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Leveraging the use of Novel Lunar ISRU and ISRP Processes with Space Based Solar Power

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Two of the most impactful areas of lunar research are In-Situ Resource Processing (ISRP) and In-Situ Resource Utilisation (ISRU). These in-situ methods will be the fundamental building blocks allowing humans to explore and inhabit the lunar surface. ISRU and ISRP methods will allow locally found lunar regolith to be processed and used for life support, energy generation, construction, etc. This will reduce the amount of raw material brought to the moon from Earth, reducing launch costs, and accelerating lunar infrastructure development. An important and abundant resource that will be used to leverage the development of energy intensive ISRU and ISRP technology is space-based solar power (SBSP). ISRP and ISRU processes require large amounts of power that can be generated through SBSP via satellites orbiting the moon that beam power to a receiver on the lunar surface. In this work, we review and discuss several ISRP methods enabled by SBSP that convert lunar regolith into useable materials. We present a novel method of material processing that can be enabled by SBSP, and discuss the considerations that will need to be made for its development. We also present several ISRU use cases for materials produced through ISRP. Lastly we analyze ISRP and ISRU applications with a specific focus on using the processed materials to further build and maintain SBSP.

I. Introduction

With increasing interest in space exploration from private industry, government, and academia, there has been greater efforts to develop novel space technology. Many see the moon as the primary location for attaining near-term goals in space development, which could then be continually developed for further exploration beyond the moon. In order to successfully allow humans to inhabit and research the moon, a lunar infrastructure must be developed to sustain life on its surface.

Two of the most critical areas of lunar research are In-Situ Resource Processing (ISRP) and In-Situ Resource Utilisation (ISRU). Lunar ISRP and ISRU are the respective methods of processing and using resources naturally found on the Moon's surface for desired applications.[1] The ISRP and ISRU processes follow material acquisition, which includes mining, excavation, and transporting the material to a processing plant. Material acquisition topics will not be discussed in this paper. However, it is of note that the material acquisition processes are important to the in-situ use of lunar material. The ISRP and ISRU methods will involve the processing and use of lunar regolith, the outermost lunar surface. This layer typically ranges from depths of 5-15 meters depending on the region with particle sizes ranging from tens of microns to large rocks, with majority of grains ranging from 40-100 microns.[2] Lunar regolith is a blanket of unconsolidated rock covering the lunar surface as a result of meteoroid impacts and impacts from charged particles from the sun and other stars.[3] The composition of lunar regolith is a mixture of metal oxide particles and consists of many useful components, such as oxygen, iron, aluminum, silicon, etc.[4] and can be a useful material in itself as a whole for certain applications.[5] Of note based on the soil composition, lunar regolith is approximately 45% oxygen by weight,[6] which will be an incredibly useful resource for lunar inhabitation. Using in-situ materials will reduce the amount of material required to be brought from Earth to the moon during missions, reducing the cost of lunar missions and allowing cargo space for other resources during launch. Overall, these processes will be the fundamental building blocks for humans exploring and inhabiting the lunar surface. One major challenge with ISRP and ISRU methods is that they require immense amounts of power. The power requirement is largely due to the heat required to physically alter the regolith for many of the processes.[7] For reference the energy required to melt 1 kg of regolith, which is common for material processing, can be calculated to be approximately 1.5 MJ.[8] Additional power would then be needed to maintain a set temperature of regolith and to conduct a select process on the material.

Space-Based Solar Power (SBSP), first presented in 1968 by Peter E Glaser,[9] presents a desirable solution to the power requirement for ISRP and ISRU methods. Solar energy is an abundant source of power in space and up to 1367 W/m^2 is received by the moon. This is also a source of power that will nearly always be available as shadowing of the solar arrays will be limited. SBSP consists of using large solar arrays to harness large amounts of electrical energy, which can then be transferred to a receiver near the power usage site via a laser or microwaves, and converted back into useable electrical energy.[10] There have been many concepts proposed for SBSP designs such as the rectangular reference system as defined by NASA,[11] the reflective mirror and sandwich panel concept as proposed by Kobe University,[12] and NASA's bell shaped sps-alpha concept.[13] All of these concepts are on an incredibly large scale with areas of several square kilometers, weighing hundreds or thousands of metric tonnes, with proposed power production on the order of hundreds of megawatts, or gigawatts. These systems also typically consist of modular designs such that they could be constructed in pieces in orbit, and large rectennas that occupy several square kilometers on the surface of where the power will be used.

Wireless Power Transmission (WPT) technologies such as microwaves or lasers have been in ideation and development for several years, and will be critical for transferring this power over long distances through space. Many research groups have focused on SBSP and WPT for space-based and earth-based applications. For example, researchers at CalTech have demonstrated the ability to wirelessly transmit microwave power from a satellite in space to the Earth's surface.[14] Additionally, the SPRINT project in the UK with the University of Surrey is in development to be the first laser-based power beaming demonstration outside of a government organisation.[15] At this point in time, both microwave and laser power transmission have relatively low efficiency, require a large footprint, and are subject to environmental factors.[16] While the technology is still in development, these are promising results that demonstrate progress moving forward.

In time, SBSP technologies could be developed to a technological readiness level that allow for large-scale transfer of energy from orbital space to the surface of an inhabited body. One notable feature of SBSP is the scalability of the systems for power collection. In space, massive structures could be created in zero gravity to generate large amounts of power. The scalability of SBSP would allow sufficient power to be transmitted to the lunar surface for the energy intensive ISRP and ISRU methods. It is of note that nuclear power sources could produce sufficient power for ISRP and ISRU methods in a very efficient manner. However, with more private corporations having access to space, but not having access to restricted materials, alternative power sources are required. Similar to how nuclear power could be utilised more on earth, it is limited due to reasons beyond the design and capabilities of the power source. Overall, SBSP is a promising candidate to supply large amounts of energy to the lunar surface for ISRP and ISRU methods.

The current work being done in the fields of ISRP and ISRU is largely centered on the efficiencies and yields of the processes.[16] For material processing methods it is desirable to produce as much product with as little input material as possible.[17] This will ensure that material is not wasted and requires less energy to produce. For utilisation it is desirable to develop technology at full-scale to validate performance and to demonstrate the integration of ISRU components in space missions.[18] Once these methods become efficient enough, and reach a sufficient technological readiness level (TRL), they can be used at scale to build key components of lunar infrastructure.[18] In this work we seek to review high energy ISRP and ISRU methods that may be enabled by SBSP, present a novel method of material processing, and demonstrate the importance of ISRP and ISRU methods for the construction and maintenance of SBSP as well as other lunar infrastructure that will be critical for human inhabitation.

II. ISRP Methods

Regardless of the method of processing the lunar regolith, typically some initial physical processing is required in all cases to increase the efficiency and yield of desired species. This is typically a reduction in particle size through milling or other methods, followed by particle filtering to only use particles of a desired size. There are several material processing methods of varying TRLs that are being researched and developed for processing lunar material in-situ. These processes may target different elements in the lunar material to extract depending on the desired use case for the material. All of the processes are incredibly energy intense and would require large power generation that could be provided by the large proposed scale of SBSP. A summary and review of ISRP methods are described here, note that this is not a complete list of existing ISRP methods, this is simply a review of the more commonly researched and developed methods.

II.i Carbo-Thermal Methods

In carbo-thermal methods, lunar regolith is chemically reduced using carbon compounds, typically methane. The methane and regolith reduction reaction produces hydrogen and carbon monoxide.[19] These products can then be converted into methane and water using a Sabatier reaction. The water is then electrolysed into hydrogen and oxygen gas. Finally, the methane can be returned and reused in the reduction reaction. This multi-step process requires the regolith to be molten and reach temperatures above 1600 ºC[20] and produces oxygen at a theoretical 50% yield.[21] A distinct advantage of this method is the recyclability of the methane. The disadvantages of carbo-thermal methods are the high operating temperature and the possible loss of product due to the multi-step nature and inefficiencies of the method. There has been a theoretical designs of an ISRU system, weighing 940kg, that can extract 1000kg of oxygen per year.[22] A small scale carbothermal reactor has been build and tested demonstrating some capabilities of this method.[23]

II.ii Molten Regolith Electrolysis (MRE)

Electrolysis of molten regolith requires a standard electrolytic cell with an anode and cathode. When a sufficient potential is applied, the molten regolith decomposes into oxygen at the anode and metal at the cathode. The advantage of this system is that untreated regolith is the only material input used for the system and supplemental material from Earth is not required. The large drawbacks of this process are the high operating temperature of 1600 ºC to melt the regolith and the costly components for the anode. Only expensive platinum-group metals have been proven to succeed with this method and must be changed frequently.[24] A MRE reactor has been tested with an operating temperature of 1600 ºC. This resulted in an efficiency of 94% when extracting 35g of oxygen per 100g of regolith.[25]

II.iii FFC Cambridge Method

The FFC Cambridge Method is a well-documented process of reducing mineral oxides into 99%-pure metal.[26] The standard FCC process uses an electrolytic cell kept at approximately 900 ºC with a metal oxide as the cathode, a carbon-based compound as the anode, and molten calcium chloride as the electrolyte.[26] When a potential is applied across the cell, the oxide ions transfer to the anode and are released as carbon oxides (CO and CO_2).[26] When using this method on lunar regolith, the target is to release oxygen molecules. In this configuration, two known anode compounds are capable of releasing oxygen gas: (1) doped tin oxide (SnO_2), and (2) a solid solution of calcium titanate and calcium ruthenate.[21] Experimental tests have shown that the lifetime of the tin oxide is limited to a few hours due to erosion observed at the anode as well as a thin layer of calcium stannate, an insulator, coating the anode and hindering the electrochemical process.[27] The calcium mixture has been shown to release oxygen gas for over 100 hours, making anodes of the composition $CaTi_xRu_{1-x}O_3$ more desirable.[28] An experiment using the FFC Cambridge process was run with an ilmenite ($FeTiO_3$, present in lunar basalts) cathode, which was able to produce oxygen for 9 hours.[29] In the context of ISRU, the main design criteria to overcome is the need for a replenishing source of electrolyte as a portion is consumed throughout the reaction. This is not someting that could be done easily in-situ at this point in time.

II.iv Vapor Phase Pyrolysis (VPP)

When placed in a vacuum at sufficiently high temperatures, lunar regolith will evaporate. This temperature will need to be greater than 2000 ºC,[30] therefore requiring large amount of energy. In its gaseous form, the metal oxides that make up most of the regolith decompose into suboxides, metal, and oxygen.[19] This oxygen and metal can then be siphoned and cooled to be used for life support, technology, and fuel. Although VPP also requires high operating temperatures, the main attraction of this method is that it uses in-situ resources available on the moon without requiring additives. The oxygen yields of this process are 50%.[21] It is important to note that the oxygen and metals need to be cooled immediately in order to prevent the metals from recombining with the oxygen.[19]

II.v Water Electrolysis

Water electrolysis is the process of taking the water and separating it into hydrogen and oxygen. The difficulty with this method on the lunar surface is retrieving the water and refining it to a state that could be easily processed. The water content on the sunlit side of the moon is 100-412 ppm (0.01% - 0.042%),[31] and there is evidence that there are much higher volumes in the permanently shadowed regions near the poles.[21] One benefit of this method is that liquid hydrogen/oxygen rockets could deposit any excess fuel into the processing plant to produce hydrogen and oxygen. However, to use this processing method effectively with in-situ resources, much energy would need to be spent transporting and heating the water. Due to the lack of technology readiness and lack of abundant water everywhere on the lunar surface this method is not readily available.

II.vi Novel Processing Method

The project team has been working with the Laboratory for Emerging Energy Research (LEER) at the University of Waterloo to procure a conceptual, novel, material processing method. We are proposing a novel material processing method, related to MRE, that will allow for a more refined processing of regolith which may provide more benefits for certain applications. The concept builds on the principles of molten regolith electrolysis. It is known that when a sufficient voltage and current are applied to the solution of molten regolith, the metals and metal oxides will separate and could be extracted from the solution. Building on this, it is known that the decomposition of each individual metal oxide occurs at a different voltage. Table 1 demonstrates the decomposition voltages of metal oxides found in regolith is shown below.

Oxide	$-E^{o}(V)$	JSC-1 Conc. (wt%)	Lunar Soil Conc. (wt%)
K_2O	0.748	0.82	0.6
Fe_2O_3	0.842	3.44	0.0
FeO	0.986	7.35	10.5
Na_2O	1.117	2.7	0.7
Cr_2O_3	1.363	0.04	0.2
MnO	1.486	0.18	0.1
SiO_2	1.757	47.7	47.3
TiO_2	1.822	1.59	1.6
Al_2O_3	2.179	15.02	17.8
MgO	2.376	0.18	0.1
CaO	2.59	0.04	0.2

Table 1: Oxidative Decomposition Potentials of Lunar Oxide Elements at 1300K[32]

Using a stepped voltage method the species dissociation and removal will happen subsequently for each metal oxide pair, starting with potassium oxide and ending with calcium oxide. Alternatively, select groups of metal oxide pairs could be extracted subsequently. For example, if 1V is applied to the solution, iron and a small amount of potassium could be extracted from the regolith. Overall, this will decrease the amount of post processing required as higher purity products may be extracted compared to a standard MRE method. This would then reduce the cost of processing the residual materials and could provide purer metal material for certain applications after dissociation. However, one potential drawback of this method is the need to hold the regolith at elevated temperatures for a longer time as the material is processed. This would need to be weighed against the desire of obtaining a purer or moere specific end product.

The project team will continue to develop the novel material processing concept and begin experimental design of mechanical systems and tests with the LEER Lab at the University of Waterloo in the future. The lab is planning to complete small batch analysis as a proof of concept of the method. The specific research goal of the project is to accurately extract select products in succession from the molten regolith. The composition of the extracted products will be analysed to determine the quality of the procedure.

It is of note that this stepped voltage process could occur using the FFC Cambridge process, similar to MRE. It is also of note that this concept could be applied to VPP using a stepped temperature method. This would allow species to gasify and be collected subsequently, to reduce post processing of the material. Overall, with sufficient power, the proposed novel methods could provide a simpler way of obtaining high purity materials for desired applications by reducing the required post processing.

Each processing method has its advantages and disadvantages, however they all share the common goal of producing useable products from in-situ material on the lunar surface. They show the potential to produce large amounts of individual elements such as oxygen, aluminum, iron and silicon. They also show the potential to produce useful metal allows or silicon-based glass products. They will all require large amounts of power that can be supported by SBSP. Once these methods have been fully developed, they will provide several materials as described to construct a habitable living environment for people and equipment to research space more closely. The following section describes use cases for the product of the described processing methods.

III. ISRU Methods and Discussion

There are several applications for the materials derived from lunar in-situ processing methods that will help to construct a habitable lunar environment in a more economic fashion than transporting all the required material from Earth. Oxygen will be the most critically produced component from the lunar regolith. Most lunar ISRU work revolves around the production and use of oxygen. Oxygen serves numerous purposes including allowing humans to inhabit the lunar surface to perform complex research and experiments, allowing for water storage with hydrogen to support human and plant life, and acting as a fuel source, both in terms of energy to support life, and as a propellant for rockets. The production of oxygen will be critical for survival on the Moon. With the vast applications and needs for oxygen it is beneficial that lunar regolith is approximately 45% oxygen by weight.

Metals will also be incredibly useful towards developing infrastructure necessary for lunar inhabitation and survival. Metals are often overlooked in discussions of ISRP as many groups focus primarily or only on the production of oxygen.[33] Metals and metallic alloys can be extracted from the lunar regolith which can be used in construction of lunar bases, vehicles, equipment, or other structures. Ideally, the produced metals and alloys could be formed immediately after processing as the hot processing methods could allow for the metallic product to be easily shaped into whatever form is desired. For example, it may be ideal if the hot metallic products could be cast into molds for beams in construction, or for bricks in roads or launchpads. It is of note that casting is also a high-energy process, similar to the regolith processing methods described previously. SBSP can be used to generate the large amount of energy required to keep the products hot to be casted into a desirable form. If high-purity iron and aluminum can be gathered from the regolith the properties of the metal materials can be tailored towards whatever application they are trying to fulfill. Another application of high-purity metal is the use of aluminum in solid rocket fuel. Aluminum is a common additive in solid rocket fuel due to its high energy production.[34] Metals and metallic alloys could also be used in metal additive manufacturing to produce more complex parts that would otherwise need to be machined on Earth and transported to the lunar surface. This could be critical for repairing and maintaining systems that would otherwise need replacement parts shipped from earth.

Lastly, silicon-based products will be important for the development of a lunar infrastructure. Silicon materials such as glass or ceramics will serve many applications on the lunar surface. Silicon is the primary element in solar power collectors, and can be used to create solar panels for future energy production. Silicon-based glasses could also be formed to produce equipment needed for experiments, or for the construction of lunar habitats. Silicon-based ceramics could be used to create electronic devices, casings or tiles. These could be used as vehicles or equipment components or even as floor tiling for people or equipment. As silicon dioxide is the largest component of lunar regolith, it will be important to utilize it effectively as a source material.

Overall, each product of lunar regolith processing could serve a purpose in the construction of lunar infrastructure. It is also important to note that all of the products derived from in-situ lunar regolith can be used to support the development and maintenance of SBSP. As previously mentioned, silicon could be used with to other additives to create solar cells for energy production. Metals could be used to create a based structure to construct a solar array upon to either be used on the lunar surface or in orbit in SBSP. Oxygen could be use as a fuel to transport the newly created solar array into orbit as a standalone structure, or to be combined and build upon existing SBSP. In a similar way these components can be used to maintain SBSP. If the structure of an array is decaying, it could be replaced using metals derived from regolith. If a solar cell has been damaged and could potentially damage the rest of the array, it could be replaced. This use of in-situ material to create and maintain energy producing technology creates a production cycle that is more independent from earth and less dependent on materials being brought to the lunar surface.

Additionally, it is of note that the processing methods described previously could be used to recycle and reuse old equipment and material made from lunar resources. As these methods will be designed to process lunar regolith, they will be able to process parts made form lunar regolith. Pre-processing will likely be required to break down old components into a regolith like consistency in this case. This recyclable property will reduce the amount of material required from earth. Overall, there are several uses for the materials processed from lunar regolith that will help to accelerate the growth and development of a lunar infrastructure.

IV. Conclusion

In this work we discuss the importance of SBSP for future missions and settlement on the Moon and beyond. The massive amounts of power that SBSP can potentially generate will allow for ISRP and ISRU methods to be used. If a larger scale lunar factory or processing plant is to be created it will require power on the scales that are discussed with SBSP. The processing methods will be important for producing the critical infrastructure and living conditions required for people to inhabit and research the moon to achieve our space-based goals. These ISRP methods are reviewed and demonstrate the capability to gather materials crucial to life support systems, construction and power production. A novel ISRP method is presented and discusses that could provide advantages over current processing methods. Several use cases for the produced materials are discussed, notably including the development and maintenance to scale SBSP itself. All of these factors of ISRP and ISRU demonstrate that less dependence could be put on earth-based materials, which will help to reduce launch costs. While SBSP, ISRP and ISRU technology are all currently not at a point where they have been fully demonstrated, they do show the potential to be used together in space-based systems to achieve large space-based goals. As the technology develops these individual systems can be tested to demonstrate their capabilities. Once they have individually been proven, they can start to work in synergistic systems to decrease cost, and increase reliability, scale and safety. Next steps for this work include the continual development of the novel regolith processing method, the investigation of space-based systems that utilise SBSP, ISRP and ISRU methods, and the continued investigation of the applications of ISRP and ISRU to the scaling and maintenance of SBSP.

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