A POTENTIAL MODEL OF URANIUM EXTRACTION ON THE LUNAR SURFACE.

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Introduction and Background:

The overall objective of this system, the Uranium KREEP Mining (UKM) system, is to produce a total of 10 metric tons of UO_2 during the system life cycle of 10 years. By doing this, the UKM would provide enough uranium for a 10+ megawatt scale fast-breeder reactor, which would enable further growth in power production on the Moon[1]. The power produced by a megawatt scale reactor could firm up many times more capacity in variable solar power, acting as a bootstrap for development far beyond just the megawatt-hours produced by the reactor itself. This enables a snowball of lunar infrastructure construction to roll into a full lunar economy. To support that overall goal, the system will extract, separate, beneficiate, and refine KREEP-enriched regolith in the Procellarum KREEP Terrane to produce refined uranium dioxide (UO_2) powder that can either be directly mixed into fuel for a breeder reactor or processed into metallic uranium for enrichment.

The principal goal of this work is to detail an architecture that could be used to extract UO_2 from lunar regolith for a direct purchase from a customer. This is, to the team's knowledge, the first such examination of fissionable material production at an industrial scale for the Moon. As such, the architecture detailed in this paper may not be the most optimal for its purpose. It should be considered a small step in the great leap of powering a growing lunar economy.

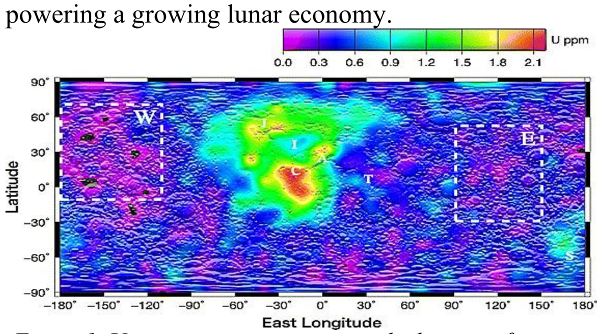

Figure 1. Uranium concentrations on the lunar surface, in pixels 9º by 9º and then curved by splines algorithms.[2]

The UKM system relies on several key background assumptions about lunar resources, environment, and infrastructure. Data from previous lunar missions have identified regions of KREEP-rich regolith that holds relatively high concentrations of uranium, particularly within the Procellarum KREEP Terrane, where U concentrations are estimated to be up to 3.5 μg/g[3] in the form of impurities in minerals such as xenotime and monazite[4], as seen in Figure 1. This has led to projections that local spot concentrations of uranium may reach 35 μg/g or higher[3]. These deposits make uranium extraction possible but require processing large volumes of regolith. With a concentration of 35 μg/g uranium in regolith, our study shows that to reach an annual production of <u>1 metric ton of UO_2, 76,000 metric tons of lunar regolith must be excavated and processed per year.</u> The physical properties of lunar regolith are also important, as most particles are smaller than 1 mm, which influences material handling and processing design. The concept further assumes that nuclear power will play a major role in supporting future lunar infrastructure, making locally produced uranium valuable as a source of reactor fuel. Finally, the system depends on supporting capabilities such as lunar launch delivery, surface operations, and communications infrastructure to enable the UKM to succeed.

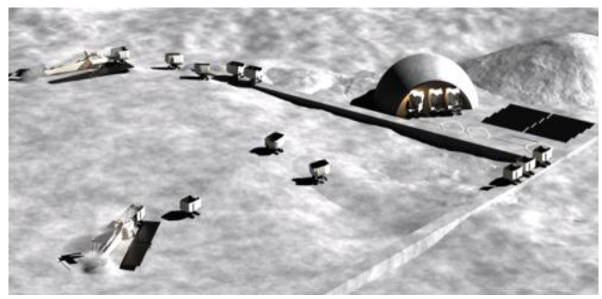

Figure 2. Representation of the deployed UKM system.

System Architecture:

The material process begins with the excavation system, where regolith is removed from the surface using a bucket chain excavator. The material is directly transferred to a transportation system made up of a fleet of transport rovers. These transport rovers capture the regolith in their cargo volume and return to the UKM operations hub, where they offload directly into the sieving subsystem. Once it has entered the sieving system, the regolith is moved through the system either by the action of specific beneficiation systems or by conveying subsystems. At the outlet of the sieving subsystem, the regolith is moved to the magnetic beneficiation subsystem. Here, regolith is separated into 3 categories based upon their magnetic properties: nonmagnetic material, KREEP-rich paramagnetic material, and ferrous material. After magnetic separation, the paramagnetic material is then fed into the refining subsystem. The refining subsystem consists of multi-step chemical processing that is required to convert uranium from its native mineral form in the KREEP regolith into refined UO_2 powder. The processes include: selective leaching of KREEP regolith in alkaline solution, precipitation of uranium concentrate from the leach solution, calcination of uranium concentrate, and hydrogen reduction to uranium dioxide as the final product. The refining subsystem also includes circularly regenerating the chemicals used as inputs to the process.

CONOPs:

Our concept of operations (CONOPs) is represented in Figure 3, which shows the flow of regolith throughout the UKM system and all types of assets within the system, resulting in UO2 powder as a product.

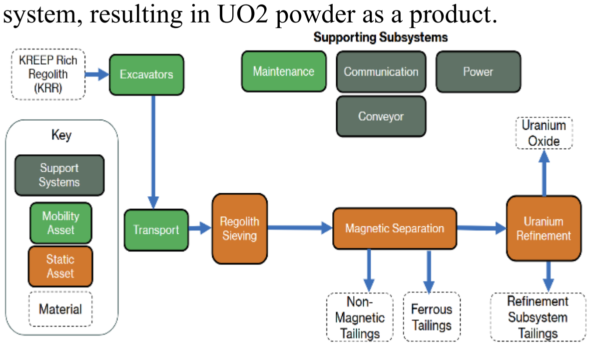

Figure 3. Graphic showing the UKM CONOPs and the full flow of regolith through the system to a finished product.

Possible Risks and Room for Improvement:

One of the greatest risks to the UKM system is that magnetic separation of lunar regolith may be less efficient than projected based on terrestrial analogs, seeing as literature surrounding magnetic separation of KREEP minerals from lunar regolith currently is scarce. This is a risk we seek to mitigate through physical testing planned over the spring months of 2026, which is shown in Figure 4. Our testbed will consist of a vibrating hopper shaking lunar regolith simulant with added monazite and xenotime (REE minerals) over a rotating pipe with permanent magnets embedded inside it. The trajectory of the simulant as it passes this magnet should separate it into two streams, one of ferrous and one of non-ferrous materials. This tests the efficiency and difficulty of magnetically separating minerals of interest out of lunar regolith simulant.

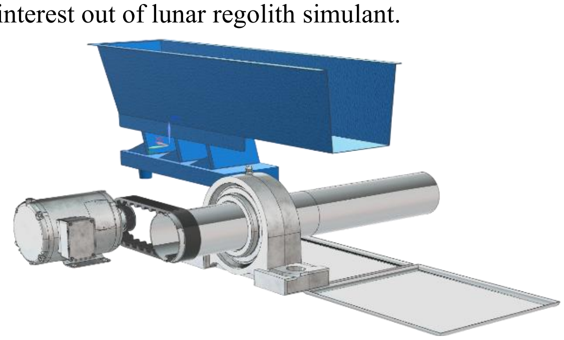

Figure 4. Illustration of our magnetic separation test showing the vibratory conveyor, motor, and rotating separator drum, as well as the particle collection trays.

Other risks faced by the UKM concept are varied. The refining process to convert raw KREEP into uranium is complex and requires significant engineering work to develop into a practical system, including testing under lunar gravity conditions. The operation of the transporters and the excavators needs to be investigated further, as well as sieving systems operating under lunar gravity and with lunar regolith. Another potential risk is that the layer of uranium-bearing minerals is surficial and thin, which will require more advanced ground-truthing to fully dismiss.

Conclusions:

While theoretically the UKM system could produce a total of 10 metric tons of UO_2 over a course of 10 years, the required regolith input for our system to produce the amount of final product could be less than what we have designed our system for. It may be that local concentrations of uranium are higher than currently shown from coarse orbital imaging, making our system produce more uranium from the same volume of regolith. The UKM system as conceived would be too massive to be cost-efficient compared to importing nuclear fuel from Earth for the foreseeable future due to launch costs. However, the UKM system could be a useful starting point for a future system if one or more of the following developments occur: the lunar economy becomes capable of providing components that otherwise would need to be imported from Earth, coextraction of uranium and other materials from KREEP becomes profitable, or significant regulatory barriers to launching nuclear fuel from Earth constrain imports. Each of these would enable the UKM system to be more profitable. Additionally, it might be that there are areas of uranium concentration much greater than the planned 35 μg/g which this system is designed to mine. If a discovery is made that shows concentrations much greater than 35 μg/g of uranium in the KREEP rich regolith areas, the volume of regolith processed may be greatly reduced. It is hoped that this project will begin a discussion on the potential of uranium extraction on the Moon, and lay the groundwork for further thought on lunar mineral processing.

References:

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