**Optical Mining at Mines – A Spallation Mining Model**

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**Introduction:** In-Space Resource Utilization (ISRU) aims to decrease costs of space exploration and space travel- eventually leading to its habitation. It will also play a strategic role in the development of both a global space economy, and more localized national space developments [1]. In the Near-Earth Object (NEO) population of asteroids alone, the United States Geological Survey (USGS) has estimated 11,000 Gtons of water and 61,000 Gtons of Iron available for recovery [2]. Cannon et al also estimated the abundance of other elements that have been detected on asteroid bodies [3] .

The Optical Mining method, developed by Trans-Astronautica Corporation, aims to harness the power of the sun to extract volatiles from NEO's for use as propellant feed-stock/consumables. This mining method delivers highly focused solar light on the surface of a 1 - 10 m asteroid to cause optically induced thermal spallation- excavating the asteroid into small fragments, and simultaneously thermally decomposing the minerals to release volatiles [4].

This presentation includes the current progress of a predictive spallation mining model based on current experiments of Optical Mining performed at Mines. Experimental and model results for excavation rate, water production rate, and surface temperatures at spallation are presented. Planned results to be presented are optimization of the Optical Mining parameter space, and a study on the application of this model to an asteroid mining campaign.

**Experimental Methods:** Optical Mining experiments were conducted under vacuum (0.1 – 3 torr) in the Apollo vacuum chamber at the Mines Center of Space Resources Lab. A 15kW Xenon arclamp bulb and a parabolic reflector were used to simulate collected sunlight in space and direct/focus the light on an asteroid simulant cake inside the vacuum chamber (Fig. 1). The asteroid simulant ("Nectar") used during experiments was developed to mimic the mineralogical composition of CI/CM asteroids. The simulant cake was positioned at various points along the beam path to test effects on excavation/water production rates of different beam irradiance distributions. Due to incorrect sourcing of the mineral ingredients (Vermiculite), the later Nectar simulant possessed Vermiculite that had been exfoliated and appeared to mainly melt rather than spall as compared to the earlier experiments. A Newmark rotary stage was used to rotate the sample to increase the mined area. 4 planar load cells and a postal scale were used to collect mass losses during the tests to calculate excavation rates. These were then compared to the average irradiance in the Full-Width Half Max (FWHM) zone of the beam. Produced volatiles were tracked using a residual gas analyzer with a 200 amu range (RGA-200), and volatiles such as H2O and CO2 were captured with a liquid nitrogen cold trap – only the latter was measured. Pressure in the main chamber and RGA-200 sampling chamber were recorded using a MKS-947 and an Inficon MPG-400 gauge, respectively. Pressure in the Apollo chamber was used to ensure that the system remained under the triple point of water(~4.5 torr), and in estimating the volatile partial pressures/masses present in the atmosphere of the chamber alongside RGA data. The collected water was left to thaw under dry air and collected in an aluminum pan placed beneath the cold-trap.

Beam irradiance values along the beam propagation path were measured with a water cooled gardon gauge system attached to 3 linear motorized stages (Fig. 1). Experiments were also conducted on the Nectar simulant cores to measure thermal and mechanical properties. This data was pivotal for use as inputs into the model.

**Modeling Methods:** A MATLAB model predicts the temperature/ stress distribution in a body and uses Weibull fracture statistics to compute a probability of failure (via thermal spalling) of the stressed material. The transient temperature solution utilizes the 1-D volumetric finite difference method that solves the heat equation numerically at each time step, with a radiation and a constant temperature B.C at the first and last node, respectively. Thermo-elastic compressive stresses are computed at each node and are used as inputs into the Weibull probability function. Additional stress contributions from morphological effects (Vermiculite expansion) are also taken into account. Several reactions are included in the model and are based on equilibrium assumptions. The surface node is also assumed to expand (in correlation with experimental observations). Once the probability value is equal to or greater than 0.5, the criteria for spallation is met and the model simulation is stopped. Due to drastically different responses of the Nectar simulant during the testing campaign, the model was tuned to predict the responses observed during experiments – based on the earlier Nectar simulant possessing un-exfoliated Vermiculite

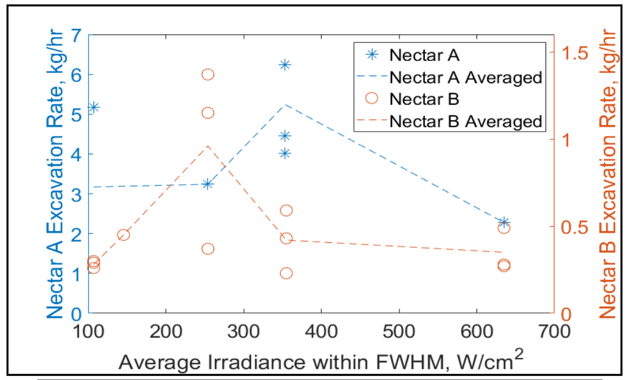
(Nectar A) and the later Nectar simulant possessing exfoliated Vermiculite (Nectar B).

**Experimental/Model Results:** A total of 24 Optical Mining experiments have been conducted to date. Fig. 2 showcases the two types of Nectar cakes undergoing Optical Mining. Plot 1 shows maximum 1-min averaged experimental excavation rates results split into Nectar A/B. The excavation rate was ~ 4 – 7x lower for Nectar B than Nectar A. Plots 2 - 3 showcase the current predicted excavation rates and comparison to their respective modeled simulant 1-min avg. excavation rates.

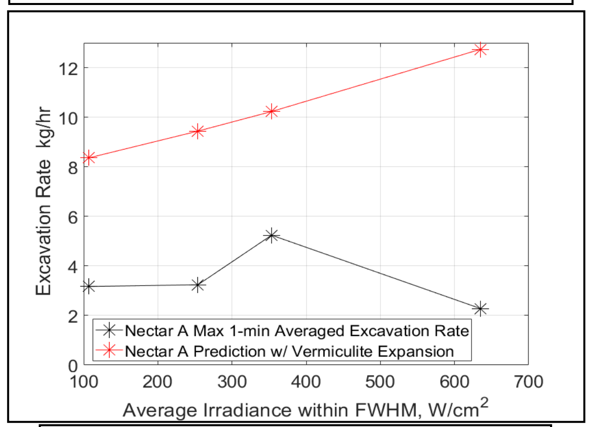
**Fig.1:** Gardon Gauge and Bulb/Reflector Assembly

**Fig.2:** Nectar A (L) and Nectar B (R) Showing Different Responses to Focused Light Under the Same Conditions

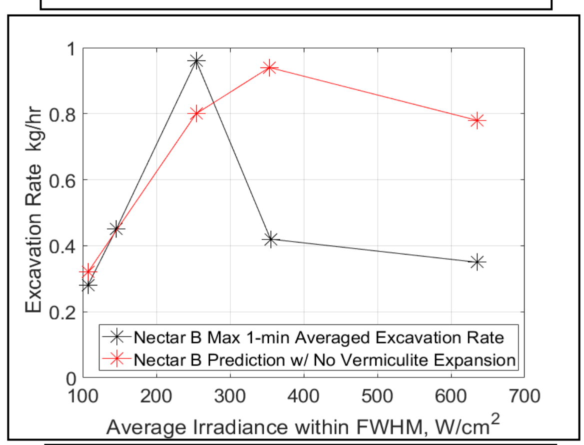
**Conclusion/Future Work:** From experimental results, it was observed there is an optimum beam irradiance distribution for excavation rate after the rate drops as the sample encounters stress relief or begins strengthening due to melting/sintering/chemical reactions. This irradiance distribution is dependent on material properties and material makeup as it occurs for different irradiance values for Nectar A and B. Experiments have also shown the importance of understanding the morphology of the material for Optical Mining, as was evinced by the conduve effects of Vermiculite exfoliation on spallation. Model results predict excavation rates within a factor of 2-3 based on tuning of model parameters for Nectar A, and have a close prediction at the 100 – 200 W/cm$^2$ irradiance range for Nectar B. When not accounting for Vermiculite expansion, the model agreement is better, and model results show an increase with irradiance and a drop off as the irradiance reaches a threshold where most of the surface begins melting causing stress relief and strengthening of material. Ongoing work includes additional physics to the model to explain the drop off in excavation rate for Nectar A/B simulant, application of the model to other materials using literature data, optimization of the process, and the application to an asteroid mining operation.




**Plot 1:** Nectar A/B Experimental Excavation Rates




**Plot 2:** Nectar A Excavation and Model Results




**Plot 3:** Nectar B Excavation and Model Results

**References:** . [1] A. J. & A. G. *Æther,* 4(2022),95-110. [2]L.K. et al. *Feasibility Study for the Quant. Assessment of Mineral Resources in Asteroids.* [3] K.C. et al. *Planet. & Space Sci.,225,*105608 [4] J. S. et al. *American Society of Civil Engineers,2016*. 507-522