In-situ Resource Utilization (ISRU) of Asteroid Materials – Concepts and Challenges

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Introduction. The utilization of material resources in space is has persistently gained interest in the last 10 years [1,2] spurred by the return to the Moon with NASA's Artemis program and the agency's Moon to Mars Architecture [3]. ESA's has established priorities and objectives for ISRU research and development through its Space Resources Strategy [4]. These roadmaps primarily focus on ISRU on the lunar surface, with asteroids being considered of secondary or later relevance. In contrast, successful asteroid and comet missions (NEAR Shoemaker, Hayabusa, Rosetta, Hayabusa2, OSIRIS-REx) have already demonstrated proximity operations at small solar system bodies, including safe touchdown and sampling. Low delta-v strategies for near-Earth asteroid ISRU operations have been developed [5,6,7] and private companies are aiming at asteroid resource prospection missions with launches announces to occur as early as 2025/2026 [8,9]. A segment of near-Earth asteroids includes some of the most accessible small-body destinations in the Solar System. The energy required for a round trip to low-Earth orbit or a distant retrograde orbit in cislunar space from these objects is considerably less than that needed for journeys to the lunar surface or Mars [10]. However, apart from accessibility of near-Earth asteroids, their actual resources and the economic feasibility of their utilization are critical for the long-term development of ISRU activities.

Asteroid ISRU use cases. There are multiple use cases of asteroid ISRU proposed, which can be roughly subdivided into truly in-situ utilization with use of the products in space (in-space economy) and in-situ processing with the goal of returning commodities to the terrestrial economy. The latter will likely require a high degree of in-situ utilization of space resources to support the processing activities and reduce the launch cadence and mass transport from Earth's surface. Such support would include the in-situ production of propellants and the manufacturing of infrastructure components such as construction elements and solar cells.

Platinum-group elements (PGEs). Historically, a strong focus has been placed on the Earth-return of PGEs from metal-rich asteroids. The distribution of Pt contents in iron meteorites shows a mode at about 10 µg/g Pt with abundances commonly ranging up to ~40 µg/g Pt [11]. These values are significantly higher than the average, economically viable, Pt contents in ore of PGE deposits in southern Africa (e.g., Bushveld Complex, Great Dyke, Uitkomst Complex), where grades vary from 0.2 to 3 µg/g Pt [12]. The enrichment relative to terrestrial ore deposits is even more pronounced for Ir, which displays a median in the range 1 to 10 µg/g Ir in iron meteorites and grades of typically 0.2 to 0.5 µg/g Ir in terrestrial PGE deposits. However, the magmatic differentiation of planetesimal cores has imposed large, order-of-magnitude variations on the PGE contents in iron meteorites, which sampled these cores at dm- to m-scale resolution. Hence, actual Ir contents at this size scale vary across four orders of magnitude, from 0.01 to 60 µg/g Ir [13]. These highly heterogeneous PGE abundances render target definition of economically feasible metal-rich asteroid particularly difficult. Lower, but much more homogeneous PGE abundances are expected in C-group chondrites, where abundances of Pt and Ir range between 0.9 to 1.6 µg/g Pt and 0.4 to 0.8 µg/g Ir [14] and are similar to terrestrial PGE ores – hence, offering questionable economic benefit while terrestrial mining and processing is significantly less costly.

Volatile elements. The recent sample returns from near-Earth asteroids 162173 Ryugu and 101955 Bennu provide a direct link between spectroscopic asteroid classes and meteorite samples. Moreover, they provide untainted evidence of the volatile contents of these primitive, CI-like bodies without interaction with Earth's surface environment. The total H_2O and H_2O-equivalent hydrogen abundances of ~6.8 wt% in Ryugu [15] and ~8.2 wt% in Bennu [16] correspond to a total of 31 to 36 Mt of H_2O in a Ryugu-sized asteroid ($m = 4.50 \pm 0.06 \times 10^{11}$ kg [17]). To put this into perspective, the total inferred H_2O inventory of the permanently shadowed regions (PSRs) of the lunar south pole ranges between 23 to 30 Mt H_2O distributed over 4600 to 5900 km^2 [18]. Hence, a single 900-m sized near-Earth asteroid of CI mineralogy holds inferred reserves equivalent to what is currently in the focus of intense lunar prospecting ambitions. Other volatiles, such as 4.4 to 6.8 wt% C and 0.09 to 0.25 wt% N in Ryugu and Bennu [15,16,19,20] add to these asteroidal resources, potentially enabling the in-space production of propellant systems, such as H_2 or CH_4 as fuels and O_2 and N_2O_4 as oxidizers. For this purpose, CI-like asteroids hold the advantage of significantly higher C/H and N/H ratios as currently inferred for the PSR ices based on LCROSS data [21].

The physical mining of asteroid regolith is, compared to the Moon, much more challenging due to the near-absence of gravity, extremely low cohesive strength, and, in consequence, a requirement for neutral balancing of reaction forces. The calcination step required to release volatiles from phyllosilicates and carbonates is expected to operate at power- and (insulation) massdemanding temperatures of up to 600 °C [22], which is unlike the moderate warming required to release volatiles from their icy state in lunar PSRs [23].

Anhydrous silicates. The residue of the volatile removal process is expected to resemble the products of natural and experimental dehydration of CI and CM chondrites, i.e., comprising mainly variably Fe-enriched olivine besides poorly crystalline Mg-Fe silicates [24,25]. Such material reacted with H_2O-based acidic reactants from the extraction process may be used to form and bond ceramic components similar to concepts explored for Martian ISRU [26]. This requires the recycling of the water released during the sintering/firing process, which is however similar to the primary calcination process and could therefore be accomplished with similar system architectures. Similar ferromagnesian silicate material is also abundantly available on S-type asteroids [27], but the lack of H_2O resources on these bodies renders chemical-thermal processing problematic.

Metallic bulk materials. Two sources of metallic or semi-metallic materials can be potentially derived from asteroidal regoliths. First, Fe-Ni alloys naturally occurring in S-type and M-type regoliths might be directly processed into structural components. However, the expected lack of volatile resources on these type of bodies requires additional logistics to provide propellants for transporting commodities back to their point of use in cis-lunar space. The anhydrous residues of calcination of C-type regoliths might be reduced to the metallic state using technologies currently developed for lunar oxygen extraction, specifically molten salt electrolysis based on the FFC Cambridge process, providing high reduction yields at moderately high temperatures [28,29]. Besides O_2 for propellant, this process is able to produce elemental Si for photovoltaics applications as well as metallic Mg, Al and Fe for structural components. It requires a supply of chloride salts, commonly $CaCl_2$, which is either to be transported from Earth or sourced locally from asteroid materials, a process subject to future feasibility studies. The reduction process yields complex alloys, which require extensive post-processing to derive usable commodities for the aforementioned applications [30].

References

[1] Starr S. O. and Muscatello A. C. 2020. Planetary and Space Science 182:104824. [2] Neal C. R. et al. 2024. Acta Astronautica 214:737-747. [3] NASA Moon to Mars Architecture Definition Document (ESDMD-001) 2024. NASA/TP-20230017458. [4] ESA Space Resources Strategy 2019. exploration.esa.int/s/WyP6RXw. [5] Ieva S. et al. 2014. Astronomy & Astrophysics 569:A59. [6] Hasegawa S. et al. 2018. Publications of the Astronomical Society of Japan 70:114. [7] Jedicke R. et al. 2018. Planetary and Space Science 159:28-42. [8] Crull D. et al. 2024. Space Resources Roundtable, abstract 13-2. [9] Lantukh D. and Helms C. 2024. Space Resources Roundtable, abstract 13-3. [10] Sercel J. C. et al. 2018. Primitive Meteorites and Asteroids, Chapter 9, Elsevier, pp 477-524. [11] MetBase.org. [12] USGS Scientific Investigations Report 2010–5090–Q. [13] Scott E. R. D. 2020. Oxford Research Encyclopedia of Planetary Science, Oxford University Press, article id. 206. [14] McSween Jr. H. Y. and Huss G. R. 2010. Cosmochemistry, Cambridge University Press, 549 p. [15] Yokoyama T. et al. 2022. Science 379:eabn7850. [16] Lauretta D. S. et al. 2024. Meteoritics & Planetary Science 59:2453-2486. [17] Watanabe S. et al. 2019. Science 364:268-272. [18] Brown H. M. et al. 2022. Icarus 377:114874. [19] Okazaki R. et al. 2022. Science 379:eabo0431. [20] Grady M. M. 2024. Abstract #1436. 55th LPSC. [21] Mandt K. E. et al. 2022. Nature Communications 13:642. [22] Harries D. et al. 2019. Abstract #6361. 82nd Annual Meeting of The Meteoritical Society. [23] Sowers G. F. and Dreyer C. B. 2019. New Space 7:235-244. [24] Ebert S. et al. 2018. Meteoritics & Planetary Science 54:328-356. [25] Nakamura T. 2005. Journal of Mineralogical and Petrological Sciences 100:260-272. [26] Karl D. et al. 2022. Open Ceramics 9:100216. [27] Nakamura T. et al. 2011. Science 333:1113-1116. [28] Lomax B. A. et al. 2020. Planetary and Space Science 180:104748. [29] Meurisse A. et al. 2022. Planetary and Space Science 211:105408. [30] Schild T. et al. Abstract PE22. 33rd Conference on Metallurgy and Materials.