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CONCENTRATION OF LUNAR PLAGIOCLASE FOR SOLAR CELLS FABRICATION. AN ISRU CONCEPTUAL ARCHITECTURE

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ABSTRACT

Solar panels are required on the Moon to provide power for human activities, especially mining and civil operations. To provide enough power and maintain human settlements working, a technical solution known as the Tall Lunar Tower (TLT) claims to be able to capture sunlight 93% of the time through solar panel structures and provide 50 kW per tower. A typical photovoltaic panel is made of 76% glass, 10% polymer, 8% aluminum, 5% silicon, and 1% other metals. Delivering these materials from Earth is expensive and risky. Fortunately, lunar regolith contains large amounts of silicon and aluminum oxides and silicates, thus, it would be feasible to use the resources in situ for metal production, hence, we just need to transport polymers, wire, and minor components from Earth. This article presents an ISRU (in-situ resource utilization) architecture to provide plagioclase concentrate, the economic lunar ore for aluminum and silicon extraction. The document details engineering aspects and technological solutions for lunar mining, including excavation, transport, and beneficiation operations; based on a hypothetical construction and deployment of TLT at the South Pole. Processing techniques such as screening and magnetic separation are discussed to evaluate their advantages and drawbacks to obtain an expected plagioclase concentration of 70% grade with 18% recovery. Finally, an outline of recommendations for industrial manufacture is discussed, considering the sequential lunar metals extraction and the quality required.

Keywords: Tall Lunar Tower, ISRU, lunar mining, lunar plagioclase, lunar metals.

INTRODUCTION

To support the incoming mission of Artemis, extraction of water, oxygen, and metals on the Moon are necessary, which involves intensive power requirements. Tall Lunar Tower (TLT) would be a power supply solution, feasible to deploy on the lunar surface taking advantage of low seismic activity, absence of wind, and low gravity of the environment [1]. In a nutshell, for one TLT (50 kW) it requires 1140 Kg of SiO_2, 75 Kg Si, and 313 Kg of Al (120 kg for panels frame + 193 kg for tower trust structure). Fortunately, silicon and aluminum are available on the lunar surface, in grades of 19.8–21.1% wt. and 7.3–14.4% wt., respectively [2]. Indeed, three lunar minerals could provide silicon and aluminum: agglutinants, glasses, and plagioclase.

Molten regolith electrolysis, or MRE, is a metallurgical technique that could provide silicon and aluminum metals in a near-pure state. However, there are some uncertainties about their refining performance in low-gravity environments, and the selection of an adequate ore would be crucial to facilitate metallic production in a high-purity state. Thus, MRE process requires adequate control of the ore supplied, removing minerals that could affect the quality of the final product. This geometallurgic philosophy is followed by the terrestrial iron industry, which uses only iron oxides as ore-bearing minerals. Although iron sulfides (such as pyrite or FeS) can also contribute to metallic iron content, sulfur (S) is hard to eliminate during refining, so iron sulfides are considered gangues (non-economic minerals). The takeaway lesson is to eliminate or lower the percentage of gangue minerals from the excavation or by concentration methods. Consequently, agglutinates are discarded as ore because they have nanophases of iron, which is a contaminant for pure silicon and aluminum; also, although glasses are an important source of silicon, they contain iron and titanium, and it is difficult to predict their real concentration. Thus, only plagioclase represents an economic ore for the process, and its beneficiation from the regolith is crucial. The overall objective is to describe an ISRU architecture that provides plagioclase concentrate to a MRE station, including the cycle of excavation, transport, screening, and magnetic separation.

METHODOLOGY

The hypothetical location to deploy the TLT is selected using Lunar Quickmap tools. Area selection is based on terrain sunlight availability (>70%), hydrogen sings nearby (0.3 – 0.4% wt. WEH), proximity to a candidate Artemis region, slope terrain (<15°), and proximity to high altitude elevations (> 7000 m). As a result, the Nobile Rim region meets all these requirements, and it is the area selected as shown in Figure 1. The mining unit must be near this area to quickly deliver the metals and materials required. The pit is close to the TLT deployment area but not next to it because of the risk of dust generation during the digging activities. Lunar dust could damage the solar panels.

The chemical and mineralogy of the lunar regolith are quite variable. Due to the absence of samples recovered from the lunar south pole, the author infers the chemical and mineralogical composition of the highland's lunar samples, which are "similar." Lunar Sourcebook data is considered for this task.

The lunar pilot plant will be powered solely by sunlight, considering its 70%-time availability. The main subsystems are: (A) the excavation (trench and excavator) and transport subsystem (hauling); (B) the beneficiation plant; and (C) the MRE reactor and refining subsystem. The regolith is excavated and delivered every day during 16 hours of continuous operation. Thus, unit A (excavation and transport) will send enough material to process and store the regolith as a stockpile, ensuring continued operation of the processing plant.

For excavation, a Backhoe loader was selected because of its low mass, low complexity, and power requirements, ideal for a short-term operation on the Moon [4]. For transportation, aspects such as distance, regolith flowability, and dust mitigation are considered for system selection. Finally, for the processing balance, screening data from terrestrial mining industry, and magnetic separation experimental data based on experiments with lunar samples are considered for full estimation. The author uses an in-house mass balance model, based on size distribution, metallurgy recovery, and mineralogic grade for different particle sizes.

RESULTS

The need analysis is established at 250 kW, which means five TLT. Considering only metals and a safety factor of about 15%, the final mass to be supplied is 3,500 kg Si and 1750 kg Al. At the same time, oxygen must be supplied to produce $SiO2$, so 3,500 kg of $O2$ is also required. The module pilot plant will operate solely on sunlight with 70% availability, so, being conservative, it considers only 63% for actual operation. We defined a throughput requirement of 0.6 kg Si/hour, 0.6 kg KgO2/hour, and 0.3 kg Al/hour to produce all the metals during one operational year.

Location

The Nobile Rim at the South Pole (see Figure 1) is considered a highland region enriched in volatiles, and in the next few years, VIPER data will be useful in determining whether water deposits exist nearby and establishing a human base there. On the other hand, based on remote sensing data, these craters nearby are considered very old, which attracts scientific interest. Indeed, Shackleton crater is 3.6 Ga ago, while Haworth, Shoemaker, and Faustini are 4.1 Ga ago [5]. Therefore, pure anorthosite (98% anorthite) an original lunar mineral crucial to interpret the crust formation, might exist in these regions. In general, lunar plagioclase is a composition of anorthite ($CaAl_2Si_2O_8$); mixed into a solid solution with albite ($NaAlSi_3O_8$) [6]. Because pure anorthosite rocks are expected at the South Pole, our plagioclase is considered 100% anorthite ($CaAl_2Si2O_8$), which means a composition of 20.2% silicon, 46% oxygen, and 19.4% aluminum.

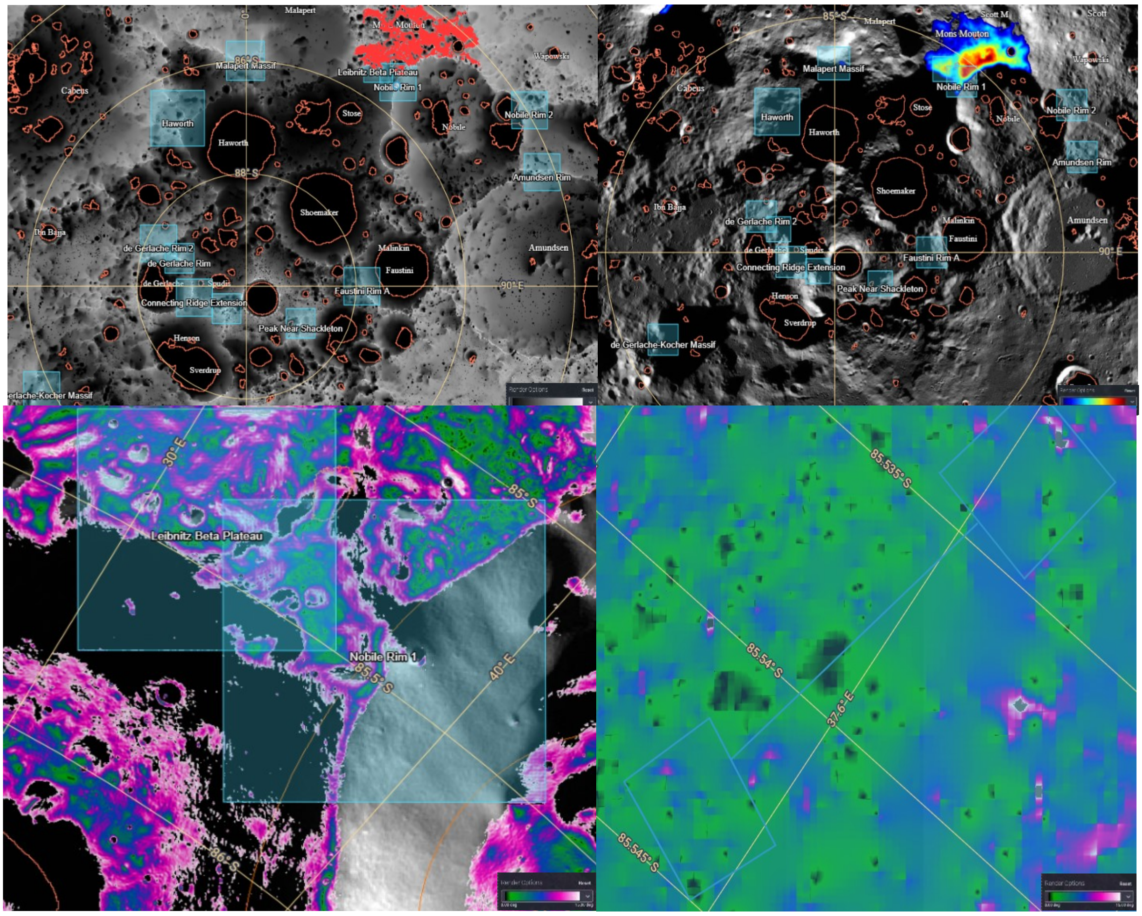


Figure 1. Site selection is based on illumination (top left), terrain height (top right), terrain slope (left bottom), trench, and processing plant (right bottom). The sky-blue squares at the left bottom are candidate regions for Artemis base camp. The map was designed by the author using Lunar Quickmap.

Excavation & Transport

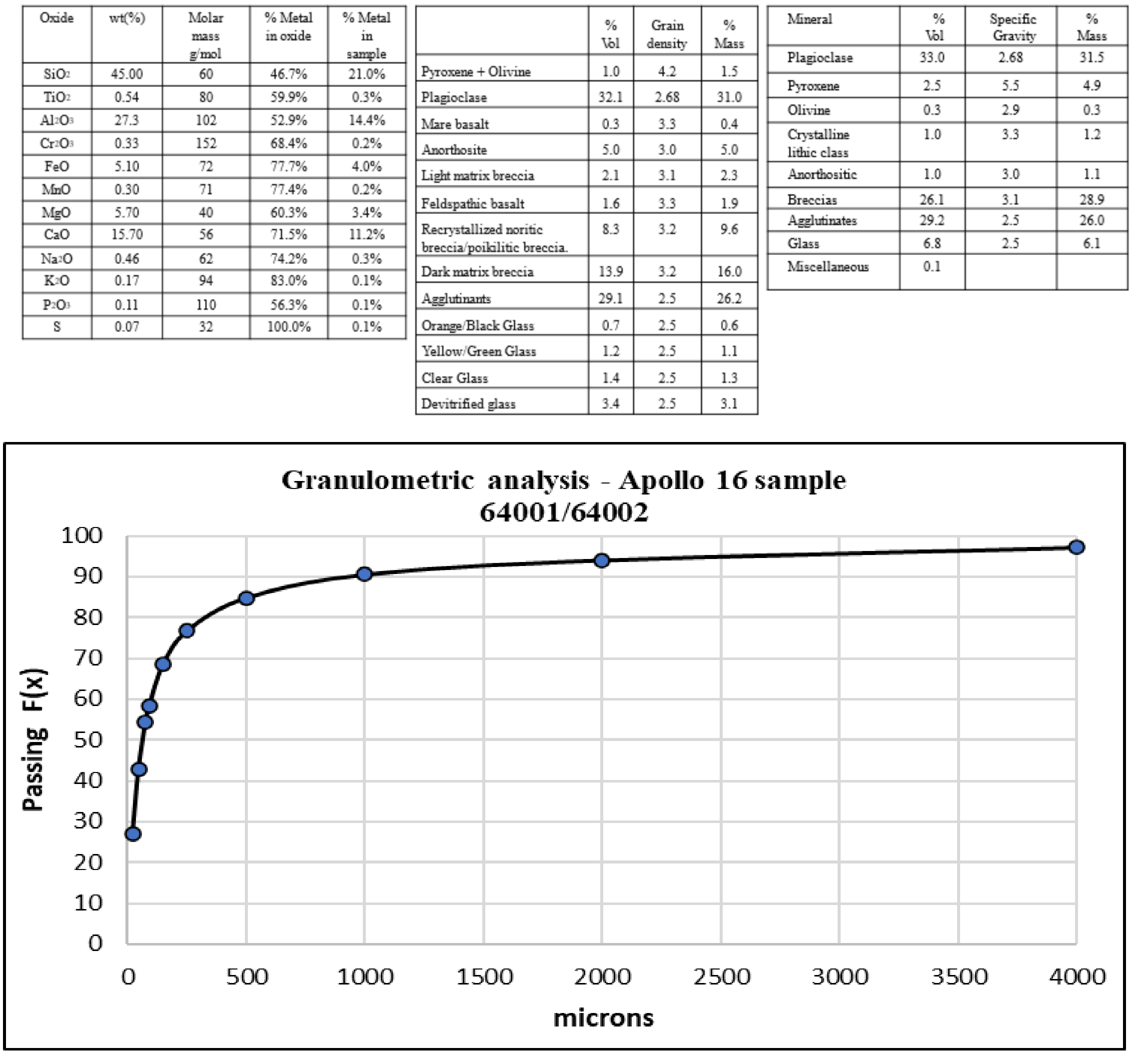
According chemical and mineralogical data presented in Figure 2, plagioclase (considered as 100% anorthite) grade is about 30% in lunar surface. Therefore, shallow excavation at 25 cm depth is enough for production purposes, which makes the operation a bit straightforward. Indeed, geotechnical parameter of regolith cohesion is estimated at 0.25–0.6 kPa with a friction angle of 46.5–50° [7], conditions feasible to overcome for current proposed extra-terrestrial excavators.

To define the mass requirement, it estimates the recovery in the concentration stage at 58 grams of pure plagioclase per 1 kg of regolith (see Figure 3). Moreover, it assumes that only 80% of the metals and oxygen from the ore can be successfully recovered as pure elements during MRE operations. Thus, a simple division of the element mass required by the element recovery and grade, as well as the ore concentrate grade and mass, establishes that 64 kg of regolith per hour must be delivered to the processing plant, which means a regolith transportation rate of 97 kg/hour for 16 hours, considering the availability of sunlight.

For the number, mass, and power of the excavation system, it considers the excavation rate (100 kg/h) and traverse speed loaded and unloaded (8 m/min and 12 m/min) [4]. In addition, it fixes the discharge rate at 800 kg/h and the transfer point distance at 10 meters. On the other hand, every hour, 17 minutes are spent only on loading, unloading tasks, and traveling to the transfer point, so the excavator only digs actual material during 43 minutes per hour, resulting in a final excavation rate value of 135 kg/hour that can be met by one excavator with a backhoe loader of 150 kg/hour. The trench area needs to be calculated based on the throughput, regolith bulk density at different depths (1.4 – 1.8), and bucket cut capacity (up to 5 cm) [4]. Considering small slices of 5 cm depth, the trench is 3,437 m^2 (surface) and 2,871 m^2 (bottom). For a trapezoid design, it corresponds to 58.6 m by side (surface) and 53.6 m (bottom), creating a slope of 6°, so the dimensions allow the excavators and hauler trucks to have traffic. For regolith transportation, wheeled haulers are a good option [8]. Considering the regolith volume transported per hour and a "swelling" effect of 11% [9] into the haul hopper, their capacity is estimated at 0.08 m^3. In addition. it is important to consider isolating the regolith with a metal gate or roof or some coating, such as Lotus Leaf [8] to mitigate dust generation. Finally, considering a maximum separation of 1 km between the mining trench to beneficiation-extraction plant (see Figure 1), a maximum slope terrain of 8%, and an elevation of 40 -45 meters between both units, the trafficability of rovers would be feasible.

Processing (Screening and Magnetic separation)

The regolith particle size is estimated at 100 microns on average. Screening is important to eliminate the coarse particles before the concentration stage. According to Figure 2, by establishing a critical size of 1 mm and assuming 100% classification efficiency for coarses, we could recover 90.5% of the total mass. In addition, for lunar mining operations, it is crucial to estimate the screening bypass. This index represents the percentage of fines and ultra-fines not classified by screening and passing directly to the oversize. On Earth, typical screening efficiency is over 60–80%, with a bypass effect of 10%–20%. These results are influenced by particle shape, flowability, and material cohesion [10]. Consequently, on the Moon, the efficiency would be lower, because of lunar regolith conditions. In general, their particle shape is considered anisotropic, with a high friction angle [7] indicating poor flowability, making it difficult for size classification. Besides, lunar surface is exposed to sunlight, and electrostatic charge exists (10+ volts), producing an electrostatic effect forming agglomerations stables and semi-stables of ultra-fine particles. All these factors will reduce efficiency and, the mass of the classified product as undersize. Further experiments are mandatory to evaluate and determine the actual screening parameters; however, a fine bypass of 30% is expected, a common value for minerals with low flowability [10], recovering only 63.3% of the original material as undersize.



Oxide	wt(%)	Molar mass g/mol	% Metal in oxide	% Metal in sample
SiO_2	45.00	60	46.7%	21.0%
TiO_2	0.54	80	59.9%	0.3%
Al_2O_3	27.3	102	52.9%	14.4%
Cr_2O_3	0.33	152	68.4%	0.2%
FeO	5.10	72	77.7%	4.0%
MnO	0.30	71	77.4%	0.2%
MgO	5.70	40	60.3%	3.4%
CaO	15.70	56	71.5%	11.2%
Na_2O	0.46	62	74.2%	0.3%
K_2O	0.17	94	83.0%	0.1%
P_2O_3	0.11	110	56.3%	0.1%
S	0.07	32	100.0%	0.1%

	% Vol	Grain density	% Mass
Pyroxene + Olivine	1.0	4.2	1.5
Plagioclase	32.1	2.68	31.0
Mare basalt	0.3	3.3	0.4
Anorthosite	5.0	3.0	5.0
Light matrix breccia	2.1	3.1	2.3
Feldspathic basalt	1.6	3.3	1.9
Recrystallized noritic breccia/poikilitic breccia.	8.3	3.2	9.6
Dark matrix breccia	13.9	3.2	16.0
Agglutinants	29.1	2.5	26.2
Orange/Black Glass	0.7	2.5	0.6
Yellow/Green Glass	1.2	2.5	1.1
Clear Glass	1.4	2.5	1.3
Devitrified glass	3.4	2.5	3.1

Mineral	% Vol	Specific Gravity	% Mass
Plagioclase	33.0	2.68	31.5
Pyroxene	2.5	5.5	4.9
Olivine	0.3	2.9	0.3
Crystalline lithic class	1.0	3.3	1.2
Anorthositic	1.0	3.0	1.1
Breccias	26.1	3.1	28.9
Agglutinates	29.2	2.5	26.0
Glass	6.8	2.5	6.1
Miscellaneous	0.1		

Figure 2. Data collected from [6] and [11] as input values into the model. Chemical analysis (top left), mineralogical analysis (top middle and right), and granulometric data (bottom).

The second step is to eliminate ultra-fine particles because the concentration techniques do not work on those ranges (<44 microns), and agglutinates grade is significant. Currently, there are two commercial options in terrestrial mining. First, we can use cyclones to eliminate ultra fine particles (<44 microns) and recover the "coarses" as underflow stream for sequential processing. The second option is high-frequency screening used in terrestrial mining, with a history of successful results in fine and ultra-fine particles (< 75 microns).

Quality product requirements establish a final purity grade of 98% Al for structural purposes (Al 6063). The maximum impurity concentration is 0.6% silicon, 0.35% iron, 0.9% magnesium, and 0.1% titanium [12]. On the other hand, the metallurgical grade for silicon is 98–99% purity, and impurities are at most 0.7% aluminum, 0.9% iron, and 0.1% magnesium [13]. Thus, it is notable that iron is an important contaminant for the final products, so iron oxides and glasses enriched with iron must be removed during the concentration stage. We propose magnetic separation following this strategy: a) apply inverse concentration to collect and remove the agglutinates and glasses by high-intensity magnetic field in two stages; and b) apply conventional concentration to obtain the plagioclase with a minimum concentration of glasses by low-intensity magnetic field in one stage. According to [14], a magnetic field of 65–7470 x 10^{-6} cc/gm is enough to separate the agglutinates as a concentrate (55% grade) and less than 2% plagioclase. The tail of these previous magnetic stages is the final ore feed for the subsequent separation.

In the final stage, plagioclase will be separated from other non-magnetic materials by a magnetic field of about 0.75 x 10^{-6} cc/g. It expects to obtain a concentrate at 95% purity for grains over 44 microns [14]. For the particles below this size, it assumes there is no separation (40.5% purity), so the final concentrate is estimated at 70% grade and 18% recovery. In our mass balance, global recovery and grade results are calculated for the complete particle size distribution to reconcile the final mass obtained. The author uses the mineralogical data of sample 64421, published in Lunar Sourcebook [6], and the results of magnetic separation experiments published by [14] for different particle sizes. The results are presented in Figure 3.

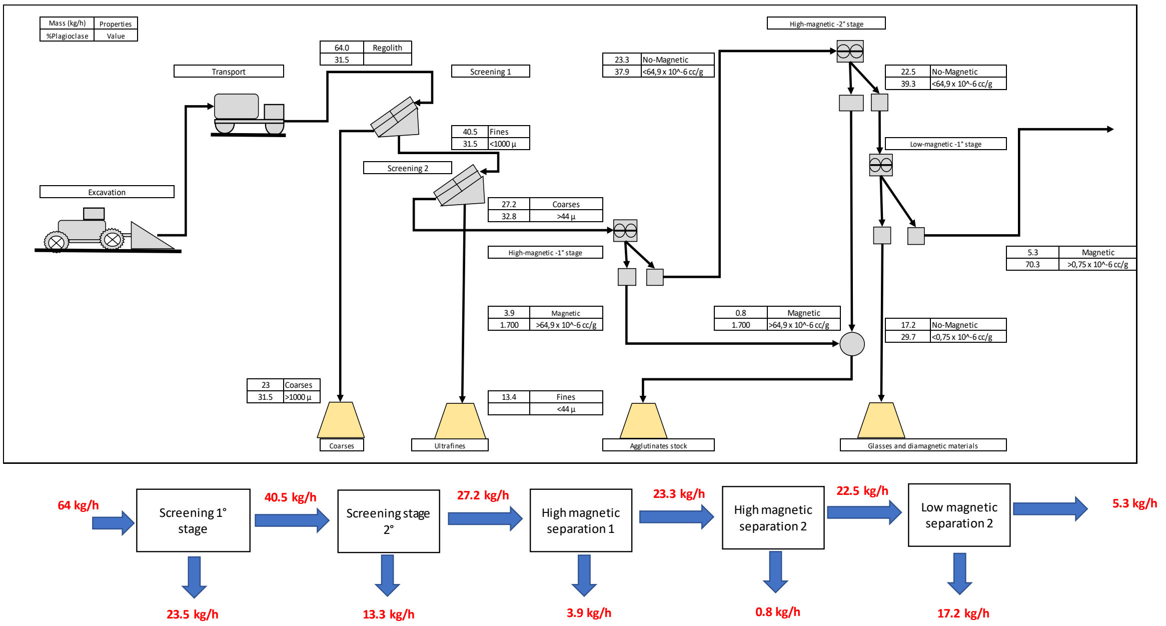


Figure 3. Mass balance of plagioclase concentration

Extraction and refining stages

The ore concentrate (plagioclase) is added to a MRE reactor during 18-24 hours per batch. While silicon is feasible to be reduced at 1800 K, 800 Amps, and 1.5–2.0 V, an increase in temperature and power is required to refine aluminum (2100 K, 3.5 V, and 600 A) [15]. Oxygen gas is obtained during metal reduction and requires a refining stage (e.g., fractional distillation) to remove other volatiles. Moreover, metal refining stages must be addressed to obtain the purity and mechanical performance required. Then, pure silicon is divided into two flows: A) For manufacturing glass, pure silicon and oxygen would be combined in a reactor at 1600 °C, and the molten material would be deposited into molds for slow cooling. A high purity of oxygen is required to prevent the appearance of undesirable "bubbles" in the solar panels. B) Pure silicon in a monocrystalline state is obtained, and machining techniques will convert the material into laminated layers or small parts. On the other hand, aluminum is extracted as pure metal in bars or rectangular molds, also requiring a machining shop for the fabrication of angles and bars.

DISCUSSION

The fabrication of TLT requires the production of pure metals and pure compounds on the lunar surface. Although the MRE process is a good technique to obtain oxygen and lunar alloy metals as bulk materials, an ore control geometallurgy approach should be addressed to classify and separate different lunar ores and generate stockpiles for independent metal extraction and subsequent obtention of high-purity products. Thus, for solar cell fabrication, plagioclase is an important ore to supply aluminum and silicon. The ore grade in the lunar highlands' regolith is on average 30%, and the mineral is presented as single grains at coarse size, able to be beneficiated from regolith.

The excavation seems feasible on the Moon due to the low digging depth required and geotechnical conditions, which are feasible to overcome by current concepts. In addition, considerations for regolith flowability must be considered during hauling activities, and the assistance of a vibratory mechanism on their hoppers would be required. to accelerate the loading and unloading activities. An important consideration is the dust generation during regolith transport, and the assistance of a sintering system on pavement roads is required. The adherence of dust to the equipment surface is inevitable. This is an issue for the visual operation of the equipment, causing false readings, coating and contamination of the sensors, abrasion, failures during the seal, abrasion in joints, and rotating surfaces, among others. Indeed, there are other transportation options [8]. For instance, tubular drag chains work into an isolation chamber, reducing dust generation. Nevertheless, poor regolith flowability is a latent risk for obstruction, and a continuous monitoring and maintenance strategy must be defined, increasing the system risk. Other transportation options evaluated were aerial cableways, which only work in topography with high altitude differences between the excavation zone and processing plant. Finally, railcar transportation looks like a good option for the future because of its requirements of steel or iron alloys, which are more complicated to produce on the moon in the short term.

In this simulation, to ensure the quality of the solar panels, the content of iron and titanium minerals must be eliminated completely before the reduction stage. Magnetic separation seems the best candidate, superior to electrostatic separation. Although the data published by [12] would be considered a proof of concept for plagioclase concentration, further tests must be applied in order to validate its feasibility. Moreover, information from other lunar ISRU strategies, such as ilmenite concentration, will be valuable to adjust the parameters of the magnetic field. In addition, for further tests, the use of lunar simulants should be carefully considered because they do not represent adequate properties such as maturity or a low degree of liberation, which influence the final recovery. An additional consideration is that even if the concentration is 100% effective, nanophases of iron in plagioclase are still present, so strategies for material refining to eliminate iron at the molten stage must also be considered in the final flowsheet. MRE is an interesting technique for lunar applications, however, important unknowns related to the thermophysical properties of liquid alloys and their behavior of solidification processes, multiphases, crystal and grain alloys growth must be defined at lunar conditions. Although a low-gravity environment is an advantage for pumps system and fluid transportation, it affects the molten material flowability complicating the discharge and transfer activities which utilizes gravity as motion force.

CONCLUSION

Humanity is planning to land on the lunar surface soon [7], to start the preparation for the next landing destination: Mars [16]. Both destinations require a complete and sustainable industry for local use of resources. Lunar regolith is a mix of different minerals, and while ilmenite is the most important ore in the lunar Marias, plagioclase is the same for the highlands and the lunar South Pole. To produce aluminum and silicon in a metallurgical grade, lunar regolith must be processed to eliminate agglutinates, glasses, and coarse and ultrafine particles to lower the grade of iron in the final products. Thus, a beneficiation plant, including operations such as screening and magnetic separation, is required. Based on previous experiments, plagioclases would be feasible to beneficiate on an industrial scale. However, regolith properties such as cohesion and electrostatic charge will impact the results of the screening operation, so it is important to consider this in future system designs. Although the main metallurgical routes for ore beneficiation and metal extraction in pure or semi-pure forms are presented and discussed in this paper, there are several unknowns in the mineralogical parameters and behavior of molten material in a vacuum and low-gravity environment, so more tests must be developed in the next few years for a final plant configuration. Finally, new strategies such as artificial intelligence for ore control must be included in the ISRU plans to offer the best quality of products for the future manufacturing industry.

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