High Frontier: Roadmap to the Regolith Age. D. Crull[1], L. A. Bowersox[1] and S. M. Hallam[1], [1]Karman+ (11365 Main St. Broomfield, CO 80020; d.crull@karmanplus.com).

Introduction: The exploration and cultivation of asteroid resources mark the beginning of a transformative era in materials science, which we call the "Regolith Age." Karman+ is pioneering full-scale asteroid mining operations with regolith capture and processing as a featured aspect of our strategic roadmap. Our multi-mission plan begins with High Frontier, an inaugural mission scheduled for launch in February 2027, targeting a near-Earth asteroid (NEA) to demonstrate kilogram-scale regolith excavation. Subsequent missions include the deployment of a GEO-based satellite servicing "space tug" to extend satellite operational lifetimes, and ultimately, an asteroid-sampling mission aimed at extracting water from regolith to refuel the space tug in orbit. Additionally, we outline a research initiative focused on developing techniques for extracting and processing asteroid-derived water into usable propellants. Central to this initiative is our manufacturing and distribution of high-fidelity asteroid simulant. We invite collaboration from the scientific community to establish an ecosystem of research and innovation using this simulant for additional use cases, thereby advancing the frontier of space-based materials science.

Asteroid ISRU in three missions:

High Frontier. The inaugural High Frontier mission [1], set for launch in February 2027, will demonstrate kilogram-scale regolith collection from near-Earth asteroids (NEAs) using a Touch-And-Go (TAG) method. The spacecraft is designed in-house, featuring an integrated, cost-effective architecture with a dry mass under 300 kg, powered by Solar Electric Propulsion (SEP). Advanced autonomous navigation methods validated by previous NASA missions—such as Deep Space 1 [2], Deep Impact [3], and Stardust [4]—will be utilized, employing optical triangulation with beacon asteroids to achieve precise rendezvous and material capture from selected targets and a novel surface excavation mechanism deployed to capture a kilogram scale sample [1].

GEO servicing mission. Prospective customers require a reliable "space tug" capable of relocating and extending the operational life of aging GEO satellites. Each servicing contract will generate annual revenue during a three- to four-year mission span. We aim to launch our initial space tug, based on the High Frontier spacecraft design, by late 2027. These tugs will incorporate in-space refueling capabilities, utilizing water extracted from asteroid regolith to extend the life of the space tug.

Asteroid regolith ISRU. The third mission will involve returning asteroid material, processing it into water, and using it to refuel our space tug—positioning Karman+ as its own first customer and demonstrating a sustainable approach to GEO satellite servicing without reliance on costly future launches. Future GEO-servicing missions will leverage these regolith-derived resources to significantly reduce operational expenses and prolong satellite service life.

This spacecraft and mission architecture is intentionally modular and scalable. Current studies

indicate hundreds of hydrated asteroids are mission-accessible [5]. Our analysis of thousands of NEAs identified nearly 50 potential rubble-pile carbonaceous asteroids accessible by a 300-kg SEP-powered spacecraft. New telescopes promise a ten- to hundred-fold increase in identifiable asteroids matching our mission profile over the coming decade [6]. Our design constraints emphasize targeting NEAs reachable within months of interplanetary travel and allow flexibility in accommodating various launch windows. Although 2022 DC_5 is a leading candidate [7,8], the final target can be selected post-launch. By engineering a powerful yet compact spacecraft suitable for standard rideshare missions, this design can be generalized across numerous hydrated NEAs, offering extensive opportunities for rapid TAG missions. Critically, developing this spacecraft internally and reusing the base design across multiple missions will keep mission costs below $10 million each, enabling the delivery of asteroid regolith in-orbit at under $10,000 per kilogram.

Asteroid-based propellent:

Karman+ is exploring methods of extracting and processing asteroid-derived water into viable propellants. In summary, process would involves:

1. Excavation and Pre-Processing: Regolith is excavated from the asteroid's surface and then pulverized, employing techniques currently under development in collaboration with Johns Hopkins University.
2. Water Extraction: Hydrated minerals and volatile compounds within the regolith are heated under vacuum conditions using resistive or solar-thermal systems, releasing water vapor. This vapor is then condensed and captured for further use.
3. Storage and transport: The extracted water is securely stored in insulated and passivated tanks equipped with active thermal management systems.

4. Delivery Interface: Propellant delivery systems designed specifically for our GEO-servicing space tug would transfer the propellant in orbit.

Additionally, Karman+ is exploring advanced pathways to synthesize hydrogen peroxide (H_2O_2) using a solar-powered chemical processing pipeline specifically designed for microgravity environments. Building upon the water extraction methods stated earlier, this pipeline includes electrolysis to produce oxygen, followed by electrochemical hydrogen peroxide synthesis. Potential methods under investigation include proton exchange membrane (PEM) reactors [9,10] or carbon-catalyst electrochemical cells [11,12]. Subsequent processes involve distillation and concentration techniques to produce hydrogen peroxide suitable for use as a monopropellant.

Asteroid simulant:
Karman+ has been developing the highest fidelity asteroid simulant ever, based on recently returned samples from actual asteroids like Ryugu [13]. With the manufacturing process in hand we then developed the supply chain and processes to make simulant in very large quantities. This approach will be covered in more detail in a dedicated presentation on the subject.

Material science in the regolith age:
Leveraging our advanced asteroid simulant production capabilities, Karman+ aims to initiate extensive research initiatives focusing on innovative space-based manufacturing techniques. These efforts include exploring the direct fabrication of ceramics from regolith, a critical step toward establishing robust orbital infrastructure such as radiation shielding and sustainable space habitats.

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

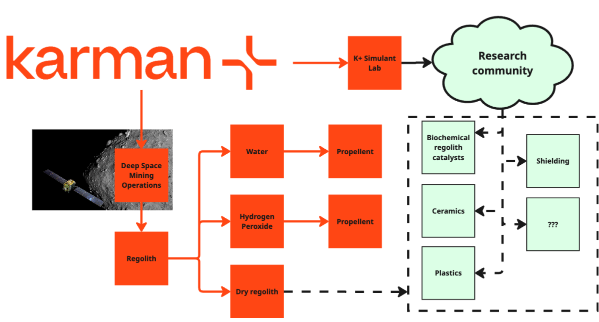

Figure 1. Regolith Age Materials Science Pipeline: Karman+ core technology (orange) includes: mining operations, propellent extraction pipeline to support GEO servicing missions (and beyond) and Regolith Simulant Lab; partnership with research community (green) includes materials science and product research driving the full array of ISRU products (dotted rectangle) to power the space economy.

Call to action. Karman+ is developing full-scale asteroid mining operations that will return asteroid regolith to customers in space within the next few years. Furthermore, as we are developing our own high-fidelity simulant to drive innovations in regolith science and we invite researchers in materials science, chemistry, planetary geology, and aerospace engineering to consider research pathways that can leverage this simulant and ultimately derive product use cases and processing methods for asteroid regolith use in space.

Conclusion
Karman+ has a core business to develop scalable asteroid mining spacecraft and mission operations, beginning with an asteroid sample mission that is booked for launch in February 2027. Additionally, by establishing comprehensive scientific pipelines, performing rigorous material characterization, and pioneering innovative space-centric industrial processes, Karman+ is uniquely positioned to spearhead humanity's transition into a sustainable and economically viable future of extraterrestrial resource utilization. Our efforts promise to accelerate the growth of the orbital economy and fundamentally reshape the landscape of space-based materials science.

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