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Review on quarrying methods suitable for space mining missions

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Keywords

asteroid mining, shaped charge explosives, space economics, space mission planning, asteroid 16 Psyche

Review on quarrying methods suitable for space mining missions

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Abstract

In this review paper, existing mining techniques and technologies are scrutinized for the purpose of superterrestrial use. Different aspects and challenges of a space mining mission are examined in light of the viable iron-nickel quarry operation on M-Type (metallic) asteroids. The research and findings presented in this work cover different disciplines of science and engineering, including Geology, Rock Engineering, Space Exploration, and Explosives Engineering. The particular focus of this study is on the application of shaped charge explosives in military munitions, oil well perforations, tunneling, open-pit mines, and bolder fracturing that could be deployed in asteroid mining missions. The central proposal of this research is a methodology to carve out a solid iron-nickel quarry slab, properly shaped to enter Earth's atmosphere and land independently, without spacecraft or landing capsule, thus offering an economically feasible solution to space mining.

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1. Introduction

With an increasing Earth's population and GDP per capita, the global production and consumption of various minerals have steadily increased for over a century [1,2]. The extractable ores of the world's geologically scarcest raw materials (e.g., antimony, molybdenum, nickel, zinc, tungsten) may be exhausted within a century or less [3]. All the while, a mix of political turmoil and natural scarcity are contributing to fears that mineral resources will not be able to sustain technological progress in the future. As supplies dwindle and demand grows, a new industry of space exploration and asteroid mining may offer a solution to the inevitable raw materials shortages that threaten the future of the global economy. Human civilization might never dream of mining the Earth's core. But M-type (metallic) asteroids contain a virtually unlimited supply of iron and nickel, as well as rare and precious metals like platinum, gold, iridium, palladium, osmium, ruthenium, and rhodium [4]. The future of mining and the world's economic growth can be recharged by the trillion-dollar space industry, with private-sector investments surpassing government-sponsored space programs.

Existing mining techniques employing drilling and blasting might not be practical on M-type (metallic) asteroids. Drilling blast holes in iron-nickel rock would be a difficult task on Earth, given the support of heavy machinery and electrical power. On an asteroid, it would be extremely challenging even if a one-ton drilling rig was brought over and anchored in near-zero gravity. In a more distant future, traditional mining methods applying drilling, blasting, crushing, and enrichment of crude ores will almost certainly be invented and refined for the purpose of asteroid mining. However, the initial exploratory missions will have to rely on existing technologies in order to prove commercial viability of asteroid mining. Pioneers will be looking for adaptable mining techniques not requiring industrial machinery and suitable for near-zero gravity on an asteroid.

This paper reviews the application of shaped charge explosives as a replacement for traditional

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drilling and blasting methods. The unique capacity of shaped charge explosives to focus explosive energy into powerful narrow jets and the ability to penetrate through metallic material at significant depth will make them particularly useful tools for asteroid miners. They are widely used in military anti-armor weapons, as well as in civil engineering [5,6]. Moreover, the Oil and Gas Industry adopted shaped charges to create perforation tunnels in oil wells. Construction engineers use shaped charges to cut thick metal beams and reinforced concrete columns during demolition. The mining and tunneling industry applies shaped charges to break large boulders and create holes in rock faces [7]. On an asteroid, shaped charge explosives can easily be handled by an autonomous rover and provide precise, directed energy to help with rock quarry mining tasks while eliminating the need for drilled holes. If required, secondary liquid explosives can be placed in the holes created by shaped charges for accurate and controlled blasting operations.

The ability to cut out a solid rock monolith from the iron-nickel core of an asteroid could offer a scalable and commercially viable operating model to space miners. For engineers and asteroid mission planners, it would significantly simplify the task of Earth's atmospheric entry and completely remove landing mass limitations attributed to a spacecraft design. In other words, a properly shaped 100-ton (or more) solid piece of iron-nickel rock protected by a heatshield [Section 5.2], crash-landing independently, will be at a lower cost than completing the soft-landing of a 100-ton SpaceX Starship with several tons of asteroid rock onboard. Looking a bit further out in the future, the Nuclear Pulse Engine (NASA project Orion) could be pushing a 10,000-ton iron-nickel block towards Earth [Section 5.1].

2. Mission planning, optimal size of an asteroid rock, estimates of propellant consumption

In this section, SpaceX Starship's current specifications are applied in a rough estimation of propellant consumption for the mission to the NEO (Near Earth Object) asteroid [8] with the task of bringing back a 100-ton solid monolith of iron-nickel rock to a low Earth orbit. Asteroid mining mission to 16 Psyche in the Asteroid Belt between Mars and Jupiter could involve trajectory distances 10 times longer than to the NEO asteroid and might not be feasible, at least within the next 10–15 years. NASA's OSIRIS-REx mission's total travel distance from Earth to NEO asteroid Bennu was approximately 280,000,000 km [9]. But NASA's 16 Psyche Mission is expected to travel 2,400,000,000 km [10]. SpaceX Starship will require a propellant depot along the way in order to reach 16 Psyche and return back. However, asteroid prospecting missions to NEO asteroids [Section 5] may be possible within a few years of SpaceX Starship becoming operational.

2.1. *Consideration of shape, weight and center of mass*

Proportional shape and a predictable center of mass in a carved-out solid piece of iron-nickel rock are necessary conditions for successful transportation from an asteroid to a low Earth orbit (LEO) as well as for atmospheric entry and landing. In the authors' assessment, the Truncated Square Pyramid (Pyramidal Frustum) [Section 6.1], with a mass of 50–200 tons, would be the most practical shape in terms of asteroid quarry excavation economics and Earth's atmospheric entry considerations. To maintain the center of gravity, rotating about a fixed axis can be conveyed to the rock monolith during space travel.

2.2. *Assessment of spacecraft's propellant capacity requirements for the mission to the NEO asteroid*

There are 4 main stages of the mission to an asteroid that require propellant expenditure considerations (Table 1).

This section reviews the 4th stage of the mission and calculates required propellant consumption, assuming that SpaceX Starship will be refueled to capacity in LEO [12] before accelerating toward an asteroid. It is necessary to mention that the earlier design of the SpaceX Raptor engine changed from Hydrogen to Methane fuel (LOX oxidizer). However, it does not significantly affect the feasibility study

Table 1. The main flight stages involving propellant burning on the mission to an asteroid.

Stage #	Description	Spacecraft
1	Liftoff from Earth to get to a LEO (low Earth orbit)	SpaceX Super Heavy booster 1st stage SpaceX Starship Interplanetary
2	Accelerate from LEO toward NEO Asteroid	SpaceX Starship Interplanetary
3	Decelerate/maneuver around an asteroid	SpaceX Starship Interplanetary
4	Accelerate 100-ton rock from NEO Asteroid towards Earth	SpaceX Starship Interplanetary or Space Tug [Section 5.1] [11]

and preliminary calculations for LOX + LH_2 propellant presented in this paper. Methane fuel, although less powerful than hydrogen, is significantly cheaper, easier to handle, and requires smaller tanks and less insulation (saving on spacecraft's weight). Most importantly, methane burns cleanly without residue in the engine, which is critical for reusability.

SpaceX Starship Interplanetary will have to burn approximately 40–60% of its total propellant mass [12] to get on a trajectory towards the NEO Asteroid and then decelerate/maneuver around an asteroid. Given the SpaceX Starship propellant capacity specifications (Table 2) and the results of preliminary calculations [Section 2.3], there should be enough propellant left to accelerate a 100-ton piece of NEO asteroid towards Earth. For comparison, we can look at the OSIRIS-Rex NASA mission sent to NEO asteroid Bennu in 2018, where the spacecraft burned approximately 40% of its total propellant onboard to achieve a cruise phase towards the asteroid after Earth gravity assist [9].

NASA is actively developing solutions to bring a small nuclear reactor to the Moon or an asteroid in order to be able to produce oxygen for astronauts and fuel for spacecraft from locally available water ice to avoid launching it from Earth. This will be critical for sustainable mining operations on asteroids. The necessity to launch from Earth all the propellant required for a return trips will greatly diminish the total amount of cargo destined for an asteroid mission as well as seriously undermine the sustainability of asteroid mining operations.

2.3. Calculate the amount of propellant required to accelerate a 100-ton piece of asteroid towards earth

Below are approximate calculations for the total propellant mass required to accelerate a 100-ton block from the NEO asteroid towards Earth. The following numbers were used in our calculations (Table 3):

Since the total mass is equal to 100,000 kg [rock] + 10,500 kg [Space Tug dry mass] + 9750 kg [propellant] = **120,250 kg**, we can calculate the acceleration *a* by using Newton's second law

Table 3. SpaceX raptor engine specifications and other parameters used in propellant requirements calculation.

Calculation parameter	Value
SpaceX Raptor engine – thrust [13]	2200 kN
SpaceX Raptor engine – mass flow [13]	650 kg/s
Space Tug – dry mass [Section 5.1] [11]	10,500 kg [100,000 kg]
SpaceX Starship Interplanetary – dry mass [12]	
Cargo (asteroid rock)	100,000 kg
Engine burning time	30 s
Total propellant required to accelerate to a speed of 549 m/s (delta-v)	650 kg × 30 s = 19,500 kg
Propellant mass loss fraction (linear average)	50%
Total propellant mass adjusted to propellant mass loss fraction	19,500 × 50% = **9750 kg**

$$a = \frac{1 \times 2200000N\ [\text{1 engine}]}{120250\ \text{kg}\ [\text{calculated mass}]} = 18.3\ \text{m/s}^2$$

One Raptor engine burning full blast could accelerate a 100-ton block by 18.3 m/s^2. Within 30 s of the engine burning, the spacecraft's speed relative to an asteroid will be up to $18.3\ \text{m/s}^2 \times 30\ \text{s} = 549\ \text{m/s} = 1976\ \text{km/hr}$.

That is to say, 1 Raptor engine firing for 30 s will accelerate a 100-ton piece of asteroid rock to a speed of **549 m/s.** Our calculated delta-v (change in velocity) to **549 m/s** when returning rock monolith from an NEO asteroid to Earth can be compared to the delta-v of **277** m/s NASA's spacecraft OSIRIS-Rex received after main burn thrust to set it on a course from NEO asteroid Bennu back to Earth [9]. If Starship (100-ton dry mass) is used to accelerate asteroid rock, the same calculated amount of used propellant (19.5-ton) will achieve a delta-v of **314 m/s.**

Based on the above calculations, asteroid mission planners can anticipate propellant consumption of approximately 15–30% of the mass of spacecraft + cargo in order to accelerate toward Earth from a NEO asteroid.

3. Feasibility of asteroid mining

As SpaceX Starship inches closer to operational readiness and NASA's cargo flights to the Moon are

Table 2. Spacecraft's propellant capacity vs propellant required to get a 100-ton asteroid rock on a trajectory towards earth (comparison table).

Spacecraft	Maximum propellant weight capacity
SpaceX Super Heavy (1st Stage) [12]	3400 ton
SpaceX Starship Interplanetary (2nd Stage) [12]	1200 ton
NASA Space Shuttle external tank	735 ton
Fuel required to accelerate 100-ton rock from NEO asteroid toward Earth	16.5 (LOX) + 3 (LH_2) = **19.5 ton** (see our calculations below) LOX to LH_2 fuel mixture ratio is on average 6:1

expected to start by 2025, commercial asteroid mining will soon become possible, even if not quite practical yet. In 10–15 years, asteroid "16 Psyche" might be within reach for future private mining ventures.

"M-type Asteroids are composed of up to 80% iron and 20% a mixture of nickel, iridium, palladium, platinum, gold, magnesium, and other precious metals such as osmium, ruthenium, and rhodium" [14]. To highlight the effect of the **differentiation process** occurring during planet formation (semi-liquid state), we can compare platinum (Pt) and lead (Pb). These elements with very similar atomic weights (Pt: 195.084 u, Pb: 207.2 u) have analogous abundance in Earth's core and in the solar system as a whole. But in the Earth's crust, lead (Pb) is much more abundant than platinum (Pt). A simplified explanation of this disparity is that 99% of the platinum (Pt) sunk to the center of the planet at the beginning of the Earth's formation. But lead (Pt) usually exists in the sulfide compounds (PbS, PbS2) which makes it light enough to be fairly abundant in Earth's upper layers. The element composition of M-type asteroids is expected to be very similar to the Earth's core.

If a successful scientific mission to an asteroid can return 1 kg of material back to Earth, a commercial mining mission will have to bring tons of material in order to be considered profitable. It would be difficult to predict what amount of asteroid rock brought back to Earth (or to the Moon) would make the business of asteroid mining commercially viable. But what is certain is that the potential for scalability is the key to planning a successful asteroid mining operation. In practical terms of conceptualizing the operational efficiency of asteroid mining, a 100-ton (or more) solid section of asteroid entering the Earth's atmosphere and landing independently, without spacecraft, would be a solution worthy of consideration. Especially when compared with the conventional wisdom of bringing several tons of asteroid rock in the Starship's (or a similar spacecraft) cargo bay and making a soft landing on Earth's surface. Burning fuel to land reusable spacecraft carrying asteroid rocks will hardly be a scalable solution on Earth, at least until rare earth metals are refined and processed directly on asteroids, or on the Moon.

Iron-nickel solid slab (Fig. 1c) can be properly shaped to optimize the center of gravity required for controlled atmospheric entry. Heatshield and a small parachute [Section 5.2] can be attached to guarantee that touchdown speed will not exceed 500–700 km/h. Landing a 100-ton solid slab somewhere in the Sahara Desert should not be too risky, and crash-landing would not present a dilemma for the mission planners.

There is a precedent of a large metallic asteroid landing on Earth without breaking apart. The 60-ton iron-nickel slab, the Hoba meteorite (Fig. 1b), landed in Namibia less than 80,000 years ago. The Earth's atmosphere friction slowed the asteroid to the degree that it impacted the surface at terminal velocity (around 1200 km/h), remaining intact and causing minimal excavation [15].

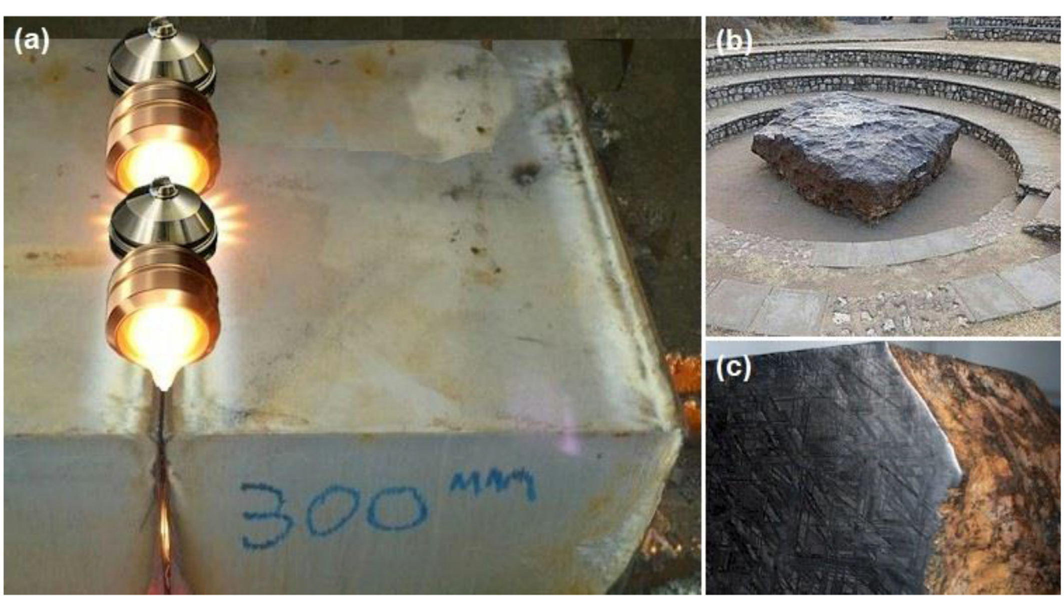

Fig. 1. (a) Illustration of a 300 mm industrial steel slab that can be used to test shaped-charge combinations. Illustration composed of elements sourced from [36,37]; (b) The 60-ton iron-nickel slab, the Hoba meteorite, landed in Namibia [15] Figure sourced from [38]; (c) A 2300 kg Casas Grandes iron meteorite. Figure sourced from [39].

A 2.8 kg specimen of the Hoba meteorite (Fig. 1b) was sold for $59,062 at a Los Angeles international auction (2021). Under the most modest estimates, a 100-ton iron-nickel asteroid slab containing rare heavy metals could cost at least $100 million dollars on Earth. Given the SpaceX promise of rapid reusability and $200 per 1 kg (or less) cost of space lift to LEO, $100 million could very well pay for a Starship's trip to the Near Earth M-Type asteroid.

4. Use of shaped charge explosives in iron-nickel asteroid quarry

Any mining excavations on the asteroid will most likely involve blasting operations. Given the properties of a dense iron-nickel core of an M-type asteroid, even if excavation of a solid slab is not a goal, drilled blast holes will still be required to place explosives in an asteroid quarry. Drilling a 2-m hole through a solid iron-nickel material [Section 6.3], outside of factory settings, would be a daunting task on Earth. On an asteroid, it could be prohibitively expensive for a commercial venture. On the other hand, a custom-designed charge explosive can blast a hole with precision without heavy machinery and a power source. In the case when drilling on an asteroid may still be required, creating pilot holes with shaped charge explosives could greatly speed up the process. It is possible to use a combination of shaped charge explosives [Section 6.1] in order to achieve highly calibrated and concentrated explosive energy that can efficiently cut through metallic material.

Military engineers use shaped charges like M3A1 Shaped Charge (18 kg) to create a big crater in the ground [Section 6.3]. It could be used to remove a significant layer of dust and debris that is expected to cover the asteroid's solid iron-nickel core. The dust mitigation technological solutions are currently being developed for NASA's Artemis Moon mission. Planners for asteroid missions will have to develop strategies for dealing with dust after the use of explosives on the asteroid's surface.

5. Outlines of a successful asteroid mining operation

NEO M-Type (metallic) asteroids (suspected but not confirmed yet) are shown in (Table 4).

5.1. Step-by-step process workflow

This section sketches the process chain of iron-nickel slab production and transportation in future quarry mining operations on an asteroid.

a. In the iron-nickel quarry on an asteroid, the monolith excavation perimeter will be outlined (Fig. 2).
b. In the center of the planned monolith, two holes will be blasted to affix anchoring rods (Fig. 2).
c. Anchoring rods providing a secure connection between the spacecraft and the rock monolith will be welded (cold welding) or otherwise secured into the blasted holes (Fig. 2).
d. Specialized software will calculate the precise placement and inclination angles for shaped charge explosives (Fig. 2).
e. An autonomous rover will place shaped charges on the monolith perimeter according to a calculated plan.
f. Detonation of shaped charges will blast the rock monolith cleanly from the ground and set it afloat around the asteroid. Separate steps can be taken to control the position of a free-floating rock monolith with cold gas thrusters and a control unit.
g. The transporting spacecraft will rendezvous with a rock monolith, securely connect with attachment rods and accelerate an iron-nickel piece of asteroid towards low Earth orbit (LEO). When a space refueling station becomes available, a light space tug with auxiliary fuel tanks will accelerate the iron-nickel monolith, then detach and return to the refueling station (Fig. 3). An iron-nickel block can be sent towards Earth every month or so to have a conveyor-like operation.
h. A separate spacecraft will take hold of asteroid rock in low Earth orbit (after the Aerocapture orbital transfer maneuver [Section 5.2]) and prepare it for atmospheric entry and landing.
i. A nuclear pulse propulsion or external pulsed plasma propulsion could be considered for scaling up asteroid mining production (Fig. 4).

NASA's Psyche mission is due to launch in 2023 on a mission to explore a strange, metal-dominated asteroid that may have once been part of the core of

Table 4. Near earth M-type asteroids.

Asteroid Name	Asteroid Details
3554 Amun [16]	M-type Aten asteroid. Its estimated diameter is 3.3 km. Planetary scientist John S. Lewis calculated the value of 3554 Amun at $20 trillion [16]
1986 DA [17]	1986 DA is a metallic asteroid, classified as a near-Earth object of the Amor group, approximately 3 km in diameter. With high radar brightness, it was predicted to have 100 thousand tons of platinum group metals [17]

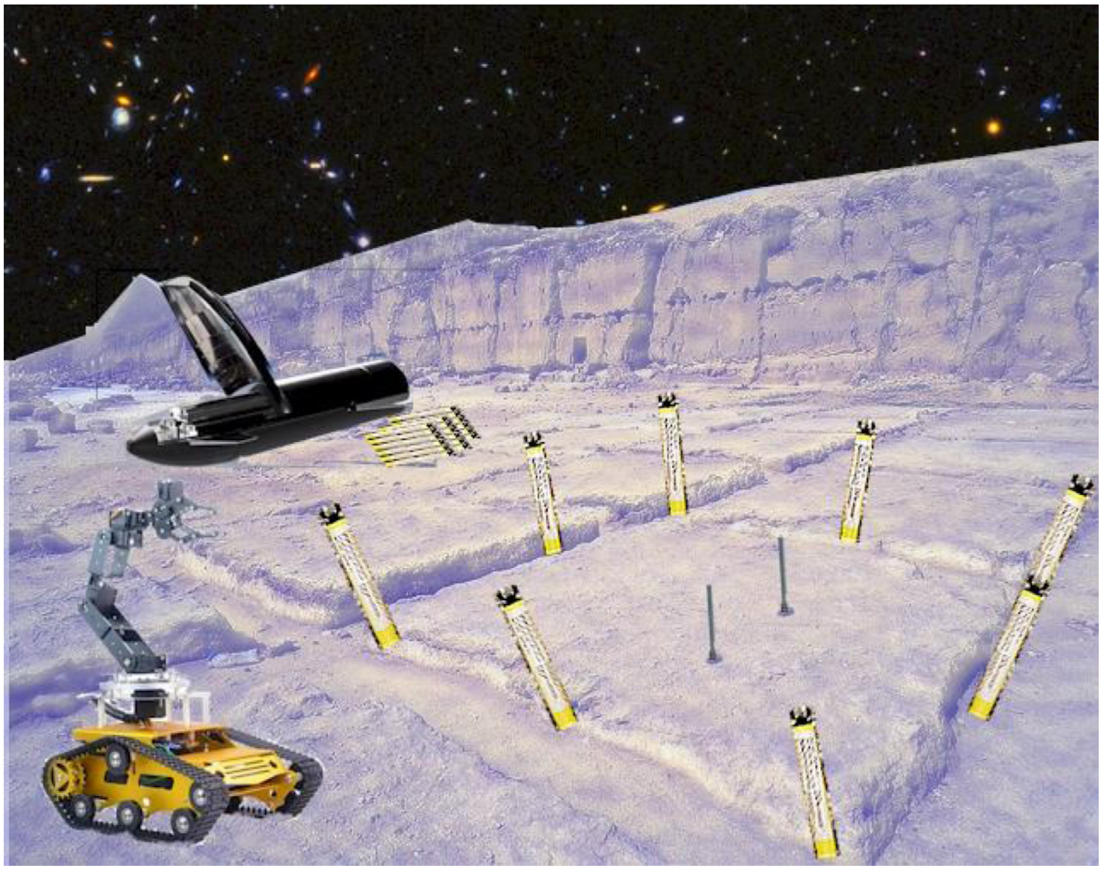

Fig. 2. Ultimately, asteroid mine developers will be able to precisely calibrate a combination of explosives in order to break free a solid iron-nickel monolith properly shaped for transportation back to Earth. Illustration composed of elements sourced from [40−42].

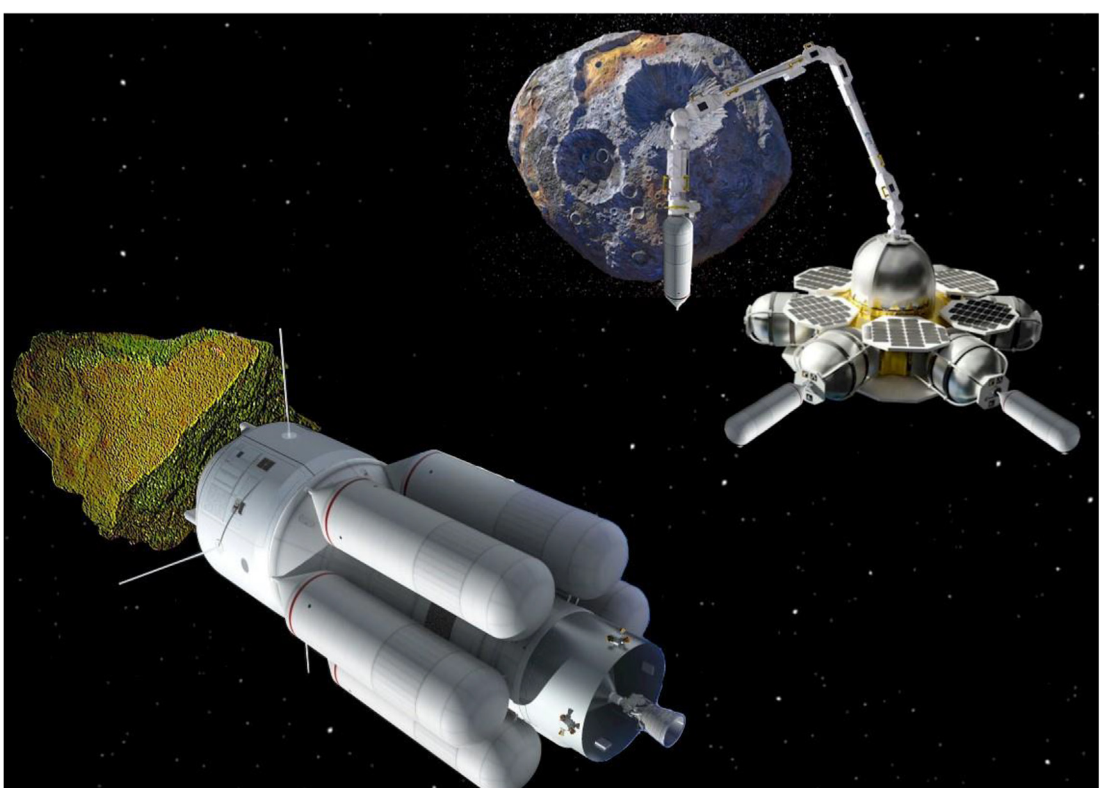

Fig. 3. Visualization of Space Tug with auxiliary fuel tanks and Space Refueling Station [11]. Visualization composed of elements sourced from [43−46].

Fig. 4. Visualization of Nuclear Pulse Engine (NASA project Orion) pushing a 10,000-ton iron-nickel block towards Earth. Visualization composed of elements sourced from [47–49].

a long-dead planet. If NASA's probe to "16 Psyche" discovers areas potentially suitable for quarrying and extraction of solid iron-nickel monolith, the conceptual research in this paper could become relevant [18].

5.2. Atmospheric entry with inflatable heat shield

In this paper, we proposed an alternative approach to the final part of the journey of the asteroid mining mission: the iron-nickel monolith's independent atmospheric entry and Earth's landing. Suggested methodology is essential to having a positive outlook on the future scalability of asteroid mining operations. This concept, of course, is not applicable to more common rocky asteroids that would most likely break apart at moderate pressure during atmospheric entry. The properties of iron-nickel rock in the Earth's core (similar to M-Type asteroids) are still not understood well enough to evaluate with confidence the stresses and stability of the monolith during Earth's landing. Protecting asteroids with an inflatable heat shield (decelerator) would help to reduce g-forces and improve predictability during atmospheric entry.

It is expected that rock monolith arriving from an asteroid will perform an "Aerocapture" orbital transfer maneuver using a single pass through Earth's atmosphere to achieve lower speed and LEO insertion.

Technological solutions discussed in this section are already under development. The European Union project H2020 EFESTO with the goal of improving the European Hypersonic Inflatable Aerodynamic Decelerator (HIAD) for re-entry vehicles (VEGA upper stage). The current mission foresees a controlled entry phase (Ballistic Coefficient of about 30 kg/m^2) and combined use of a HIAD (4.5 m diameter class) and parachutes [19]. For the purpose of this article, HIAD (inflatable heat shield) designed to protect and slow down a 100-ton rock, will have to be scaled up to 20–30 m diameter, assuming higher heat loading will be allowed. A supporting structure retaining the rock monolith on the heat shield will be added as well.

The approach of bringing solid iron-nickel rock monolith through the Earth's atmosphere independently, with the help of an inflatable heat shield (Fig. 5), has engineering advantages when compared to a spacecraft or a landing capsule making atmospheric reentry followed by a soft landing. With rapid deceleration and quick rotation during descent, a 500–700 km/h speed at touchdown would be impossible for a spacecraft like SpaceX Starship. However, it is not a significant concern for mission planners when returning a solid piece of rock to Earth.

The design of the reentry capsule, a portion of a spacecraft that returns to Earth, has not changed much since the 1970th. It would be hard to expect a rock monolith carved out from the asteroid quarry to match the aerodynamic stability of a reentry capsule. This is why, in this paper, we suggest the use of an inflatable heat shield. Even if an inflatable heat shield survives only for a minute or two during atmospheric entry, it can help to break initial speed, maintain the proper angle of descent, and transfer kinetic energy to heat energy in the atmosphere. A small parachute (Fig. 5) could limit the asteroid's speed before crash landing.

Multi-skip reentry: In order to reduce pressure on asteroid rock, it is possible to divide the heat and force of re-entry into multiple events. "Skipping" re-entry offers the benefits of lessening the g-forces the vehicle entering the atmosphere is subject to while traveling 40,000 km/h and lowering the instantaneous heat flux of the vehicle and its heatshield. Skip re-entry is a flight trajectory where the spacecraft goes in and out of the atmosphere several times before landing [21].

5.3. Asteroid belt reconnaissance probes

Asteroid mining ventures will be examining economically practical ways to prospect asteroids in NEO orbits as well as in the asteroid belt. This

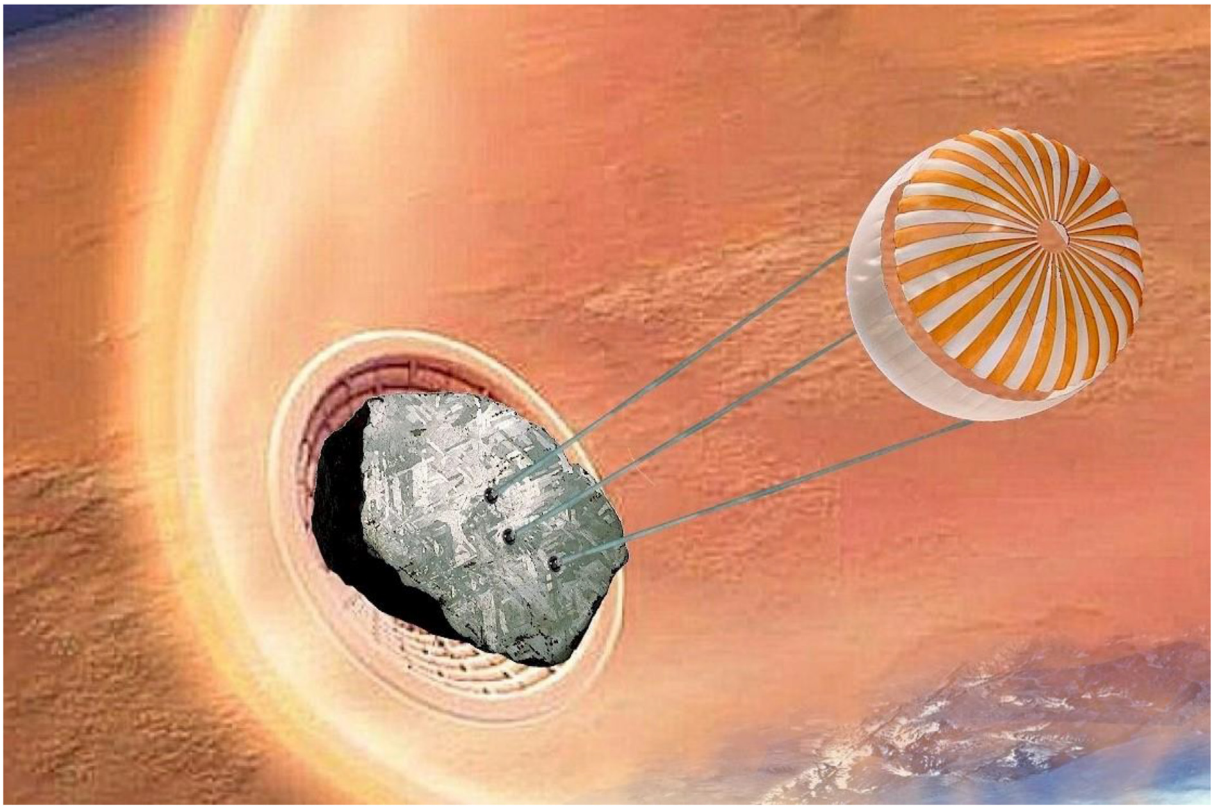

Fig. 5. Visualization of an inflatable heat shield and a small parachute attached to a rock monolith during Earth's atmospheric entry [20]. Visualization composed of elements sourced from [50–52].

section outlines one possible approach to designing micro (less than 1 kg) asteroid prospecting probes:

- Spacecraft in Lunar orbit equipped with a 20–30 mm gun will shoot probes in the form of bullets towards asteroids of interest. In a vacuum, a gas-explosion-driven muzzle velocity could reach 2000–2500 m/s. The achieved delta-v should be sufficient to reach most of the asteroid belt.
- The design of the probe, capable of withstanding around 10,000 G's, will be very basic and include a camera, battery, electronic timer and communication system using a laser light emitter. To mitigate possible trajectory deviations caused by gunpowder inconsistency, a group of 5–10 bullet-sized probes will target one asteroid of interest.
- These probes will not be able to receive commands or adjust the course. Before leaving the barrel of the gun, each probe will be pre-programmed to take several pictures after a specific period of time and transmit them with a light emitter (1 W laser diode) to a space-based optical communications telescope. The precise time for transmission can be pre-programmed as well.
- The receiving telescope, also serving as a data relay to Earth, will be located within 1–5 million kilometers from the probe in order to achieve a signal transmission rate of approximately 1000 baud.
- A scenario when one of the bullet probes hits the asteroid while the following behind probe takes pictures of spectra can also be contemplated.

6. Shaped charge explosives application in asteroid mining

A shaped charge is an explosive charge shaped to focus the effect of the explosive's energy into a narrow straight jet (Fig. 6b). Different types of shaped charges are currently used for various purposes, including cutting and forming metal, initiating nuclear weapons, penetrating armor, or perforating wells in the oil and gas industry [5,6]. The Monroe effect is the focusing of blast energy by a hollow or void cut on the surface of an explosive. The earliest mention of hollow charges occurred in 1792. Although Monroe's discovery of the shaped charge was widely publicized in 1900 in Popular Science Monthly, the importance of the tin can "liner" of the hollow charge remained unrecognized for another

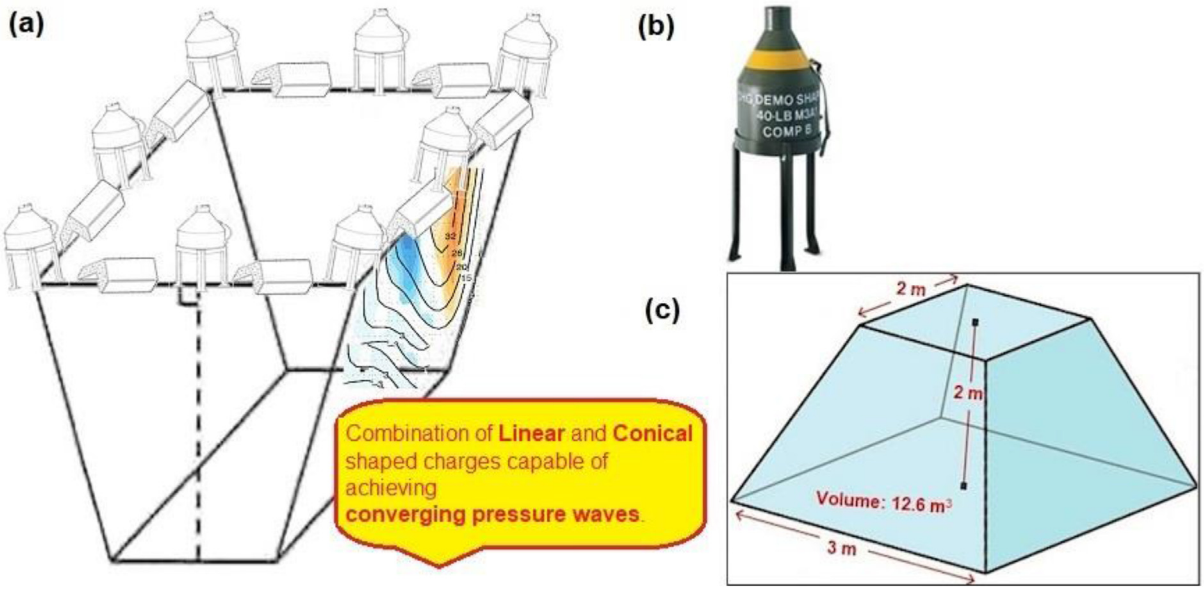

Fig. 6. (a) A hypothetical illustration of a combination of shaped charges [25] Illustration composed of elements source from [53–55]. (b) M3A1 Charge contains a 38 cm stand-off, 13.3 kg Composition B explosive [26] Figure sourced from [56]. (c) Shape/size of 100 metric tons (iron density).

44 years until the technique was published in the 1945 issue of Popular Science describing how shaped-charge warheads worked [22]. It was this article that at last revealed to the general public how the fabled Bazooka actually worked against armored vehicles during WWII.

An important topic in mining feasibility studies was the creation of blast holes for explosive columns, using shaped charges. Clark, Rollins, Brown, and Kalia developed a drill-and-blast method of tunneling [23]. "Rather than individual holes, entire blast rounds were drilled. In addition, shaped charges were then placed at the bottom of the enlarged holes. Here, they had a combined effect of drilling further ahead and simultaneously blasting the previously drilled rock, usually with the help of additional conventional explosives placed in the hole. Using this technique, a 1.8-m diameter opening was excavated about 1.5 m into a dolomite quarry face. The holes drilled in a rock by shaped charges typically have a length/diameter ratio between 15 and 50. At the optimum design condition, drilled depths range from the value of 2.6 D for quartzite to the value of 9.5 D for St. Peter sandstone" [23].

6.1. Combination of shaped charge explosives, self-amplifying nature of converging detonation waves

Asteroid mining mission planning will depend heavily on the total weight of shaped charge explosives, other explosives, and equipment required for the task of carving out a solid monolith from an iron-nickel asteroid core. Extensive research and testing will have to produce the most powerful, efficient, and lightweight combination of explosives specifically designed for an iron-nickel quarry on an asteroid.

Similar to conventional techniques of drilling and blasting in granite or limestone quarry, on an asteroid, a carefully arranged combination of shaped charge explosives will be essential to achieve wall-to-wall fracture in a quarry wall with minimal and well-controlled damage to a rock monolith itself. Traditional methods of drilling through the rock might not be possible on an asteroid, especially in the earlier missions. A portable power source and heavy equipment capable of drilling through the iron-nickel core will be prohibitively heavy and cumbersome to be considered for asteroid missions, at least within the next 10–15 years. To replace the need for drilling equipment, holes in iron-nickel rock can be blasted by shaped charge explosives. Then, if necessary, liquid explosives can be pumped in for precise calibration of the force required to create a wall-to-wall fracture in a rock.

Instead of launching liquid explosives from Earth, local water ice could be used for **Frost Wedging**. Frozen ice can split rock with borehole pressure up to 207 MPa [24].

The combination of shaped charge explosives can generate converging pressure waves capable of splitting rock in an iron-nickel quarry (Fig. 6a) [27]. Importantly, pressure waves generated by multiple shaped charge jets exploding simultaneously at converging angles have a potential for efficient iron-nickel rock splitting techniques [27].

As a substitute for genuine tests on an iron-nickel rock from an asteroid, strategies for shaped-charge combinations can be studied on industrial steel slabs (Fig. 1a).

6.2. Precision blasting techniques with shaped charge explosives

As mentioned earlier in this paper, shaped charge explosives have been widely used in various engineering practices, but there have not been many studies of shaped charge applications in rock and mining operations so far [5,6,28,29]. An interesting experimental result from Rollins and Clark [28] shows that jet penetration velocities into granite can be up to 10,000 m/s for the most effective metallic shaped charge liner jet, and the maximum penetration is about 18 cm in granite (Fig. 7). Their results indicate high jet penetration capability in rock formations. This would suggest a possible application of shaped charges in asteroid mining quarries. However, the exact composition and

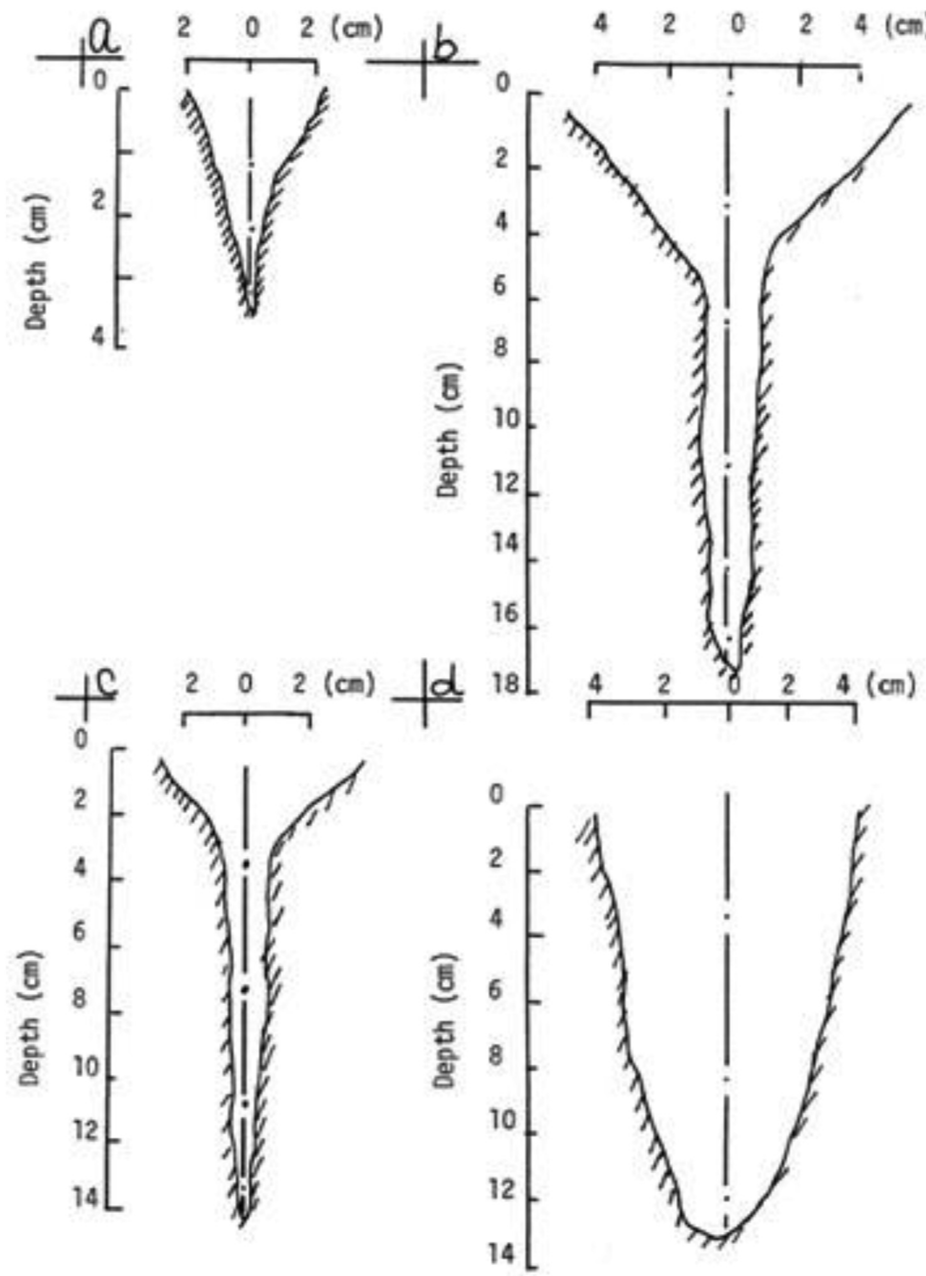

Fig. 7. Typical hole profiles in granite [28,30].

structure of the hard iron-nickel rock in the core of M-type asteroids must be well known in order to select a suitable shaped charge liner design capable of efficient hole creation in the asteroid rock. In addition, a methodology to clear out blast holes from debris in a vacuum and zero gravity will have to be developed. The secondary liquid explosives could be less effective if it were pumped into holes containing loose rock and dust. These techniques, although known for some time, are not widely used in the industry and will require special research, testing, and development [6].

6.3. What would it take to make a 200 cm hole in iron-nickel rock?

This section examines the hole-making potential of a common military demolition Shaped Charge M3A1 **(18 kg)**. According to specifications, M3A1 (Fig. 6b) has a **cavity diameter of 27 cm** and can blast (at least) 54 cm long, 5 cm diameter hole in steel armor plate (Table 5) (Fig. 8) [26]. A typical modern shaped charge, with a metal liner on the charge cavity, can penetrate armor steel to a depth of **seven or more times** the diameter of the charge, though greater depths of 10 CD (charge diameter) and above have been achieved [22]. Thus, it is possible that the shaped charge liner of M3A1 can be improved and optimized to achieve a maximum (**7–8 times of the diameter**) penetration depth of **200 cm**. However, it is hard to predict at this point how many 18 kg shaped charges (or similar ones) will be necessary on an asteroid to free up a 100-ton iron-nickel monolith. As mentioned earlier [Section 6.1], the total weight of required explosives will be a major constraint for asteroid mining mission planners.

There are a lot of studies and patented solutions of shaped-charge combinations for the purpose of oil

Table 5. Table listing penetration capacity of common demolition shaped charge explosives [26].

Material	Specifications	M2A4, Shaped Charge (7 kg)	M3A1, Shaped Charge (18 kg)
Armor plate	Penetration	30.48 cm	At least 50.8 cm
	Average hole diameter	3.81 cm	6.35 cm
Reinforced concrete	Penetration	91.44 cm	152.4 cm
	Average hole diameter	7 cm	8.89 cm
Soil	Penetration	213 cm	366 cm
	Average hole diameter	17.78 cm	36.83 cm

Fig. 8. Experiments on standard shaped charge. For general research, the 56 mm standard shaped charge is adopted. The jet tip velocity is 6453 m/s, and that of the tail is 1179 m/s. The length of the jet at 80 mm standoff equals 111.5 mm [31].

well perforators. Similar research evaluating the effectiveness of shaped-charge combinations conducted specifically for the purpose of asteroid mining will be required, possibly, on metallic materials like industrial steel slabs (Fig. 1a).

6.4. Innovative research in shaped charge explosives

In 2003, studies were reported of large shaped charges with a conical liner having opening angles from 60 to 100° with a caliber of 711 mm and a length of 724 mm [32]. Scaling the size of shaped charges is an important issue in scientific research. For large shaped charges (Fig. 9), the liner metallurgy is harder to control, and the explosive loading is more difficult to predict. Large shaped charges with diameters bigger than 40 cm are rarely used (except for missile warheads), and their jet formation is much harder to predict with consistency [33].

In the vast majority of manufactured shaped charges, the mass of the generated jet does not exceed 10–30% of the mass of the shaped charge liner. In addition, the maximum speed of the cumulative jet in standard shaped charges is restricted, which leads to a decrease in the diameter and depth of the perforated hole [32]. In the late 1990s, Academician V. F. Minin (Russia) proposed and investigated a new method for the formation of large mass cumulative jets in shaped charges, which was later patented. The new principle of the formation of cumulative jets was called **hyper-cumulative jet**, which can be formed by the shaped charge shown in (Fig. 10). In the performed theoretical and experimental studies, it was found that the mass of the shaped charge jet can be 60–80% of the weight of the shaped charge liner while maintaining or exceeding the maximum speed typical for "classic" shaped charges [32,34].

Fig. 9. Outside view of extremely large shaped charge liner used in Russian cruise missiles [32].

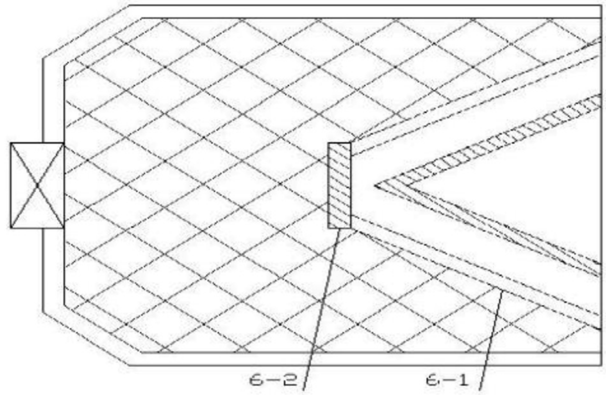

*Fig. 10. Example of shaped charge design that can form a hyper-cumulative jet. Notice the steel barrier "6–2" that makes jet formation much more massive and energetic (**hyper-cumulative**) [32].*

6.5. Tandem shaped-charge, super-caliber hole, extending maximum penetration depth

On Earth, if rock engineers would like to achieve a 1–2 m hole in the rock face, they could explode sequential shaped charges in the same spot, gradually increasing penetration depth. In an asteroid quarry setting at near-zero gravity, lacking equipment and ever-present suspended dust and debris, one would like to simplify planned methods of rock splitting and extraction. This is where the use of Tandem Shaped Charge high explosives could help to eliminate the need for follow-up explosions.

A tandem-charge or dual-charge weapon, as shown in (Fig. 11), is an explosive device or projectile that has two or more stages of detonation. Dual charges are also effective at increasing the potency of warheads when used against structures (such as bunkers) [35].

If follow-up explosions are required to achieve the necessary penetration depth in an asteroid iron-nickel quarry, then shaped charges designed for the Super-Caliber Hole could be a practical solution. A super-caliber hole means a hole larger than the charge diameter (CD) making the hole. This allows repeated insertions of same-size charges into the existing hole, increasing its depth and shock-fracturing across all layers and in all directions. This is only possible using the super-caliber charge.

Super-caliber charge design spreads the explosive energy of a collapsing liner into a stretching hollow cylindrical jet that produces a super-caliber hole. Since the shaped charge produces a super-caliber hole, follow-on charges can be aligned and propelled deep into the formation through the primary super-caliber hole made by the number one charge. The hollow cylindrical jet formed from the charge is efficient in making an existing hole deeper.

7. Concluding remarks

- The remarkable and largely unexpected success in the development of low-cost space lift capabilities spearheaded by SpaceX brings the feasibility of space mining much closer than we thought just a decade ago.
- The proposal to extract iron-nickel slab from an asteroid quarry followed by independent atmospheric entry and Earth's landing offers a potentially profitable operating model for space miners.
- There is a reason to think that we may finally be reaching a new stage in space exploration driven primarily by private entrepreneurs and large corporations. SpaceX's recent achievements (in cooperation with NASA), as well as upcoming efforts by Boeing, Blue Origin, and Virgin Galactic, open new perspectives and heightened our expectations of new discoveries.
- With increasing GDP, increasing demand for various metals, and increasing mining production, the extractable ores on Earth will become less and less sustainable. Accordingly, asteroid mining may become both possible and even necessary in the future.
- Shaped charge explosives have great potential to be adopted in space mining since they have been successfully used for penetration of hard rock and thick metals in mining, construction, oil, and gas industries. However, it is necessary to study the mechanical properties of the asteroid rock in order to develop shaped charges of a special design well suited for blast operations in the asteroid quarry.
- The technical feasibility assessment of the NEO asteroid mining mission is becoming more compelling as the low-cost space launch lift capabilities pledged by commercial companies like SpaceX turn into reality.
- There are substantial technical, logistical, and even legal challenges in getting space mining off the ground. It will require new research and development investment from government and commercial entities.

Ethical statement

The authors state that the research was conducted according to ethical standards.

Funding body

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Conflicts of interest

None declared.

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References

[1] Zhang ZX, Hou DF, Aladejare A, Ozoji T, Qiao Y. World mineral loss and possibility to increase ore recovery ratio in mining production. Int J Min Reclamat Environ July 28 2021: 1. https://www.tandfonline.com/doi/full/10.1080/17480930.2021.1949878.

[2] Brown TJ, Idoine NE, Raycraft ER, Shaw RA, Hobbs SF, Everett P, Deady EA, Bide T. World mineral production. 2012. http://nora.nerc.ac.uk/id/eprint/519784/.

[3] Henckens ML, Van Ierland EC, Driessen PP, Worrell E. Mineral resources: geological scarcity, market price trends, and future generations. Resources Policy; Sep 1 2016. https://www.sciencedirect.com/science/article/pii/S0301420716300861.

[4] Sisir K. Mondal. Platinum group element (PGE) geochemistry to understand the chemical evolution of the Earth's mantle. J Geol Soc India May 15 2011:2. Springer, https://link.springer.com/article/10.1007/s12594-011-0039-y.

[5] Cooper PW. Explosives engineering. Willey-VCH, Inc.; July 19 2018. https://books.google.com/books?hl=en&lr=&id=mvRlDwAAQBAJ&oi=fnd&pg=PP2&dq=P.W.+Cooper.+Explosives+engineering&ots=atjROjjte1&sig=2p10ouNrxYqvtaOmEc9h0wkTZn0#v=onepage&q=P.W.%20Cooper.%20Explosives%20engineering&f=false.

[6] Zhang ZX. Rock fracture and blasting: theory and applications. Oxford: Butterworth-Heinemann/Elsevier; April 19 2016. https://www.elsevier.com/books/rock-fracture-and-blasting/zhang/978-0-12-802688-5.

[7] Brady BH, Brown ET. Rock mechanics and mining engineering. Rock Mechanics; January 25 2007. https://miningandblasting.files.wordpress.com/2009/09/rock-mechanics_for-underground-mining.pdf.

[8] Mini psyches' give insights into mysterious metal-rich near-Earth asteroids. University of Arizona; Oct 1 2021. https://phys.org/news/2021-10-mini-psyches-insights-mysterious-metal-rich.html.

[9] The OSIRIS-REx asteroid sample return mission. IEEE; June 8 2015. https://ieeexplore.ieee.org/abstract/document/7118989.

[10] How NASAs Psyche mission will explore an unexplored world. December: NASA; 20 2021. https://www.jpl.nasa.gov/news/how-nasas-psyche-mission-will-explore-an-unexplored-world.

[11] Spacecraft: space tugs. March 12 2015. Bisbos.com. http://www.bisbos.com/space_tugs.html.

[12] Seedhouse Erik. Starship. Springer; May 12 2022. https://link.springer.com/chapter/10.1007/978-3-030-99181-4_9.

[13] Alejandro G. Belluscio. SpaceX advances drive for Mars rocket via Raptor power. NASASpaceFlight.com; March 7

REVIEW

2014. https://www.nasaspaceflight.com/2014/03/spacex-advances-drive-mars-rocket-raptor-power/.
[14] Simpson Lizzie. What are asteroids made of? Structure & composition. Starlust; January 16 2023. https://starlust.org/what-are-asteroids-made-of/.
[15] Martin Beech. Towards an understanding of the fall circumstances of the Hoba meteorite. Springer Nature; August 8 2013. https://link.springer.com/article/10.1007/s11038-013-9421-7.
[16] Lewis John S. Mining the sky: untold riches from the asteroids, comets, and planets. National Space Society; September 23 1997. https://web.archive.org/web/20120514073218/http://www.nss.org/resources/books/non_fiction/NF_011_miningthesky.html.
[17] 1986 DA. IAU minor planet center. December 25 2022. https://www.minorplanetcenter.net/db_search/show_object?object_id=6178.
[18] Elkins-Tanton Linda T, Asphaug Erik, James III F Bell. Distinguishing the Origin of asteroid (16) Psyche. Springer; 26 December 2021. https://pubmed.ncbi.nlm.nih.gov/35431348/.
[19] Bonettia D, Dietleinb I, Fedelee A. Advanced European Re-entry system based on inflatable heat shields. ResearchGate; October 12 2020. https://www.researchgate.net/publication/349217239_Advanced_European_Re-Entry_System_Based_on_Inflatable_Heat_Shields_Detailed_Design_EFESTO_project.
[20] Dodson Brian. NASA to test IRVE-3 inflatable reentry system. June 18 2012. New Atlas, https://newatlas.com/nasa-irve-3-inflatable-reentry-system/22974/.
[21] Sun Hongqiang, Zhang Shuguang. Skip Re-entry trajectory detection and guidance for maneuvering vehicles. Lockheed Martin; February 18 2020. https://www.mdpi.com/1424-8220/20/10/2976?type=check_update&version=2.
[22] Kennedy Donald R. History of the shaped charge effect: the first 100 years. Los Alamos National Laboratory; January 27 2019. https://apps.dtic.mil/dtic/tr/fulltext/u2/a220095.pdf.
[23] Brown JW. Statistical study of rock drilling by hypervelocity jets from explosive shaped charges. University of Missouri-Rolla; January 1 1971. https://scholarsmine.mst.edu/cgi/viewcontent.cgi?article=2852&context=doctoral_dissertations.
[24] Matsuoka Norikazu, Murton Julian. Frost weathering: recent advances and future directions. Wiley Online Library; May 27 2008. https://onlinelibrary.wiley.com/doi/10.1002/ppp.620.
[25] Banadaki MD, Mohanty B. Numerical simulation of stress wave induced fractures in rock. Int J Impact Eng February 1 2012:16–25. https://www.researchgate.net/publication/257239583_Numerical_simulation_of_stress_wave_induced_fractures_in_rock.
[26] EXPLOSIVES AND DEMOLITIONS. Characteristics of boreholes made by shaped charges. Headquarters Department of the Army; July 11 2007. https://info.publicintelligence.net/USArmy-Explosives.pdf.
[27] Mahdi Mohammad, Banadaki Dehghan. Stress-wave induced fracture in rock due to explosive action. University of Toronto; Jun 9 2010. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwjGk5XnkcH1AhU8k4kEHaJ_BeoQFnoECAQQAQ&url=https%3A%2F%2Ftspace.library.utoronto.ca%2Fbitstream%2F1807%2F27567%2F1%2FDehghanBanadaki_Mahdi_201011_PhD_Thesis.pdf&usg=AOvVaw3zUmTRjEg4HitUcFBPerU_.
[28] Rollins RR, Clark GB. Penetration in granite by jets from shaped-charge liners of six materials. Int J Rock Mech Min Sci Geomech Abstr May 1 1973:45–55. https://scholarsmine.mst.edu/cgi/viewcontent.cgi?article=3040&context=doctoral_dissertations.
[29] Naeem K, Hussain A, Abbas S. A review of shaped charge variables for its optimum performance. Eng Technol Appl Sci Res December 1 2019:4917–23. https://www.etasr.com/index.php/ETASR/article/view/3153/pdf.
[30] Brown JW. Statistical study of rock drilling by hypervelocity jets from explosive shaped charges. University of Missouri-Rolla; February 1 1971. https://scholarsmine.mst.edu/cgi/viewcontent.cgi?article=2852&context=doctoral_dissertations.
[31] Guo Min, Zu Xu-dong. Xiao-jun Shen Study on liquid-filled structure target with shaped charge vertical penetration. Defence Technology; December 6 2019. https://www.sciencedirect.com/science/article/pii/S2214914718306068.
[32] Minin IV, Minin OV. Shaped charges - siberian state. University; March 10 2013. https://studylib.ru/doc/2531691/kumulyativnye-zaryady—sibirskij-gosudarstvennyj-universitet.
[33] Shire Jason, Polly Richard, Waddell Jesse, George Budy, Bootes Tom. Design synthesis of large shaped charges for missiles. Raytheon; August 30 2011. https://ndiastorage.blob.core.usgovcloudapi.net/ndia/2011/gunmissile/Tuesday11808_Shire.pdf.
[34] RPG-7V anti-tank rocket launcher ammunition. GunRF; September 20 2018. https://gunrf.ru/rg_granatomet_ps-7_pg-7vr_eng.html.
[35] Collier Nick. "Super-Caliber hole," "A nonhydraulic means to complete wells.". Innovative Defense LLC; August 1 2016. https://www.hartenergy.com/exclusives/nonhydraulic-means-complete-wells-176047.
[36] Bob Haslam Engineering. "PROFILE CUTTING", https://bobhaslam.com.au/featured_item/the-key-to-cutting-300mm-plate-is-holding-a-consistent-direction-speed/ Accessed May 25 2022.
[37] DynaEnergetics. "Puncher Charges", https://dynaenergetics.com/products/Shaped-Charges/Shaped-Charges#DynaSlot Accessed March 10 2022.
[38] Flickr. "Meteorite di Hoba". Sergio Conti, https://www.flickr.com/photos/sergioconti/15682150765/ Not modified. License: https://creativecommons.org/licenses/by-sa/2.0/ November 1 2014.
[39] Encyclopedia Of Meteorites. "Casas Grandes (Iron, IIIAB)", https://encyclopedia-of-meteorites.com/Meteorite?id=5285 Accessed March 20 2022.
[40] Egyptphoto. "Pyramid of Khafre quarry marks", https://egyptphoto.ncf.ca/pyramid%20of%20Khafre%20quarry%20marks.htm Accessed February 5 2022.
[41] XiaoR GEEK. "6DOF Smart Robot", https://www.xiaorgeek.net/products/6dof-metal-rc-robot-arm-metal-tank-car-180-horizontal-rotation-app-ps2-handle-control Accessed February 6 2022.
[42] Nextwider. "Space News". Peerapat Chuejeen, https://www.nextwider.com/spacex-starship-full-flight-animation/ November 3 2020.
[43] Bisbos.com. "Dornier Space Tug", http://bisbos.com/space_tugs.html Accessed February 12 2022.
[44] Spacenews.com. "Design concept for Orbit Fab's Tanker-002". Jeff Foust, https://spacenews.com/orbit-fab-announces-in-space-hydrazine-refueling-service/ August 30 2022.
[45] Innovationnewsnetwork.com. "Asteroid 16 Psyche". iStock/24K-Production, https://www.innovationnewsnetwork.com/revealing-the-mysterious-origins-of-asteroid-16-psyche/12458/ June 10 2021.
[46] Wikimedia.org. "The European robotic arm", https://commons.wikimedia.org/wiki/File:The_European_robotic_arm_extends_out_from_the_Nauka_module_(iss067e034865)_(cropped).jpg Accessed February 26 2022.
[47] Fantastic-Plastic.com "Project Orion Battleship (1963)", https://fantastic-plastic.com/ProjectOrionBattleshipPage.htm Accessed May 15 2022.
[48] Risk.net. Peter Madigan, https://www.risk.net/regulation/dodd-frank-act/2453370/unresolvable-clearing-houses-pose-enormous-risk April 5 2016.
[49] Salon.com. "Meteorite from outer space". Matthew Rozsa, https://www.salon.com/2022/12/07/an-extinction-level-asteroid-that-could-someday-hit-earth-was-found-hiding-near-venus/ December 7 2022.
[50] Techjuice. "NASA presents its supersonic parachute". Sajeel Syed, https://www.techjuice.pk/nasa-supersonic-parachute-mars-mission-2020/ November 1 2020.
[51] Newatlas.com. "NASA inflatable reentry vehicle during plasma phase of Mars landing (Image: NASA)". Brian Dodson,

https://newatlas.com/nasa-irve-3-inflatable-reentry-system/22974/ June 18 2012.
[52] Meteoriteguy.com. "Mundrabilla 1: 23.2 gram endcut", https://meteoriteguy.com/catalog/mundrabilla.htm Accessed June 10 2022.
[53] 911metallurgist.com. "SHAPED CHARGE", https://www.911metallurgist.com/rock-boulder-exploding-techniques/ Accessed May 30 2022.
[54] Havoc.com "Linear cutting charge", https://havoc.com.au/explosive-products/focused-charge-info Accessed May 30 2022.
[55] Journals.ametsoc.org. "EDDY – CTRL differences", https://journals.ametsoc.org/view/journals/clim/32/2/jcli-d-18-0415.1.xml Accessed May 20 2022.
[56] Knowledge management. "Shaped charge", https://www.ordn.navy.mi.th/km/knowledge/2561/060-61.pdf Accessed May 30 2022.