PROJECT KHEPRI: FEASIBILITY STUDY OF MINING ASTEROID BENNU. S. Maharaj[1], A. Chhabra[1], A. Gee[1], E. Richardson[1], J. Empey[2], H. Abdul-Nabi[3], E. Frost[3],A. Talukder[3], L. Richards[3], G. Boyala[4], A. Gremm[4], A. Gungor[4], A. Taghipour[4], M. Bielle[5], J. Qiu[5], A. Raj[5], and C. Dickinson[1,6], [1]University of Toronto (27 King's College Cir, Toronto, ON M5S, saanjali.maharaj@mail.utoronto.ca), [2]University of Waterloo (200 University Ave W, Waterloo, ON N2L 3G1, jempey@uwaterloo.ca), [3]University of Western Ontario (1151 Richmond St, London, ON N6A 3K7, habdulna@uwo.ca), [4]University of Alberta (116 St & 85 Ave, Edmonton, AB T6G 2R3, boyala@ualberta.ca), [5]University of Arizona (1200 E University Blvd Tucson, AZ 85721, maxb24@email.arizona.edu), [6]MDA Ltd. (9445 Airport Road, Brampton, ON, Canada L6S 4J3, cameron.dickinson@mda.space).

Motivation: Water has been identified as a critical resource for development of robust cis-lunar infrastructure. It is a potential source of clean-energy propellant and an essential consumable for humans or agriculture on crewed trips to the Moon or Mars. Furthermore, in-situ utilization of this important resource would avoid high costs of launching from Earth.

The OSIRIS-REx mission provided a complete survey of the asteroid Bennu and will return regolith samples to Earth in 2023, making Bennu a well-understood and low-risk target [1]. OSIRIS-REx's spectral analysis revealed that Bennu is composed of roughly 0.49% to 0.91% hydrogen by mass on the surface, and between 4.4% and 8.1% water by mass [2]. While certain types of rocks or "boulders" are targeted with a known spectral abundance of hydrogen (higher end), an average value is roughly 6.26% by mass of water, meaning with a mass of 73.29 billion kg, Bennu contains 4.588 billion kg of water. With a current valuation of launch costs being roughly USD$8000/kg, that values the water on Bennu at USD$37 trillion. Given this valuation, a mission to mine water from Bennu poses great economic value.

Introduction: The Khepri Project (2022) comprised a team of international students, academics, and industry subject matter experts that worked on the technical feasibility, business case, and political aspects of mining asteroid Bennu for water. An overview of the Khepri Project's proposed design and results are presented herein.

The feasibility study outlined a multi-year mining mission, in which robotic explorers would be sent to Bennu, culminating in tonnes of water extracted for transport back to cis-lunar space for immediate use. 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.

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 paper outlined the various elements considered in this feasibility study, culminating in a basic mission concept. First, background was examined with a focus on relevant reference missions and existing methods and technologies. Following the review of the literature, trade studies were conducted to define the overall mission architecture in terms of orbital vs. surface operations, and single vs. multi-vehicle architecture. Trade studies for specific mechanisms included gripping (microspine vs. soft-body vs. rigid-body), crushing (inspired by lemon-juicer, auger, tunnel-boring machine, nutating engine concepts), processing of boulders (solar power, nuclear power, solar and battery power), and the disposal of tailings (surface vs. orbital disposal).

Mission Architecture: The broad alternatives for mission architecture were broken down into orbital operations and surface operations. The result of the trade study based on metrics of water yield, fuel consumptions, debris impact, complexity and duration was that orbital operations are superior. This multi-vehicle architecture involves a 'picker' spacecraft descending to the surface, collecting a boulder and transporting it to orbit where processing occurs on the mothership (*Fig. 1*). The finalized systems for the mission are presented below in further detail.

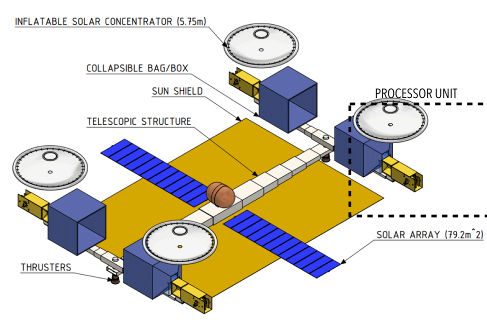

Fig. 1: Mothership Architecture.
The processor units are spin around a pivot to create a low-gravity environment for processing.

Systems Design: The system-level and subsystem-level requirements were derived and the details of the design illustrate a potential path to flight.

Gripper. This mechanism is required to pick up the boulder from the surface of Bennu regardless of the shape or orientation and without crushing it. The result of the trade study was that a rigid-body gripper *(Fig. 2)* was superior to microspine and soft-body grippers.

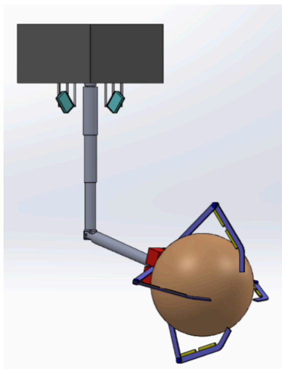

Fig. 2: Gripper

Processor. As previously determined, the boulder would be processed to extract water on the mothership in orbit, so multiple boulders can be processed simultaneously. The most efficient method would be to first crush the boulder to increase the overall surface area. The trade study for the crushing mechanism concluded that a mechanism similar to a Tunnel Boring Machine (TBM) face *(Fig. 3)* is the best option. Processing the crushed regolith into water is to be accomplished by Optical Mining. This process uses a condenser to focus sunlight onto the stream of regolith so the solar energy can facilitate water generation via dehydroxylation. The water is then collected using a cold finger mechanism.

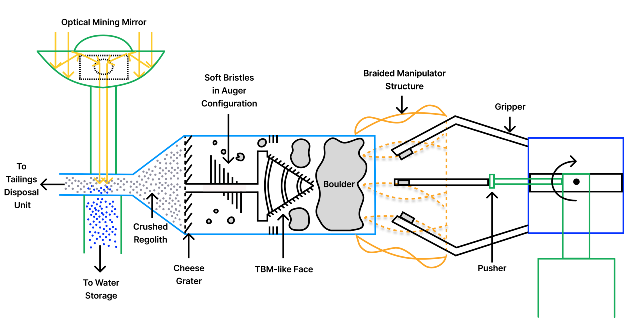

Fig. 3: Crushing Mechanism

Tailings Disposal. This mechanism is required to adhere to policies regarding space debris while not affecting Bennu's orbit. A trade study found that it was preferential to dispose of the tailings on Bennu's surface rather than in orbit. To increase the security of the disposal, a sealed bag is to be used. The material selection study concluded that carbon nanotubes would be ideal, and the sealing mechanism was chosen to be a stitcher *(Fig. 4)*.

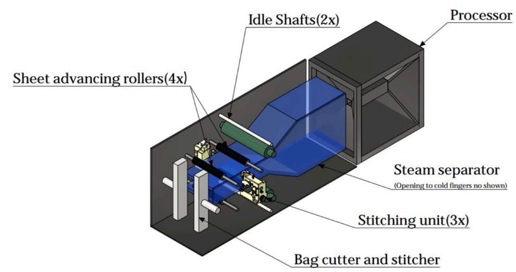

Fig. 4: Tailings Disposal Unit

Budget: The mission cost estimate was also presented. The proposed design had a $1.5 billion dollar budget, which was broken down by the launches, mass of the spacecraft, and labour and non-labour costs of construction, testing, and operations.

Conclusion: There is a certain level of confidence in the launch and timeline calculations, and the processor method leverages current technologies. However, some elements of this mission must be further researched in future. These include the development of the thrusters, fleshing out the TBM concept in further detail, and developing physical models of the tailings disposal unit for testing.

Overall, the Khepri Project outlined a preliminary concept that would allow humanity to leverage Bennu's abundant water resources for the benefit of future space missions.

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