Moon exploration with the Deep Space Gateway The Lunar exploration itself.

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Abstract—Since the end of the Apollo program, no one has set foot on the Moon again. For decades, no human missions to the Moon have been prepared. Today, NASA launches its Deep Space Gateway project which consists in a space station in the vicinity of the Moon. This station is an ideal starting point for Lunar exploration by humans and further human space exploration. A conceptual study of this project is developed in this report.

1 INTRODUCTION

THE Moon is the closest celestial body to the Earth and has fascinated centuries of people. But it was not until 1969 when the first human, Neil Armstrong, Mission Commander of the Apollo 11 mission and Lunar Module Pilot, was able to step out on the Moon.

This project takes a closer look on the possibility to live on the Moon by building a Lunar base and extracting water from the surrounding Lunar soil. The base is intended to house a crew of four people, and crew members would stay during periods of six months. This would provide a great opportunity to examine and evaluate the psychological and physical impacts on humans during long-term stays on a different celestial body as well as provide a testing ground for technologies for future missions. This would be a stepping stone towards Mars and even deeper space manned missions.

1.1 Background

This Lunar base would be a first step towards an even more desired and bold goal which is to send people to Mars, and eventually make them live on the Martian soil. The thought behind establishing a Lunar base first is the ability to test out technologies and theories in a place where humans have been to before, and is closer to Earth. Here the crew could experience how it is to live on a foreign celestial body for a longer period of time. Another thing that would be tested here is water extraction, from the Lunar regolith since there is ice embedded in the soil. This process could also be used on Mars, or to mine water on asteroids as well.

Being able to mine water in larger quantities on other planets or in space would provide a big benefit for space missions, as there would be no need to send water from the Earth anymore, assuming it is even possible. Hopefully this would make possible the expansion of the Lunar station and in the future to start to produce liquid oxygen and liquid hydrogen as fuel to the Deep Space Gateway. Water and fuel sources directly in space would lower the launch mass significantly for a Mars mission and would also favor the setting up of missions towards deep space.

1.2 Aim of the project

This conceptual study of the Deep Space Gateway (DSG) project focuses on the human exploration of the Moon. It is divided into four axis : the DSG design, the transport system between DSG and the Lunar surface, the Lunar exploration itself and the overall coordination of the previous axis. This document presents to the reader the Lunar exploration itself, on which our study will focus on.

Our main objective is to make possible

for a four people crew to live on the Moon during six months. This challenge raises different questions, as where to explore the Moon, the life support system for our crew, how to protect the crew from the space environment, what scientific experiments have been chosen to be conducted on the Lunar soil, the power required and so on. So as to fulfill those requirements, our study will focus on the construction of a Lunar base and water mining.

1.3 Structure of the report

The structure of this report is divided into *Introduction*, *Construction of a Lunar base*, *Mining of regolith* and *Conclusion* sections.

The *Construction of a Lunar base* section gives an insight of where the base will be built, as well as a description of the method used. Furthermore, a description of the Lunar soil is given, and the *Water mining* section describes and compares two methods of collecting water. Finally, in the *Conclusion* section, it is discussed what development is to expect for this base in terms of autonomy and further studies.

2 Construction of a Lunar base

2.1 Location of the base

The selection of the location of the base is of great importance. It has indeed consequences on what is possible to do there, and it has also an impact on the trajectory used from the DSG to the Lunar soil. Two main criteria for the location of the Lunar base have been studied : concentration of ice in the soil and the amount of sunlight. As water extraction is one of the goals of this project the concentration of water is prioritized. This criterion puts the base around one of the poles which are more rich in water [1].

However, the need for sunlight in order to power the base using solar power severely limits the options for base locations around the poles. The Shackleton crater is the best option for the Lunar base as a part of the ridge of the crater is almost continuously lit. The Shackleton crater is almost in the center of the south pole. Its exact location and shape can be seen in Figure 1. The base can be built in the crater, below its ridge, and the solar panels for the power generation can be placed on the ridge so as to benefit from maximum sunshine.

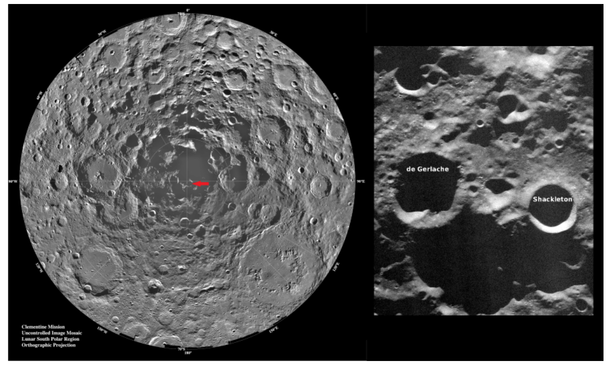

Fig. 1. Shackleton Crater

2.2 Regolith

Regolith is the thick layer that covers the entire Lunar surface. It is composed of fragmental and unconsolidated rock material. Its characteristics are the following [2] :

- Regolith (fragments of meteorite impacts) of the size of the ash
- Average size about $19\mu m$ (40% smaller than a hair)
- Composition: SiO2 (44.72%) and Al2O3 (14.86%)
- Properties: magnetic, very porous, serrated, sharp, allergenic.
- There is also iron, calcium and magnesium bound in ores such as olivine and pyroxene.

NASA estimates to 0.01 kWh the electrical energy needed to extract 1 kg of regolith and that one percent of regolith is icy water. [3] So as to extract the icy water from the regolith, the whole has to be heated to 100°C above the ambient temperature to transform the icy water into gas. The water is then separated from the regolith and can be collected and stocked after filtration.

2.3 The Lunar base itself

A station is indispensable for long stays on the Moon. The crew as to be protected from the harsh environment of space, that is to say in our case vacuum, radiation and micrometeoroids or small debris. Therefore, knowing the need, the Lunar base is designed. Each building is big enough to host a crew of four astronauts and provides protection, housing, life support systems, as well as a work and recreation areas. The housing, life support and recreation systems are similar to the ones of ISS, and will then not be further detailed in this report.

An inflatable dome is used to start building the base. The advantage of this is that only a relatively small and lightweight capsule (1000 kg) has to be brought to the Moon. The inflatable dome is stored in the capsule and is then inflated on the Lunar surface. After that, the capsule serves as airlock for the building.

The dome has an inner diameter of 12 m and the exterior shell of the inflatable dome is tight and pressure resistant. However, this is not sufficient to protect the inside of the dome from radiation and micrometeoroids. Therefore, an outer shell of Lunar regolith is build with a 3D-printing technology, as described in sections 2.5 and 2.6. The printed wall has a thickness of 0.8 m hollow closed cell structure, which provides best mechanical properties at a minimum of used material, and guaranties a shelter from micro meteoroids. To get a sufficient protection from radiation, another shell of 0.7 m of loose Lunar regolith is put by the excavation rover on top of the printed shell. Not printing the whole wall has the advantage that you have to bring less binder from the Earth to the Moon. [4] [5]

An overview of what the building would look like is given below in the Figure 2.

Fig. 2. Lunar base [6].

2.4 Power supply of the Lunar base

Solar panels are chosen to power the base. Because of their cost to energy performance, they are a proven technology and also a safer choice than nuclear energy since there is no need for handling the radioactive waste.

The solar panels are placed around the rim of the Shackleton Crater, since this area receives sunlight around 85% of the time [7]. Multijunction GaAs solar cells would be used in the panels. These cells have an efficiency of around 30% and even achieved higher efficiencies in laboratory settings [8]. A power reserve consisting of lithium ion batteries also provide power to the base when the solar panels are not lit.

The power consumption of the base is estimated to be around 50 kW. This estimation is based on the power consumption of the ISS weighted for a crew of four people instead of six and on the minimum requirement of energy for a small crew on a similar mission [9]. With a 30% efficiency, the solar panels are expected to generate about 350 W/m^2. The solar energy output for an Earth-like orbit averages around 13650 W/m^2 [10]. This results in an area of at least $143m^2$ of panels to power the base. However, an area of around 175 m^2 has to be sent to the Moon for safety reasons, due to the need of recharging the batteries after a period of darkness (Lunar night) and solar panel degradation.

2.5 3D-printing

The 3D-printing system is selected because it offers new possibilities and advantages. Compared with ready to use modules, it is not necessary to bring large structures from the Earth to the Moon. As a result, maintenance can be performed on site and walls can be build as thick as needed to shield from radiation and micrometeoroids. Furthermore, the amount of manipulated material is much less important with this method than if one wants to build an underground shelter which requires a lot of drilling. This then also results in a positive energy aspect, since drilling is for instance really energy demanding.

For all of these reasons, we orientate our work on the ESA research on 3D-printing on the Lunar surface. The 3D-printing system is installed on an independent movable rover. The printing process is detailed in the following. 3D-printouts are built up layer by layer. As printing material, Lunar regolith dust and a binding solution are used. Lunar regolith dust is composed of various types of particles, such as rock fragments, mono-mineralic fragments and various kinds of glasses. A more detailed description is given in Section 2.2. The density is about 1.5 g/cm3 [11]. To print one layer, regolith is mixed with the binder, which is made out of magnesium oxide and salt. Due to the environmental constraints, the nozzle to insert the binder into the dust is placed under the surface of the regolith layer. This method permits to reduce the sublimation of the binder which we have in a limited amount brought from the Earth. With 3D-printing technology it is possible to print various cross section designs of the wall. Aiming to decrease the amount of binder needed and to ensure good mechanical properties of the wall, a hollow closed cell structure is used [4][5].

Two rovers are used to print one building, which permits to build the station within three months.

2.6 Lunar Rover

During the missions, we aim to explore the Lunar surface, build the Lunar station, perform geological analyzes of the Lunar soil and collect large amounts of regolith for the water extraction. A rover such as the one shown in Figure 3 is a perfect and versatile solution. The most important task of the rover once the building is finished is to collect regolith from the Lunar surface. Therefore, the rover works as an excavator with a shovel in its front, as seen in the Figure. The shovel is able to carry a 110 kg load.

Furthermore, the rover has a drilling unit to get soil samples. A further useful tool is a connectible robot arm. With this arm, the rover can plug a connecting expandable tube from the Lunar station to the door of the crewed landing module. This arm can also assist in a lot of operations. It is divided into four movable pieces, has a total length of 5 m and can rotate around 6 axes.

Finally, the rover is powered by two radio nuclid batteries as the one used on the Mars rover Curiosity [12]. It can then work and interact absolutely independent from sunlight or recharging. The batteries provide 1.5 kW for 6 months at a 50 % workload. The rover needs 1.5 kW at a mass of 1250 kg [13]. For very power intensive tasks, such as breaking material from the ground, it has an additional Li-Ion battery. In long term thinking, the batteries can be exchanged with water fuel cells if the water production from regolith works sufficiently well.

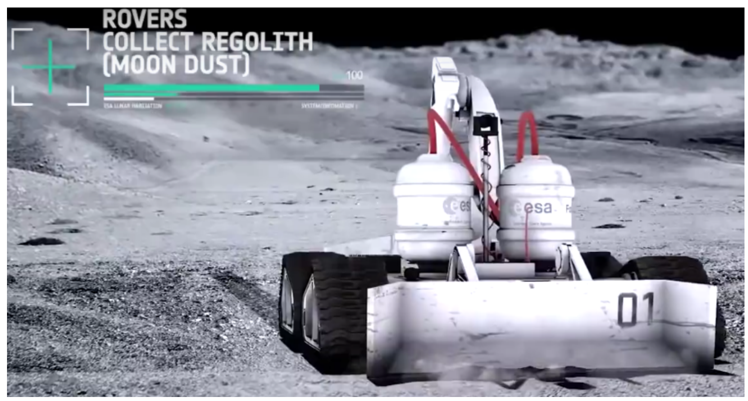

Fig. 3. 3D-printing and multipurpose rover [6].

3 Mining of regolith

3.1 Pre-study notions

3.1.1 *Water management*

The following Table 1 details the various needs of water for one person each day in space.

To be as close as possible to realistic technologies, the values of the water recycled through the Sabatier Process and through the Water Recovery System are the ones provided by the NASA for the ISS. One can obtain the amount of fresh water per day by subtracting the needs of water by the amount of water recycled, which gives 6.5 kg/day for a crew of 4 persons.

TABLE 1
Water cycle [14] [15] [16]

Need	kg/day/person
Food	1.2
Drinking	1.3
Toilet flush	0.89
Laundry	0.5
Dishes	0.89
Eva	0.08
Creation of O_2	1.41
Total	6.28
Total H_20 recycle (Sabatier process)	-0.86
Total H_20 recycle (Water Recovery System)	-3.8
Total of fresh water needed	**1.62**

3.1.2 Regolith ice content

One can assume that the Lunar soil is homogeneous. This approximation will be largely used in 3.2.3 so that to simplify the model, but since the ice content varies depending on the mining area, we wish to be able to determine at least approximately the ice content of a regolith sample.

To do so, consider a container (dimensions a, b and c) filled with regolith. Using a balance scale adapted to the Moon gravitational field (around $\frac{g_{Earth}}{6}$), we then know both the volume $V = a.b.c$ and the mass m_{tot} of the regolith sample.

Consider now the following data:

TABLE 2
Density data ρ.

	LDA ice [17]	Lunar soil [11]
Value $[kg/m^3]$	940	1500

In this Table, LDA stands for Low Density Amorphous, since we expect to find ice under this state in the Moon environment.

Since we have: $m_{tot} = X\rho_{LDA} + (V - X).\rho_{soil}$ where X is the volume of ice in the sample, we then have:

$$X = \frac{V.\rho_{soil} - m_{tot}}{\rho_{soil} - \rho_{LDA}} \quad (1)$$

and:

$$content = \frac{X}{V} \quad (2)$$

An example is given in Table 3:

TABLE 3
Example of calculation of the ice content of a sample.

Length*width*depth $[cm^3]$	m_{tot} $[kg]$	% ice content
40*40*20	47	5.6

This method is nonetheless approximative since it doesn't take small rocks into account for example. It has then to be improved, but gives good basis to a new and more accurate model.

Moreover, the weight scale needs to be precise enough to catch up with the weight variations due to the ice content.

3.2 Methods of extraction

3.2.1 The dish Stirling

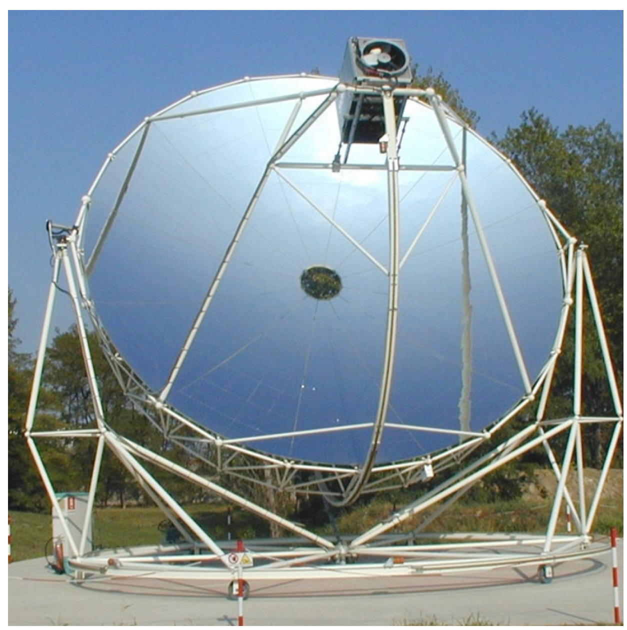

Fig. 4. Photo of a solar dish Stirling [18].

The dish Stirling is the first technological proposition to heat the regolith and extract water from it thanks to the thermal energy of sunlight. Archimedes used the same type of device to concentrate the solar rays to burn the sails of the Romans in order to defend the city of Syracuse in Sicily. As shown above with Figure 4, the solar energy shines onto the reflective concentrator and is focused through the aperture of a receiver localized at the focal point of the dish. Since, there is no atmosphere on the Moon, the radiations from the Sun are not absorbed and could be fully used. The regolith would be thus upon the collector, and the heat transforms the icy water into gas. Currently, the overall efficiency of such a devise is 0.53 [19] and solar radiation provide a power of 1366 W/m^2 on the Moon. Moreover, 117 kW of heat are needed to separate 1kg of water from the regolith. Therefore, a two meter diameter dish would provide 1476 W of heat, enough to extract the 12 kg of water per day from the regolith.

3.2.2 Study of two types of microwaves

Another method to mine water is to use a microwave to heat the regolith. The principle is the same as for the parabolic mirror : thermic energy is given to the regolith to increase its temperature until the ice sublimates. Then, a water recovery system is used to collect the vapor and stock it under liquid or solid form.

From there, two options were studied : the first one is to use an open bell-shaped device which would be put on the floor to send waves directly into the soil and collect the water directly within the bell. The second option is to use a closed device which looks like industrial microwaves already used on Earth. Both methods have pros and cons: an open device requires to send waves in the downwards direction. Since the waves are evanescent, the result is that the losses are great and a lot of energy has to be provided to counterbalance these losses. It is not the case in a closed microwave where the electromagnetic waves are reflected on the walls of the device, however this method requires to carry regolith into the device. Those considerations are summed up in Table 4.

Given the results of this Table, a closed microwave is a better option for this mission, as it needs way less energy to heat the regolith.

TABLE 4
Comparison between the open and closed microwaving devices.

Device type	Advantage	Drawback
open	no need to collect regolith	high energy
closed	lower energy	need to collect regolith

The closed device is then studied in 3.2.3.

3.2.3 Microwaving icy compounds

For this study, the microwave is considered as a black box whose input is electric energy (provided by an external source), and the output is heating energy (given to the regolith in the device). As announced in section 3.1.2, we will from now on consider that the lunar soil is homogeneous, constituted of regolith without small rocks and containing 1% mass of ice, content given by the NASA report [3].

So as to calculate the heating energy which has to be provided to the frozen regolith, one can proceed to a thermodynamic reasoning. Considering that our system is the the frozen regolith, we can determine the variation of energy due to the heating from a temperature T_1 to a temperature T_2 (temperature of sublimation of ice water in vacuum [20]) of the entire system, and then calculate the variation of energy due to the sublimation of the LDA ice only (first to sublimate). The heating process is assumed to be isobaric, which permits to establish that:

$$Q = \Delta H = \Delta H_{T_1 \to T_2} + \Delta H_{sublimation} \tag{3}$$

where ΔH is the variation of enthalpy and Q the heat received by our system. Then:

$$\Delta H_{T_1 \to T_2} = (m_{LDA}.c_{p-LDA} + m_{regolith}.c_{p-regolith}).\Delta T \tag{4}$$

and, for the ice only:

$$\Delta H_{sublimation} = (\Delta h_{fusion} + \Delta h_{vaporization}).n_{LDA} \tag{5}$$

where $n_{LDA} = \frac{m_{LDA}}{M_{LDA}}$ is the number of moles of ice in the sample, M_{LDA} = 18 g.mol^{-1} is the molecular mass of the LDA (frozen water), Δh is its molar latent heat of change of state, c_p is the isobaric mass heat capacity of a body and $\Delta T = T_2 - T_1$.

If one wants to produce 12L of water per day with this process (3L per person of the crew for a daily food and water drinking consumption, with a margin compared to Table 1), the need in regolith is of $m_{tot} = \frac{m_{LDA}}{icecontent} = 12$ tons. As a reminder, 1L of water has a mass of 1kg, and 1kg of ice provides 1kg of water. In the following calculations, $c_{p-regolith}$ is replaced by c_{p-sand} which corresponds to a much more known silicate compound.

For the calculations, the following values will be used:

TABLE 5
Comparison between the open and closed microwaving devices.

Parameter	Value
m_{tot} [kg]	12000
M_{LDA} [$g.mol^{-1}$]	18
T_1 [K]	100
T_2 [K]	150
c_{p-sand} [$J.kg^{-1}.K^{-1}$] [21]	800
c_{p-LDA} [$J.kg^{-1}.K^{-1}$] [21]	2090
Δh_{fusion} [$J.mol^{-1}$] [22]	6010
$\Delta h_{vaporization}$ [$J.mol^{-1}$] [22]	44000

Given those figures, we calculate an energy needed of 36.4 kWh. This energy, for 12L of water, can also be expressed for one liter : 3.0 kWh. This result is consistent with the one given by NASA in its report (2.8 kWh.kg^{-1}) [3]. The variation might be due to differences in data, such as the heat capacity of regolith replaced by the one of sand. The thermal power needed to provide such an amount versus time is then given by the curve of Figure 5, obtained with Excel.

As one can see in Figure 5, the shorter the time, the higher the power. The power increases drastically below five hours of production. The trend curve permits to obtain a direct formula to calculate the power for a given time : $P = \frac{363.58}{t}$, where P is in kW and the time t in hours.

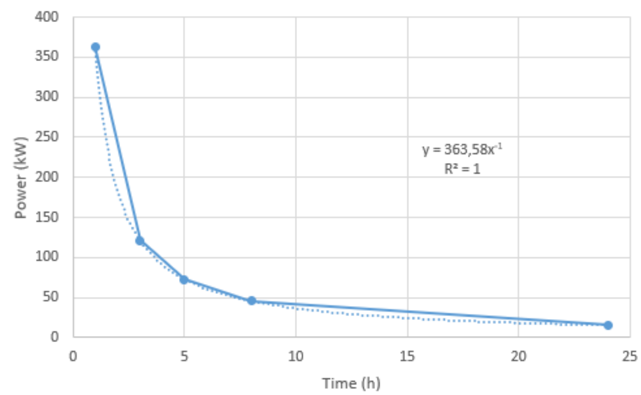

Fig. 5. Power required to produce 12L of water versus time.

3.2.4 *Comparison of the methods*

Two methods to extract water from regolith have been developed in 3.2.1 and 3.2.3. Both methods heat the icy regolith to do so, and then require to collect it from the ground (thanks to a nuclear powered rover as detailed in the 3D-printing section). The two methods also require a system to collect, filter and stock the water. But there are still different aspects on which these methods are completely different.

TABLE 6
Comparison between the dish Stirling and the microwave devices.

Device type	Advantage	Drawback
Dish Stirling	low energy several devices	quite large light dependent
Microwave	light independent modular production	quite large high energy

Table 6 details the advantages and drawbacks of both methods. A common drawback is the size of the devices. Even if not known precisely, we expect them to be able to carry and heat up big amounts of regolith. Concerning the energy consumption, the dish Stirling shows all its efficiency : since it is only reflecting the solar rays (and maybe track the Sun), the device does not need energy whereas the microwave is all the time turned on to work. However, the microwave is much more practical since it is not dependent on the Sun, whereas the dish Stirling cannot work during the Moon nights (around two terrestrial weeks). This can be counterbalanced by the fact that, since the dish Stirling does not need energy, one can build several of them in different areas so that we are able to ensure a constant production. Nevertheless, the microwave has another advantage : its production is modular, which means one can produce more water in less time if necessary.

A typical off-nominal case would be a temporal breakdown of the device or polluted water. In the case of the dish Stirling, we have no possibility to fasten the water extraction. With the microwave, this is feasible by increasing the power input. Thanks to the model given in 3.2.3, a member of the crew can easily determine the quantity of regolith he needs to collect and the power required just by entering the quantity of water needed and the time available.

All of these reasons lead us, for the beginning of the mission, to choose the solution of the microwave which is more modular. During a crisis scenario, extra batteries could be used to supply the extra power required (mechanical batteries for instance). One might however be aware that this solution is more risky since we may have only one microwave for energetic reasons (power supply is limited).

3.3 A step forward : extraction of fuel and oxygen from regolith

The production of hydrogen and oxygen from asteroids, moons or others planets than the Earth is a crucial step for deep space exploration and for the self-reliance of a space crew. This part is to be considered for our mission only if the phase of water production is a success. Moreover, the aim would be to provide enough fuel to do a round-trip from the Moon to the DSG with the spacecraft.

3.3.1 *First solution*

The first solution is to extract the regolith, then the water from it and finally do an electrolysis to obtain pure hydrogen and pure oxygen. Table 7 below gives in details the amount of energy required to produce hydrogen and oxygen with this solution.

TABLE 7
Solution 1 [23][24]

	Energy
Extraction of regolith then water	3.8 kWh/kg of H_2O (electric + thermal)
Production of H_2 electrolysis	45 kWh/kg H_2 (electric)
Production of O_2 from electrolysis	5 kWh/kg O_2 (electric)
Total energy required	**83 kWh/kg H_2** **9.2 kWh/kg O_2**

3.3.2 *Second solution*

The second solution is to extract the fuel directly from the regolith, through diverse reactions. Since oxygen represents at least 40% of the Lunar soil (in mass), one can understand the interest of this method. Dioxygen would be produced thanks to the reduction of silicon dioxide SiO_2:

$$SiO_2 \longrightarrow Si + O_2$$

Moreover, the grains of the Lunar regolith absorb the hydrogen of the solar winds and can release it when it is heated to 700°C. The concentration of hydrogen is estimated to 100 ppm in the Lunar soil. Table 8 below gives in details the amount of energy required to produce hydrogen and oxygen with this second solution.

TABLE 8
Solution 2 [23]

	Energy
Extraction of regolith	0.01 kWh/kg regolith (electric)
Extraction of H_2	2,25 kWh/kg H_2 (thermal)
Reduction of SiO_2	9.31 kWh/kg O_2 (electric)
Total energy required	**2,35 kWh/kg H_2** **9.85 kWh/kg O_2**

3.3.3 Comparison and selection of a solution

One can notice that both solutions require roughly the same amount of energy to produce 1kg of oxygen. However, the second solution requires much less energy than the first one to extract 1kg of hydrogen (2.35 kWh/kg of H_2 against 83 kWh/kg respectively, that is to say 35 times less). This can be explained by the important amount of energy that is required to heat the regolith to release the hydrogen. Furthermore, the concentration of hydrogen is significantly lower than icy water in regoltih. All in all, the second solution is the most efficient solution to produce fuel.

3.3.4 Estimation of power

Assuming that a one round-trip with the cargo is done every three months, we can find the power needed to extract the necessary amount of fuel. According to the transport group, 8700 kg of hydrogen and 34800 kg of oxygen are needed to achieve the round-trip. The power needed to produce the fuel is equal to the power to produce both hydrogen and oxygen. If we assume that the fuel production operates 24 hours per day during 3 months, thus the total power needed is 169 kW. One can notice that this is just an estimation but such an amount clearly emphasizes the need to change from solar electricity to a new major source of electricity to produce fuel, for instance nuclear electricity.

4 Conclusion

The Shackleton crater has been chosen to print our building due to the high probability to find big quantities of icy regolith there. Moreover, this crater offers a maximum sunlight on its rim where the solar panels, which power the base, are located. Thanks to the 3D-printing rovers, the setup of the base will be entirely autonomous before the crew arrives, and then directly provides a protective shell. The housing module provides every necessity for the crew, including life support system with recycling of water and oxygen. Nuclide batteries are the main source of energy for the rovers for independence and mobility. Extracting water is of major importance during this mission and is done by microwaving the regolith, which requires a lot of energy but has the advantage to be independent from sunshine.

All of this constitutes the main objectives of the mission. However, many improvements can still be made: wastes could also be microwaved instead of being just stocked away, so as to extract even more water and reduce the losses. Since the microwave already runs all day long, a new one should be built to fulfill this purpose, but this is a way to increase the reliability of this system thanks to redundancy.

Concerning the base itself, a new building could be built, either at the same location, or more possibly in a new area of the Moon. More research could then be made, for example in space farming which is another key point of deep space exploration, and this new area would be explored as well. The major need for this is to bring a new crew of astronauts from Earth, but exploring different areas of our natural satellite is the best way to learn about it, and might provide us new tools to understand the formation of our Solar system and universe.

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