Starforge: A viable, near-term path to asteroid mining

R. Westerdahl[1], [1]Turion Space (rwesterdahl@turionspace.com) P. Sullivan[2], [2]Turion Space (psullivan@turionspace.com)

Introduction: The world relies on fragile, geographically concentrated supply for platinum-group metals (PGMs) and other critical minerals used across catalysts, semiconductors, precision weapons, sensors, and advanced hardware. For the first time in history, the necessary technical means and an expanding space ecosystem enable the profitable extraction of precious metals from near-earth asteroids at scale. The technology continues to advance rapidly, but even with current propulsion and ISAM capabilities, frequent commercial launches allow us to begin this journey today. The Starforge program will turn metals abundance into industrial capacity in space while strengthening supply-chain security on Earth.

LL Chondrites: While metallic M-class asteroids have long been proposed as the natural focus of early space mining efforts, planetary geologists have noted that LL chondrites may actually present a more tractable and scalable pathway for extracting platinum group metals and gold. Several interlocking factors make LL-type bodies particularly advantageous.

Coarsely comminuted nature. LL chondrites are already "pre-crushed" by their history of shock, brecciation, and impact processing. Unlike M-class metallic bodies, which are dense monolithic iron-nickel structures requiring massive energy to cut, drill, or melt, LL chondrites exist as fragmented aggregates. This natural comminution reduces both the energy input and equipment complexity required to liberate metal-bearing phases.

Consistent and reliable PGM content. Studies of LL5 and LL6 subtypes show a repeatable abundance of precious metals in accessible sulfide and alloy phases. [1] While the grade is not as high as in some M-class samples, the *consistency* is far greater—M-class compositions remain uncertain, ranging from PGM-poor nickel-iron cores to enriched fragments. H chondrites contain the *highest* fraction of Fe-Ni metal (~19% by mass) [2], but that metal is relatively *poor* in precious metals (only ~28 ppm). By contrast, LL chondrites have much less metal overall (~1–5%), but that small fraction is *very enriched*, often carrying 50–220 ppm precious metals [3]. This makes LLs far more "ore-like," and reliable feedstock chemistry is more valuable than speculative jackpot grades.

Embedded volatiles for in-situ processing. LL chondrites typically contain a few percent water bound in hydrated minerals. This modest but sufficient volatile content is a major enabler: water can be liberated, liquefied, and looped into refining processes as solvent, coolant, or reaction medium. In contrast, M-class bodies are bone-dry, requiring costly water imports to operate hydrometallurgical flowsheets.

Abundance and accessibility..LL chondrite-like S-complex asteroids make up a large fraction of the near-Earth asteroid (NEA) population [4]. This translates directly into a broad portfolio of candidate targets in energetically favorable orbits, lowering delta-v costs and diversifying operational risk. H and L chondrites are more common but don't provide the same precious metals grades per unit mass processed. M-class bodies are far rarer and tend to cluster in the main belt, requiring much longer transfer times.

Mission Objectives: The primary mission objective is to build and deploy Starforge-1 to an asteroid in the next decade to generate >$500M/year, accounting for deflationary price effects due to the sudden rise in supply.

The major cost drivers are Starforge vehicle size (determined by target refining rate) and the amount of propellant to take it from earth orbit to the target asteroid location.

System Architecture: The overall architecture consists of multiple mission phases, operational or staging zones, vehicle types, and process loops. The mission phases include construction and maneuver, initialization, and steady state. The operational zones include Depot in LEO, the Shipyard construction and logistics staging zone, and the asteroid operations zone. The vehicles include Starforge, Shipyard, Depot, Fast Transport, and support vehicles (Droids) built upon existing Turion vehicles.

Initialization and manneuver. Starforge-1 construction will take place at Shipyard in a GEO+1000km orbit at an inclination of 23.4°. This is to align the staging zone with the plane of ecliptic (instead of equatorially) to be optimally positioned for the largest fraction of NEAs from a delta-V minimization perspective.

The Starforge-1 torus will be assembled from multiple 'section' elements that are effectively Titanium alloy sheet metal plates folded together and launched in a stacked configuration. Pre-launched Transporter Droids will dock with these stacked sheet metal sections for transport from LEO to Shipyard, where Fabricator Droids will unfold the sections and weld them together to form the shell.

Following Starforge shell assembly, individual refining and subsystem equipment will be launched to LEO and similarly transported to Shipyard orbit and then secured onto Starforge-1 and enclosed with a final round of titanium sections.

While Starforge-1 is being assembled, Shipyard and Depot will be constructed in parallel. Shipyard will be built using the same section-based construction methodology and designed to expand in scale for up to five simultaneous Starforge v2 builds. Beyond material staging, Shipyard centralizes the heavy infrastructure needed for propellant production and storage. Depot will be a single structure with large krypton tanks, body-mounted solar arrays, two TIE thrusters for station keeping, and a docking mechanism for transferring Krypton from its primary tank to the Transporter Droid vehicles.

Finally, the water onboard Shipyard will undergo electrolysis to form the H2 and O2 cryopropellant that will then be transferred to Starforge-1 for its maneuver to the target asteroid by each docked Fast Transport Vehicle firing their engines simultaneously whilst using differential throttle control to ensure adequate control authority during the maneuver phase.

Upon arrival at the target asteroid, a rotation rate of ~4.5°/s will be induced to provide Earth-like gravity in the outer ring sections.

Initialization. Before Starforge-1 can begin mineral processing, sufficient water inventory must be built. For ISRU water production on LL-chondrites (assuming a range of 1–2% bound water in hydrated silicates like phyllosilicates [2][3]), microwave dielectric heating is a feasible method to liberate water. Microwaves penetrate the regolith, directly heating hydrated minerals volumetrically, which releases water vapor that is then condensed to liquid. At a sustained rate of ~9 t/h, steady-state processing can be initiated within 3–4 months.

Steady-state. During steady state operations, four process loops will be taking place outside of the refining processes within the Starforge torus. The Collector loop will consist of Collector Droids scooping regolith from the asteroid and taking it to Starforge. The Starforge <> Shipyard process loop will consist of transporting refined precious metals and extracted water from Starforge to Shipyard and then returning to Starforge. The Shipyard <> Depot loop will consist of Transporter Droids taking refined ore from Shipyard, transporting it to LEO for handoff to an empty upper stage of a fully reusable launch vehicle, and transporting future Starforge construction material from LEO to Shipyard (and refueling at Depot when needed). Finally, the Ground loop is simply the transport of new Starforge construction material from Ground to LEO and refined ore payloads from LEO to Ground for final processing.

Refining Process: The refining process within Starforge will consist of the primary refining line, a water generation process, a slurry recycling process, and an oxygen and hydrogen generation process.

Comminution. Because the torus will provide 1 G equivalent, modified commercially available comminution and separation equipment capable of the desired material flow rates will be utilized.

Leaching and distillation. A key objective of the refining cycle is to eliminate the need for consumables to minimize any additional required resources from Earth once processing begins. This is feasible with the resources available on LL-Chondrite asteroids using a closed-loop, hybrid microbial/chemical process employing robust recycling measures.

In the first leaching stage, the bacteria oxidizes FeS to generate sulfuric acid in-situ, replacing the need for aqua regia or cyanide. The same acidic environment promotes dissolution of halide-bearing phases, transferring halides into the circulating aqueous phase as chloride.

From there, an evaporation/distillation subsystem simultaneously concentrates the sulphuric acid, captures halides, and recovers 99% of water for recycling to the leach tanks.

The concentrated H_2SO_4 is routed to a heated polish leach stage, while the HCl is electrochemically regenerated and then used as a final oxidizing halide leach before the output is dried and shipped back to Earth.

O2/H2 Generation. A subset of water that is generated and/or recycled will be tapped off to an independent O2 and H2 electrolysis process. Some O2 would be utilized in the bioleaching tanks, whilst the rest would be liquified and stored for use as propellant on the Fast Transporter vehicles that are transporting refined ore (or water) back to the shipyard

Conclusion: While ambitious, our research and current engineering efforts show the above is possible within the next decade. We believe mining asteroids will be the economic forcing function for humanity to expand into the solar system, and we envision multiple Starforge refineries, each producing materials that profitably enable robust supply chains while reducing humanity's impact on Earth.

References:

[1] Gilmour, et al. (2020) *Meteoritics & Planetary Science, 55, Nr 3.* 679-702

[2] Dunn (2010) *Meteoritics & Planetary Science, 45, Nr 1.* 123-134

[3] Kargel (1994) *Journal of Geophysical Research Vol. 99, No. E10* 21,219-21,141

[4] Vernazza (2008) *Nature, 454,* 858-860