Forging the Regolith Age: Scalable Mechanical and Chemical Asteroid Simulants for ISRU Innovation.

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Introduction: Karman+ seeks to bring In-Situ Resource Utilization (ISRU) to reality, not tomorrow but today. With our High Frontier mission launching in February 2027 we will be laying the foundation for commercial mining operations in space by traveling to a near-Earth asteroid (NEA) and demonstrating the extraction of regolith in quantities thousands of times higher than ever done before. Meanwhile, there is work to be done to ensure that this material's utility can be maximized.

If the new space economy is to thrive in earnest we must push the envelope of what is possible with the materials we will have readily available in space. To do this we must first evaluate all possible products that can be made with things like regolith, sunlight, and minimal additional reagents and then identify technologies on the critical path for these products and thus enable their use in space.

Accessing massive quantities of regolith on Earth in the near term is unlikely, so Karman+ has worked with Dr. David Karl and TU Berlin to formulate extremely high fidelity regolith simulant based real asteroid samples (E.G. Ryugu). This regolith simulant is designed and manufactured to have realistic chemical and mechanical properties, enabling the development of ISRU technologies immediately here on Earth

This discussion is intended to serve as an invitation and challenge to join us on this journey. Karman+ seeks to collaborate with other groups that share our dream to embrace the Dawn of the Regolith Age and bring ISRU to reality through action not conjecture.

Asteroid-Simulant: As previously mentioned, to enable the development of critical ISRU technologies it is vital for Karman+ to have access to ample supplies of chemically and mechanically accurate carbonaceous asteroid simulants. To address this challenge Karman+ has been working with Prof. David Karl from TU Berlin to develop the possibly highest fidelity asteroid simulant ever by using information obtained from recently returned samples from actual asteroids like Ryugu. With the simulant manufacturing process in hand we developed the supply chain and processes to make extremely high quality simulants in very large quantities.

The simulant manufacturing process consists of agglomerating research grade minerals and chemicals in proportions that have been identified to be representative of what is found in returned regolith samples. The process is as follows; first our proprietary ingredients are mixed with water and placed under vacuum. The mixture is then exposed to extreme cold, analogous to what is experienced in the space environment. This process dries the material and creates realistic geotechnical properties like porosity and cohesive strength. The resulting material is then fractured into smaller pieces through thermal and mechanical shock to create realistic particle sizes and distributions. Finally, the simulant is packaged and stored in vacuum bags to ensure it remains intact until it is ready to be used.

Karman+ has the capability to make a variety of versions of simulants depending on the customer's needs. Such examples include, an ultra high fidelity simulant that has improved chemical accuracy, a low cost purely mechanical simulant, and the general purpose mechanical and chemical simulant. As well, the grain size can be adjusted as needed, ranging from small boulders to ultrafine powders. By investing in our manufacturing capabilities and diligent work with suppliers we are also able to provide simulants in quantities of several tons. This process is conducted in our environmentally controlled research laboratory. Where safety, storage, and contamination concerns are mitigated.

As a company that will be mining regolith, we are committed to continuously improving our simulant to be as accurate as possible as it is integral to our mission. This will be accomplished by incorporating information obtained from our missions and others to NEAs, and from the improved understanding of regolith composition of the greater scientific community.

Karman+ will consider licensing or even open sourcing our detailed manufacturing processes and recipe if interest is sufficiently high and we encourage ideas.

Water Extraction: At the forefront of the Karman+ Phase 1 business model is the extraction of water from regolith and its conversion into useful propellant. Demonstrating this process is the first goal post we must pass to legitimize ISRU. To do this we have partnered with Johns Hopkins University and begun the development of regolith processing, volatile capture, and propellant generation systems for demonstration in our second and third missions. The missions will consist of servicing GEO satellites by providing additional Delta-V generated by water extracted from mined regolith.

Despite this being an ambitious milestone, water extraction from asteroid regolith is only one of many uses for regolith. To truly initiate the regolith age we must push ourselves to do more.

Using the Whole Buffalo: The phrase "using the whole buffalo" originates from Indigenous peoples of North America, particularly the Plains tribes like the Lakota, Blackfoot, and Cheyenne, who relied heavily on the American bison (often called buffalo) for survival.

When they hunted a buffalo, they used every part of the animal—not just the meat. The hide became clothing and shelter, bones were used for tools and weapons, tendons became thread, and organs had various uses from food to containers or ceremonial purposes. Nothing was wasted.

Here we apply this concept to the regolith Karman+ aims to mine. While we could just take the water and leave it, the "dry" regolith still has value. We can continue to use it and refine it into other useful products through processes like sabatier methanation, Fischer–Tropsch synthesis, and synthetic biology. These form the foundation for converting mineral-derived inputs into usable fuels, materials, and life support commodities [1, 2, 3, 4]. Finally, even as loose dirt, this regolith provides invaluable benefits. It can provide micrometeorite shielding, thermal mass, radiation shielding, and rotational inertia for artificial gravity on space stations. Continuing to unlock and enable new technologies such as off the shelf autonomous robots to be used in space safely and reliably.

Call to Action: This initiative represents just the beginning. By employing our high-fidelity asteroid simulant, we envision enabling numerous opportunities for groundbreaking materials research and fostering global collaborations with diverse research teams.

We invite chemists, geologists, materials scientists, mechanical engineers, and space resource enthusiasts to consider potential research projects or innovative applications using our carbonaceous-like asteroid simulant. Karman+ actively supports open-source research projects leveraging our simulant and seeks direct partnerships similar to our collaborations with institutions like the Colorado School of Mines, TU Berlin, the University of Tokyo, Lulea Technical University, and Johns Hopkins University. For further collaboration opportunities and information, we will create and maintain a dedicated online community at www.karmanplus.com.

Conclusion: Karman+ is developing an extensive operation for the development and distribution of asteroid simulant that not only drives our own research and development, but seeks collaboration with others. We plan to execute on this by enabling other organizations to do their own research and development of ISRU technologies through the use of our simulants and active collaboration on improving our understanding of what materials exist on the surface of near earth asteroids and how we can leverage their use. Only together can we enter the Regolith Age.

References:

[1] Montague, M. G., et al. (2012). *The role of synthetic biology for in situ resource utilization (ISRU)*. Astrobiology, 12(12), 1135–1142.

[2] Götz, K., et al. (2023). *Power-to-plastics: Techno-economic assessment of olefin synthesis from CO_2 and renewable energy*. SSRN.

[2] Ducat, D. C., et al. (2012). *Engineering cyanobacteria to generate high-value products*. PNAS, 109(8), 2678–2683.

[3] Tanaka, T., et al. (2020). *Autotrophic production of polyhydroxybutyrate from CO_2 by Cupriavidus necator*. Metabolic Engineering, 61, 69–76.

[5] NASA. (2013). *Regenerative CO_2 Reduction by Sabatier Reaction for ISS*. NASA Technical Reports.

[6] Lasseur, C., et al. (2021). *Sabatier and OGS systems on ISS and perspectives for Mars*. Life Sciences in Space Research, 30, 84–91.

[7] Dry, M. E. (2002). *The Fischer–Tropsch process: 1950–2000*. Catalysis Today, 71(3-4), 227–241.

[8] van der Laan, G. P., & Beenackers, A. A. C. M. (1999). *Fischer–Tropsch synthesis: Kinetics and water–gas shift reaction*. Catalysis Reviews, 41(3–4), 255–318.