PROJECT KHEPRI

FEASIBILITY REPORT

Image from: NASA

MINING ASTEROID

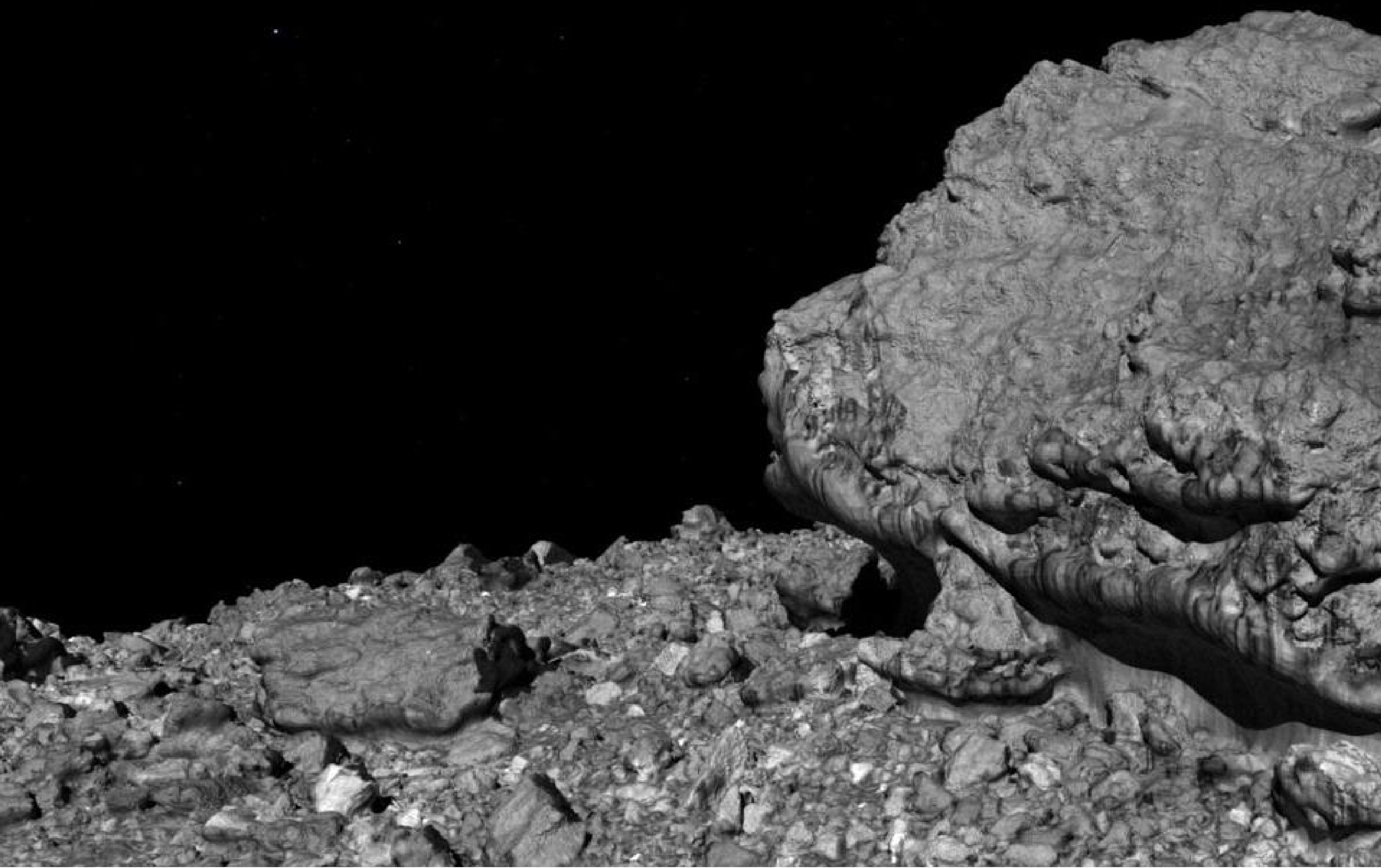
BENNU

KHEPRI

Water has been identified as a critical resource for development of robust cis-lunar infrastructure. Providing a potential source of clean-energy propellant and/or an essential consumable for humans or agriculture on crewed trips to the Moon or Mars while avoiding high costs of launching from Earth is thus a highly desirable element to cis-lunar infrastructure.

The OSIRIS-REx mission provided a complete survey of the asteroid Bennu and will return regolith samples to Earth in 2023, making this a well-understood and low-risk target that is estimated to be around 6.26% water by mass.

The Khepri Project comprises a team of international students, academics, and industry subject matter experts working on the technical design, business case, and political aspects of a mission to mine asteroid Bennu for water.



This multi-year mission would see robotic explorers sent to both an orbit around Bennu as well as to Bennu's surface, culminating in tonnes of water extracted for transport back to cis-lunar space for immediate use. Additionally, mining asteroid Bennu is an unprecedented scientific opportunity to study the formation of our solar system - large-scale operations could enable kilogram-scale samples across Bennu's surface and subsurface.

Such an endeavor would provide new opportunities for synergy with other industries, such as Canada's well established mining sector. Future mining of near-earth asteroids provides additional resources (e.g. rare earth elements) to support Canada's manufacturing sector as well.

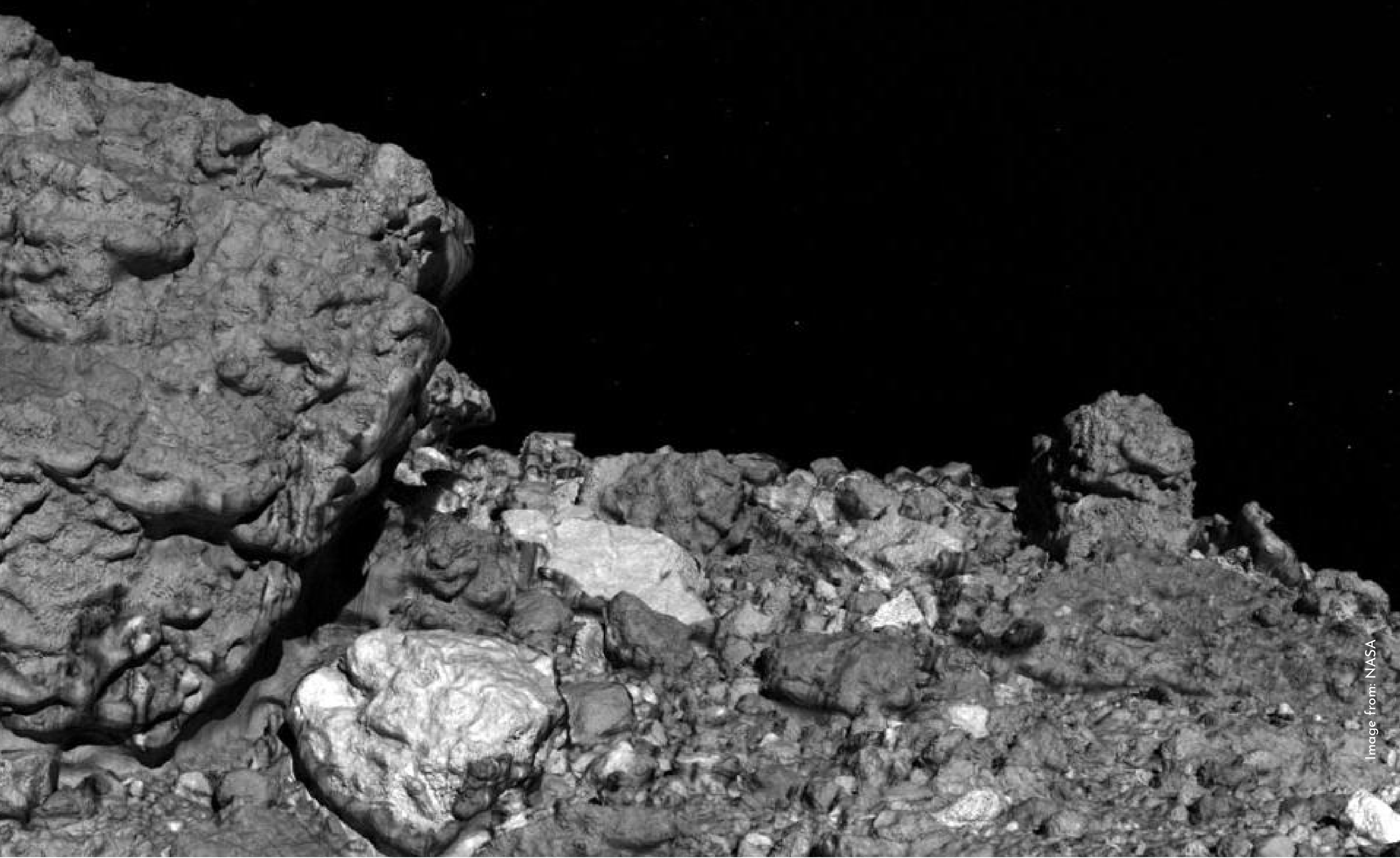


Image from: NASA

Project Objective

The goal of this study is to make an engineering, business and policy case for a proposed asteroid mining mission for the Canadian Space Agency and other interested commercial parties. Water has been identified as a critical resource for development of a robust cis-lunar infrastructure. Providing a potential source of clean-energy propellant as well as an essential consumable for humans or agriculture on crewed space exploration missions, while avoiding high costs of launching from Earth is thus a highly desirable element to cis-lunar infrastructure.

The OSIRIS-REx Mission's spectral analysis revealed that Bennu has on average 6.26% water by mass. With Bennu's measured mass of roughly 73.3 billion kg and a current valuation of launch costs being roughly $8000/kg, this values the water on Bennu at approximately $37 trillion. Given this valuation, this poses great economic value for Canada and a space mining industry to mine water at Bennu.

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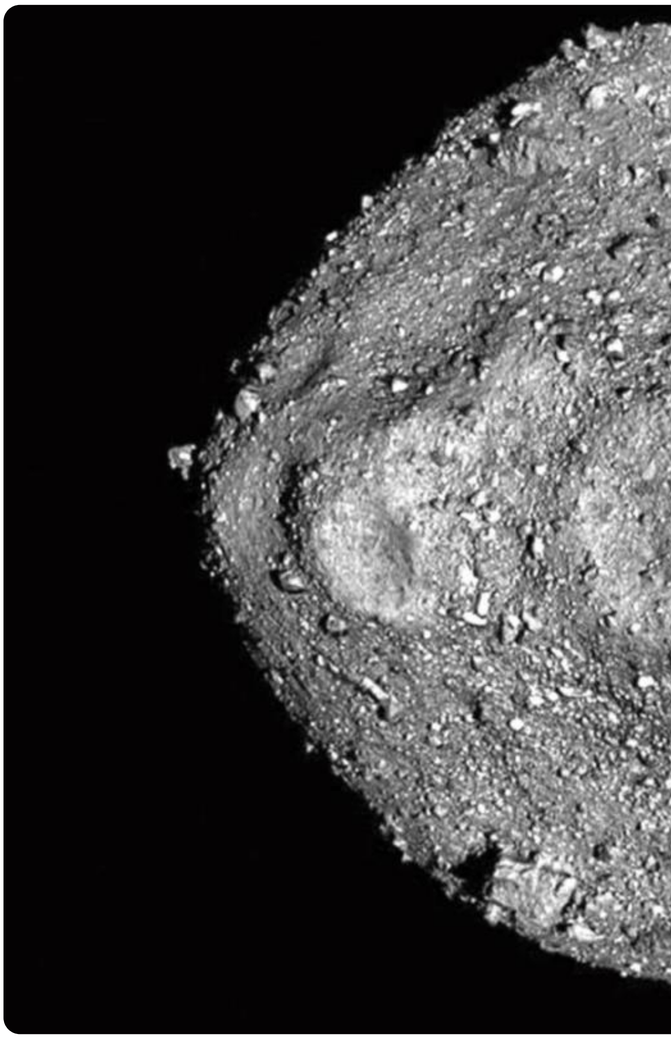
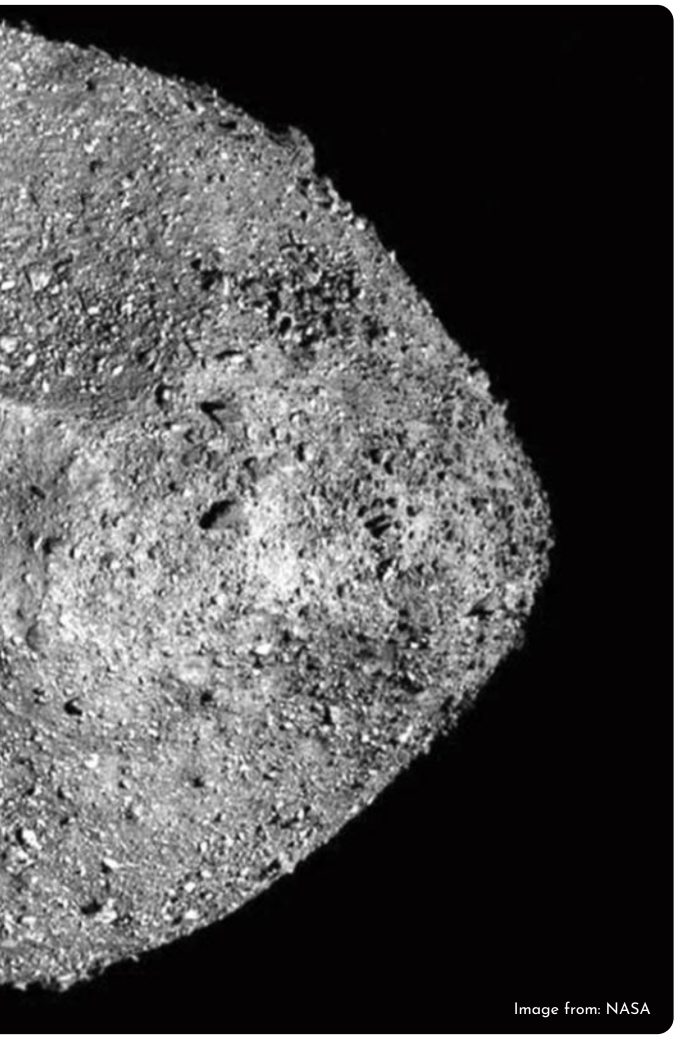


Market

The Bennu market is expected to have some similarities with the Lunar market and new emerging markets such as cannabis. Like the cannabis market, a Bennu market would require international playgrounds, a shift from public investment to a combination with private, as has been occurring in the USA, and non-Space companies' involvement. This makes an asteroid mining market very interesting and attractive.

Investment

Investors in both the public and private sectors would likely be required with us aiming for a 50/50 split between private and public investment, with participation at the mission onset from the government, and with the private sector contributing over time. An initial test mission, which would likely be needed to prove many technologies, would need to be funded by the government to help attract private investment. Space missions typically have a low ROI, which makes it difficult for investors to have confidence. Such a mission could likely have a lower bound expected ROI of 30%, similar to that of Space X's Falcon 9 ROI of 27%, with no maximum ROI. The mission design aims for an ROI of 100%, though the feasibility to achieve this figure would need to be tested.



Budget

The mission was designed for a $1.5 billion dollar budget, with $300 million allocated for two Falcon Heavy launches to get the mission started. That leaves $1.2 billion for the construction and operation of the craft. The labour costs would consist of about 50% of the non-launch cost budget which comes out to $600 million dollars and is distributed into four phases, 10% for the 1st phase, 25% for the 2nd phase, 35% for the 3rd phase, and 30% for the final 4th phase. These four phases and their $600 million budget include the expenses of continued operations for the duration of the mission. This leaves $600 million for materials and testing equipment and any non-labour expenses for the mission. Typical space mission budgets are much larger than this figure, but if the terrestrial technologies can be proven for space, and commercial off the shelf (COTS) parts can be utilized, it may be feasible to meet such a budget.

Budget Breakdown

Cost Budget by Mass	Mass (kg)	Money ($M)
Fuel (Water) - Roughly $1/250kg	13756	~0
Mailman	2000	60.5
Mothership	19922	603.1
Pickers (4)	3930	119.0
Water Tanks (2)	1000	30.3
Total (excluding water)	39642	1200.0

Feasibility Of Policies

There is currently no law explicitly addressing space resource extraction. While states and scholars alike are continuing to come to a consensus that extraterrestrial mining does not conflict with existing space law, there are still considerable gaps in the legal framework that should be addressed before mining is feasible.

Existing Legal Landscape

The Outer Space Treaty is widely considered to be the foundation of international space law. Article I states that space activities "shall be carried out for the benefit and in the interests of all countries" and that there is a freedom of use. Article II establishes the non-appropriation principle, clearly prohibiting traditional means of acquiring territory, sovereignty or rights over land. Article VI creates state responsibility of private actors in space and requires state "authorization and continuing supervision". Further, Article VII creates liability for states for damage caused by space objects, including those from private actors. There is some agreement that extraterrestrial mining would not conflict with the non-appropriation principle and falls within the freedom of use. There is less consensus on what would be considered 'for the benefit of all' and there is a need for a regulating framework at both the international and national level.

Industry Recommendations

There is an opportunity for industry, Canada and the international community to work towards enabling space mining. While this legal framework is developed, one scheme would be for industry to contribute a portion of profits to be set aside, such that later it could be used for the 'benefit of all'. This would be conducted in cooperation with the Canadian government. Regardless, any industry looking to launch a mining endeavour will need to work with a state that will be willing to assume responsibility for their activities in space under Article VI and VII. Further, industry can continue to progress scientifically through demonstration of mining technologies, towards future mining Asteroid Bennu.

National Recommendations

National legislation may be controversial with some State actors, but it can still provide much-needed security for the private sector and can contribute to the development of soft law at an international level. For these reasons, and to ensure that Canada takes advantage of this opportunity to be at the forefront of space mining, it is recommended that Canada pass national legislation similar to that passed by the United States, Luxembourg and the United Arab Emirates. This is an opportunity for Canada to contribute distinctly to the development of international law, given that Canadian mining law is amongst the most thorough.

The current legal framework is not sufficient to regulate extraterrestrial mining. To enable space mining, it is recommended that industry continue to advance technologically and work with the government, Canada pass national legislation and the international community work towards developing soft law principles.

International Recommendations

Coupled with adopting national legislation, Canada should continue to cooperate through international fora to develop non-legally binding principles, otherwise known as 'soft law' to contribute to a bottom-up approach. While national legislation can contribute to a bottom-up approach, international coordination is needed to ensure that property rights are recognized internationally, not only within national borders, and to mitigate potential risk and conflict. It is now the responsibility of the international community to come to consensus and provide the necessary oversight to create a more thorough set of principles, regulations, or laws, granting governments and private actors the freedom to operate in the space mining sector.

Feasibility Of Mining Bennu

Bennu is an aqueously altered Carbonaceous Chondrite rubble pile asteroid that formed from a parent body hundreds of kilometres in size that was destroyed in a large impact. What this means is: Abundant water – up to 6.7% by weight in some areas can be found on Bennu in the form of clay minerals, which comprise up to 67% of the material in its boulders.

Although the average water content of Bennu is 6.2% by weight, local relative variation is approximately 16%, offering opportunities to high-grade the surface for increased profit. It was determined that variation in water content is closely tied to rock type. Two major classes of rocks can be defined on Bennu that arise from variation in the parent body: large, dark boulders that are interpreted as a type of rock called regolith breccia, which consists of angular chunks of older rocks broken apart through impacts and recemented. These rocks formed near the surface, while the other rock type that consists of bright, smooth boulders formed deeper underground. The bright boulders were subjected to more intense hydrothermal alteration which converted the original minerals to clays, which contain abundant hydrogen and oxygen in the form of hydroxyl ions trapped within their crystal structure. The result is an abundance of high-grade, easily detectible ore scattered across Bennu's surface.

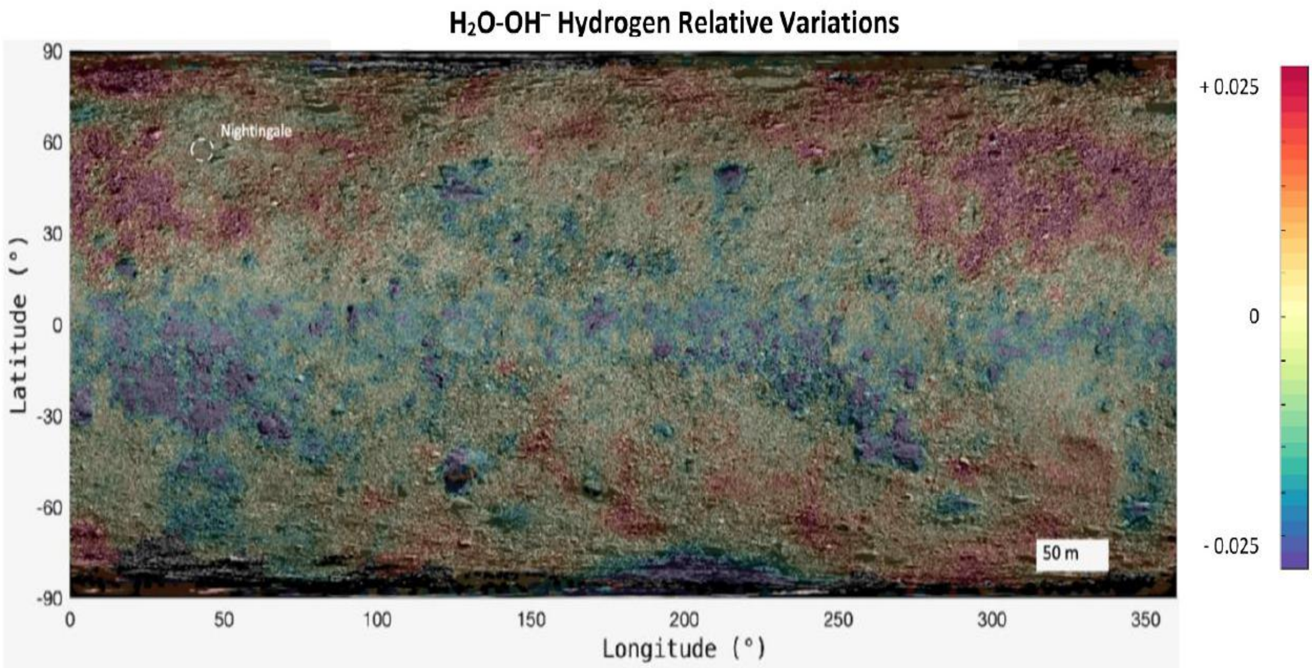
The large dark boulders were formed on the surface of Bennu's parent body. They are weak and soft which causes them to crumble upon impact

The bright and smooth boulders are those which formed beneath the surface. These are strong and brittle, causing them to crack upon impact

GLOBAL HYDROGEN DISTRIBUTION MAP

The Khepri project mapped the global distribution of bright, smooth, boulders and found that they are heavily concentrated in the Northern hemisphere. We estimate that there are approximately 80,000 of these bright boulders in the 1-3m size range between 60 degrees north and south, which would allow for fulfillment of the mission's production requirements several times over.

Previous work by Praet et al. using spectroscopic data from the OVIRS instrument aboard NASA's OSIRIS-REx spacecraft mapped the global variation of hydrogen on Bennu. We found that the areas of highest water content identified in that paper agree well with our distribution maps of high-albedo boulders. The total variation in water may be as great as 60% relative to the average, which emphasizes the value of targeting water rich boulders.



Global hydrogen variation map from Praet et al. demonstrates the patterns in hydrogen content on Asteroid Bennu's surface.

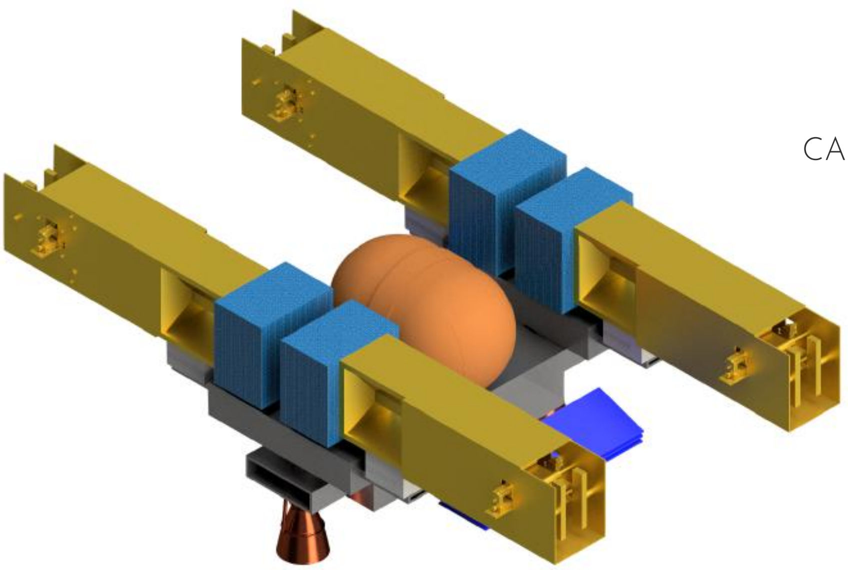
Feasibility Of Mining Mission

ROBOTICS FOR USE IN MINING

The boulders present on Bennu provide well defined targets for extraction. Such "bite-sized pieces" could be retrieved robotically using present day technology.

Pursuing such a mission provides an opportunity to demonstrate novel surface operations on small bodies leading to future asteroid mining endeavors. These include: use of autonomous robotic elements; improved in-situ resource utilization (ISRU) technologies; and deep space rendezvous. This multi-year mission would see robotic explorers sent to both an orbit around Bennu as well as to Bennu's surface, culminating in tonnes of water extracted for transport back to cis-lunar space for immediate use.

The concept mission conceives 4 different robotic elements to achieve the goal of mining Bennu: a "mothership" (which will carry out the processing of Bennu materials); a "Minecart" (which will transport boulders from the surface to the mothership); a "Mailman" (which transports vehicles from cis-lunar space to Bennu and transports water back); and a "Water Tank" (which would simply contain collected water).

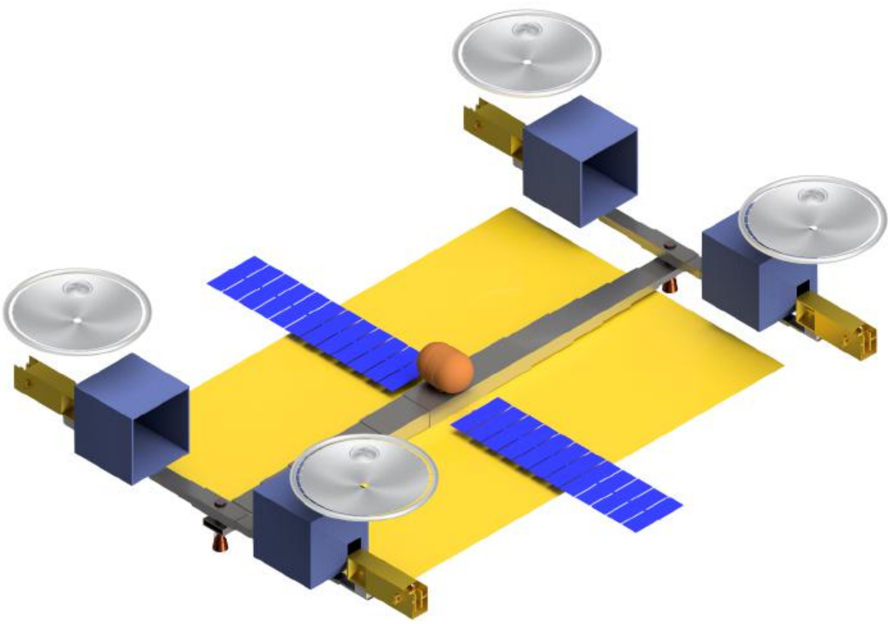


CAD model of the processor/mothership in the launch configuration.

Moving Boulders Off The Surface

Bennu has a microgravity environment, which has benefits for the required thrust to interact with Bennu, but introduces dangers with the potential debris would could be created by impingement Bennu's almost cohesionless surface. This interaction would be completed by the Minecarts. The Minecart supports a boulder gripper and ferries boulders between the Bennu surface and the processor on orbit. The boulders are held securely by the gripper until deposited at the boulder crushing mechanism on the processor. There are four Minecarts launched and are docked on the mothership, each weighing at most 4 tonnes. Multiple Minecarts can be operational concurrently and independently to maximize the processing efficiency. They communicate with the mothership directly during operation and are recharged when redocked with the mothership. The propellant refueling capability is also available, but the fuel capacity on Minecarts is expected to last for a significant portion of the mission. Despite this, because the delta-V requirements in Bennu's environment are so low, not much fuel is needed over the entire mission.

The Minecart design uses currently available technologies; however, the grappling of surface boulders would represent a new challenge. This has, however, been partially demonstrated through the capture of vehicles on ISS (Known as "Free Flier Capture"), and modifications for the unstructured nature of Bennu's boulders could be done. Similar technologies such as dexterous robotic manipulators and specified end effectors could be used to collect boulders off the Surface of Bennu. Maneuvering to and from the surface of Bennu has been demonstrated via the OSIRIS REx mission.

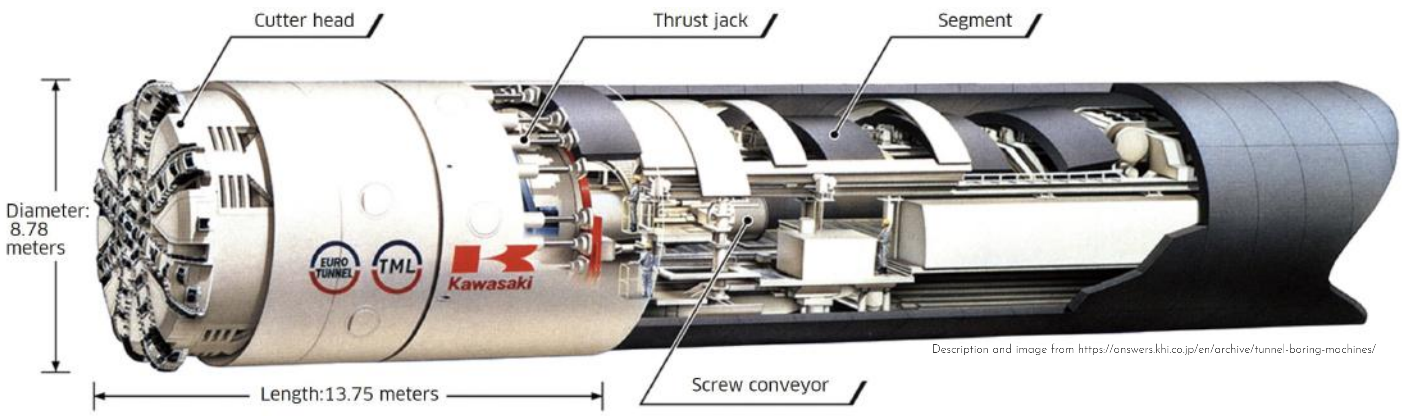


CAD model of the processor/mothership in the deployed configuration.

Crushing Boulders

The boulders can be processed either as a whole or as a crushed particulate. There are benefits of crushing the boulder material first, namely increased surface area so faster rates of heat transfer and faster water extraction. Crushing a boulder into small particles could be done many ways, with inspiration taken from terrestrial mining techniques. The boulder material is very brittle and can be thought of as analogous to chalk, which is very different from hard ore typical harvested in Earth mining. When the Channel Tunnel Boring Machine bored the Chunnel, it interacted with similar soft limestone rock. This indicates that tunnel boring machines could be used in this space application. The exact geometry and design of such a tunnel boring machine face would have to be designed, analyzed and tested, but could be done with some technological investment, and could be demonstrated in orbit with a Bennu-regolith simulant.

The structure of the Channel Tunnel Boring Machine built by Kawasaki in 1991. The cutter head is rotated to excavate the tunnel. The tunnel walls are built through the connection of ferroconcrete segments, which are secured into place by the thrust jacks.



Feasibility Of Water Extraction

DEHYDROXILATION

The release of water trapped with the surface materials of asteroid Bennu requires heating to 900C and trapping the resulting water vapour. This is a known process done terrestrially and therefore, it is quite possible with minimum technological investment.

OPTICAL HEATING

Several technologies were considered in provided sufficient power to heat the boulder material to 900C, and ultimately solar condensation was selected owing to its high efficiency, and abundant supply of solar energy from orbit.

Optical Mining uses concentrated solar power to excavate carbonaceous chondrite asteroid surfaces and reduce the asteroid to fragments while releasing volatiles. Experimental evidence is shown that supports the Optical Mining method. Asteroid simulant materials have been tested and shown to release volatiles readily. Although this technology is new in space, it is well understood and would require a modest investment to demonstrate such a technique in orbit.

Stages of the Optical Mining process:

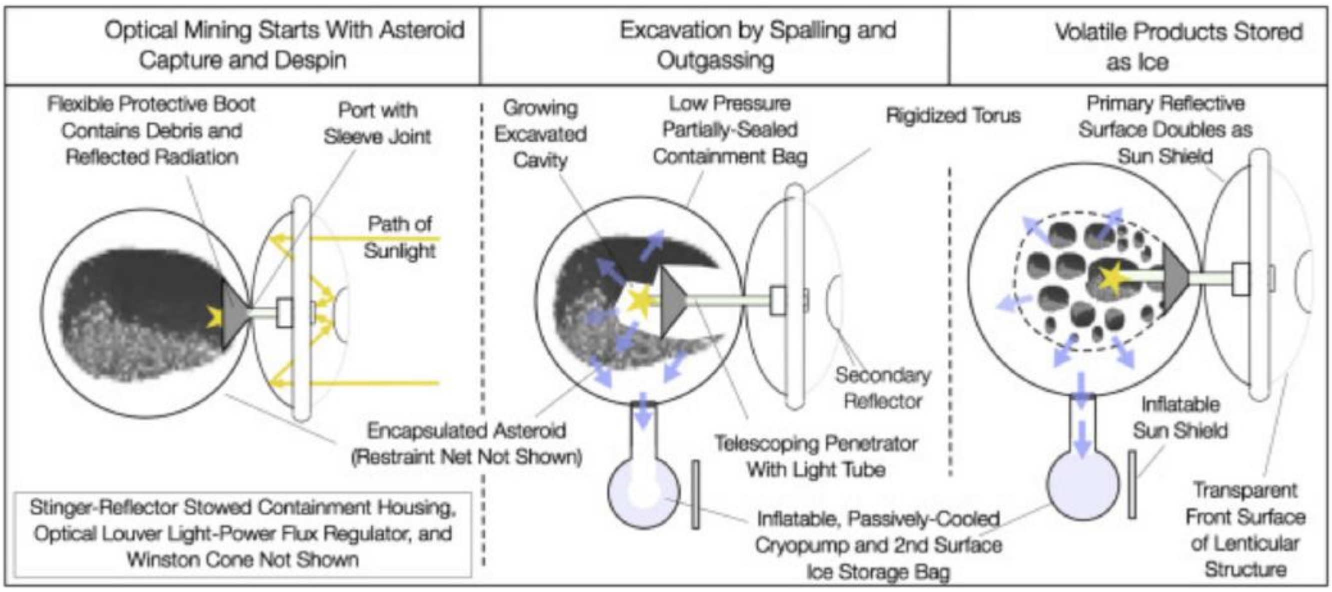
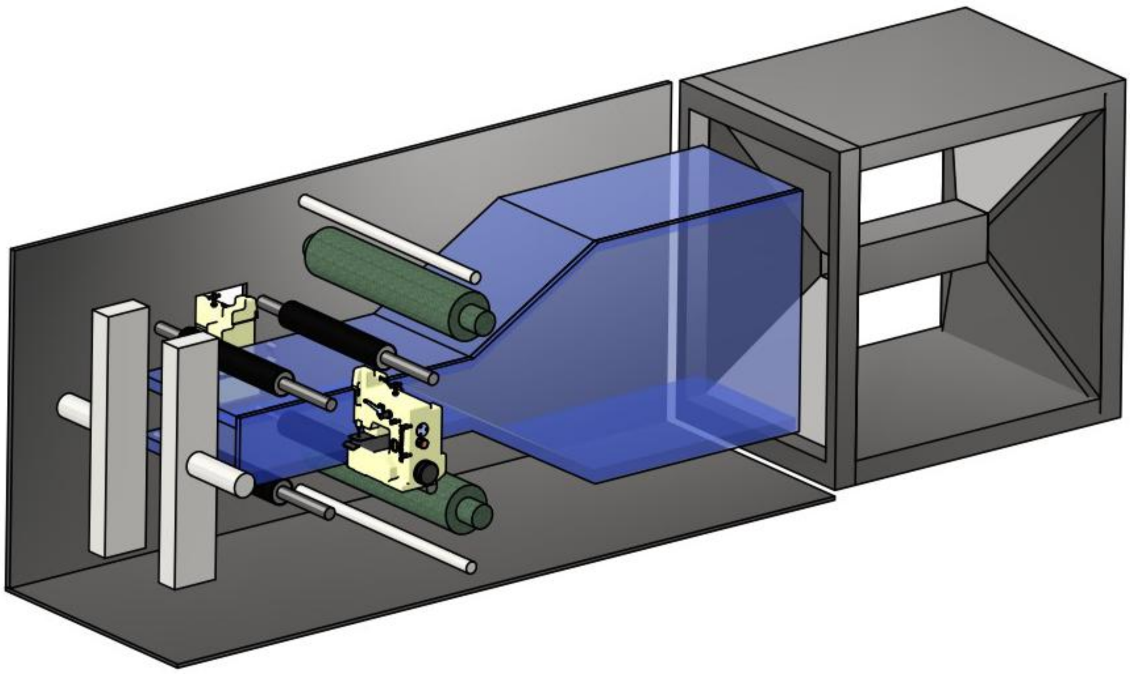


Image from: Sercel, Joel C., et al. "Practical Applications of Asteroidal ISRU in Support of Human Exploration." Primitive Meteorites and Asteroids, Elsevier, 20 July 2018, https://www.sciencedirect.com/science/article/pii/B9780128133255000094.

TAILINGS DISPOSAL

To keep in accordance with space debris policies and to ensure the orbit of Bennu is undisturbed, the disposal of the mining tailings must be considered. The tailings must be secured and can either be disposed of in a stable orbit or back on the surface of Bennu. The proposed design involves sealing the tailings in a CNT bag and placing them on the surface of Bennu. This should also ensure that the tailings will not interfere with other mission infrastructure.

CAD model of proposed tailings disposal system

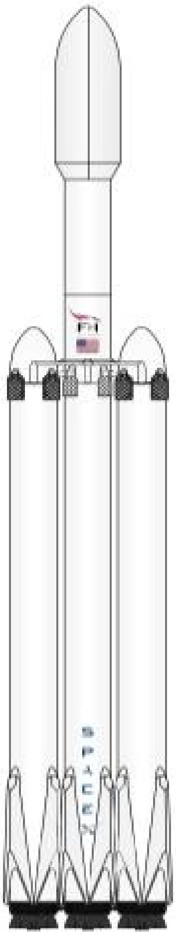


Feasibility Of Proposed Mission

The proposed mission utilizes current launch vehicles, such as the Falcon Heavy. The concept would fit into two launch vehicles while meeting mass requirements, one launch for the main mothership, and the other for the other mission components, namely the mailman, the minecart, and the water tanks.

After launch, each payload must complete several deep space maneuvers to set the correct trajectory for Bennu. This transit from Earth to Bennu is known and has been demonstrated by OSIRIS-REx.

Many thrusters in development use liquid oxygen and hydrogen propellant, such as the BE-7. This type of propulsion is necessary to generate large enough thrusts to move the massive payloads, but also to be able to use the eventual mined water as propellant, so that all required propellant does not need to be brought to Bennu for future return trips to cis-Lunar space. Such propulsion systems would be required by the mothership and mailman.



The Falcon Heavy launch vehicle developed by SpaceX.

Image from:
https://historicspacecraft.com/Rockets_SpaceX.html

One area for development would be the electrolysis of water in order to make use of water collected at Bennu as a propellant source. Electrolysis is a well-known process employed on terrestrial systems; however the rate of electrolysis would have to be set to match the demands of the thrusters. This would minimize storage requirements of liquid hydrogen - a known technical challenge owing to hydrogen escaping most containment systems.

Deployable architectures, which would be required by nearly all the spacecraft in order to fit inside the launch volumes, are common to space missions. Once in space or at the final destination, periods of egress would allow the spacecraft to deploy to the desired configuration.

A final procedure critical to mission feasibility is docking mechanisms and operations. This includes docking of the water tanks to the mothership, pickers to the water tanks and mothership, and mailman to the water tanks and customer station in cis-Lunar space. Autonomous docking operations have been demonstrated by the SpaceX Dragon and are currently being considered for Gateway.

SpaceX Dragon docking to the International Space Station

Image from: https://www.businessinsider.com/spacex-crew-dragon-capsule-nasa-demo1-mission-iss-docking-2019-3

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