

# POLITECNICO DI TORINO

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**Master of Science in Petroleum and Mining Engineering**



Master Thesis

**Thermal Enhanced Water Recovery on the Moon**

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## DEDICATION AND ACKNOWLEDGEMENTS

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This thesis is dedicated to my dear family Georges and Latife who have continuously provided support and encouragement during the hardships of my entire academic career. I've always learned to work hard for the goals I have in mind thanks to their positive examples.

I owe them a debt of gratitude for all of their love and encouragement in my life. I appreciate you for providing me the drive and determination to pursue my dreams. My sincere gratitude also extends to my aunts, uncles, and cousins, who I consider fortunate to have at my side.

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Many thanks to my friends for their patience and encouragement during many difficult times. I can't name everyone, but you're always on my mind.

Thank you for always being there for me, Lord.

This thesis is only the beginning of my journey.



## ABSTRACT

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Number of space exploration missions have increased in the recent year. One of the main challenges is the resources of energy as the demand of energy increase exponentially with the distance from Earth. Most of rocket propulsion system are based on LOX and LH2, water is considered very critical for the production of the fuel so water extraction from lunar regolith might be tempting in order to produce directly and on the spot rocket fuel so rocket will not have to go back to earth for a refill.

A practice called thermal water recovery is one of the simplest methods that will aid us in the production of lunar water using a drill rod that has specific dimension. We have utilized a 3D model that consists parts for gas motion, pressure drop, mass balance, sublimation and fluid flow in porous media. Our calculations and assumptions rely on the use of Darcy's Law, Ideal Gas Law and Heat Transfer by conduction.

It was clear that the extraction of water from Lunar Regolith needs high temperature, which means that any heating below the 1000 W will lead to a negligible amount of vapor.

Our study takes into account the fact that water even at high temperature might even solidify specially when there is a change in the pressure of the system due to the capture or the escape of vapor.

We conclude that an extraction with one drill will be a power needing process. In addition that also all the properties are just about one type of regolith while in fact there are countless conditions where even the initial water content might change to 10%.

For the future a detailed study about the pressure and pressure profile will help realize a better simulation with better constraints.

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## LIST OF ACRONYMES

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CE5	Chang-E 5
CUG	Chinese University of Geoscience
DSM	Dark Side of the moon
ESA	European Space Agency
LDEM	Lunar Digital Elevation Model
LH2	Liquid Hydrogen
LOLA	The Lunar Orbiter Laser Altimeter
LOX	Liquid Oxygen
NASA	National Aeronautics and Space Administration

# 1 INTRODUCTION

---

*“I believe that this Nation should commit itself to achieving the goal, before this decade is out, of landing a man on the moon and returning him safely to earth”* -John F. Kennedy’s answer to the joint session of congress on Urgent National Needs (25 May 1961).

Since the beginning of times, Man was interested in astronomy as it influenced some ancient beliefs and cultures and even managed to document some astronomical events such as the movements of the sun and the moon in the Babylonian Astronomy and formulating theories and mathematical equations in an attempt to explain the universe such as Eratosthenes’ breakthrough by calculating earth’s circumference. On July 20<sup>th</sup> of 1966, the impossible was considered possible and Neil Armstrong became the first human to step on the moon and walked around for three hours thus beating a challenge for mankind and this led to an evolution in space science and technologies where higher goals were fixed. Afterwards, three nations worked on lunar expedition on three different programs and declared a race to space science excellency.

Lunar expedition brought men a critical information that can be simplified as water on the moon, that sets a goal of water recovery from the moon and with the increase of astronomical activities this water can be used as a go point for cryogenic propellants that are used in high-performance engines. Typically, cryogenic propellants are LOX (liquid oxygen) and LH2 (liquid hydrogen) and these can be produced on the Moon surface from the electrolysis of water which is trapped in the moon soil. one process to extract the water is the thermal recovery, by heating the soil and recovery the water vapor at the surface [1].

However, A practice called thermal water recovery enables the extraction of surface lunar water that is present under the form of ice. The use of this water for generating rocket propellants and refueling can be a way to reduce the distance taken by a spaceship to refuel by forming refuel stations directly on the moon and this will prove to be cost

efficient. As the moon is abundant in natural resources and its vicinity to earth, it is considered as an ideal platform for the development of new technological activities and futuristic plans that can facilitate further and deeper space missions.

Even though water extraction from lunar soil can be revolutionary, it has never been done before and only few studies regarding it were published. Hence it is still not clear if it is feasible, proving the need for a well detailed simulation and a deep discussion of the results.

The aim of this project is to develop a thermal water recovery method while considering lunar conditions and obeying the rules of physics to make future missions and expeditions easier and others feasible. It investigates the heat applied and the water phase change and water flow through a porous medium identified as Lunar Regolith and finally the phase of recovered water.

In this report, the reader will find the development of an engineering design for a thermal chamber in which lunar conditions are valid and a well detailed study about heat transfer and fluid flow inside a porous media to ensure the physical possibility of water extraction using thermal methods.

## 2 BACKGROUND

---

This Chapter documents theoretical backgrounds that are crucial for this study. This discussion will help the reader understand previous knowledge and expeditions that lead to the selection of the current topic. First of all, section 2.1 discusses the presence of water on the moon. Section 2.2 will outline the expeditions that gave us a brief description of lunar properties while also proving the presence of water on the moon. Finally, section 2.3 explains the concept of sublimation that will be the focus of our study.

### 2.1 LUNAR WATER

Water is an inorganic chemical substance and the main constituent of the earth's hydrosphere; it covers 71% of the Earth's surface and hence the latter is called the blue planet. But the latest scientific breakthrough was the detection of Water Traps near the surface of Lunar Regolith as it was proven in the Amundsen crater near the lunar south pole [2]. This water inside of the Regolith's pores is basically Ice due to the Moon's Temperature and Pressure which is completely different than Earth's condition and this Ice could be warmed enough to sublimate in the near vacuum conditions near the surface of the moon [3]. After Acknowledging water presence, studies were done on the perfect method for extraction and how much will it benefits Mankind.

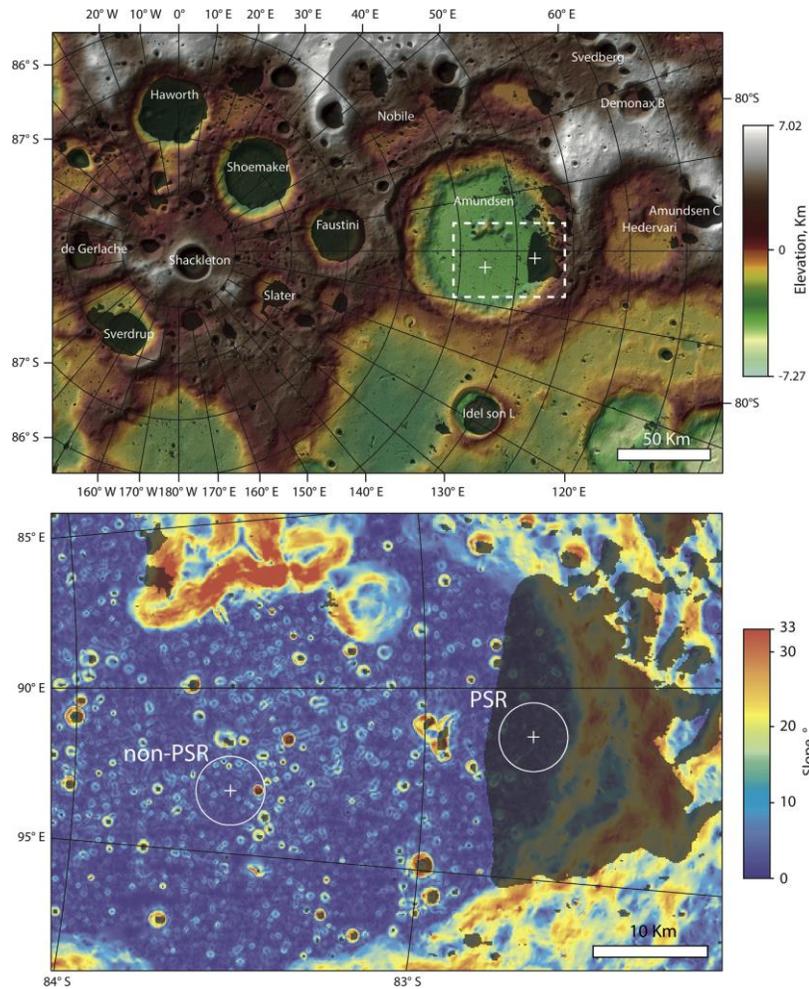


Figure 1 Top – Lunar south polar region. Bottom – Slope map at 120 m/pixel of the study region ('DSM\_75S\_120M') (Mazarico et al., 2011)

In Figure 1 Lunar south polar region in south polar stereographic projection illustrated with colored hill shade of LOLA elevation at 20 m/pixel ('LDEM\_80S\_20M\_FLOAT'). Regions in permanent shadow calculated at 120 m/pixel are plotted as darkened areas ('LPSR\_75S\_120M\_201608'). Named craters are labeled and the white dashed box marks the area plotted in the lower panel. The two targets in Amundsen crater are marked with a white '+'. Inside the DSM\_75S\_120M area, a 3 km radius from the targets is marked and used to delineate observations of target areas from those of the surrounding terrain.

The studied purpose for water extraction from lunar regolith will be its usage as green rocket propellant [4]. If accomplished there would be a chance to build rocket refueling stations directly on the moon without making spaceships return to earth and that will facilitate space expeditions having the moon as the starting point of an expedition instead of earth.

## 2.2 EXPEDITIONS

Two of the most important expeditions that were done are Apollo and Chang'e by respectively the United States of America and The People's Republic of China that have globally leading Space Agencies. These two expeditions have given proof about water presence in lunar surfaces along with some constraints and fixed parameters that could be used for further research.

Results might differ from one expedition to another hence a description for each one's results will be cited in the paragraph below.

### 2.2.1 Chang'e

Among the different Chang'e Expeditions the most fruitful one for this research is the 5<sup>th</sup> one also known as the Chang'e 5. This expedition was able to prove the presence of water marking the first-ever time scientists have found on-site evidence of the substance and that was by lunar lander that detected signs of water molecules along with the use of a spectrometer to analyze the composition of the regolith which lead to a result of water concentration of less than 120 parts per million [5].

The CE-5 has detected a dielectric permittivity of the regolith around  $2.96 + i0.03$  while the thickness of the regolith varies from 1.5m to 8m with a median value of 5m[6].

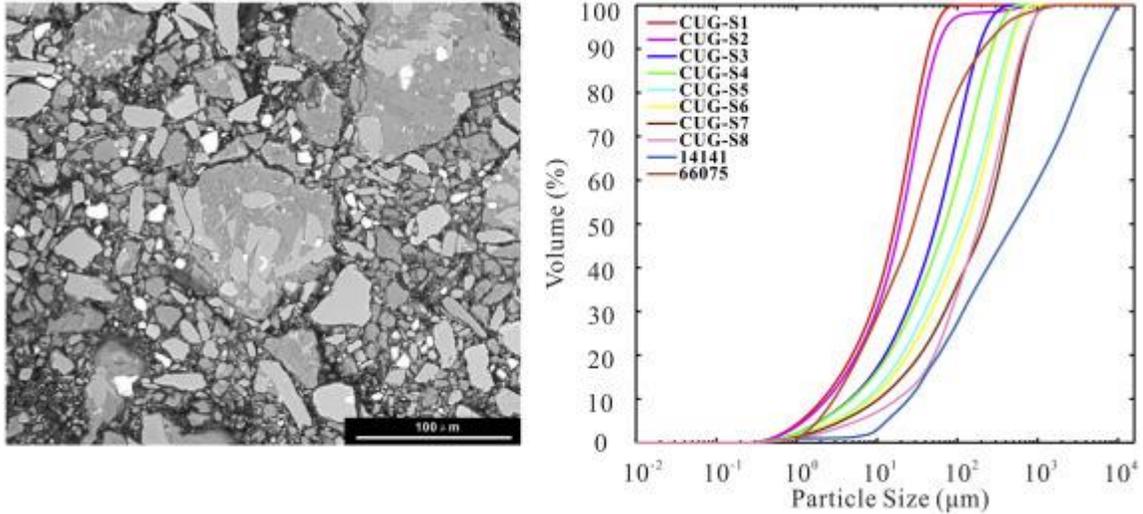


Figure 2 SEM photo of Chinese University of Geoscience at Wuhan (CUG)- single bondS1; Cumulative weight distribution curves of the grain size of CUG-series lunar simulants and Apollo soils.

As shown in Figure 2 the regolith particles in from the CE-5 are similar in shape to the Apollo soil, and it is possible to say that grain size varies from 16.8 to 190.2 μm. The compaction of Lunar regolith increases with depth, and it was 65% in the top 15cm and >90% below 30 cm, in addition the compaction controls physical properties like thermal conductivity, shear strength, compressibility, etc. The main physical properties were estimated along different images from CUG and the results were a bulk density varying from 1.4 to 1.97g/cm<sup>3</sup>, a void ratio around 0.36 to 1.05, cohesion from 2.08 to 5.50kPa, and an internal Friction angle that varies from 31.0 to 34.6° [6].

## 2.2.2 Apollo

The Apollo program is a multi-expedition program by the National Aeronautics and Space Administration that succeeded in landing the first humans on the moon and that includes more than one trip to the moon with results about different aspects. Before Apollo 17 the moon was considered dry and not until after collecting regolith samples and having extended studies on them by NASA that they were able to get traces of water and hydroxyl.[7]

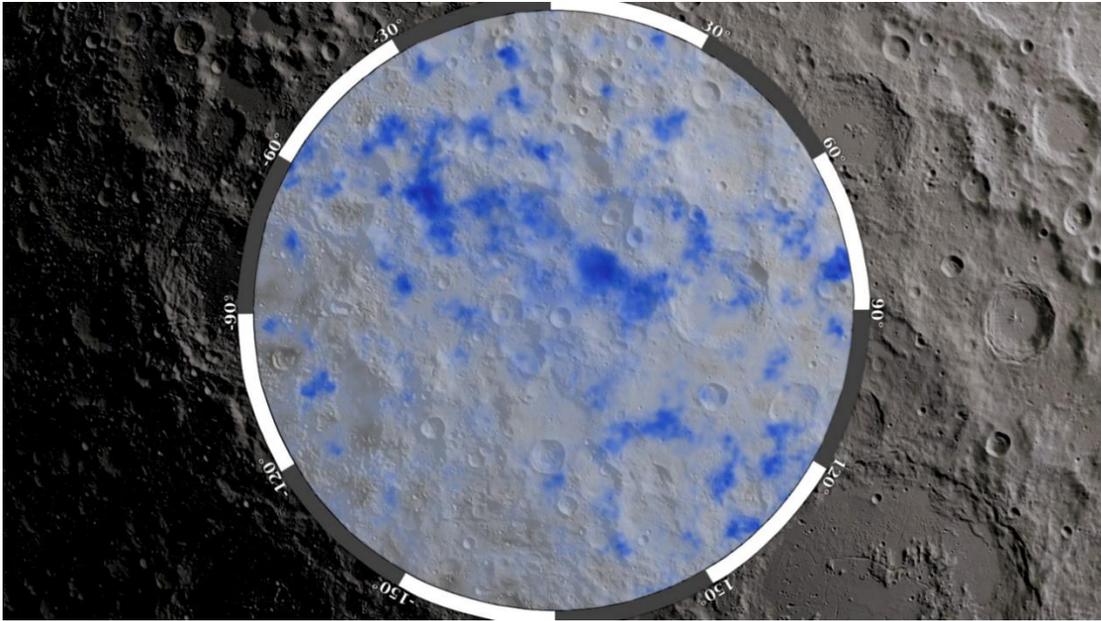


Figure 3 Areas of the Moon's south pole with possible deposits of water ice, shown in blue. The map is based on data taken by NASA's Lunar Reconnaissance Orbiter. Credit: NASA

Regolith properties vary depending on the surface covered but in a general way it is possible to say that the grain size is in the range of 10 to 200 $\mu$ m and that the bulk density ranges to more than 3g/cm<sup>3</sup> and as it was said earlier that strictly depends on the sample and its original surface.

Void Ratio varied from 32% to 58% from the closely packed state to the loose one while also depending on the depth so 44% was chosen as a mean value for the void ratio or the porosity[8] . Finally for Cohesion and Internal Friction Angle the table below will show how there a variation depending on the bulk density of the rock.

Density g/cm <sup>3</sup>	Cohesion kPa	Internal Friction Angle deg
0.99	0.3	13
1.43	0.1	17
1.60	0.5	19
1.70	3.0	14

Table 1 The bulk density, the cohesion, and the internal friction angle from the experimental data (Jaffe, 1973)

## 2.3 WATER SUBLIMATION

Water Sublimation is the conversion of a solid to a gas or vapor  $Solid + Heat \rightarrow GAS \text{ or } Vapor$  with the heat declared as heat of sublimation termed by  $\Delta H_{subl}$  in this endothermic reaction. The Phase Diagram of a Substance might help predict the sublimation conditions[9] .

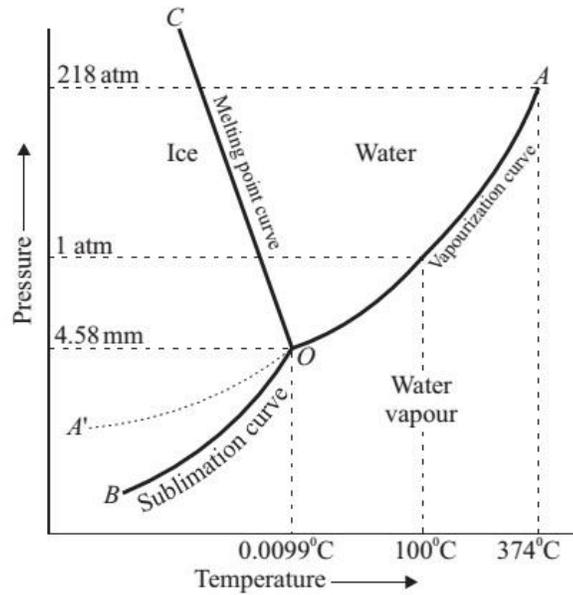


Figure 4 Water Phase Diagram

Figure 4 represent the phase diagram of water and indicates the presence of sublimation of Snow and Ice at temperatures and pressures providing a path crossing the curve BO which is the Sublimation Curve.

In a chamber with low humidity, small water droplets were frozen at a temperature  $T$  and then monitored. After  $T$  becomes less than  $0^{\circ}C$  the droplets are considered as solid and due to water expansion, the droplet did form a coned shape but several minutes the traces of evaporation were starting to be seen until the initial volume of water ( $4.4\mu L$ ) disappears [10].

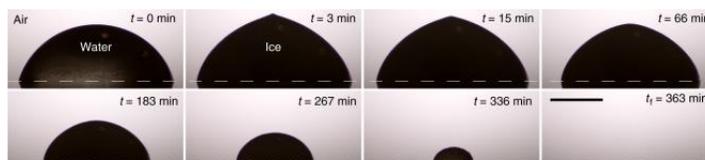


Figure 5 Evaporation of a pointy ice drop. Scale bar 1 mm.

If Sublimation Conditions exist, Lowering the Pressure will not result in an increase of sublimation rate because sublimation rate is independent from pressure variation and highly dependent on temperature, hence a decrease in temperature will lead to a decrease in sublimation rates. Studies Indicate that under moon conditions, over 50% of water ice can be subjected to Sublimation in the right conditions leaving behind the residual solid ice [11].

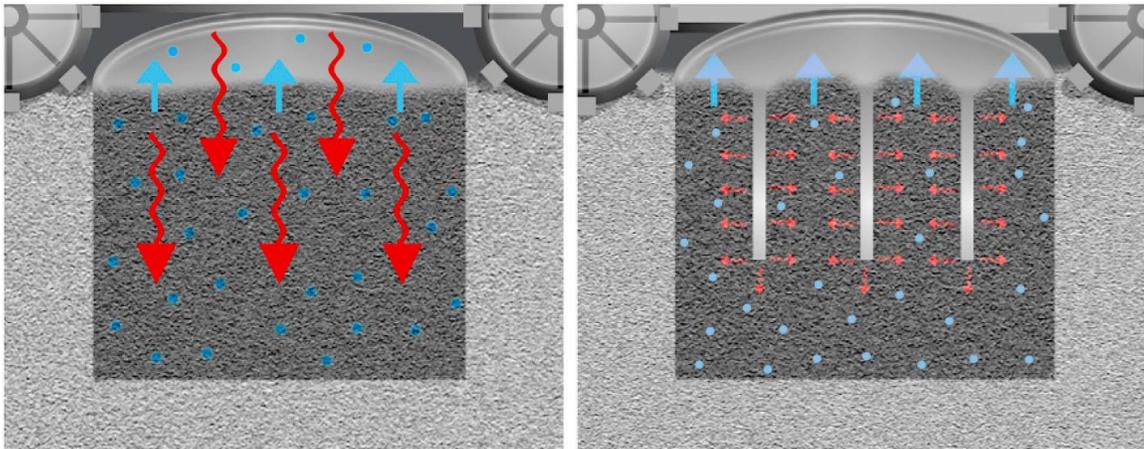
Presence of Regolith particles can have a large effect on behavior of water ice, where increasing proportions of dust in the ice fraction might lead to the loss of light H<sub>2</sub>O to the vapor phase while increase the percentage of Deuterium inside of the residual water which will make it heavier water and that can be a problem in the sublimation process [11].

### 3 THERMAL WATER EXTRACTION

---

This chapter focuses on the water extraction methods that were previously studied on a physical and numerical scale and were proven applicable and these methods will be considered as a base to our study.

Thermal extraction technologies are very important for contaminated soil treatment due to their ability to meet quickly and reliably cleanup standards, however sometimes high temperature can lead to a damage in soil depending on its properties. Usually this type of remediation is used for specific scenarios including presence of hydrocarbons along with water [12].



*Figure 6 Heating configurations considered in our thermal water extraction model: (left) Homogeneous surface heating; (right) Heated metal rods inserted into the regolith volume. The heaters could for example be carried by a rover. The surface would be capped by a cold plate dome to collect the vapor escaping from the top surface. Red arrows: heating; Blue arrows: vapor motion.*

In this study, thermal methods are used for the extraction of lunar water from regolith and that can be realized by considering the use of a heated metal rod in the near surface part of the regolith or a uniform surface heating method where the surface of the regolith will be heated with a constant heat.

Water is one of the most critical elements in this type of remediation and thus due to its dielectric properties it will assist this remediation by vaporizing and being able to move upwards. For example a suggested method implies that it is possible to extract water by

drilling metal rods in the ground or by uniform surface heating and those recoveries are very dependent on several factors such as the heating power and method, and basically heating power should be around the kW level[13].

This configuration mimics a portable/mobile resource extraction instrument that can be carried by the rover. Water vapor can be collected for further use as a resource by means of cooling plates covering the heated surface.

## 4 MODEL DESCRIPTION

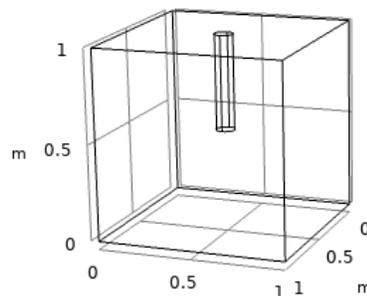
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Chapter 4 describes the design of our model and the assumptions taken in order to simplify our work by taking into account the geometry and the parameters and constants in section 4.1 along with the boundary conditions that were applied to our model in the section 4.2. After the overall description is defined, the reader will find it simpler to comprehend the model taking into our simulation.

### 4.1 GENERAL DESCRIPTION AND ASSUMPTION

To study the extraction of water from lunar regolith, we consider a soil volume of a  $1 \times 1 \text{ m}^2$  surface and a 1 m depth in order to simplify further calculations. The heating method used is heating the soil by a metal rod, where a rod is inserted in the center of the soil and produce a constant heat of  $10^4 \text{ W}$ .

We divided the volume under consideration into identically sized three-dimensional cells to compute the thermal development of the regolith as it is heated (cubes of 0.5 m side). Cell components are rock, water ice and a void that will be later filled with water vapor during the upcoming simulation. On the moon we have near vacuum conditions so our initial Pressure  $P_0$  is approximately 0 Pa.



*Figure 7 3D model of Lunar Regolith with a heating rod.*

Assumptions were considered to simplify our system:

- Initial soil properties: The regolith is taken as homogeneous at 150 K, 200K [14] with a defined constant porosity of 30% which correspond to the average porosity of the Appolo samples[15]. Densities of the rock and ice are respectively 2650 and 900 kg/m<sup>3</sup> with an assumption of water ice content to be 5% in weight of the total weight which will result in a mixture of 1770 kg/m<sup>3</sup>. The chosen heat capacity is 920 J/kg/K [16].
- Soil thermal conductivity is considered as constant, but the conductivity of regolith is relatively small in comparison with the ice conductivity (0.015 and 13 W/mK) so a weighted conductivity is 0.7 W/mK [17]. Heat capacity of ice, viscosity of vapor are considered constant for our entire system.

In the table below all the fixed parameters and model constant are classed with the values of permeability, conductivity and heat capacity [13].

Table 2 List of Parameters

<i>Parameters</i>	<i>Name</i>	<i>Value</i>	<i>Unit</i>
$R$	Ideal gas constant	8.31	K <sup>-1</sup> m <sup>3</sup> kPa/kmol
$M_{H2O}$	Molar mass of water	18	kg/kmol
$T_{init}$	Initial soil temperature	150,200	K
$P_0$	Initial pressure	0	Pa
$\varphi$	Porosity	0.3	
$\mu$	Viscosity of water vapor	1.85E-05	Pa.s
$k_{drill}$	Drill permeability	0	m <sup>2</sup>
$k_{soil}$	Soil permeability	2.6E-12	m <sup>2</sup>
$\kappa_{soil}$	Soil thermal conductivity	0.7	W/mK
$\kappa_{drill}$	Drill thermal conductivity	50	W/mK
$cp,ice$	Ice heat capacity	2040	J/kg/K
$cp,drill$	Drill heat capacity	466	J/kg/K
$cp,vapor$	Vapor heat capacity	2000	J/kg/K
$cp,rock$	Rock heat capacity	920	J/kg/K
$\rho_{drill}$	Density of the drill	7500	kg/m <sup>3</sup>
$\rho_{ice}$	Density of ice	900	kg/m <sup>3</sup>
$\rho_{rock}$	Density of the rock	2650	kg/m <sup>3</sup>

## 4.2 BOUNDARY CONDITIONS

Before we discuss the calculation method in our system, this subparagraph is an overview of the assumed boundary conditions of our model to provide a simple model and it can be used as a start for our analysis.

For our thermal model, the assumptions for boundary conditions were taken and the boundaries were considered adiabatic where there is no heat transfer between our system and the outside environment and applies the formula below with  $Q$  being the heat rate:

$$Q = 0 \text{ J/s}$$

Now boundary conditions were taken for our pressure and flow system where our boundaries have a constant pressure  $P_b$  that is equal to 0 Pa due to near vacuum conditions.

## 5 METHOD

---

In Chapter 5, we discuss the methods, formulations and assumptions used in order to calculate the variables that define our study like pressure, temperature, mass of sublimated vapor and mass diffused. We divide this chapter into 4 parts. First, Heat transfer in porous media 5.1 where we take into account system properties so we can calculate the temperature in our cell divided model. Sourcing water vapor 5.2, discusses the presence of sublimation or condensation depending on the pressure and saturation pressure. Gas motion 5.3, deals with darcy's law to calculate vapor diffusion to adjacent cells and to the outside depending on the pressure difference between cells and the pressure difference between cells and the outside using boundary conditions. And finally, water and mass balance 5.4, discusses the mass of solid phase, mass of vapor diffused, and mass of vapor remaining.

Our method is a time and physics depending method so we have specified study time divided into time step and in each time step we will undergo the same steps that were previously declared and in order to verify the convergence of our model the a mass balance at the end of our calculation will take place proving that water mass was conserved and there's no mass losses so the initial mass will be equal to the trapped vapor mass, total diffused vapor mass and the remaining solid mass.

The method is summarized in the below figure:

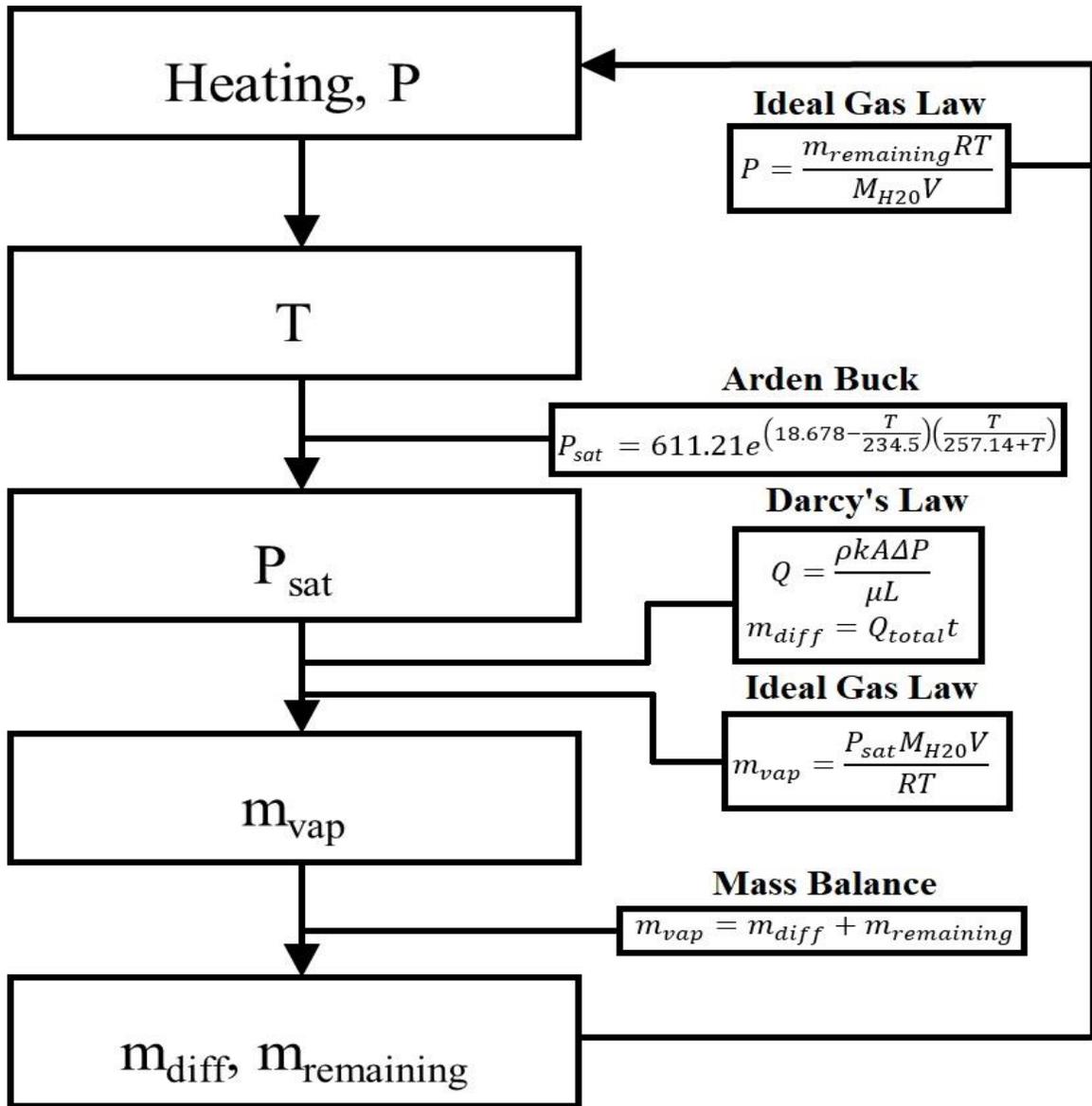


Figure 8 Simulation and Study Plan.

## 5.1 HEAT TRANSFER IN POROUS MEDIA

Heat transfer will be computed on a software named COMSOL Multiphysics which is a simulation software that takes into account pre-declared physics. COMSOL simulations are done using the right equations to obtain results based on the inputs and boundary condition after setting a time and a time step. The Heat transfer in porous media module will be used.

First, we declare our initial temperature of 150 K and 200K since the temperature of lunar regolith is estimated to be in the range of 150-250K [18] to the software and that temperature represents the total system and even the temperature at the boundaries.

Then we declare our Porous Medium after setting the geometry previously talked about with a no convection assumption in order to simplify our model, and we specify our properties like heat capacities  $c_{p,rock}$  and  $c_{p,ice}$  and their weighted average so we can have a heat capacity  $c_p$  for our system, the bulk density of the solid composition and that density will be equal to the average value depending on ice content and it is  $\rho$  with a value of  $1770 \text{ kg/m}^3$  and is considered constant and finally, we declare the average thermal conductivity  $\kappa_{soil}$  equivalent to  $0.7 \text{ W/mK}$  and the porosity  $\phi$  of  $0.3$ .

After dealing with the porous medium part, we specify boundary conditions previously mentioned of adiabatic boundaries applying the formula:

$$-n \cdot \mathbf{q} = 0$$

Where  $\mathbf{q}$  is the Heat flow and  $n$  is the directional normal vector.

Finally, we need to precise our heat source which is previously declared as a cylindrical geometry while precisising the heat produced by it and which is considered as constant up to  $10 \text{ kW}$  along with its properties like density, thermal conductivity and heat capacity previously cited in Table 2 List of Parameters Table 2.

Afterwards the software will start the simulation using the heat formula declared below:

$$\begin{aligned} (\rho C_p)_{eff} \frac{\partial T}{\partial t} + \rho_f C_{p,f} \mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q} &= Q_t \\ \mathbf{q} &= -k_{soil} \nabla T \end{aligned}$$

Since we considered no convection so the formula will be used without the convection part:

$$(\rho C_p)_{eff} \frac{\partial T}{\partial t} + \nabla \cdot \mathbf{q} = Q_t$$

With  $T$  being the Temperature in Kelvins.

## 5.2 SOURCING WATER VAPOR

After computing the temperature, we calculate how much water will sublimate or condensate in each cell and to be able to do this we need to compare the cell pressure with the saturation pressure  $P_{sat}$  which is calculated using the Arden-Buck equation:

$$P_{sat} = 611.21e^{\left(18.678 - \frac{T}{234.5}\right)\left(\frac{T}{257.14 + T}\right)}$$

T being the cell temperature in degrees Celsius and the  $P_{sat}$  will be calculated in kPa. Taking the saturation pressure in comparison to the cell pressure P, if P is greater than  $P_{sat}$  then vapor will condensate and if it is the reverse case then we will have sublimation of ice.

The question here is how much water is being sublimated, and it can be solved by calculating the vapor mass depending on the saturation pressure while considering that the volume here is the total pore volume since gas will occupy the entire pore volume.

$$m_{vap} = \frac{P_{sat} M_{H_2O} V}{RT}$$

We start with a Pressure P of 0 kPa since we consider near vacuum conditions and the pressure variation afterwards will depend on the Darcy Law and on the Gas Motion in the next part to compute the remaining vapor mass and using the ideal gas law, we can compute the new pressure of our system:

$$P = \frac{m_{remaining} RT}{M_{H_2O} V}$$

With the mass remaining  $m_{remaining}$  in Kg, the Universal gas constant with a value of  $8.314 \text{ K}^{-1} \text{ m}^3 \text{ kPa/kmol}$ , the Volume V which is equal to  $0.3 \text{ m}^3$  where fluid might exist and finally  $M_{H_2O}$  the molar mass of water which is equal to  $18 \text{ kg/kmol}$ .

### 5.3 GAS MOTION

After checking the possibility of gas presence, then we compute if the pressure difference leads to motion from a cell to its neighboring cell or to the outside, we apply Darcy's law along our x, y, and z direction to calculate the mass crossing the borders of the cell with the assumption that the bottom border of the system does not allow the vapor diffusion and the Pressure at the boundaries is always equal to 0 kPa.

The darcy law formula is represented in the equation below:

$$Q = \frac{\rho k A \Delta P}{\mu L}$$

With  $Q_m$  being the mass flow rate of vapor in kg/s,  $L$  the distance to the cell border depending on our cell division and equal to 0.5m,  $A$  the cross section of the border with a value of 0.5x0.5 m,  $\Delta P$  as the pressure difference in Pa, a bulk density  $\rho$  of 1770 kg/m<sup>3</sup> and the rest of the parameters soil permeability  $k$ , viscosity  $\mu$  are previously declared in Table 2.

The term  $\frac{k \Delta P}{\mu}$  represents the darcy velocity which reflects the velocity of which mass diffuses from a surface to another and it is affected by the pressure difference so having a higher pressure difference will lead to having a higher darcy velocity.

After calculating the mass flow rate, it is possible to compute the mass diffused at each time step by multiplying the flowrate with the time step in seconds:

$$m_{diff} = Q_{total} t$$

This diffusion mass will reflect the mass that diffuses to neighboring cells along with the mass that diffuses to the outside.

## 5.4 WATER PHASE AND MASS BALANCE

After computing the mass that sublimates and the mass that diffuses from each cell at each time step at first, we compute the mass remaining in the solid phase:

$$m_{solid} = m_{cell} - m_{vap}$$

With  $m_{cell}$  being the initial cell mass at first and for each time step it will take the value of the solid mass directly or the solid mass plus the vapor mass if we have condensation computed in the previous time step. While in case we have sublimation again the remaining vapor mass will be added to the newly sublimated mass.

$$\text{Sublimation } m2_{vap,i} = m_{vap,i} + m_{remaining,i-1}$$

With  $m2$  being the new mass due to new sublimation along with vapor mass remaining from the previous time step.

$$\text{Condensation } m2_{vap,i} = m_{vap,i}$$

$$m_{remaining,i-1} = 0$$

$$m_{solid,i} = m_{solid,i-1} + m_{vap,i-1}$$

Reflecting the condensation of the water vapor if the pressure is greater than the saturation pressure and we the transformation of vapor to ice again.

At the end step of our model, we check the mass that diffused through the outside boundaries of the system and the mass that remained and their sum should be equal to the initial mass and in that manner we check the convergence of our calculations.

## 6 RESULTS

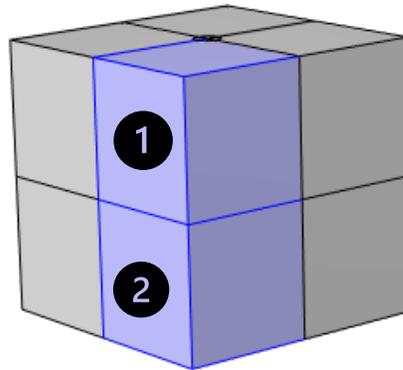
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This chapter includes the most important findings of the study that was discussed in 5. The results are placed for two different initial temperature starting by 150k and for two time ranges one at 5 days while taking a time step of one hour to have a detailed temperature and pressure evolution graph.

In this study results concerning the temperature, sublimated mass, mass diffused and saturation pressure will be shown on graphs for each one of the cells taken into study after considering our system as a symmetric system and taking 2 cells one in the upper layer and the other directly below it in the second layer where diffusion will only be present between them and the outside without vapor diffusing to adjacent cells in the same layer due to same temperature and saturation pressure conditions.

After obtaining some results, at the 150 K initial temperature the diffused mass that will be obtained will be very negligible with respect to the initial mass inside of our system so it is enough to display results at a heating value of 10000 W while for the 200 K mark we can start our simulation from 1000 W to 10000 W.

The cells where we are starting our simulation before going to the rest of our system are highlighted in the figure below:



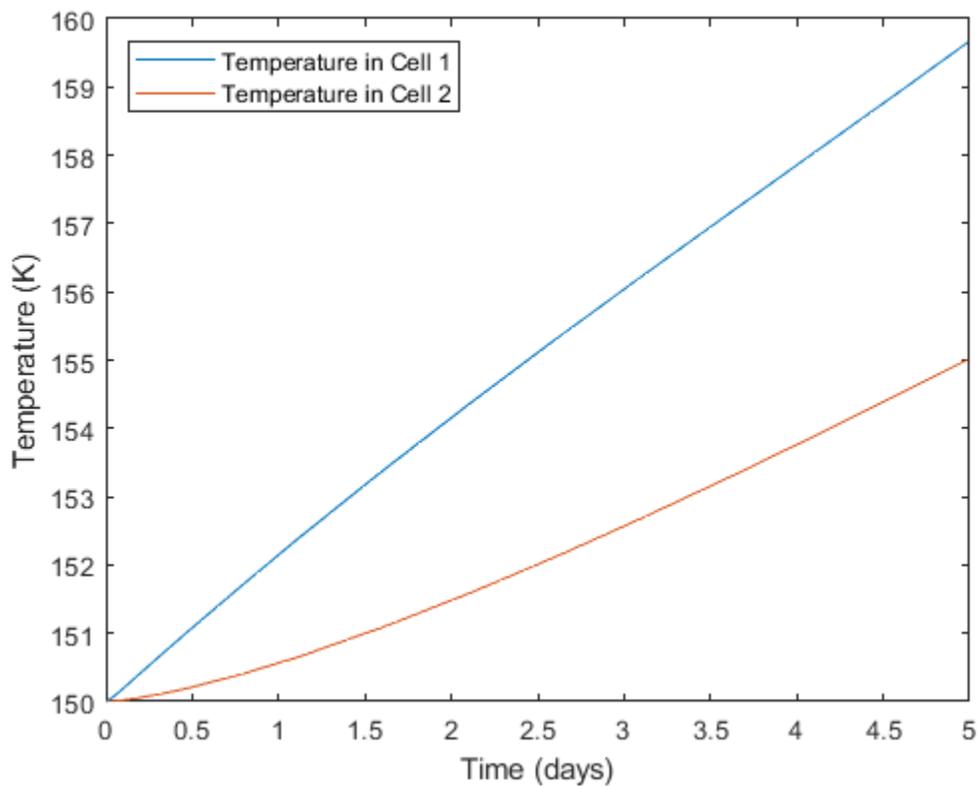
*Figure 9 Studied Cells in our system - Highlighted in blue with cell one being the upper cell and cell 2 the lower cell.*

After taking a subsystem of 2 cells we can say that our system is divided to 4 subsystems like the studied one and we can directly compute the mass diffused based on the diffused mass between each cell and the outside.

## 6.1 SYSTEM WITH AN INITIAL TEMPERATURE OF 150 K

Using the pre declared method in the previous chapter, the temperature was computed on COMSOL Multiphysics using the heat transfer in porous media physic. That temperature is considered as the average temperature for each cell or block at a time step of 1 hour for a time of 5 days with a constant heat of up to 10000 W.

Starting with a time of 5 days the temperature is shown in the figure below with data from COMSOL and plotted on Matlab.



*Figure 10 Temperature of the cells vs time at 10000 W for 150 K*

The temperature graph clearly shows how cell 1 is being heated more than cell 2 due to the presence of the rod along cell 1 without it passing through cell 2. For cell 1 after 5 days it reaches the 159.6 K and for cell 2 it reaches 155 K.

After computing the temperature of the cells, the saturation pressure of each of the cells is calculated on Matlab and it was shown in the next graph:

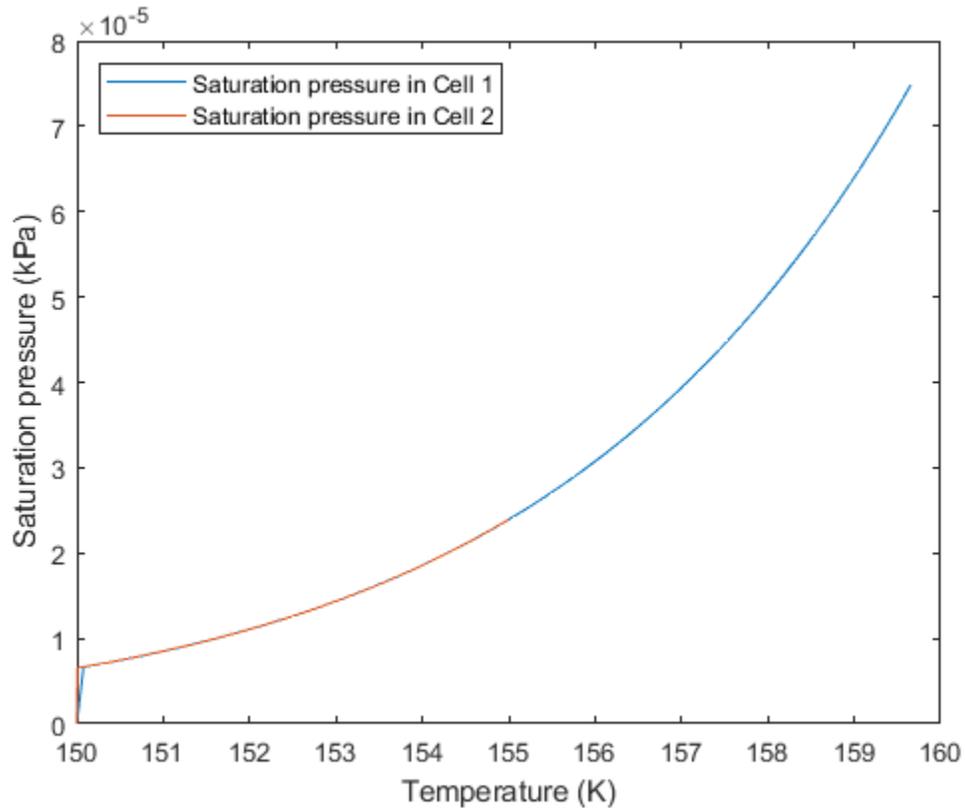


Figure 11 Variation of Saturation Pressure vs Temperature at 10000 W for 150 K

Initially as it was considered we assumed that there was no room for sublimation then from the next step onward there was a sublimation or a condensation depending on the pressure after mass transfer with the saturation pressure for the cell 1 reaching a value of  $7.5E-05$  kPa and cell 2 a value of  $2.4E-05$  kPa.

Now in the next step the sublimation mass was calculated using the ideal gas law with the saturation pressure and for each time we show how much water sublimates/condensates and using Darcy's Law we can see the diffusion and thus checking the pressure variation. In our System the pressure variation is always smaller of the saturation pressure so in every case we have vapor that is generating in our system.

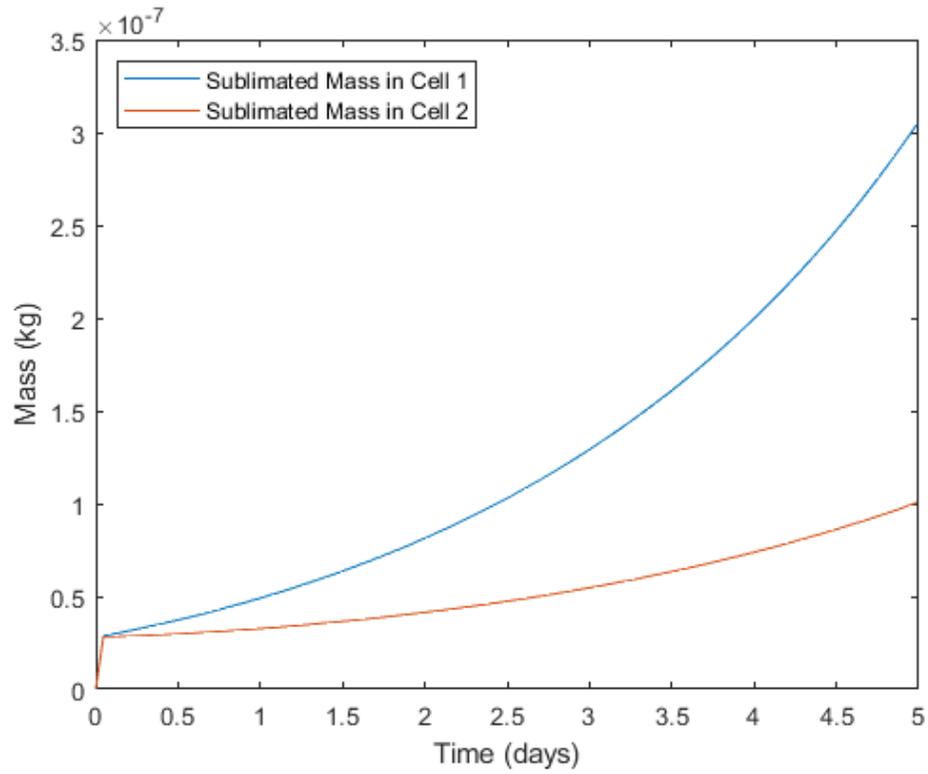


Figure 12 Sublimated Mass for each Cell at 10000 W for 150 K

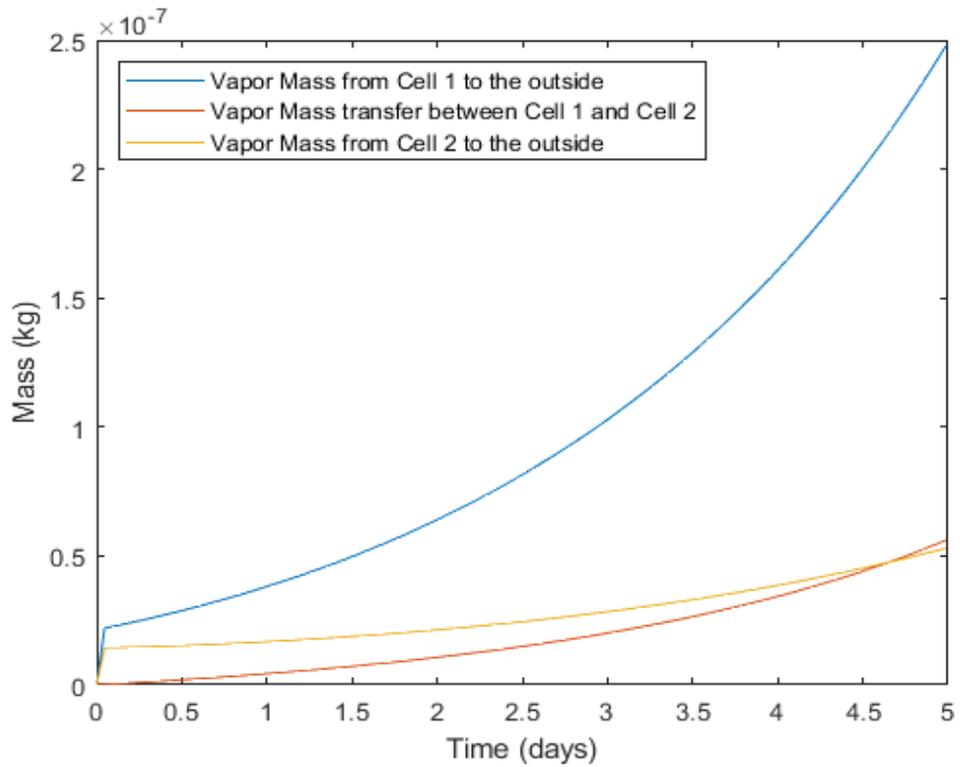


Figure 13 Diffused Mass for each Cell at 10000 W for 150 K

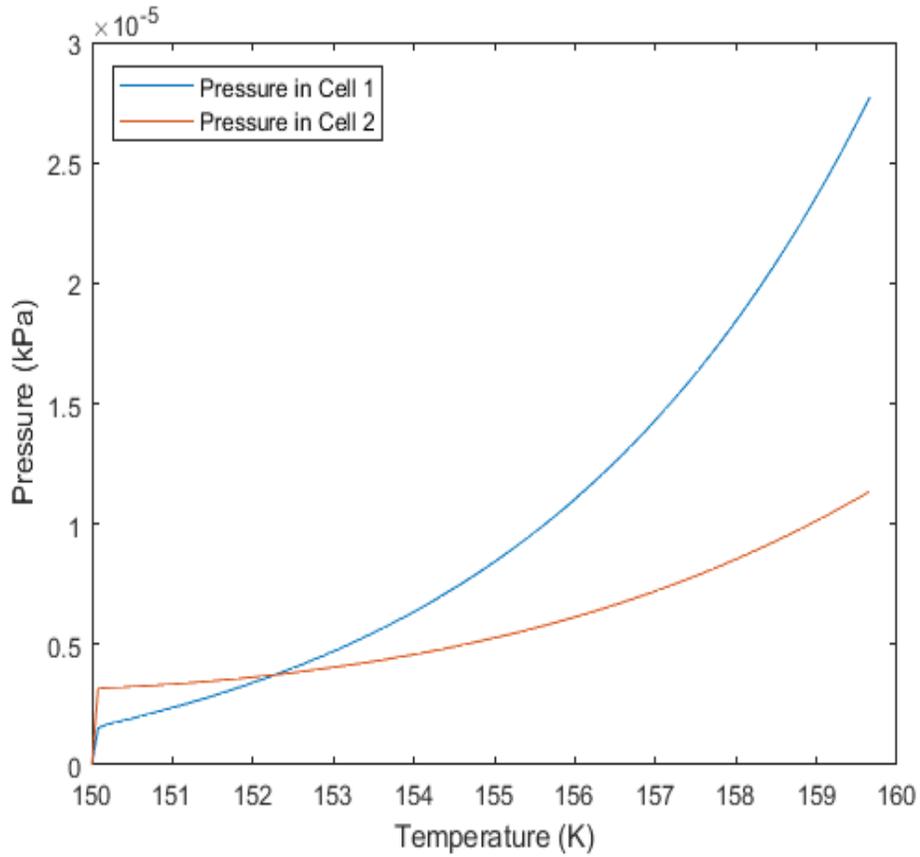


Figure 14 Pressure after Mass transfer at 10000 W for 150 K

Due to migration of vapor some of the sublimation vapor will diffuse out of the cells the new pressure will be computed by the remaining vapor mass.

Running the system as it was described in the first part we focus on getting the diffused vapor from cell 1 through its top boundary and the total mass considering the 4 subsystems will be a value of 5.44E-05 kg.

## 6.2 SYSTEM WITH AN INITIAL TEMPERATURE OF 200 K

Having an initial temperature of 200 K we display results for both 1000 W and 10000 W to get a well defined value of the diffused mass and to see how much vapor we can extract from our system.

Using the same methodology as 5 we display the same results we previously displayed in 6.1.

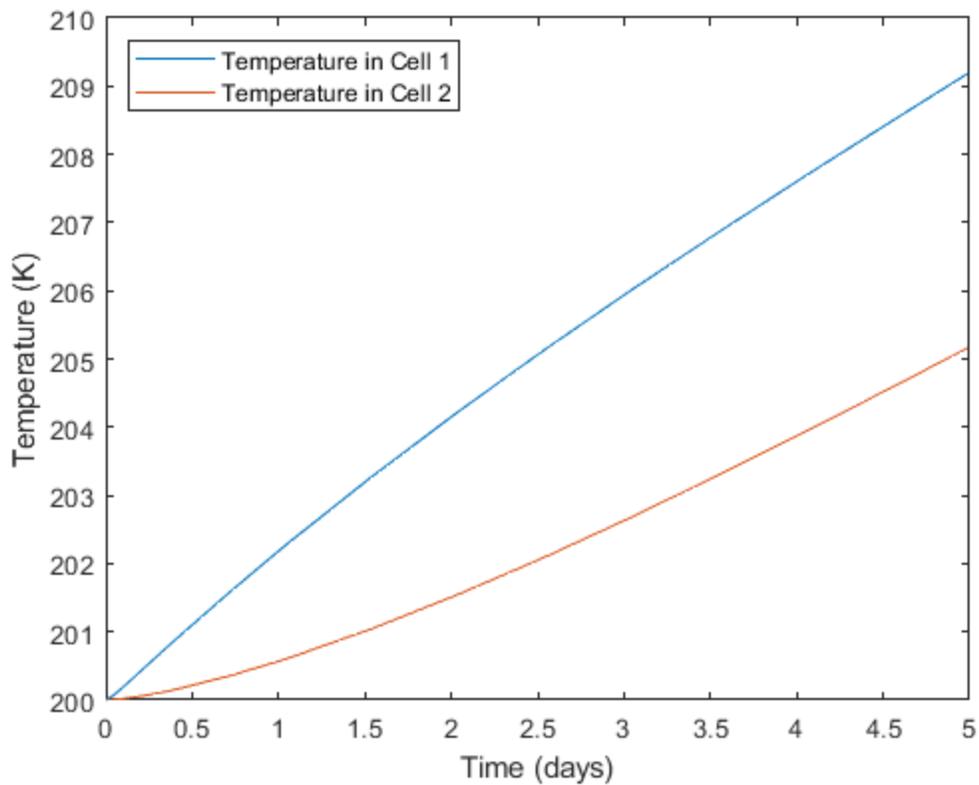


Figure 15 Temperature of the cells vs time at 10000 W for 200 K

The temperature took the same path as the one in 6.1 and was increased up to 209 K for cell 1 and 205 K for cell 2.

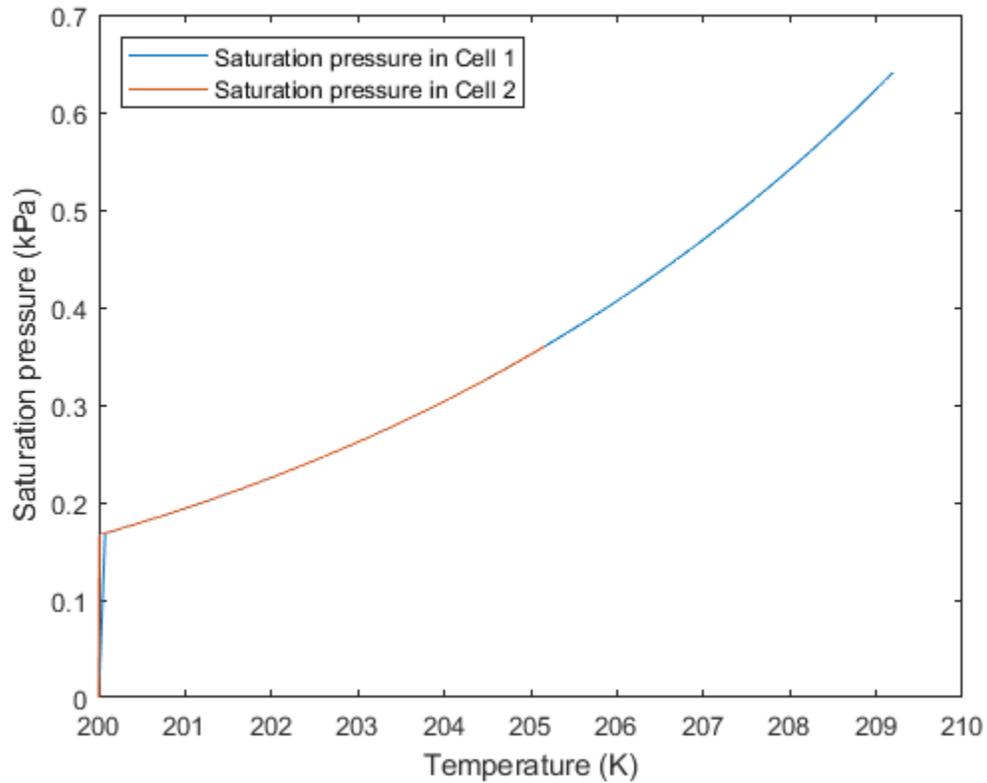


Figure 16 Variation of Saturation Pressure vs Temperature at 10000 W for 200 K

The Saturation Pressure curves are also the same curve due to the Arden Buck formula with  $P_{sat}$  for cell 1 having a max value of 0.65 kPa and  $P_{sat}$  for cell 2 with a value of 0.37 kPa.

With these saturation Pressure it is very clear how much temperature enhances the saturation pressure. For cell 1 at 150 K the  $P_{sat}$  max was  $7.5E-05$  kPa that means it increased more than 1000 times with our new initial temperature of 200 K.

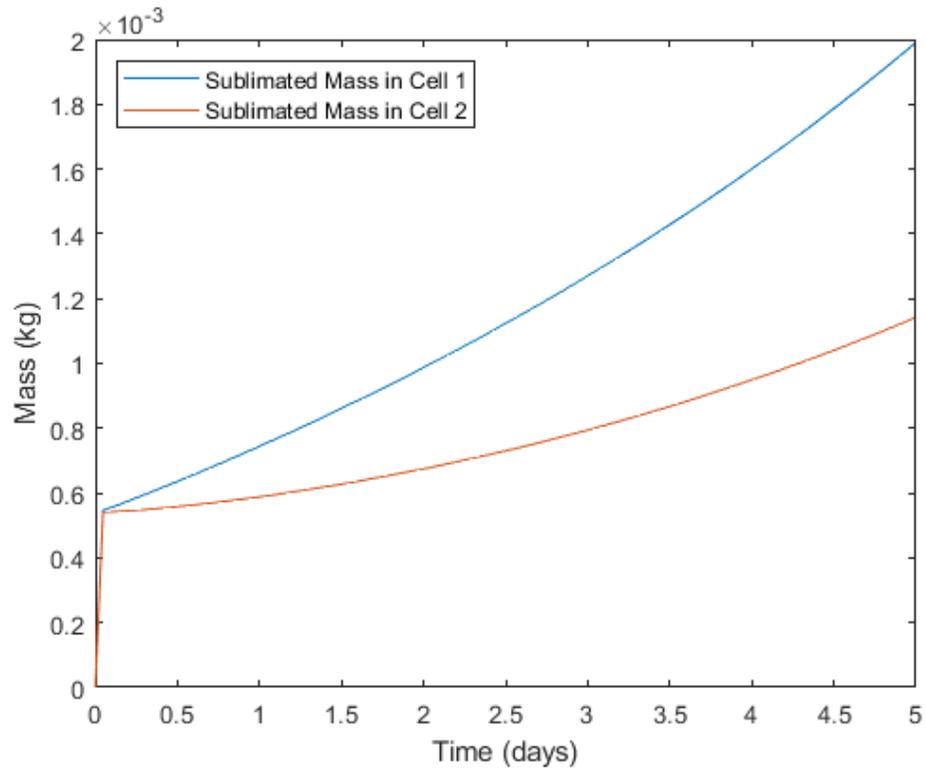


Figure 17 Sublimated Mass for each Cell at 10000 W for 200 K

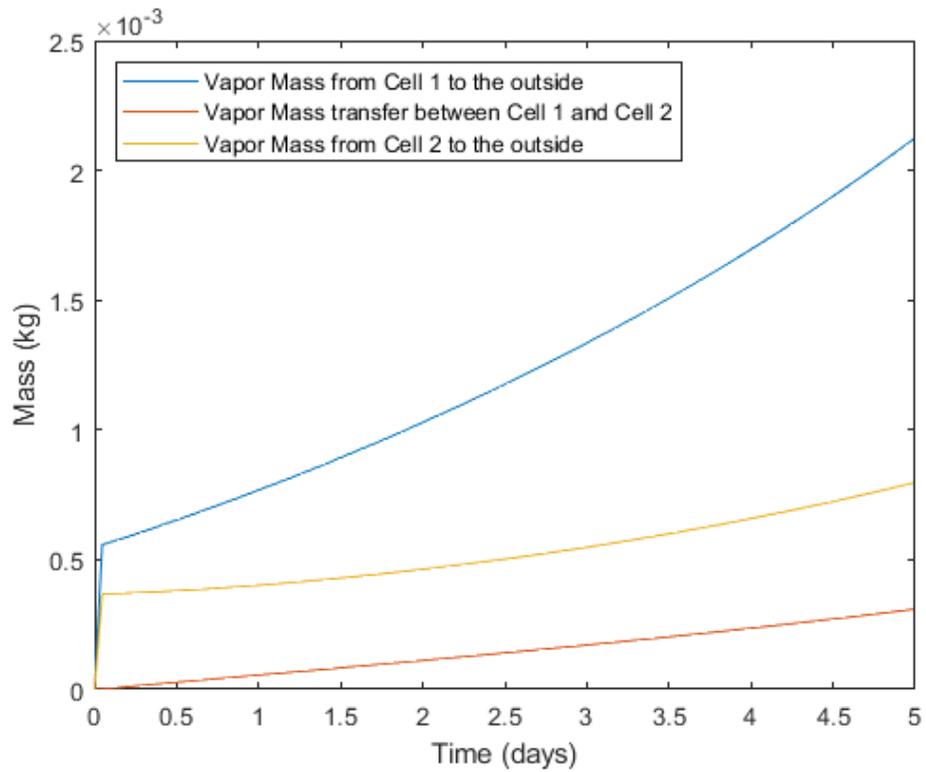


Figure 18 Diffused Mass for each Cell at 10000 W for 200 K

Figure 17 and Figure 18 show the mass that sublimated at each time step and how much mass diffused at the same time step. For the beginning of our system due to bigger pressure differences than the ones for the 150 K case, in some parts the mass that can diffuse at the chosen time step is higher than the mass that sublimates so to alter our system we consider that the mass diffused is the total mass sublimated without any vapor remaining inside of the system while disregarding the residual vapor.

For example at a time of 1 h we have a sublimated mass of  $5.4E-04$  kg in cell 1 but the mass that can diffuse is bigger so that's where we will apply our assumption. While the pressure will change to the initial pressure of near vacuum conditions of 0 kPa.

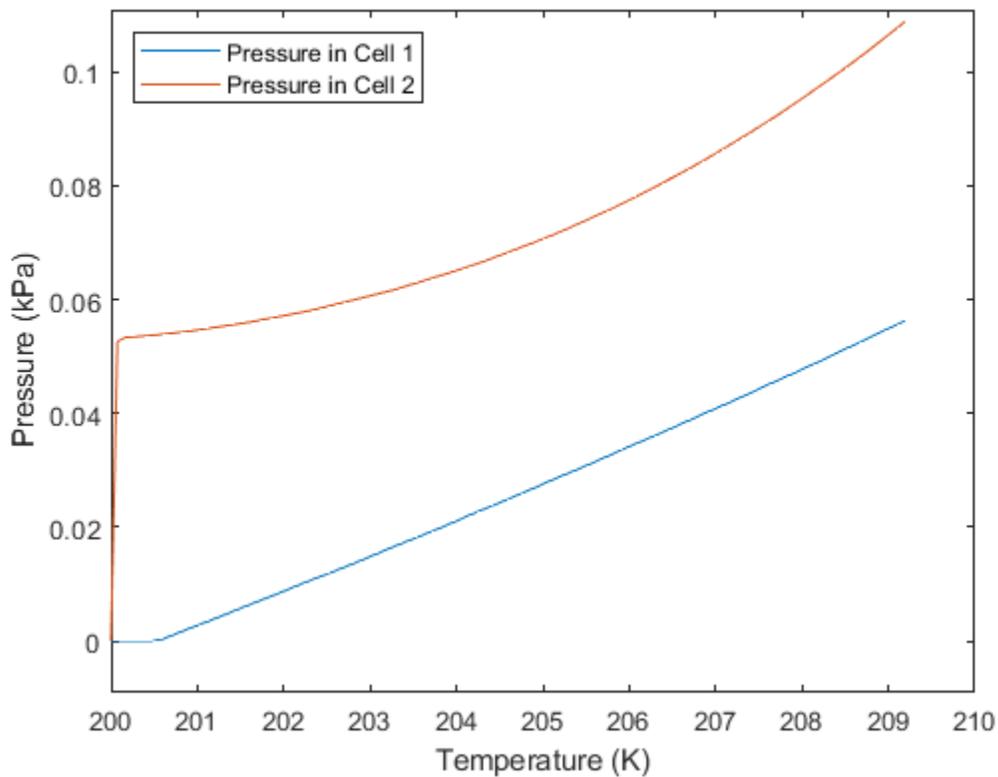


Figure 19 Pressure after Mass transfer at 10000 W for 200 K

The figure above shows that at temperature below 201 K we have a pressure of 0 which means that there were no mass remaining in our system and it was shown by Darcy's law that there was a diffusion through upper and outside lateral boundaries along with transfer to the second lower cell.

### 6.3 FINAL MASS RESULTS

We run new simulations for 100 W and 1000 W for both 150 and 200 K in addition to a new simulation of 250 K and 10000 W, the results of the extracted mass are placed in the figure below:

<i>Temperature (K)</i>	<i>Q (W)</i>	<i>Mass Extracted (kg)</i>
150	100	1.55E-05
	1000	1.71E-05
	10000	5.40E-05
	100000	2.6732
200	100	0.3961
	1000	0.4382
	10000	0.7552
250	10000	6.04E+01

*Figure 20 Final Results*

For us to claim 70% and more in 5 or more days we need at least a temperature of 250 K with a Heating Value of 10 kW or 150 K and 200 K with a heating value nearly 100 kW.

After checking the results it is very clear that heating is slightly affecting the results since temperature is not heavily increased after heating is done. But the initial temperature will affect the outcome since a rod is not sufficient for a great variation in temperature.

### 6.4 CONVERGENCE CHECK

After we have results from the numerical method on Matlab, we run a simulation on COMSOL Multiphysics with the Darcy Flow module by declaring all the properties of 4 and using the results for the mass flow rates and declaring them on COMSOL we find the Pressure variance while doing a stationary study for each time step and the obtained

results were nearly identical to the pressures obtained by the Arden Buck and Ideal Gas Law.

## 7 CONCLUSION

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In this chapter we can find the most important finding from our study. A quick report of the results are briefed in section 7.1 while section 7.2 discusses the improvements and recommendation for future model improvements.

### 7.1 FINDINGS

We designed a thermal enhanced water recovery model by creating a 3D model for lunar soil. This model is based on the conduction heat transfer equation to compute the temperature variation, the Arden Buck equation to compute the saturation pressure, the ideal gas law for sublimation mass calculation and Darcy's law for mass transfer in the regolith sample. We studied the case of heating using one drill.

Over a period of 5 days if we want to consider that we are not extracting a negligible percentage of water, we need an initial temperature more than 200 K with a heating power in the order of kW even though the results does not show great variation in mass percentage when increasing the heat. This extraction recovery will be highly dependent on the soil temperature if we have a heating value below 200 K initial temperature and on heating value above 200 K, so the preferred heating properties for an efficient extraction will be dependent on the initial conditions we have for initial temperature.

### 7.2 FUTURE IMPROVEMENTS

For a more precise model, a more detailed and accurate study of lunar regolith properties should be done alongside a well studied pressure profile for initial pressures. Our method is one of the simplest methods but requires a heating value of 1 W-100 kW power levels over few days to have a considerable recovery. Studies suggest that a similar type of extraction can be valuable over a period of time is when our system gives

back 40 kg per days [19]. Here in this study we showed that this can be achieved easily with a temperature high enough of an order +10kW.

The use of hollow drills, a greater quantity of much thinner drills (needles), or additional volume controls, such as the insertion of heated side walls before heating runs, are all potential strategies to improve extraction efficiencies. The analysis of such solutions will be one of our model's upcoming applications.

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