A POTENTIAL MODEL OF URANIUM EXTRACTION ON THE LUNAR SURFACE

J.P. Charles[1], M. F. Engel[1], C.T. Fortuin[1], J. Johnson[1], M.T. Nguyen[1], and S.J. Sprotte[1], evenly contributed. LunarUraniumMining@gmail.com
[1]Colorado School of Mines, Center for Space Resources, 1310 Maple St., GRL 234, Golden, CO, 80401.

Introduction:

This poster summarizes the KREEPy Crawlers SPRS592 project, the Uranium KREEP Mining (UKM) system. The team originally set out to study development of rare earth elements (REE) on the lunar surface for both return to earth and lunar consumption. After preliminary investigation, we decided to instead pursue development of uranium resources in KREEP with the expectation that the lunar economy would need nuclear fuel sooner than other REEs. The UKM was designed to produce 2 metric tons of fuel-grade uranium dioxide per year in the Procellarum KREEP Terrane. By engaging in this project, our group found the three main difficulties to creating this system were:

1. Extracting and beneficiating sufficient quantities of KREEP-rich regolith,
2. Refining a uranium-rich stock of regolith into uranium dioxide (UO_2) powder, and
3. Finding some way to pay for all this!

Here we'll lead you through our process, focusing on those three main elements, the lessons we learned while addressing them, and how those lessons can be applied to the nascent industries of lunar mining, beneficiation, refining, and production.

Location and Site Description:

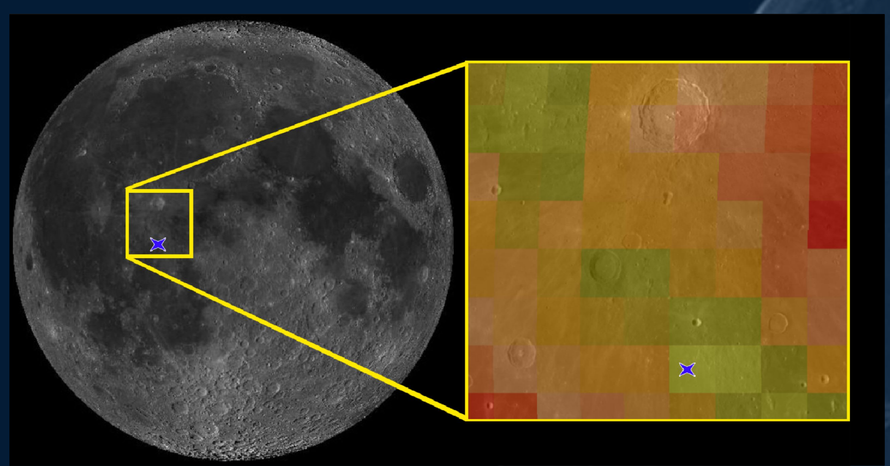


Figure 1. Rough location of our site on the lunar surface, inside of the Procellarum KREEP Terrane, south of Copernicus Crater, in the star on this thorium heat-map.

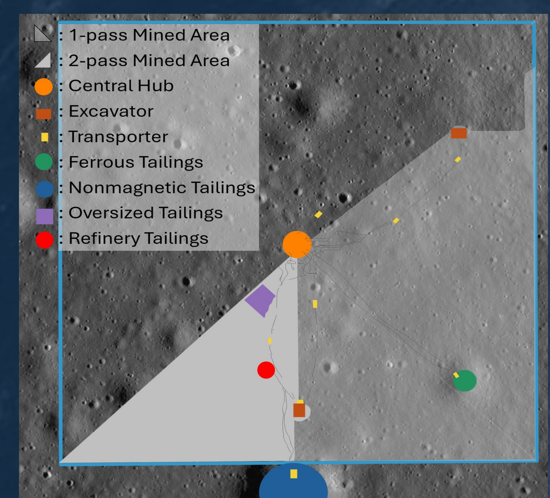


Figure 2. Hypothetical layout of UKM project site,~1 sq km.

CONOPs:

Here is a description of the chain of events that a mass of regolith goes through. This starts at the lunar surface, and ends with separate piles of tailings and a small amount of UO_2. Figure 3 below visualizes these steps for the UKM system.

1. Excavate regolith from surface and deposit into a Transporter.
2. Move regolith to Central Hub.
3. Transporters dump regolith into sieve.
4. Sieve removes coarse particles.
5. Use vibratory conveyors to move regolith to magnetic separator.
6. Remove ferromagnetic particles from regolith.
7. Remove non-magnetic particles from regolith.
8. Convey remaining paramagnetic regolith into the Refinery.
9. Chemically process paramagnetic regolith to get UO_2 and deposit all tailings into hoppers.
10. Deposit UO_2 into a container for transport to customer.

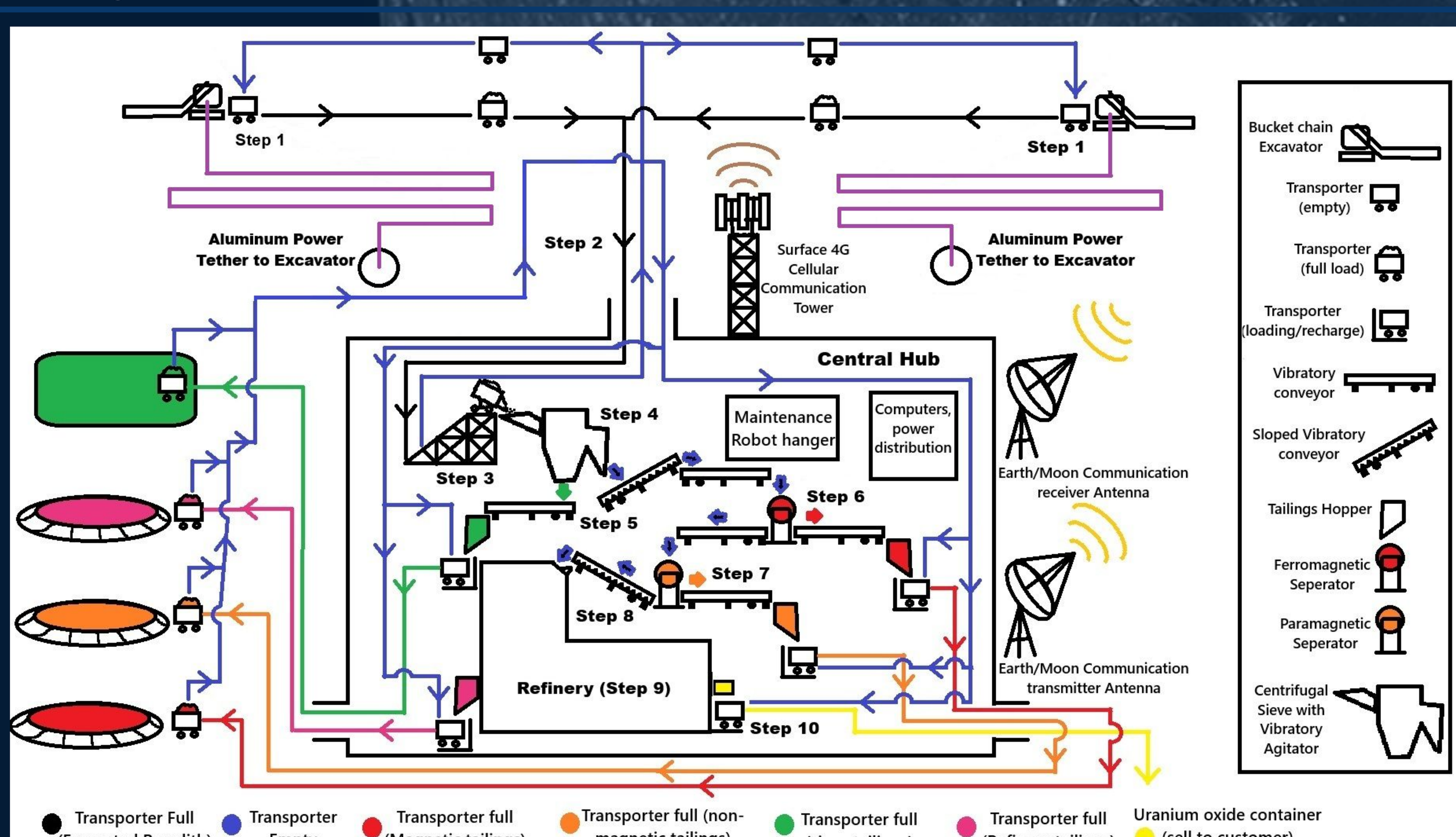


Figure 3. System CONOPs, color coded, detailing each step a mass of regolith takes through the UKM system as it progresses.

Excavator & Transporter

Excavators are the means of removing KREEP Rich Regolith (KRR) from the lunar surface. The excavation subsystem consists of two tethered bucket chain excavators. These are mobile subsystems capable of traversing and excavating regolith from the lunar surface.

The Transportation subsystem is made up of six vehicles that move the excavated lunar KRR, regolith tailings, and final products between the excavators, Central Hub, tailings sites, and receiving areas on the lunar surface. Each transporter will receive KRR from an excavator or regolith from a material hopper containing one of our tailings streams, and will be able to deposit that regolith either into the sieving subsystem or onto a tailings pile. Transporters have an internal battery for power and are charged at the Central Hub during down time or while dumping excavated regolith into the sieving subsystem.

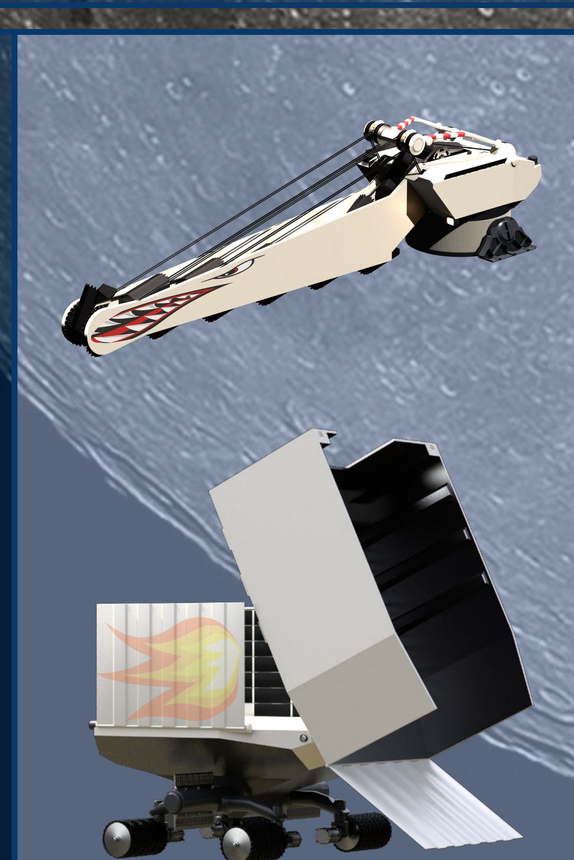
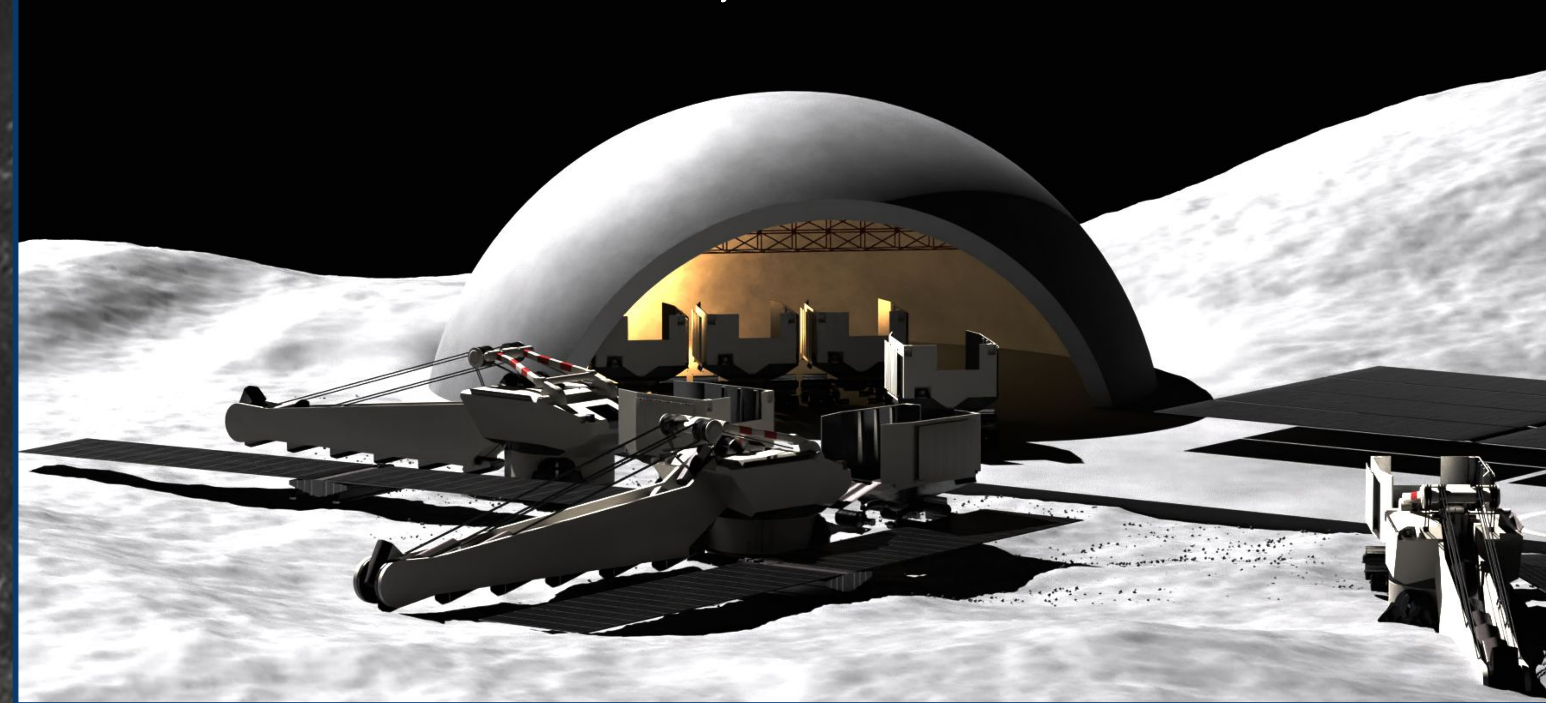


Figure 4. The excavator and transporter designs, as rendered by artist Marko Krcmar for the UKM system. Tether for the excavator not shown, image not to scale.

The Sky Is Not The Limit!



Magnetic Separation Description

The process of magnetic separation is used to separate different minerals from a fine, sandy stream of material based on magnetic strength. This would be valuable for the development of uranium resources on the lunar surface because of the fine size of regolith, and because of the relatively strong paramagnetic properties of the uranium-bearing minerals in KREEP, monazite and xenotime (Wang, 2024; Abaka-Wood, 2016). There exists heritage for magnetic separation of these minerals in terrestrial mining (Wang, 2024; Abaka-Wood, 2016; Kim and Jeong, 2019).

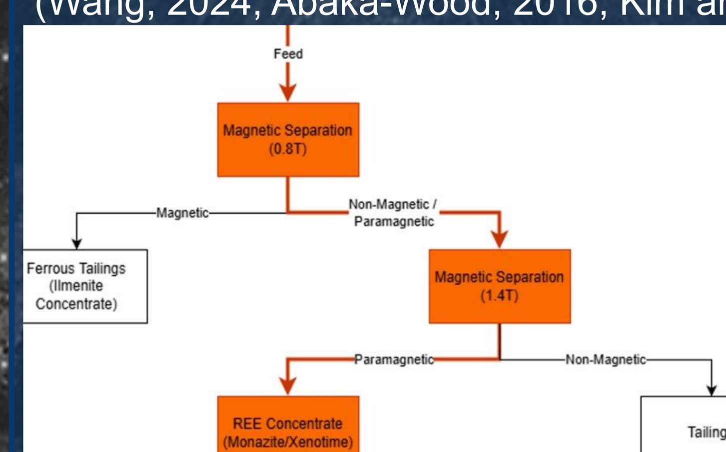


Figure 5. Magnetic Separation Block Diagram of our planned process.

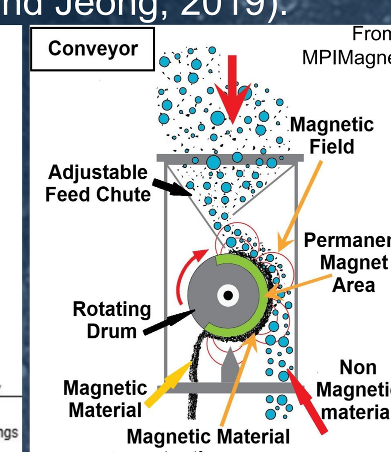


Figure 6. Earthly magsep system.

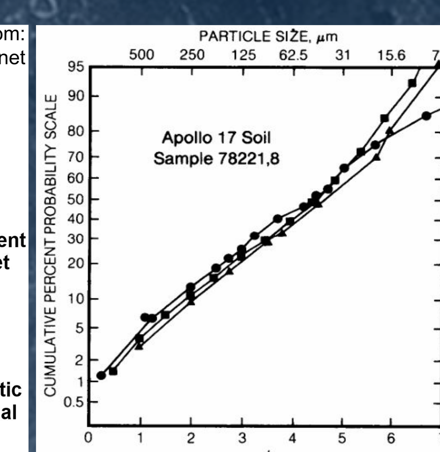


Figure 7. Regolith particle size (Vaniman,1991).

Refining Process

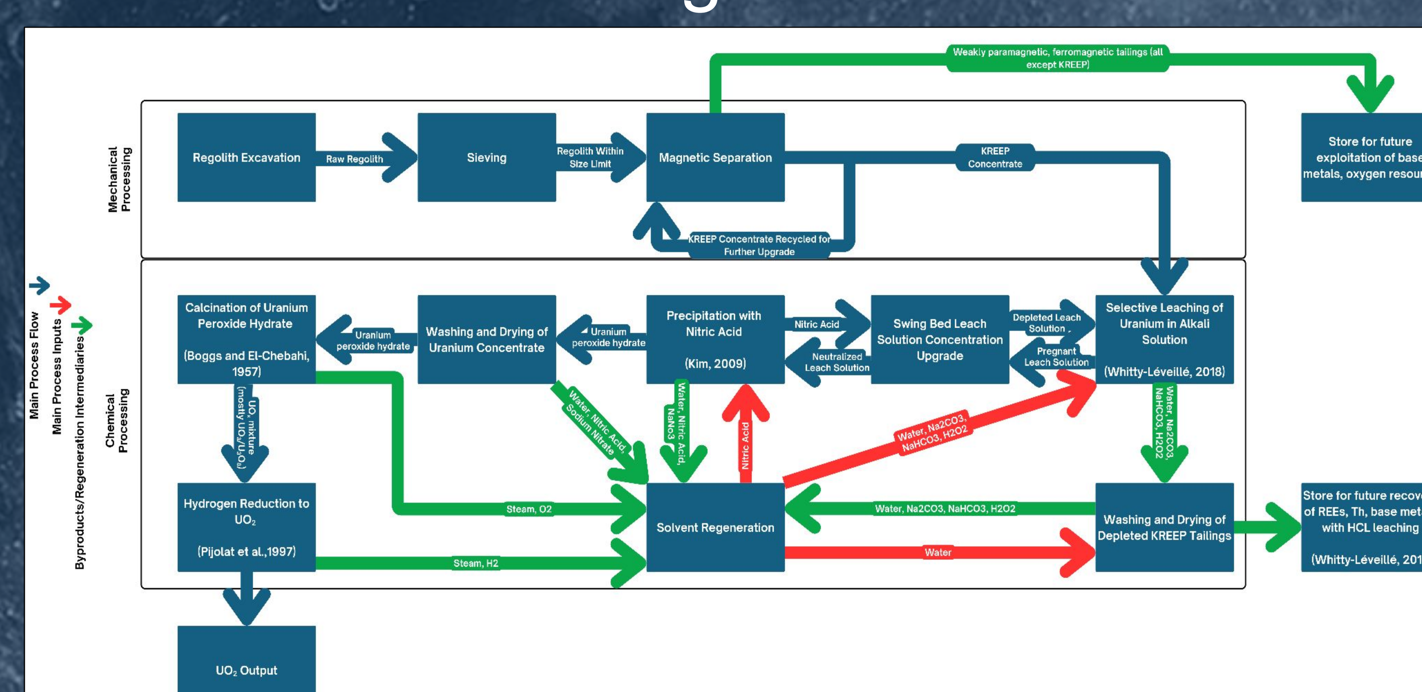


Figure 8. Refining Process Block Diagram, showing the flow of regolith and chemical agents through the refinery.

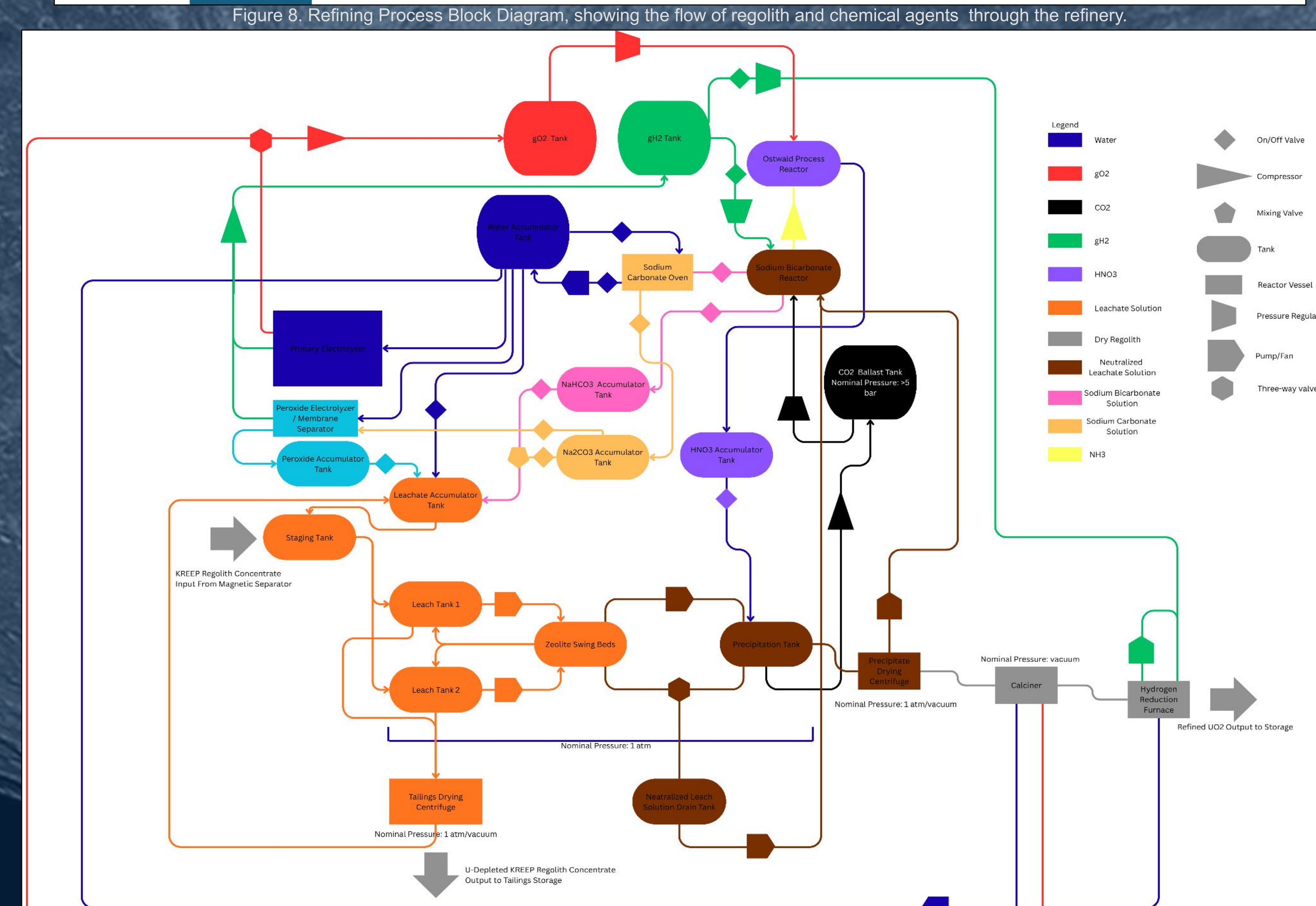


Figure 9. Refining System Fluid Schematic, showing how the chemical processes will extract uranium and reclaim the chemical inputs.

Magnetic Separation Testing

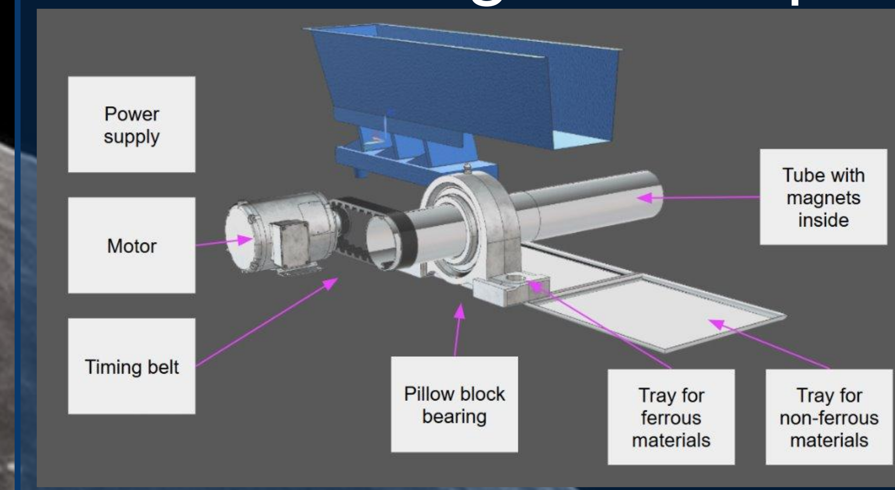


Figure 10. Magnetic Separation Concept Model, showing our general testbed layout for the DET.

Figure 11. Magnetic separation of magnetite particles in our testbed.

A design evaluation test was carried out to prove our magnetic separation system was viable for beneficiation of KREEP regolith, with the purpose of developing lunar uranium resources. Unfortunately, ESH concerns with monazite required the use of substitutes for our initial tests of the subsystem. JSC-1A was used with the addition of a known quantity of magnetite to test the effectiveness of the magnetic separation, and our results were better than expected.

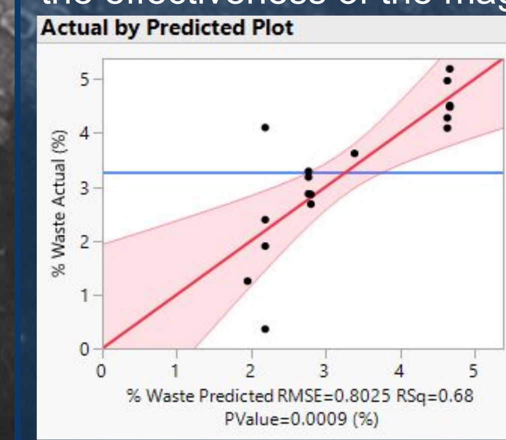


Figure 12. Test results, showing waste over different runs.

Figure 12, left, shows the waste across 18 of our 19 test runs. “Waste” in this case refers to material which entered but did not leave the system; material that stuck to magnetic pipes or that the vibrating conveyor couldn’t shake off. Our waste was <5% by mass, three times less than our paper assumed. When the JSC-1A was altered with more magnetite, we found greater masses of magnetic material were deposited than without magnetite, indicating the system was functioning as intended at separating ferromagnetic from nonmagnetic particles.

Financial Analysis

Initially we believed that the UKM system would be economically impractical. The cumulative mass of our system, 116 metric tons, meant that even if bulk price-per-kg to the surface drops to $130,000, launches would cost $15 billion before any other costs. We then found that an assumed price of $50,000 per kg of UO_2 would generate $100 million per year. However, adding in ~$50 per kg for tailings that pass through our magnetic separation system would generate $5.25 billion of additional revenue a year. The finances only work if we sell tailings.

Year	Engineering Team Salary (25 crew, 10% raises)	Ground Control (facilities rental)	Controller Salaries (32 crew, 10% raises)	Power ($60/kWh, 5%/yr increase)	Lump Payments (Launch, Build, etc)	Total
1	2,500,000	0	0	0	150,000,000	152,500,000
2	2,750,000	0	0	0	50,000,000	52,750,000
3	3,025,000	2,500,000	0	750,000,000	17,245,510,000	18,001,035,000
4	3,327,500	5,000,000	3,200,000	1,435,968,000	0	1,447,495,500
5	3,660,250	5,200,000	3,520,000	1,464,687,360	0	1,477,067,610
6	4,026,275	5,408,000	3,872,000	1,537,921,728	0	1,551,228,003
7	4,428,903	5,624,320	4,259,200	1,614,817,814	1,050,000,000	2,679,130,237
8	4,871,793	5,849,293	4,685,120	1,695,558,705	0	1,710,964,911
9	5,358,972	6,083,265	5,153,632	1,780,336,640	0	1,796,932,509
10	5,894,869	6,326,595	5,668,995	1,869,353,472	0	1,887,243,932
11	6,484,356	6,579,659	6,235,895	1,962,821,146	0	1,982,121,056
12	7,132,792	6,842,845	6,859,484	2,060,962,203	0	2,081,797,325
13	7,846,071	7,116,559	7,545,433	2,164,010,313	0	2,186,518,376
13.5	8,630,678	7,401,221	8,299,976	2,272,210,829	0	1,148,271,352
Total	**64,687,458**	**69,931,757**	**59,299,735**	**20,608,648,212**	**18,295,510,000**	**38,155,055,810**

Table 1. Estimated costs of the UKM system, year by year.

Year	Cost (USD)	Revenue (USD)	Annual Net (USD)
1	152,500,000	0	(152,500,000)
2	52,750,000	0	(52,750,000)
3	18,001,035,000	0	(18,001,035,000)
4	1,447,495,500	5,350,000,000	3,902,504,500
5	1,477,067,610	5,350,000,000	3,872,932,390
6	1,551,228,003	5,350,000,000	3,798,771,997
7	2,679,130,237	5,350,000,000	2,670,869,763
8	1,710,964,911	5,350,000,000	3,639,035,089
9	1,796,932,509	5,350,000,000	3,553,067,491
10	1,887,243,932	5,350,000,000	3,462,756,068
11	1,982,121,056	5,350,000,000	3,367,878,944
12	2,081,797,325	5,350,000,000	3,268,202,675
13	2,186,518,376	5,350,000,000	3,163,481,624
14	1,148,271,352	0	(1,148,271,352)
Totals:	38,155,055,810	53,500,000,000	15,344,944,190
		Net Present Value:	**Internal Rate of Return:**
		$15,344,944,190	***14%***

Table 2. Costs, revenue, and estimated IRR of the UKM system.

Conclusion:

The scope of the UKM system can’t be fully represented on this poster. What is shown provides a general overview of the entire system and some of the accomplishments, difficulties, and surprises encountered during its development.

The refining system and its regenerative chemical reclamation processes are, to the authors’ knowledge, the first attempt at defining an ISRU system theoretically capable of producing uranium nuclear fuel on the Moon. There remain significant obstacles before such a system could exist, including; production of leak-tight mechanisms with sufficient service life for loading regolith into leach tanks, cost-effectively securing sufficient quantities of water at lunar mid-latitudes, and demonstrating the circularity of the proposed regeneration processes.

The physical test stand we built for the magnetic separation test proved more difficult to assemble than we had ever envisioned, but once assembled it proved more efficient than our assumed figure of 15% loss. If similar success can be replicated with a full scale system using KRR, the viability of the UKM system for UO_2 production could be significantly improved.

The financial analysis and its implications are the most surprising result of the UKM project. The envisioned product of the system, UO_2 fuel, generates a fraction of the revenue of selling the much more plentiful tailings of the UKM system. The magnetic separation makes three unique streams of regolith concentrated in minerals of interest that would have uses for other industries on the Moon. Since a principle cost is launching the hardware needed for excavating and separating the regolith, this implies that one of the best models for early lunar prospectors may be to focus on excavation and separation rather than a specific targeted product. We can make more money from companies unwilling to pay the upfront launch costs!

The key takeaway from this project is that fully capturing the value of each constituent of the regolith is critical to the viability of lunar mining. Mineral extraction projects like the UKM system may become more viable if we view them as an ecosystem of cooperating and specialized extraction processes, centered on one major mining and separating operation.

References

- Abaka-Wood, G. B., addai-Mensah, J., & Skinner, W. (2016). Magnetic separation of monazite from mixed minerals. CHEMECA 2016. https://www.researchgate.net/publication/311440437_Magnetic_separation_of_monazite_from_mixed_minerals
- Boggs, J. E., & El-Chehabi, M. (1957). The thermal decomposition of uranium peroxide, uo4.2h2O. Journal of the American Chemical Society, 79(16), 4258–4260. https://doi.org/10.1021/ja01573a003
- Kim, K., and Jeong S. Separation of Monazite from Placer Deposit by Magnetic Separation. (2019). https://www.mdpi.com/2075-163X/9/3/149
- Kim, K.-W., Kim, Y.-H., Lee, S.-Y., Lee, J.-W., Joe, K.-S., Lee, E.-H., Kim, J.-S., Song, K., & Song, K.-C. (2009). Precipitation characteristics of uranyl ions at different PHS depending on the presence of carbonate ions and hydrogen peroxide. Environmental Science & Technology, 43(7), 2355–2361. https://doi.org/10.1021/es802951b
- Krcmar, Marko (2025, 2026), commissioned artist for the UKM system. https://www.artstation.com/krklord
- Pijolat, M., Brun, C., Valdivieso, F., & Soustelle, M. (1997). Reduction of uranium oxide U3O8 to UO2 by hydrogen. Solid State Ionics, 101–103, 931–935.
- Vaniman, D., Reedy, R., Heiken, G., Olhoeft, G., & Mendell, W. (1991). THE LUNAR ENVIRONMENT. https://www.lpi.usra.edu/publications/books/lunar_sourcebook/pdf/Chapter03.pdf . (7)
- Wang, W., Li, E., Li, Z., Zhu, W., & Wang, Y. (2024). Recovery of Xenotime and Florencite from Silicate Minerals Using a Combined Technique of Magnetic Separation and Flotation. Minerals, 14(11), 1073. https://doi.org/10.3390/min14111073
- Whitty-Léveillé, L., Reynier, N., & Larivière, D. (2018). Rapid and selective leaching of actinides and rare earth elements from rare earth-bearing minerals and ores. Hydrometallurgy, 177, 187–196. https://doi.org/10.1016/j.hydromet.2018.03.015

Access to the Paper:

Acknowledgments: Thanks to Dr. Dreyer and Dr. Sowers for constantly giving us valuable advice to push the project forward. Thanks to the Lunargy team for their input regarding lunar power costs, and Gerrit Bruhaug for insight on nuclear materials.