ROCKETM
A Propulsive Excavation System

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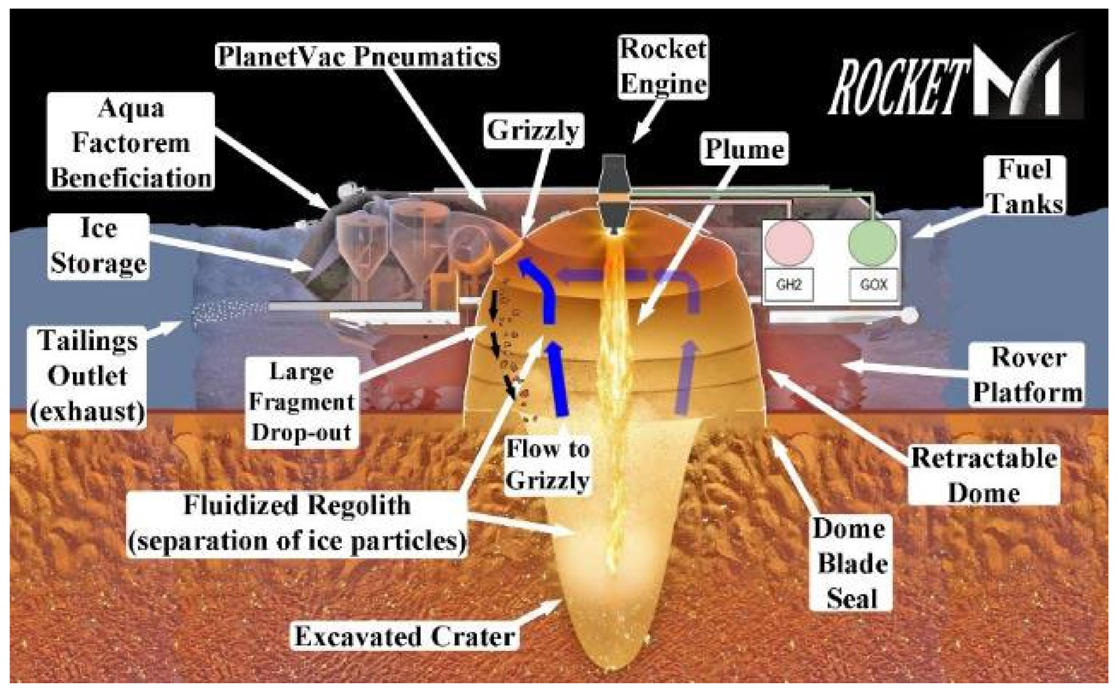
1. Abstract

- Lunar regolith and subsurface water ice are two key resources within the lunar ecosystem, and explorers will need systems to excavate and transport these materials across the surface of the Moon.
- Astrobotic is developing the RocketM system (**Resource Ore Concentrator using Kinetic Energy Targeted Mining**), a concept designed for efficient extraction of surface and subsurface material on non-terrestrial planetary bodies.
- A dome is sealed to the regolith surface, creating a volume that holds pressure, and a small rocket thruster within the collection dome fires into the regolith to liberate the material.
- Test results demonstrate that on average RocketM excavate 3.2 times more ice than propellant expended in the excavation process. Additionally, a portion of the extracted ice could also be processed to replenish propellants for the RocketM system.

2. System Overview

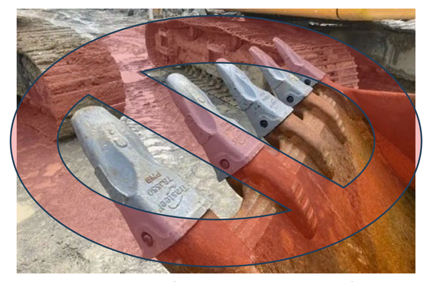
- The mobile system will traverse terrain to the desired excavation point, perform excavation operations, then return excavated material to the desired delivery point
- Major system components
  - **Rocket Excavator**: A small rocket (aprox. 50-100 lbf) that fires a plume into the regolith surface to induce deep cratering.
  - **Dome Collector**: This is the central dome that interfaces with the regolith surface and forms a seal along its perimeter to maintain a pressurized environment.
  - **Extractor**: Extracts granular material and ice from the dome and passes it to the beneficiation subsystem.
  - **Beneficiation Subsystem**: Separate ice material from granular regolith material
  - **Mobility Platform**: An LTV-class rover for transportation to/from excavation sites

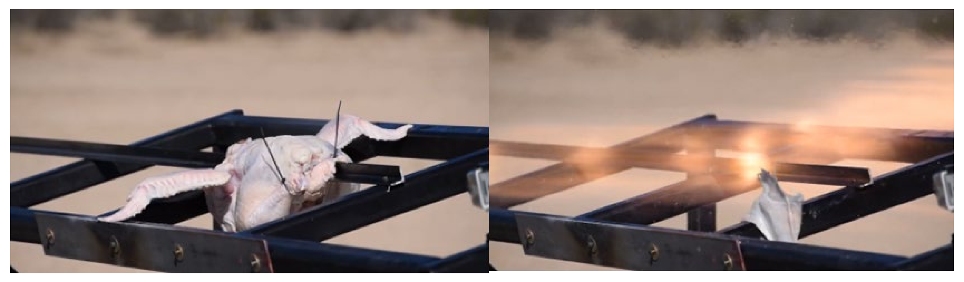


System overview developed for NASA's Break the Ice Lunar Challenge

3. Key Benefits / Concepts

- Excavation by rocket plume removes concern of tool wear from continuous contact with abrasive regolith.
- Active deep cratering was studied during work for PSI tests.
- Rockets are primarily designed to accelerate gases at high velocity. Kinetic energy of the plume is significant while heat transfer to the surrounding area is limited.


Terrestrial excavator teeth (Credit: enstruc.com)

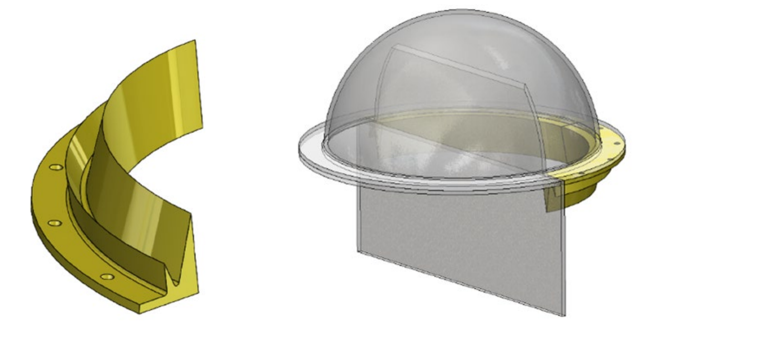

Ablative "turkey test"


Regolith deep cratering demonstrated during plume-surface interaction testing

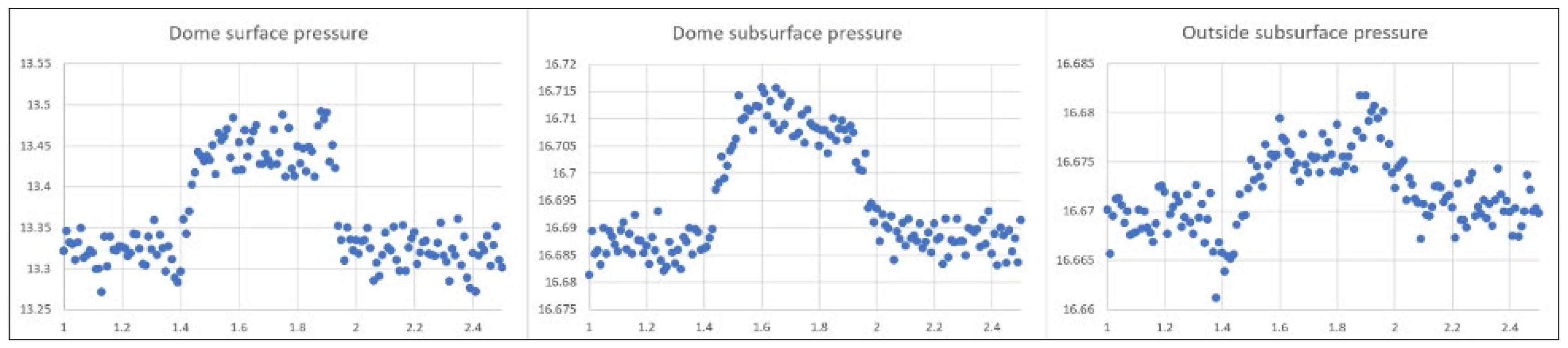
NASA SBIR Phase I Activities

4. Preliminary Cold Gas Testing

- Developed sub-scale dome with regolith-interface seal
- Used compressed nitrogen gas to include cratering, and tested different pulse durations (long pulse vs. multiple short pulses)
- Measured pressure within the dome at surface-level, within the dome below surface-level, and outside the dome below surface-level
- Conclusions: Seal design allows pressure to be held within the dome


(left) Dome seal Design; (right) Split-view dome prototype with seal affixed

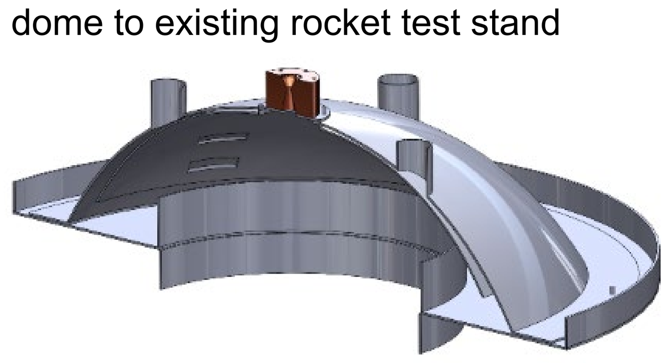

Cold gas test setup with nitrogen gas nozzle, dome prototype, split view window, and post-test measurement

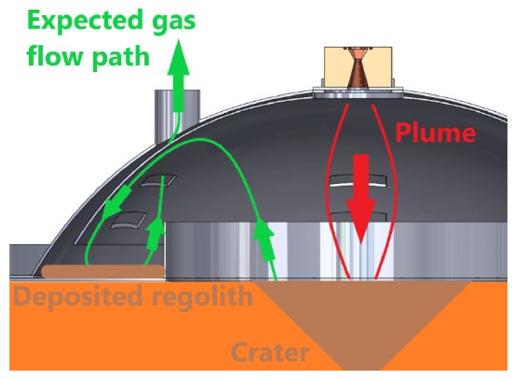


Pressure measurements at various positions of test setup

5. Hot Fire Testing – Dome Design

- Designed wide, shallow dome based on analysis of deep cratering from previous test programs
- Nested and separable domes with collection tray fabricated from commercial cooking woks
- Affixed dome to existing rocket test stand


Cutaway of RocketM dome interior



Expected flow path for dome gases


Fabricated dome; Removeable top for inspection between test fires


Dome integrated with rocket test stand

6. Hot Fire Testing – Setup & Test Parameters

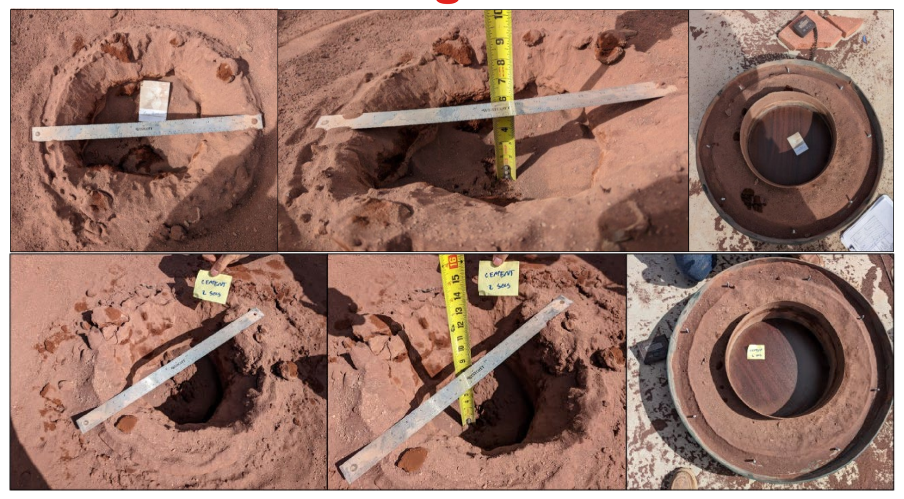
- Regolith simulant types: Dry, discrete ice, and cemented ice
  - Icy simulants 3% water by mass and prepped using liquid nitrogen
- Utilized existing PSI rocket engine; 100 lbf (450N) GCH4/GO2, heat sink cooling
- Rocket pulse durations types: 1 pulse @ 2s; 4 pulses @ 0.5s each
- Instrumentation: Pressure sensors in dome; TC's in dome; TC's in regolith subsurface; humidity sensor in exhaust; mass of the collection plate; regolith compaction; propellant flow rates and pressures


Prepping icy regolith with liquid nitrogen


Simulated cemented icy regolith


Thermocouples placed to detect thermal transfer into regolith adjacent to crater

7. Hot Fire Testing

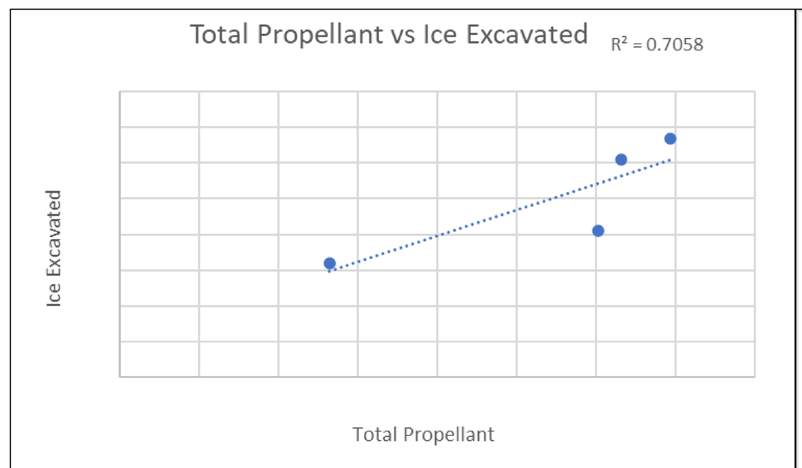

Post-test measurements after test fire


Active test fire; Dome exhaust venting

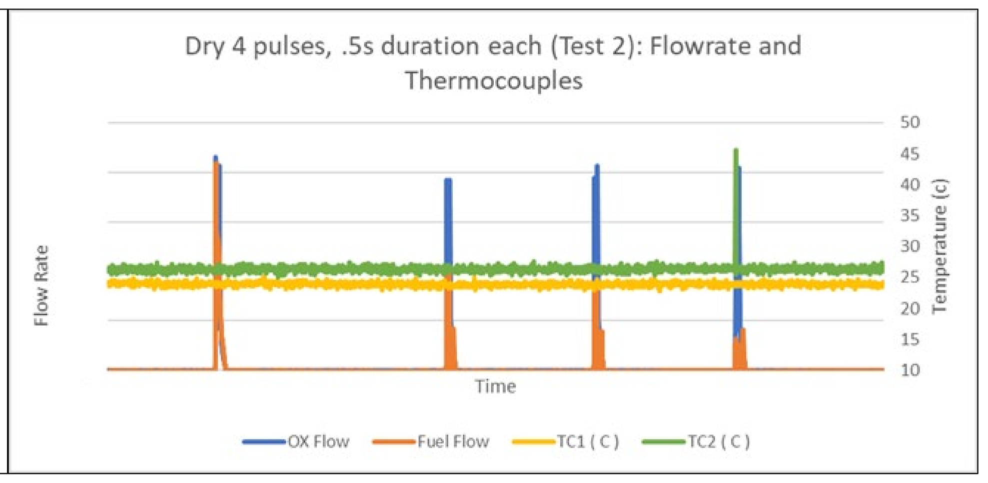

Melted ice observed in collection tray after hot fire; The team theorized that ice crystals were likely collected, but then melted due to sitting in 80° F ambient conditions before observations could be made after each test

8. Results & Future Work

- On average RocketM excavated 3.2 times more ice than propellant expended
- Engine issues caused variable thrust, but demonstrated how mass removed correlates to thrust level
- No increase in regolith temps on any test (volatiles conserved)
- Future Work
  - Implementation of beneficiation system on exhausts
  - Integration with LTV-class mobility system
  - Evaluate capability for collection of non-water volatiles and bulk regolith



Mass of ice excavated vs. Mass of propellant expended



Propellant flow rate and Temperature vs. Time