Solar Panel and Coating Manufacturing From Lunar Regolith Decomposition

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Introduction

In the future planetary surface missions to the moon, including colonization and infrastructure building, utilizing the local sources and materials is going to have a vital role in expanding mission capability by providing mission requirements. In addition, improving the capability of production by using local materials is also increasing the payload capacity. This concept is called "in-situ resource utilization (ISRU)" and has been developed rapidly in recent years.

This development has been creating new working areas and plans which makes the mission longer and more efficient. Moreover, while planning a space expedition's schedule, energy capacity and production are determinative parts of operation capacity. In this particular part, the main problems of producing and carrying energy are high costs, vast energy losses and possible risks. It means that bringing the sources from the Earth or using nuclear power is not a sustainable solution. The use of solar energy, which is highly accessible and efficient in the space environment, is one of the most feasible solutions to this problem.

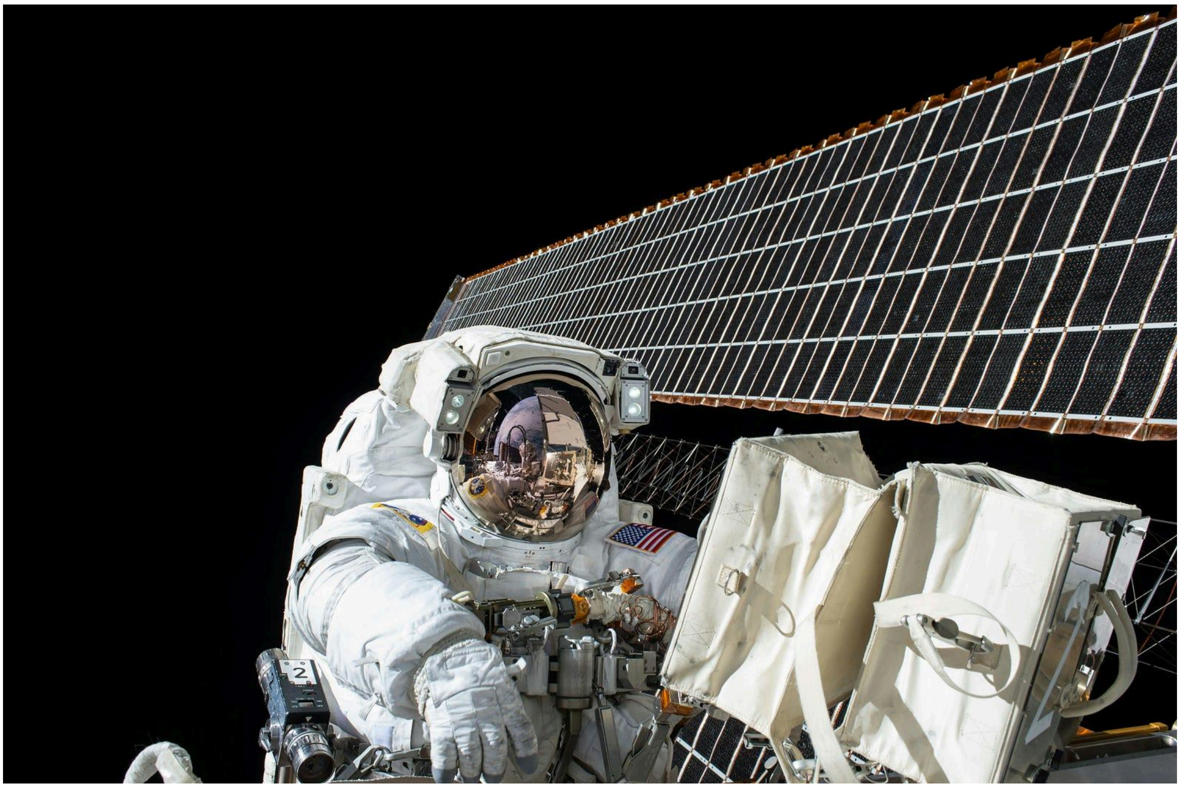

Image 1: A photo of an astronaut and solar panel by NASA

Under these circumstances, solar panel production by the ISRU method becomes a promising alternative. This concept enables more for lunar exploration and can be mostly produced by local materials such as Si (silicon) and Al (Aluminum).

Why Do We Need Surface Missions?

Extending human occupancy on the Moon empowers scientific research and lowers the prices of space missions since launch or landing costs will radically decrease. An important milestone in prolonging human activity is providing resources such as hydrogen, oxygen, silicon and other metals by extracting them from the ground. These materials can be malleable to beneficial shapes so that they can be used in manufacturing.


Image 2: A step of an astronaut on the lunar regolith by NASA

During the Apollo missions, the lunar lander payload was about 6000 kg. With SpaceX's reusable Starship, this could increase to 100 metric tons, supported by refuelling in Earth's orbit. Advancements from the International Space Station and SpaceX's cost-effective Falcon 9 highlight the feasibility and importance of Moon surface missions for further exploration and technological progress. These missions envision building an operational base for interplanetary expeditions, necessitating in-situ resource utilization (ISRU) to provide energy resources directly from the Moon's surface, as transporting energy from Earth is prohibitively expensive.

While nuclear power has been considered, its risks and technological challenges make it less viable. In contrast, solar energy is more beneficial and accessible, making ISRU-based energy production one of the best options for sustaining lunar operations and supporting future missions.

Lunar Geology

The geology and mineralogy of lunar regolith material were studied from the samples from the Apollo and other missions and are considered an approximate overview of the geology, geochemistry, geophysics, and mineralogical compositions at the Apollo landing sites on the Moon. Pyroxenes, plagioclase feldspars, and olivines are the dominant minerals found on the lunar surface.

These mostly contain silicon and aluminum oxides plus lower quantities of iron, magnesium, calcium, and sodium. Lunar rocks are made up of minerals and glass, with silicate minerals making up over 90% of the volume of most lunar rocks, which are excellent candidates for lunar oxygen production.

Corresponding lunar soil simulants such as JSC-1 (Johnson Space Center 1) and MLS-1 (Minnesota Lunar Simulant 1) were prepared for ISRU studies. These simulants help researchers understand the potential for using lunar materials in various applications, particularly for extracting oxygen and other useful elements.

The surface of the Moon consists of two main geological units. One is the ancient, light-coloured lunar highlands; the other is the darker lunar mare ('seas') filling the large impact basins located mainly on the near side. The chemical compositions of the lunar regolith occurring in these units have been derived from soil samples taken in the Luna and Apollo missions as well as from remote sensing measurements.

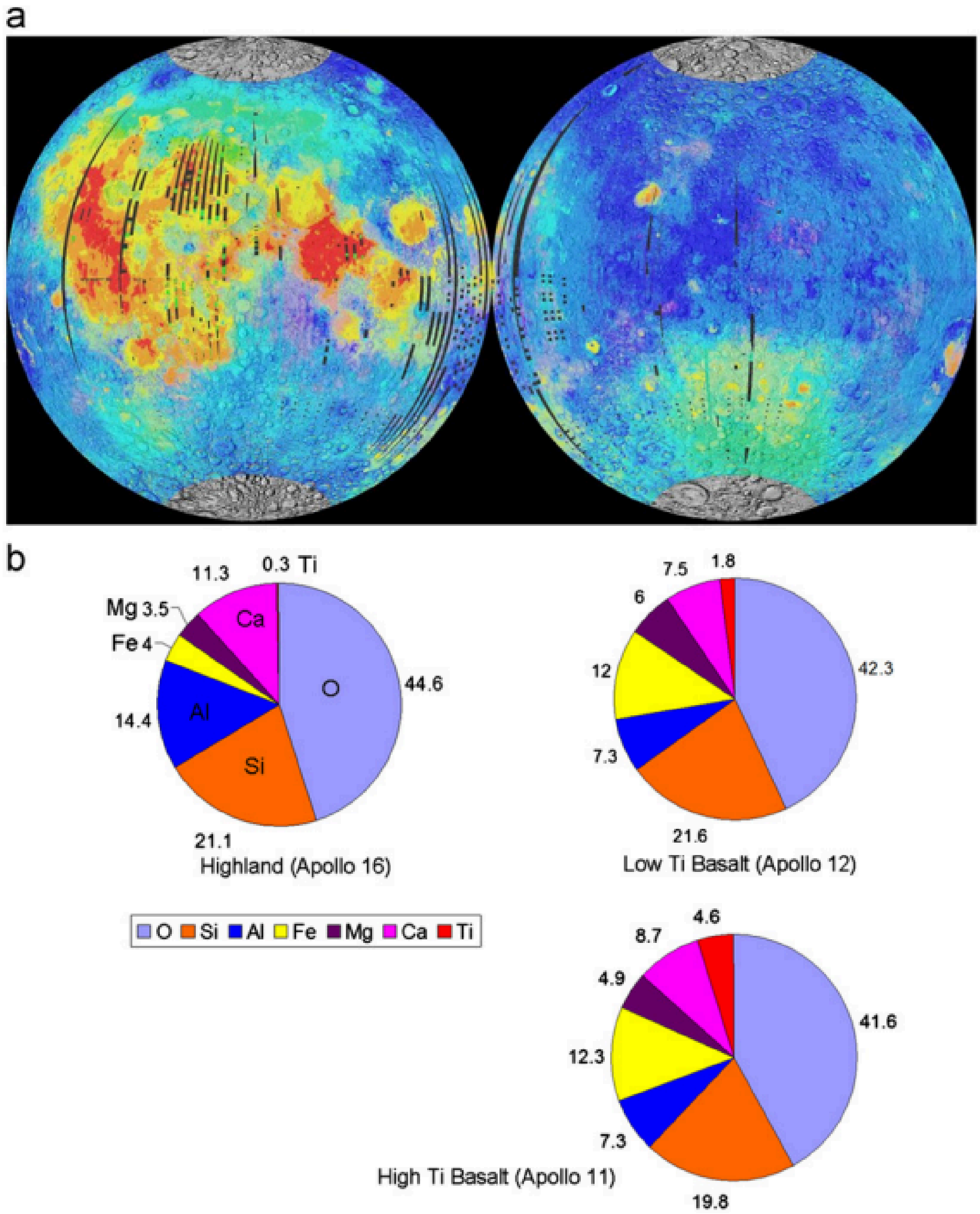

Image 3: The distribution of rock types on the Moon by "C. Schwandt et al. / Planetary and Space Science 74 (2012) 49–56"

The lunar highlands are composed predominantly of anorthositic rocks and contain more than 90% by mass plagioclase in the form of calcium-based anorthite ($CaAl_2Si_2O_8$) and small quantities of magnesium- and iron-bearing minerals such as pyroxene ((Mg, Ca, Fe)-SiO_3) and olivine ($(Mg, Fe)_2SiO_4$). The lunar mare is composed of basaltic lava flows which contain varying proportions of plagioclase, pyroxene, and olivine as well as ilmenite ($FeTiO_3$).

Depending on whether the titanium dioxide (TiO_2) content in the basalts is above or below 6% by mass, these are further subdivided into 'high-Ti' and 'low-Ti' categories. The differentiation in titanium content influences the physical and chemical properties of the basalts, impacting their potential use in various applications on the Moon.

In-depth studies, in the form of prospecting missions and sample return missions, will need to be conducted once a landing site for a lunar base is selected. This is necessary since fluctuations between different landing sites can be significant and will have an impact on any In-Situ Resource Utilization (ISRU) application. Variations in olivine content, for example, will change the melting point of the regolith, as the ratio of different olivine minerals such as forsterite and fayalite will have an impact on that, along with variations in magnesium oxide and iron oxide content.

Raw Materials For Solar Panels

Glass, widely used for various applications on Earth, is commonly employed as a substrate for semiconductor devices. In space, glass can serve numerous purposes, such as substrates or backplates for semiconductor devices and electronics, windows, pipes and tubes, fibres, formed objects, thermal insulation foams, and low-density aerobraking heat shields. Since 1979, it has been recognized that diverse types of glass could be beneficial on the Moon.

For instance, in 1986, researchers investigated processing lunar materials using microwave melting. Therefore, it is essential to identify which terrestrial glass manufacturing processes are adaptable to the lunar environment and can use regolith as a raw material. Silicon dioxide forms the primary component of most terrestrial glasses, with other oxides modifying properties like melting point and colour. This adaptability is crucial for the potential production of glass components for solar panels, where glass can be used both as a protective coating and a substrate for photovoltaic cells, enhancing durability and performance.

Image 4: Photo of four types of lunar regolith: EAC-1 (top left), JSC-2A (top right), LHT3M (bottom left), and FJS-1 (bottom right). The scale bar is in cm. Source: https://link.springer.com/article/10.1007/s10853-018-3101-y

On Earth, soda lime glass is the most common type, and while it is well understood and potentially usable on the Moon, basaltic glass made from lunar regolith and igneous rocks will likely be the only feasible option on the lunar surface. Understanding and adapting glass manufacturing processes to utilize available lunar materials will be crucial for supporting various applications in a lunar base, including the construction of solar panels, which are essential for sustainable energy production on the Moon.

Examples of Different Lunar Regolith Simulants and Their Compositional Information

Oxide	JSC-2A	LHT-3M	EAC-1	FJS-1
SiO_2	47.50	46.70	43.70	49.14
Al_2O_3	15.00	24.40	12.60	16.23
Fe_2O_3	3.50	4.16	12.00	4.77
FeO	7.25	–	–	8.30
MgO	9.00	7.90	11.90	3.84
CaO	10.50	13.60	10.80	9.13
Na_2O	2.75	1.26	2.90	2.75
K_2O	0.80	0.08	1.30	1.01
TiO_2	1.50	0.41	2.40	1.91
MnO	0.18	0.07	0.20	0.19
P_2O_5	0.80	0.15	0.60	0.44
Total	98.78	98.73	98.40	97.71

Table 1, source: https://link.springer.com/article/10.1007/s10853-018-3101-y

	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total
Apollo 14	48.1	1.7	17.4	10.4	0.14	9.4	10.7	0.7	0.55	0.51	–	99.6
JSC-1	47.71	1.59	15.02	10.79	0.18	9.01	10.42	2.7	0.82	0.66	0.11	99.01
MLS-1	52.69	1.01	15.91	12.28	0.22	5.41	9.36	1.9	0.58	0.14	0.5	100
NEU-1	44.92	2.87	17.23	13.09	0.34	4.37	9.44	3.79	3.01	0.54	0.4	100

Table 2, source:
https://www.researchgate.net/publication/312548187_Lunar_Soil_Simulant_Electrolysis_Using_Inert_Anode_for_Al-Si_Alloy_and_Oxygen_Production

Review of the Tables

The tables provide the chemical compositions of various lunar soil simulants, along with actual lunar samples, in terms of their oxide content. The first table compares JSC-2A, LHT-3M, EAC-1, and FJS-1 simulants, while the second table compares Apollo 14 lunar soil with JSC-1, MLS-1, and NEU-1 simulants.

The primary oxides listed include SiO_2, Al_2O_3, Fe_2O_3, FeO, MgO, CaO, Na_2O, K_2O, TiO_2, MnO, and P_2O_5. Each simulant has a unique composition, reflecting different geological units and preparation methods designed to mimic the actual lunar regolith.

Correlation Between Simulant and Composition Information

- **Silicon Dioxide (SiO_2)**: All simulants and samples have a high SiO_2 content, ranging from approximately 43.70% to 52.69%, indicating the dominance of silicate minerals, which are crucial for glass manufacturing.
- **Aluminum Oxide (Al_2O_3)**: The content of Al_2O_3 varies significantly among the samples, from 12.60% to 24.40%, which affects the glass formation properties such as durability and melting point.
- **Iron Oxides (Fe_2O_3 and FeO)**: The presence of iron oxides is important for the melting behaviour and colouration of glass. The combined iron oxide content ranges from about 3.50% to 12.28%.
- **Magnesium Oxide (MgO) and Calcium Oxide (CaO)**: These oxides are also crucial for modifying the properties of glass and their content varies widely across the simulants.
- **Other Oxides (Na_2O, K_2O, TiO_2, MnO, P_2O_5)**: These oxides are present in smaller quantities but are essential for specific glass properties like thermal expansion and chemical durability.

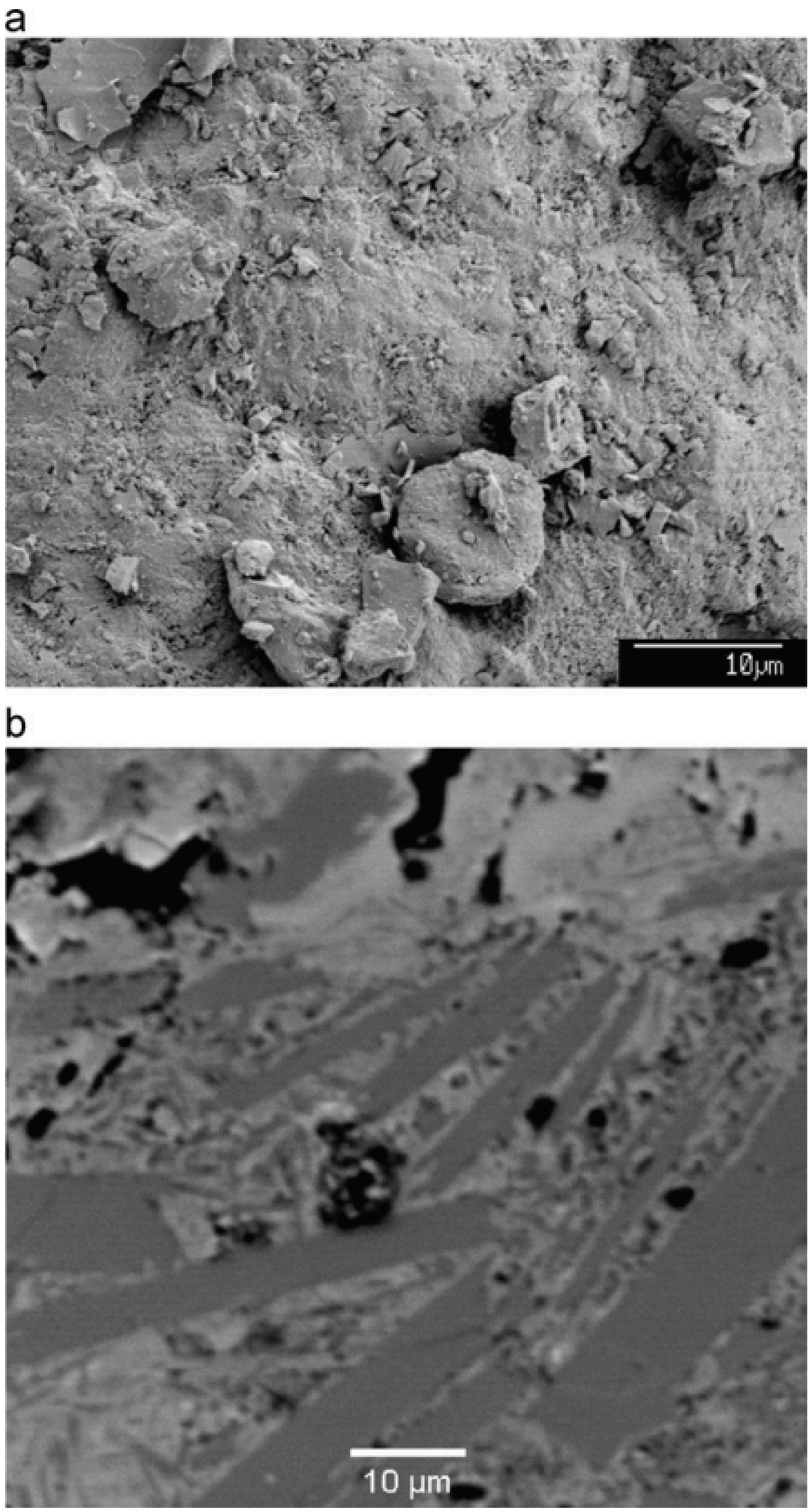

Image 5: Electron micrograph of lunar simulant JSC-1; the darker areas are Al and Si-rich, and the lighter areas are Mg and Fe-rich. Complete black areas are the pores. Source: "https://www.sciencedirect.com/science/article/abs/pii/S0032063312001821"

Conclusion Paragraph About Tables

The chemical compositions of the lunar soil simulants shown in the tables provide a detailed insight into the potential raw materials available for glass manufacturing on the Moon. High silicon dioxide content across all samples indicates that lunar regolith is suitable for producing silicate-based glasses, which are essential for various applications including solar panel substrates and protective coatings. The substantial presence of SiO_2 ensures that the basic structure for glass formation is readily available, making it feasible to develop glass products directly on the lunar surface.

The variability in aluminum oxide, iron oxides, magnesium oxide, and calcium oxide among the simulants suggests that the properties of the resulting glass can be finely tuned to meet specific requirements. For instance, higher Al_2O_3 content improves the glass's resistance to chemical and thermal stresses, making it ideal for solar panel coatings. Additionally, the presence of iron oxides affects the melting behaviour and colour of the glass, which can be optimized for different lunar applications. These variations highlight the need for precise control and understanding of the regolith's composition to produce high-quality glass suited for specific uses.

Overall, the simulants provide a promising foundation for developing sustainable glass manufacturing processes on the Moon, leveraging local materials to support solar panel production and other critical infrastructure for lunar colonization. By utilizing the inherent properties of the lunar regolith, it is possible to create durable, effective glass components that are essential for the establishment and maintenance of a long-term human presence on the Moon.

Extraction of Materials for The ISRU Process

Commencing the production and coating of solar panels entails the challenging task of sourcing essential materials from the Moon. Establishing this process and equipping it with the necessary tools warrants a careful evaluation of methods to ensure efficiency. Key considerations in selecting the optimal approach include the temperature requirements, output yield, requisite tools, and cost-effectiveness. These metrics are pivotal in determining the viability and success of lunar material extraction for solar panel manufacturing.

- **Vapour phase pyrolysis:** Vapour phase pyrolysis is a relatively straightforward method that necessitates high temperatures exceeding

2000°C. It primarily targets metal oxides, especially those of iron and silicon. However, it can also partially decompose oxides of magnesium, calcium, and aluminum, yielding around 50% oxygen. The reaction products emerge in the gas phase, requiring rapid cooling to prevent reversions.

- **Sulphuric acid reduction:** Sulphuric acid reduction is tailored for ilmenite-rich feedstocks. Initially, the material undergoes a reaction with hot concentrated sulphuric acid, forming iron sulphate, titanium sulphate, and water. The subsequent steps involve dilution and cooling to precipitate iron sulphate, hydrolysis of titanium sulphate to produce titanium dioxide, and electrolysis of the re-dissolved iron sulphate to yield iron and oxygen. Despite its efficacy, the process complexity and relatively low oxygen yield for low ilmenite content feedstocks are notable drawbacks.

- **Electrolysis of molten lunar regolith:** Electrolysis of molten lunar regolith, known as the Magma process, is a straightforward technique for extracting oxygen and metals on the Moon. This method requires an electrolytic cell operating at temperatures up to 1600°C to melt the regolith. Applying a potential causes oxygen to evolve at the anode and metal to deposit at the cathode. The process uses un-beneficiated multi-component lunar feedstock and does not need Earth-sourced reagents. Selective metal extraction based on oxide stability is possible through potential control, yielding metals like iron and silicon, and potentially titanium if present. However, the high operating temperature is a significant drawback. The formation of free magnesium can degrade silicon quality, and the highly corrosive silicate melt poses engineering challenges. Additionally, only expensive platinum group metals, particularly iridium, have shown long-term promise as anode materials.

- **Electrolysis of solid lunar regolith:** Electrolysis of solid lunar regolith is a recent advancement based on the FFC-Cambridge process for electro-deoxidation of metals and metal oxides. The method involves an electrolytic cell operating at around 900°C with molten calcium chloride ($CaCl_2$) as the electrolyte. In this setup, a lightly-sintered porous metal oxide body serves as the cathode, and a carbon-based material like graphite is the anode. The applied potential is high enough to decompose the cathode but not the electrolyte. Oxide ions are expelled from the cathode into the electrolyte, transported to the anode, and released as carbon oxide (CO/CO2) gas. This process allows oxide reduction within the solid-state cathode without consuming the molten salt electrolyte. The FFC process is versatile and applicable for metal winning and alloy synthesis from oxide precursors.

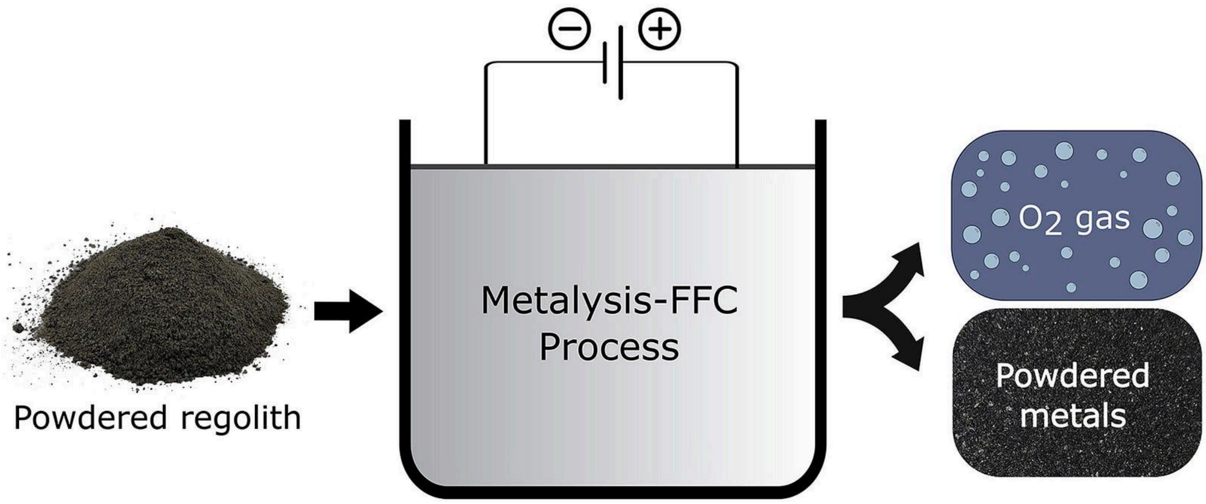

Image 6: Scheme of electrochemical extraction, source: "https://www.sciencedirect.com/science/article/abs/pii/S0032063319301758"

Comparison Between ISRU Extraction Methods

Among the four oxygen extraction methods evaluated for use on the Moon—vapour phase pyrolysis, sulphuric acid reduction, electrolysis of molten lunar regolith, and electrolysis of solid lunar regolith—their viability varies significantly based on temperature requirements, efficiency, and overall capability. Vapour phase pyrolysis, although conceptually simple and capable of moderate oxygen yields, requires extremely high temperatures (over 2000°C), making it less practical for lunar application due to the immense energy demands and technical challenges associated with maintaining such high temperatures.

Sulphuric acid reduction operates at lower temperatures and is efficient for ilmenite-rich feedstocks, but its complexity and lower oxygen yield for feedstocks with less ilmenite content limit its utility. This method involves multiple steps, including the use of concentrated sulphuric acid and subsequent electrolysis, making it less straightforward and more resource-intensive compared to other methods. Additionally, its dependency on ilmenite-rich feedstocks restricts its applicability across different lunar regions.

The Magma process, or electrolysis of molten lunar regolith, offers a straightforward approach with a reasonable oxygen yield of around 50% and the ability to process multi-component feedstocks without requiring Earth-sourced reagents. However, its high operating temperature (up to 1600°C) and the highly corrosive nature of the silicate melt present significant engineering challenges. The need for durable anode materials, such as expensive platinum group metals, further complicates its implementation and scalability for long-term lunar missions.

Conversely, the electrolysis of solid lunar regolith, derived from the FFC-Cambridge process, operates at a more manageable temperature (around 900°C) and provides efficient oxide reduction in the solid state without consuming the electrolyte. This method's ability to handle various metal oxides and produce multiple valuable byproducts, combined with its lower energy demands, makes it an efficient and versatile method. However, it requires further optimization for lunar conditions to fully realize its potential. Considering temperature, efficiency, and capability, the electrolysis of solid lunar regolith appears to be the most promising method for lunar oxygen extraction, balancing lower energy requirements with effective and adaptable processing capabilities.

How To Build a Solar Panel In Space?

Solar Panel Parts

- **Solar Cells**: These semiconductor devices exploit the photovoltaic effect to convert incident solar radiation into electrical energy. Typically composed of doped silicon or other semiconductor materials, solar cells generate electricity as photons of light dislodge electrons from the semiconductor's atoms, creating a flow of current.

- **Supporting Structure**: The structural framework of the solar panel comprises materials such as aluminum or composite alloys, providing mechanical support and alignment for the solar cells. Its design optimizes load distribution and stiffness to withstand mechanical stresses during launch and operation.

- **Covering Material**: Often constructed from low-iron tempered glass or advanced polymer films, the cover layer serves as a protective barrier for the underlying solar cells. It facilitates high transmission of incident sunlight while offering resistance to abrasion, ultraviolet radiation, and thermal cycling.

- **Wiring and Connectors**: The electrical interconnections between individual solar cells and the spacecraft's power system consist of conductive materials such as copper or aluminum. These conductors are routed through insulating substrates and connectors, minimizing resistive losses and ensuring reliable power transmission.

- **Thermal Management System**: Employing passive and active techniques, the thermal management system regulates the temperature of the solar cells within an optimal operating range. Heat pipes, thermoelectric coolers, and radiators dissipate excess heat generated during solar radiation absorption and maintain thermal equilibrium.

- **Deployment Mechanism**: Utilizing mechanisms such as shape memory alloys, motor-driven actuators, or pneumatic systems, the deployment mechanism facilitates the controlled extension or retraction of the solar panel's surface area. Precision engineering ensures reliable deployment while minimizing mass and complexity.

- **Mounting Hardware**: Aerospace-grade fasteners, brackets, and attachment points secure the solar panel to the spacecraft's structure. These components endure high mechanical loads and vibrational forces during launch and maintain the desired orientation relative to the Sun for optimal energy capture.

Image 7: Photo of solar panels of ISS by NASA

In conclusion, space solar panels are meticulously engineered systems optimized for operation in the harsh conditions of space. While sharing similarities with terrestrial solar panels in their fundamental principles, they exhibit key differences in design and construction. Space solar panels prioritize lightweight materials, robust structural integrity, and efficient thermal management to withstand the rigours of space travel and prolonged operation in orbit.

Additionally, they often feature deployable configurations to maximize surface area for sunlight capture while minimizing volume during launch. These specialized adaptations ensure reliable and sustainable power generation for spacecraft missions, distinguishing them from conventional solar panels tailored for terrestrial applications.

Glass Type of Solar Panel

The harsh conditions of the space environment, characterized by high levels of radiation and extreme temperature fluctuations, pose significant challenges for the materials used in space solar panels. In this context, basaltic glass, a form of volcanic glass derived from basalt rock, has emerged as the preferred choice due to its exceptional suitability for these demanding extraterrestrial settings. Basaltic glass possesses a unique combination of properties that make it well-equipped to withstand the rigours of the space environment, including its lightweight nature, potential for in-situ resource utilization, and enhanced durability and longevity. These factors collectively position basaltic glass as a superior material for enhancing the efficiency and cost-effectiveness of space solar panels.

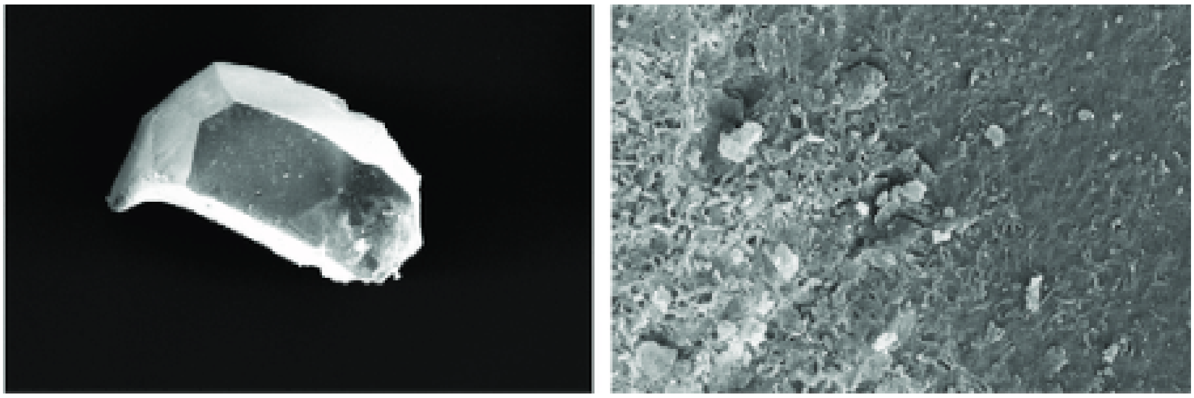

Image 8: Electron migrographs of basaltic glass, source: "https://www.researchgate.net/figure/Scanning-electron-micrographs-of-the-basaltic-glass-used-in-the-present-study-Figure-b_fig3_253328894"

Basaltic glass has recently garnered significant attention as a promising material for space solar panels. Its unique characteristics make it particularly well-suited for the harsh conditions of the space environment. One of the primary advantages of basaltic glass is its exceptional durability and resistance to radiation, which is crucial for maintaining the efficiency of solar panels in the high-radiation environment of space.

Additionally, basaltic glass exhibits superior thermal stability, allowing it to withstand the extreme temperature fluctuations experienced in orbit. Furthermore, the lightweight nature of basaltic glass contributes to reduced launch costs, making it an economically viable option.

Moreover, basaltic glass can be sourced from lunar or Martian basalt, potentially enabling in-situ resource utilization for future space missions, thereby reducing the dependency on Earth-based materials. Collectively, these attributes position basaltic glass as the preferred material for enhancing the longevity, efficiency, and cost-effectiveness of space solar panels.

Processing the Lunar Regolith Simulant

To initiate the processing phase, it is crucial to eliminate denser materials, particularly those enriched in iron. This operation, known as beneficiation, enhances the range of feasible processing methods and increases yield efficiency. According to Schleppi et al. (2021), beneficiation comprises three primary steps: drying, sieving, and magnetic processing.

- **Drying and sieving:** Prior to magnetic separation, simulants were dried at high temperatures for two hours and subsequently sieved. The simulants were divided into groups based on grain size. Following sieving, only the remainders from specific grain size groups were retained, while the other groups were discarded as waste. The combined weight of these retained grain size groups varied for each simulant. These retained groups were then subjected to electromagnetic separation.

- **Electromagnetic Separation:** The methodology involved utilizing varying electromagnetic field intensities across different grain size groups to categorize samples into five distinct types based on their magnetic properties: hm, high, fair, low, and non. Following each separation, the regolith simulants were divided into magnetic and non-magnetic fractions, where 'non-magnetic' refers to material unaffected by the specific magnetic field used.
  Subsequent runs with stronger magnetic fields uncovered magnetic susceptibility in previously non-magnetic portions of the regolith. This approach is akin to scenarios involving space solar panels, where materials must be sorted based on their response to specific environmental conditions or energy inputs. Such methods are crucial for optimizing resource utilization in extraterrestrial environments, ensuring efficient operation and maintenance of space-based solar arrays.

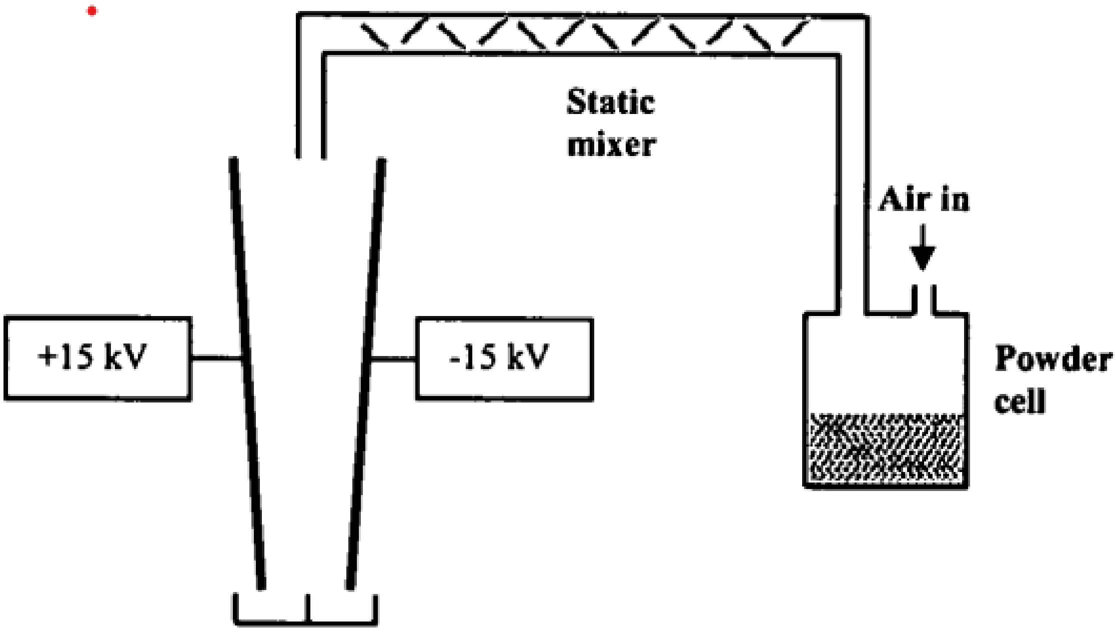

Image 9: Scheme of charge separator set-up in ambient, sourced by NASA

Heating or Microwave Processing For The Outcome Materials

In the manufacturing of space solar panels using in-situ resources, efficient processing methods for lunar regolith are crucial. Two primary techniques are employed: microwave processing and traditional heating. Each method offers distinct advantages and challenges in terms of energy consumption, adaptability to material composition, and overall cost-efficiency. Understanding these methods' intricacies is essential for optimizing regolith processing and enhancing the feasibility of constructing solar panels on the Moon.

- **Microwave Processing:** Microwave processing, known for its low energy consumption, is widely used in terrestrial applications and shows promise for lunar regolith processing. By utilizing a susceptor, which absorbs microwaves and converts them to heat, this method becomes less dependent on the regolith's composition. This susceptor-assisted approach ensures consistent processing across various regolith types but sacrifices power efficiency due to higher energy losses. The process operates at high temperatures, typically above 1100°C, requiring materials like carbon or silicon carbide as crucibles, which also act as susceptors to enhance heating. Although exact temperatures of liquefied regolith are challenging to determine, estimates suggest the regolith can reach around

1400°C. This setup effectively heats and melts different regolith simulants, demonstrating its adaptability.

- **Heating:** In contrast, the heating process involves placing magnetically beneficiated regolith samples of various grain sizes into a platinum crucible and heating them to 1550°C in a resistively heated furnace. This temperature, determined empirically, is optimal for processing the regolith. After heating for 15 minutes, the molten regolith is cast into a graphite mould and allowed to cool to room temperature before further processing. Occasionally, due to the limited thermal mass of the sample, it solidifies before casting. Increasing the temperature to 1700°C does not resolve this issue, so the sample is sometimes placed in a graphite crucible and heated for a shorter duration (3 minutes) at 1550°C to achieve the desired results.

Comparison in Terms of Energy Waste, Outcome, and Cost-Efficacy: When comparing microwave processing and traditional heating methods for regolith processing, several factors come into play. Microwave processing, especially with susceptor assistance, offers greater flexibility and independence from the material's composition, ensuring uniform heating and melting across different regolith types. However, this method is less energy-efficient due to higher losses associated with the susceptor. In terms of outcome, microwave processing can achieve higher and more consistent temperatures, which is beneficial for melting regolith effectively.

On the other hand, the traditional heating process, while being more straightforward and empirically optimized for specific temperatures, faces challenges with maintaining the molten state of the regolith due to the rapid cooling and solidification in the crucible. This method requires precise control and potentially higher temperatures to achieve similar results.

Cost-efficiency is another critical factor. Microwave processing, despite its higher initial energy losses, may offer long-term benefits due to its adaptability and efficiency in handling various regolith compositions. Traditional heating methods, while potentially more energy-intensive and requiring more frequent adjustments to prevent premature solidification, could be simpler and less costly in terms of initial setup and operational complexity.

In conclusion, microwave processing offers advantages in adaptability and temperature consistency but at the cost of higher energy consumption. Traditional heating, while potentially less efficient and more prone to operational challenges, may be more straightforward and cost-effective. The choice between the two methods would depend on specific mission requirements, available resources, and the desired balance between efficiency and operational complexity.

Coating

Efficient extraction methods significantly impact the availability of essential elements for coating space solar panels. For lunar regolith, the electrolysis of solid or molten regolith is the most effective technique for extracting aluminum (Al). The electrolysis of solid regolith involves passing an electric current through the material at high temperatures, simplifying the process and saving energy. In contrast, the electrolysis of molten regolith, which operates at temperatures above 1500°C, allows for more efficient ion movement and higher-purity aluminum. Although energy-intensive, this method provides higher extraction rates, making it ideal for large-scale operations.

Image 10: Photo of coated photovoltaic cells of ISS, sourced by NASA

Coating Materials and Process

When evaluating potential mirror coating materials for space solar panels, four metals—aluminum (Al), silver (Ag), gold (Au), and copper (Cu)—are considered for their reflective properties. For wavelengths ranging from 0.2 to 10 micrometres, these materials reflect between 70% and 90% of light for wavelengths above 1.1 micrometres. Aluminum stands out, reflecting more than 90% of light across the entire wavelength range, making it the top choice for maximizing light reflection. Using aluminum also aligns well with in-situ manufacturing methods, as it is abundant in lunar regolith and can be efficiently extracted.

While silver offers slightly better reflection in the infrared spectrum, the final choice of coating material depends on the specific application. Factors such as the absorption spectrum of multijunction solar cells, used in combination with mirrors in solar concentrators, may also influence the decision. The selection of coating materials, therefore, not only focuses on maximizing reflection but also on optimizing the performance based on the specific needs of the solar panel system.

To coat a mirror on a basaltic glass plate made from regolith, thin film deposition methods like physical vapour deposition (PVD) and chemical vapour deposition (CVD) are considered. For this project, PVD is preferred. This technique involves evaporating or sputtering a source material to create a gaseous plume or beam that deposits a film on a substrate. In thermal evaporation, the base material is heated using a resistive element, typically placed in a tungsten boat, to facilitate evaporation. PVD is usually conducted under vacuum conditions to prevent unwanted reactions, such as oxidation. The lunar surface's natural high-quality vacuum simplifies this process, making thermal evaporation the best option for coating mirrors on the Moon.

Last Processing

To increase the efficiency and strength of space solar panels, shaping and post-processing of the glass material are crucial steps. The process begins by pouring the glass material into a silver or tungsten crucible. This material is then heated using space radiation or solar microwaves.

Several methods are utilized to shape and strengthen the glass. In one approach, lunar regolith simulants are placed in graphite crucibles and heated in a microwave kiln. Samples are then transferred to an electric-heated kiln at 560°C to alleviate thermal stress and improve durability. This consistent heating and cooling process prevents shattering, which can be a significant issue if not properly managed.

Another technique involves combining regolith samples of various grain sizes and heating them in a platinum crucible at 1550°C. The molten regolith is then cast into a graphite mould and allowed to cool to room temperature. For smaller samples, the molten regolith is pressed with a graphite plunger to create thin, elongated glass pieces. This method ensures the material's strength and transparency, essential for the efficiency of the solar panels.

In the lunar environment, where convection forces are minimal, conduction and radiation are the primary heat transfer mechanisms. This slower cooling rate inherent to the Moon's conditions may reduce the likelihood of cracking, making these processes particularly suitable for in-situ manufacturing.

Comparison and Combination With The Blue Alchemist (Blue Origin's Space Solar Panel With ISRU Method)

Both the in-situ solar panel production method that is proposed and Blue Origin's Blue Alchemist aim to harness lunar resources to create essential materials and components for sustainable lunar missions. These approaches share the goal of reducing reliance on Earth-sourced materials, thereby enhancing the cost-efficiency and feasibility of long-term lunar operations. By utilizing local lunar materials, both methods significantly decrease the need to transport materials from Earth, thus reducing launch costs and increasing the sustainability of lunar missions.

The method that is explained in this writing focuses on using lunar regolith for the production of solar panels, leveraging materials such as silicon and aluminum. This approach aims to provide a cost-effective solution for creating energy resources directly on the Moon's surface. Similarly, Blue Alchemist uses regolith simulants to produce solar cells and transmission wires through molten regolith electrolysis. This process involves separating elements like iron, silicon, and aluminum from lunar regolith using an electrical current, with oxygen as a valuable byproduct for propulsion and life support.

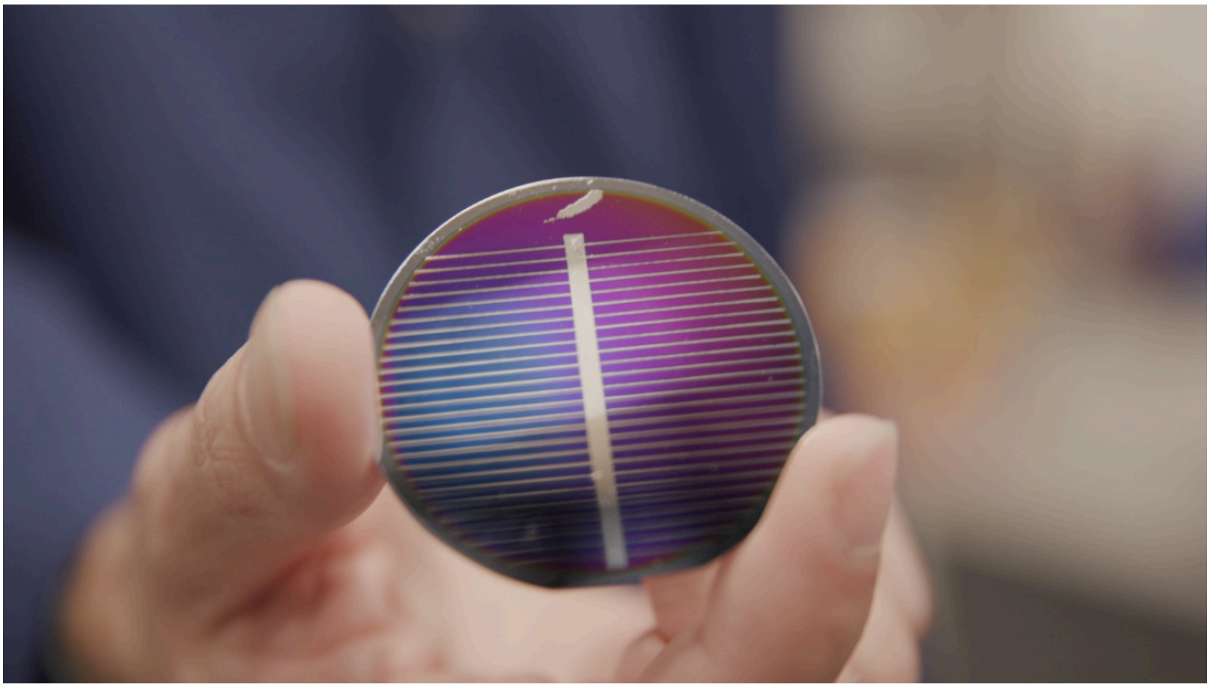

Image 11: Photo of *Blue Origin manufactured working solar cell prototype from lunar regolith simulants.*

Solar energy is a common solution in both methods due to its abundance and efficiency in the space environment. The first method highlights the use of solar energy to support mission operations, making it a key component for sustainable lunar exploration. On the other hand, Blue Alchemist focuses on producing solar cells that can generate electrical power directly on the Moon. These cells are designed to be long-lived and resistant to radiation degradation, ensuring they can endure the harsh lunar environment for extended periods.

Blue Alchemist achieves a high level of purity in silicon (99.999%), which is essential for making efficient solar cells. This is accomplished using just sunlight and silicon from their reactor, avoiding the toxic and explosive chemicals typically used on Earth. In contrast, the explained method does not specify the same level of purity or avoidance of chemicals, focusing more on the practical aspects of heating and shaping materials using lunar conditions. This difference highlights Blue Alchemist's emphasis on material purity and advanced processing techniques.

In summary, while both my proposed method and Blue Origin's Blue Alchemist share the overarching goal of utilizing lunar resources for sustainable mission operations, they differ in their technical approaches and material processing. Both approaches, however, contribute significantly to the feasibility and sustainability of future lunar missions.

Conclusion

Utilizing local materials to extend the longevity of Moon surface missions is a crucial step in enhancing future space expeditions. The in-situ resource utilization (ISRU) method significantly increases cost-efficiency by reducing the payload and necessary tools transported from Earth, thereby expanding the capabilities of scientific research in space missions.

Summary of ISRU Benefits and Technical Advancements

In future lunar missions, including colonization and infrastructure building, leveraging local resources is vital for meeting mission requirements and expanding mission capability. By using local materials, ISRU increases payload capacity, reducing the need for transporting heavy and expensive resources from Earth. The advancements in space technology, such as SpaceX's reusable Starship and cost-effective Falcon 9 rockets, highlight the feasibility and importance of Moon surface missions for further exploration and technological advancements. Establishing an operational base for interplanetary expeditions on the Moon requires ISRU to provide energy resources directly from the Moon's surface, as transporting energy from Earth is prohibitively expensive.

On Earth, soda lime glass is common, but basaltic glass made from lunar regolith and igneous rocks will likely be the only feasible option on the lunar surface. Understanding and adapting glass manufacturing processes to utilize available lunar materials will be crucial for supporting various applications in a lunar base, including the construction of solar panels, which are essential for sustainable energy production on the Moon. Extending human occupancy on the Moon lowers the costs of space missions by reducing launch or landing expenses. Key resources such as hydrogen, oxygen, silicon, and other metals can be extracted from the lunar ground and shaped into useful forms for manufacturing. During shaping and post-processing, glass material is poured into silver or tungsten crucibles and heated using space radiation or solar microwaves. This process ensures the material's strength and durability, essential for constructing solar panels.

In summary, the in-situ method dramatically increases the cost-efficiency of space solar manufacturing in the Moon environment. By utilizing local resources, we can reduce the dependency on Earth-supplied materials, lower mission costs, and enhance the scientific capabilities of lunar missions. The advancements in ISRU, combined with efficient manufacturing and extraction techniques, pave the way for sustainable and long-term human presence on the Moon, ultimately supporting broader interplanetary exploration efforts. By embracing ISRU and optimizing resource extraction and utilization techniques, we move closer to realizing a sustainable and economically viable future for lunar exploration and beyond.

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