot sink delivers heat to the thermoelectrics, these will heat up and reach thermal equilibrium. It is therefore necessary to provide a way to remove the heat of the cold side of the thermoelectrics, to keep the temperature differential across the device at a maximum.

In both Wesselink’s [14] and Malla and Brown’s [8] work it is established that polar craters are quite possibly the geographic element which achieves the lowest temperature during the lunar night, being as low as 40.1 K. Given that the mission is considered to take place at the rim of a polar crater, in principle it seems as the most reasonable choice to benefit from it.

The system could employ, as for the proposed case of the hot sink, a series of heat pipes that would exchange heat between the cold side of the thermoelectrics and the shaded crater.

Another solution could be to develop a heat rejection system for each thermoelectric module, which would accomplish the same effect by dumping the heat towards native regolith. The benefit of doing this over a pipe network would be the fact that it is a simpler system, although it should be assessed whether the native regolith could effectively reject heat during the night period, given its insulating properties.

For this work, it was considered that the temperature at the cold side of the thermoelectric array was constant, delivering 254.8 K. The main objective of this study was to assess the feasibility of using thermal storage for energy generation, and thus the assumption of a lossless heat rejection system was made. By approaching the project like this, the focus was put on designing a hot sink, keeping it at its highest possible temperature, and the relationship of this system with the thermoelectric block.

As a result, the proposed device should not be taken as ready to be prototyped, but as a reference towards what is the maximum energy which can be collected from a thermal energy storage device using thermoelectrics.
3.5. Thermoelectric Array

A thermoelectric module is a device which converts a differential of temperature into a voltage drop. It benefits from the Seebeck Effect, which is a classic example of electromotive force. Its current density is given by:

\[ J = \sigma(-\nabla V + E_{emf}) \]  

(9)

Where \( V \) is the voltage, and \( \sigma \) the conductivity [15]. The voltage obtained is due to the fact that a temperature difference will drive charge carriers inside the material (electrons and holes) to diffuse from a hot side to a cold side, and this will result in a current flow through the circuit. Figure 14, courtesy of Zhand and Zhao [16], illustrates this process. It can be seen that the device will consist of two legs, which are connected electrically in series and thermally in parallel. One is labelled as the n-type leg, and is doped with electrons, whereas the other one is the p-type leg, doped with holes. When one adds a load connecting these two legs, a thermoelectric generator is obtained.

The performance of a thermoelectric device is usually given by its figure of merit (\( ZT \)), a dimensionless parameter, which is calculated as: 

\[ ZT = \frac{\alpha^2 \sigma}{k}T \]

being \( \alpha \) the Seebeck coefficient, \( \sigma \) the electrical conductivity, and \( k \) the thermal conductivity. It is clear that, in order to increase the performance, both the Seebeck coefficient and the electrical conductivity must increase, while at the same time the thermal conductivity should be minimized [17].

However, the Wiedemann-Franz law states that the electronic part of thermal conductivity has to be proportional to the electrical conductivity. At the same time, the Pisarenko relation is limiting the simultaneous enlargement of the Seebeck coefficient and the electrical conductivity. Despite this, there has been progress regarding enhancing the power factor and reducing thermal conductivity, increasing the efficiency from a very low 4% in its inception, to the current 11-15% which can be achieved by utilizing nanostructures [18].

One important parameter to be taken into account when analysing thermoelectrics is its power generation efficiency [19]:

\[ \eta_p = \frac{T_h - T_c}{T_h} \left[ \frac{1}{\sqrt{1 + ZT_{ave}^{-1}}} - \frac{1}{\sqrt{1 + ZT_{ave}^{-1}} + \frac{1}{T_c/T_h}} \right] \]

(10)

Being \( ZT_{ave} \) the average figure of merit for both n-type and p-type thermoelectric legs, \( T_c \) the temperature at the cold side, and \( T_h \) the temperature at the hot side. It can be seen that a higher \( ZT_{ave} \) will produce a higher conversion efficiency.

N-type and p-type doped legs are usually connected in an alternate fashion, so that there is a current flow across all legs and thus, a voltage drop from one end of the system to the other. The Seebeck voltage which will be generated by such a device can be calculated by [20]:

\[ V_{ac} = n \cdot \alpha \cdot \Delta T \]

(11)
Where \( n \) is the number of thermocouples, \( \alpha \) the total Seebeck coefficient, and \( \Delta T \) is the differential of temperature between the hot and cold junction. At the same time, if the generator is driven by an electrical load, the electrical power can be calculated as [21]:

\[
P = \frac{V_{oc}^2}{2(R_{te}+R_{load})}
\]  

(12)

Being \( R_{te} \) the internal thermoelectric resistance, and \( R_{load} \) the resistance of the chosen load. In order to achieve maximum electrical power, the load resistance should equal the thermoelectric resistance. On the other hand, if maximum efficiency is desired, the load resistance should follow \( R_{load} = R_{te} \sqrt{1 + ZT_{ave} \cdot T_h} \), being \( T_h \) the absolute temperature at the hot junction [21].

A simulation environment can be created in COMSOL Multiphysics to test the thermoelectric effect, and the voltage drop across multiple elements. A basic case study was analysed, in which 81 legs were placed in series, alternating between n-type and p-type, as shown in the figure below (Figure 15):

![Figure 15 - Thermoelectric legs connected in series in a weaving pattern](image)

In the previous image, the n-type legs were coloured in blue, and the p-type legs were left in the original colour. The pattern for connecting the thermoelectrics should also be noted: Connecting the hot side of an n-type with the same side of a p-type, and the cold side of the previous leg with the following n-type, as it can be observed in the following image (Figure 16), where \( T_h \) is the hot junction and \( T_c \) the cold junction:

![Figure 16 – Connecting thermoelectric devices together creates a thermoelectric array](image)

This creates an array in which the movements of electrons and holes generate the following voltage drop (Figure 17):
By grounding one end (dark blue in Figure 17), one obtains a positive voltage at the other side of the device, which was determined to be 170 mV. This result complies with equation (11) and thus, the simulation was deemed accurate.

Although their efficiency is lower than other heat-harvesting devices, the fact that thermoelectrics do not have any moving parts makes them especially desirable for space missions, where frequent maintenance is not always a possibility. That is the reason why this technology was chosen over a Stirling engine.

In the previous chapter, it was discussed that the thermal mass was chosen to be a cylinder. As a result, the thermoelectric array will have to adapt to this shape, while attending to manufacturing feasibility.

There are a number of semiconductors which are valid thermoelectric materials. Usually, a distinction based on their working temperature range is made. Low temperatures are below 400 K, and typically have small figures of merit. Semiconductors in this range are, for instance, Bismuth Telluride (Bi$_2$Te$_3$). In the medium range one can find materials such as Lead Telluride (PbTe), with a working range of 600 – 900 K. This semiconductor is considered one of the most attractive for thermoelectric generators, and its study has been extensive due to its high figure of merit and ease of doping [22]. On the high temperature range (>900 K), materials such as Silicon Germanium (SiGe) are found.

Due to the extensive amount of previous research on PbTe by many authors, some of them even categorizing it as the most promising thermoelectric material [16], this was chosen as the thermoelectric element for the proposed device. As a result, the graph found in Figure 11 was examined, and it was determined that the temperature curve of 1000 K was the one that best suited the working range of this semiconductor, due to the fact that it was considered a middle ground between the steepness of the higher temperature ranges, and the linearity of the lower temperatures.
temperature simulations. By selecting the starting temperature at 1000 K, one assures that by the end of the 52 hour night period, the thermal mass will still provide enough heat to the generators.

3.6. Heat Rejection

In this study, two possible heat rejection methods have been discussed. The first one being radiators for the thermoelectric elements, which would need to be designed according to the temperature range of the device, the medium in which they would work, and the amount of heat which they would have to reject to said medium. A similar technology can be found in radio-isotope generators, in which there is a system which collects heat from the thermoelectric elements and distributes it outwards, towards conductive fins, with the objective of losing heat by radiation to space. An example of such a system can be found below (Figure 18):

In this device, the thermoelectric array can be appreciated in the middle of the thermocooler, and it becomes apparent that the design of such systems is conceived much later during the development phase of a product, when exact specifications and requirements are established. This is due to the fact that heat rejectors will drastically vary depending on the environment in which they are intended to work on. Since the scope of this study is to provide an insight on the design characteristics of a thermal energy storage system rather than develop a fully optimized and working product, it was decided that conceiving a thermocooler for the proposed device was beyond the scope of this project.

The other method presented is by convection with a cold reservoir, such as a polar crater. Heat pipes should be employed, which would contain a fluid that would absorb the heat from the cold sink of the thermoelectric array, and deliver it to the extreme environment of the permanently shadowed parts of the Moon.

A pipe network was also proposed for transferring the heat from the surface of the Moon, at the output of the solar concentrator, towards the hot sink. This applies for the case in which the hot sink is buried under the native regolith, and not for the simulated case, in which the thermal mass is at the surface of the Moon, and an actuator closes a lid to prevent heat from radiating when the night begins (Figure 12).

Both pipe networks present a problem which need to be assessed: If a fluid is to be moved for heat exchange, there needs to be a pump that drives said fluid. This presents a challenge, because the pump will require electrical energy, which will not be available until the system is able to produce its own energy.

To overcome this challenge, this study proposes pulsating heat pipes (from this point forward, PHP). This technology deviates from conventional heat pipes both in working principle and in
design. It is composed of a long, continuous capillary tube which is bent into many turns. As a consequence of this, surface tension effects are present, and the fluid will arrange in plug-slug units, as shown in the following image [23].

The fluid in contact with the evaporator will absorb heat, turn into gas and expand, whereas in the coldest parts of the condenser, the fluid will release energy and liquefy, shrinking. Given the amount of turns in which this phenomenon is happening simultaneously, a movement of the fluid will originate as a result of the expansion and contraction of gases inside the pipe.

This effect will take place continuously and a constant motion will be achieved, effectively exchanging heat without the need for an electric pump. [27]

As for the case of the thermoelectric generator, these heat pipes require a thermal inequilibrium to function. If the temperature between the evaporator and the condenser is the same, there will be no expansion-contraction effects, and no movement will originate.

Given the complexity of developing a simulation environment in which the phase-change forces of a fluid originate motion along a capillary tube, it was decided that the thermocooler approach was more reasonable, in which an idealized radiator would automatically dissipate the heat from the hot sink to achieve a thermal inequilibrium [28].

4. Proposed Device

In the previous chapter, an analysis of each of the system blocks which would be necessary for the conception of a thermal energy storage device was given attending to the specific conditions of the Moon, such as its extreme temperature swings, the properties of native and sintered regolith, or the illumination periods. With this information, it is possible to propose a device which benefits from some of these properties, while reducing the impact of those which make the conception of the model a challenge.

It should be emphasized that the device which was conceived attends purely to a fundamental approach, with the objective of establishing a simulation environment in which different configurations based on thermal storage could be tested. As a result, there are areas in which the device’s performances could be improved. These are left for future work as they were considered beyond the scope of this study, although insight is given on how to approach them.
4.1. Design choices for the proposed system

In section 3.2., it was established that the most optimal shape for a thermal mass would be a cylinder, due to them having a relatively low volume when compared to square shapes, while at the same time providing good thermal resistance due to the absence of corners. A number of tests were conducted in which different radius and lengths were simulated.

The main requirement for this block was to be able to provide a surface temperature which would be in the working range of the lead telluride segments throughout the duration of the lunar night at the Shackleton crater, 52 hours. Cylinders with low volume lost heat very quickly and were not able to provide thermal energy for the later stages of the night. At the same time, it is not possible to increase the size indefinitely as manufacturing issues start to arise, mainly related to excavation and 3D printing limits. A range of 0.5 – 1m is considered the excavation limit on the surface of the Moon before colliding with the bedrock.

The ideal solution came with a cylinder of 0.1m of radius and 0.5m of length. The simulation of lost heat over time can be found in the following image (Figure 20):

![Temperature profile for a buried block of sintered regolith](image)

As it can be observed, this shape would provide a temperature of around 650 K at the end of the night period. Given that the working temperature range of lead telluride was established between 900 and 600 K, and the fact that with a length of 50 cm it is not surpassing the excavation limits, this was thought to be an optimal solution for the thermal mass. For simulation purposes, it was considered as buried to avoid radiation to space although, as established before, the system would be on level with the lunar surface as shown in Figure 12.

For the thermoelectric block, it was decided to follow the series pattern that was first simulated (Figures 15 and 17), with the idea of completely covering the surface of the thermal mass to extract the highest possible energy. To avoid chemical interactions between the thermoelectrics
and the sintered block of regolith, an interface of a highly conductive material was placed in between them. The next figure shows the system that was simulated (Figure 21):

![Figure 21 - Proposed design of the thermal energy storage system](image)

The block of sintered regolith can be seen in the centre, with the interface surrounding it. Around the interface, the thermoelectric array can be found in a weaving pattern. It should be noted that, to obtain electrical energy from this system, a load must be placed between the first and last terminals. The terminals should therefore be placed next to each other to avoid unnecessary manufacturing complications. This can be achieved by having an even number of rows in the device, as seen below (Figure 22):

![Figure 22 - Loading the generator terminals](image)

In the previous image, the terminals close the weaving circuit around the thermal mass, and are placed next to each other for a load to be connected to them. This design consists of 16 rows of 9 thermoelectric elements each, which translates into a total of 144 thermoelectrics. It is clear that the semiconductors could be arranged in a more optimal pattern, such as closer to each other, to allow for more elements to be added. This number, however, was deemed appropriate attending to the length of the simulations that were needed to evaluate the system.
4.2. Simulation environment

The previous system could be simplified into slices with a thermoelectric circuit around them. This drastically reduces the amount of parts of the working environment, which enables for faster and more accurate simulations. The image below illustrates this (Figure 23):

![Simplified model of the proposed thermal energy system](image1)

As it can be seen, the thermoelectric circuit had to be arranged to account for the fact that in this instance, it is just made of one row, instead of an up-and-down pattern like the base design (Figure 20). One could argue that since the amount of thermoelectrics per row is the same as in the original design, there is a relationship of linearity between them, and stacking nine slices should yield the same result as the final device.

By approaching the simulation like this, the computation times are drastically reduced while increasing accuracy. The following image shows the meshing of the sliced system (Figure 24):

![Meshing of the sliced system](image2)
As it can be seen, the tetrahedral-based mesh was designed attending to the physics of the simulation. For areas in which the electric currents or heat transfer were not predominant, a coarser mesh was used, such as the centre of the sintered cylinder. On the other hand, areas of the thermoelectric array where the interaction between heat transfer and electric currents were critical, such as the interface between the copper connectors and the semiconductors, were refined with relatively small tetrahedrals, to offer a more precise calculation.

The equations for Heat Transfer in Solids and Electric Currents were properly coupled in COMSOL Multiphysics, and the study was simulated for 52 hours, in which the curve obtained in Figure 20 was used as the temperature of the sintered block of regolith, or thermal mass.

4.3. Results

The simulation was run attending to thermoelectric polarity and time-stepping, to allow for a time interval in which enough data points could be evaluated. The results obtained can be found below (Figure 25):

![Electric potential drop for the proposed device](image)

This picture showcases the electric potential drop over the length of the thermoelectric circuit. The electrons and holes from the n-type and p-type legs move when a temperature difference is applied to them, and this reaction is carried over to subsequent legs until the final terminal is reached. At this point in time, there is a voltage of 1.8 V when compared to the starting terminal, which has been grounded (0 V). The evolution of the voltage over the lunar night can also be obtained (Figure 26):
It can be seen that the voltage drops over time, at the same rate at which the temperature of the system decreases because of the conduction processes with the native regolith. The voltage decreases from 2.2 to 1.8 volts, which is compliant with Equation 11 for $n = 16$, $\alpha = 187 \cdot 10^{-6}$ V/K, and $\Delta T = 1000 \text{ K} - 254.8 \text{ K} = 745.2 \text{ K}$.

As mentioned before, one could see this system as $1/9$th of the initially proposed device. This would mean that if nine slices were stacked on top of each other, the total voltage produced by this system would be between 19.8 and 16.2 V.

From this, it is possible to calculate the total system power. In Equation 12 it was stated that if maximum power generation was to be achieved, the internal resistance of the semiconductors should match the load resistance between the terminals. However, giving a value for internal resistance would be inaccurate, because the sizing, positioning, and number of thermoelectrics of the sliced device were never taken into account regarding to load optimization. As a result, a range of approximate values is explored, which should give a sense of the system performance, while at the same time leaving room for future work to optimize this device.

In the literature it is stated that such systems can have global resistances as small as 10 $\Omega$ [25]. From equation 12, this would yield to a maximum average power of 0.4 Watts at any given time. Over the whole lunar night, the energy produced by this slice would be 20.8 Watt hours. Again, if this is multiplied by 9, it would yield to a power of 3.6 Watts, and a total energy of 187.2 Watt hours.

Although it may seem small, one can clearly see that the size of the thermoelectric elements has been chosen to cater to the meshing and geometry design of the system. For instance, more thermoelectric elements could be added, effectively doubling the amount of semiconductors.
per ring, from 16 to 32, without altering their shape. Although this would increase the total internal resistance of the system, the voltage would be doubled as per Equation 11.

This can be compared to the power requirements of the International Space Station. The ISS’ power requirements are estimated to be around 70 kW. One could consider that, in principle and given that there is no other source available at the time of conceiving this work, the Lunar Outpost would have the same power requirements as the ISS. If one considers a more optimal design choice in which there are 32 elements per ring, and 18 rings in total (halving the thermoelectric size and multiplying by 4 the amount of thermoelectrics), one would obtain an estimated of 14.5 W per module, which would mean that around 4800 of these modules would be needed. If those modules were to be arranged in a square pattern, there would be around 70 modules per side, and if one considers that the cross section of each module is approximately 0.25 centimetres, the extension of the array would be 17x17 metres (300 m²).

4.4. Verification of results

Although the previously obtained results comply with both the theoretical calculations (see Eq. 11 and 12), and previous work found in the literature, such as the vertical thermoelectric generator from Topal [15], it is commonly regarded as good practice to verify whether or not the system’s outputs are mesh dependent. This would imply that changing the element size of the mesh may or may not yield to different results on the voltage produced by the system.

To do this, the device was evaluated with three different mesh configurations, while keeping the rest of the parameters identical. The next three images (Figures 27 - 29) illustrate the element size for each of the simulations which were performed:

*Figure 27 – Extra fine meshing for the device*
It can be seen that while for all cases the elements used had a tetrahedral shape, the size of them are vastly different from one simulation to another. This yields into a significant difference regarding the computation time, which in some simulation environments may translate into inaccuracies around certain boundaries.

For this scenario, all three cases produced exactly the same results (Figure 26), which validates the initial simulation and establishes that they are not mesh-induced.
5. Conclusions and future work

The aim of this study was to analyse the properties of the lunar environment, with the objective of designing a thermal energy storage system that could be employed to power a future Lunar Outpost during the night periods.

It has been previously reported that on certain parts of the South Pole of the Moon, these periods can last as little as 52 hours of the total lunar cycle, while for the rest of the cycle they are constantly illuminated. At the same time, this illumination is not enough to heat up a thermal mass during the day. As a result, a solar tracker in combination of a Fresnel lens with a magnification factor of 40 was conceived for the system.

It was also noted that the properties of native regolith make the lunar soil an outstanding thermal shield, and that sintered regolith can store enough heat to feed a thermoelectric array during the whole eclipse. Therefore, the proposed system is composed of a cylinder of sintered regolith, which is heated during the day by using the aforementioned solar concentrator, while at the same time being buried in sintered regolith to avoid radiating its heat towards space. Around this thermal mass, a thermoelectric circuit was placed on a weaving pattern, creating a voltage potential between two terminals, from which power can be extracted if the system is to be loaded.

The device was tested and simulated for a total of 144 thermoelectric elements, and it yielded a mean of roughly 20 Volts over the whole night period, with a power of 3.6 Watts. At the same time it was proposed that the number of thermoelectric elements could easily be quadrupled without hindering the performance of the system, which would translate into a more respectable 14.4 Watts, although still very low when compared to other power systems.

It has been stated that the device was not optimized to serve as a replacement for current systems such as the nickel-hydrogen batteries of the ISS, but more of a test bed for future iterations which improve on the proposed design. Taking this into account, if one wanted to power the International Space Station with this system in its current state, 4800 of these elements would be needed and placing them on the Moon would span almost 300 m².

At the same time, there is a lot of room for improvement. The number of thermoelectrics used for this study was very low, because the emphasis was put on establishing a simulation environment that could be tested and could produce an output voltage, rather than optimizing a system and delivering a final product. There have been many studies about thermoelectric array patterns, and if the number of elements per ring is increased to the order of hundreds, the performance of the system should vastly increase. At the same time, the technology of said semiconductors could be enhanced. For testing purposes, only Lead Telluride thermoelectrics were used, but it has been proven that doping these elements yields to better figures of merit, as well as using nanostructures.

Future work on this project could therefore evaluate on these two topics, essentially optimizing the system. Once this has been deemed as a valid prototype, a study should focus on the heat rejection system, with the objective of balancing the heat which can be rejected from the thermoelectric array to maintain a thermal gradient, without draining the system too rapidly.

In this work, it has been proven that the Moon environment is extremely harsh, and energy storage systems will play a key role in maintaining a long duration mission. There are certainly a
high number of technologies which could be employed to solve this problem, from radio-isotope generators to nickel-hydrogen cell batteries. This study served as the base work for another interesting mechanism for energy storage, although an optimization process is needed for it to be able to substitute one of the already established systems.

The main benefit of thermoelectrics are the fact that they do not have moving parts, have an extremely long life duration, and are extremely reliable, which makes them an ideal technology for space applications. If their efficiency keeps increasing, they could become a staple in energy harvesting for space exploration missions.
6. Bibliography


