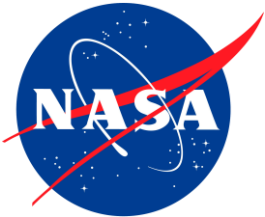


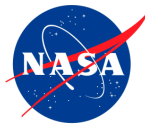
Extraterrestrial Mining Via Two Coupled Thermal-Driven Phenomena

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Marangoni Effect



- In tears of wine, a classical example of Marangoni effect, a meniscus is formed at the three-phase junction (the wine glass walls, wine, and air) then the liquid in the meniscus loosely clings to the surface of the glass. Wine contains ethanol that evaporates faster in the meniscus than in the flat bulk flat surface due to the meniscus higher surface area in relation to its small volume. Therefore, it generates an ethanol concentration gradient between the meniscus and the flat bulk causing a surface tension gradient that moves the meniscus up the walls of the glass.
- There are two driving forces that lead to Marangoni effect, gradient on concentration (tears of wine) and gradient on temperature (lunar regolith melt upwards migration).
- Marangoni effect plays an important role in many industrial applications where a surface tension gradient induces fluid flow, e.g., the cleaning process of silicon wafers and the welding process of melted metal.
- NASA STDC-1 (Surface Tension Driven Convection) experiments performed on USML-1 Spacelab missions in 1992 were designed to study thermocapillary flows in microgravity.



$$M_a = \frac{d\gamma}{dT} \frac{dT}{dx} \frac{L^2}{\eta\alpha}$$

where

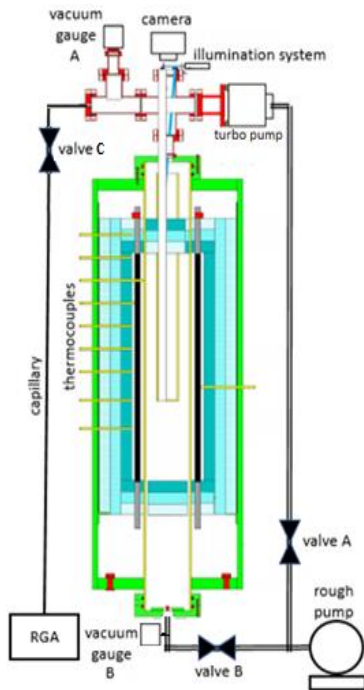
γ = Surface tension (N/m)
 η = Dynamic viscosity (Kg/(s m))
 T = Temperature (K)
 α = Thermal diffusivity (m²/s)
 L = characteristic length (m)
 x = spatial $\times$ direction (m)

Introduction

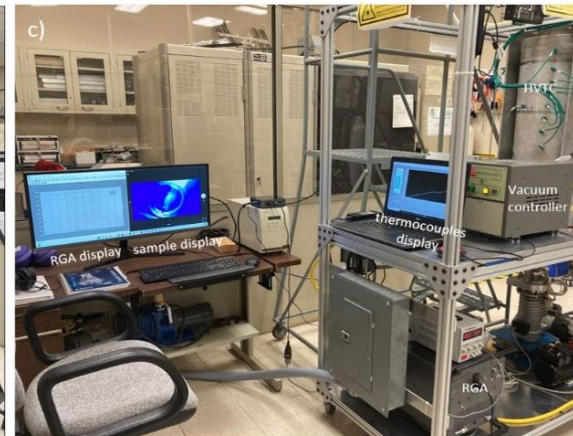
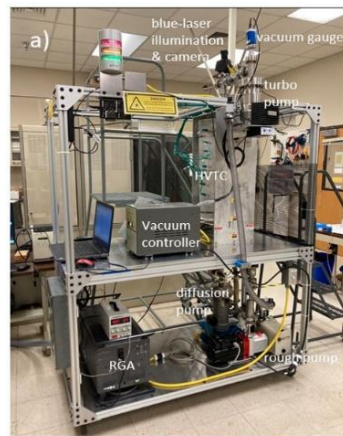


- Marangoni effect assessment on molten lunar regolith via JSC-1A lunar regolith simulant under vacuum yielded a spontaneous upwards migration of a uniform molten thin-film front as well as at bulk scale that climbed the crucible wall covering the entire wall's surface and reaching the crucible's top end.
- Further assessment on higher-temperature vacuum-driven decomposition of the uniform thin-film front as it climbed the crucible's wall revealed a significant decomposition of various simulant's metal-oxide components into their respective oxygen and metal elements strengthening the feasibility of extraterrestrial generation and fractional separation of oxygen and metals/alloys with none or minimal need for terrestrial precursors.
- These two-coupled phenomena, spontaneous material transportation at both thin-film and bulk scales via Marangoni effect and vacuum-driven decomposition open novel pathways in extraterrestrial mining and manufacturing.

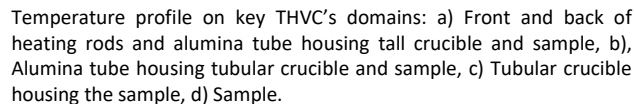
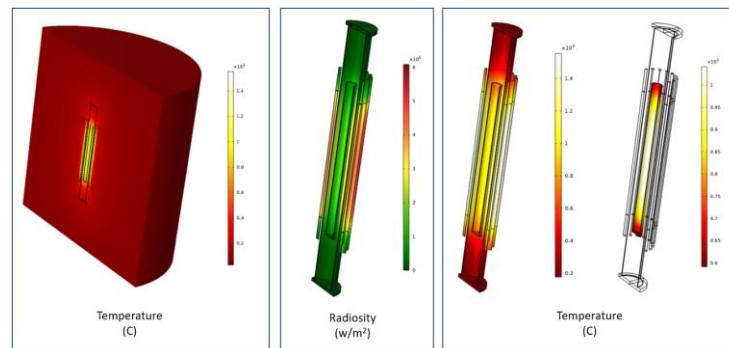
Test Stand



General schematic of THVC



Thermal High Vacuum Chamber (THVC) test stand designed and built in-house at MSFC



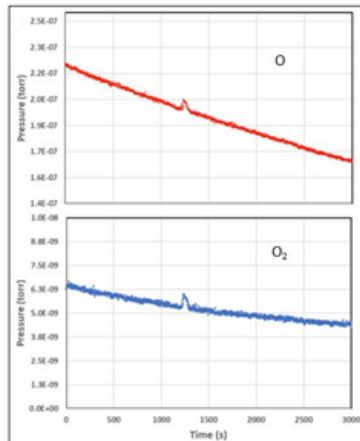
Test Outcome

a) Interior of two tubular crucibles housing the same amount (150 grams) of JSC-1A lunar regolith simulant melts generated at 1,300 C ($3.7\text{E-}3$ torr) and 1,400 C ($1.2\text{E-}3$ torr) cases respectively, b) Magnified section of the meniscus formed in both cases, c) front end of the upwards migration in both cases

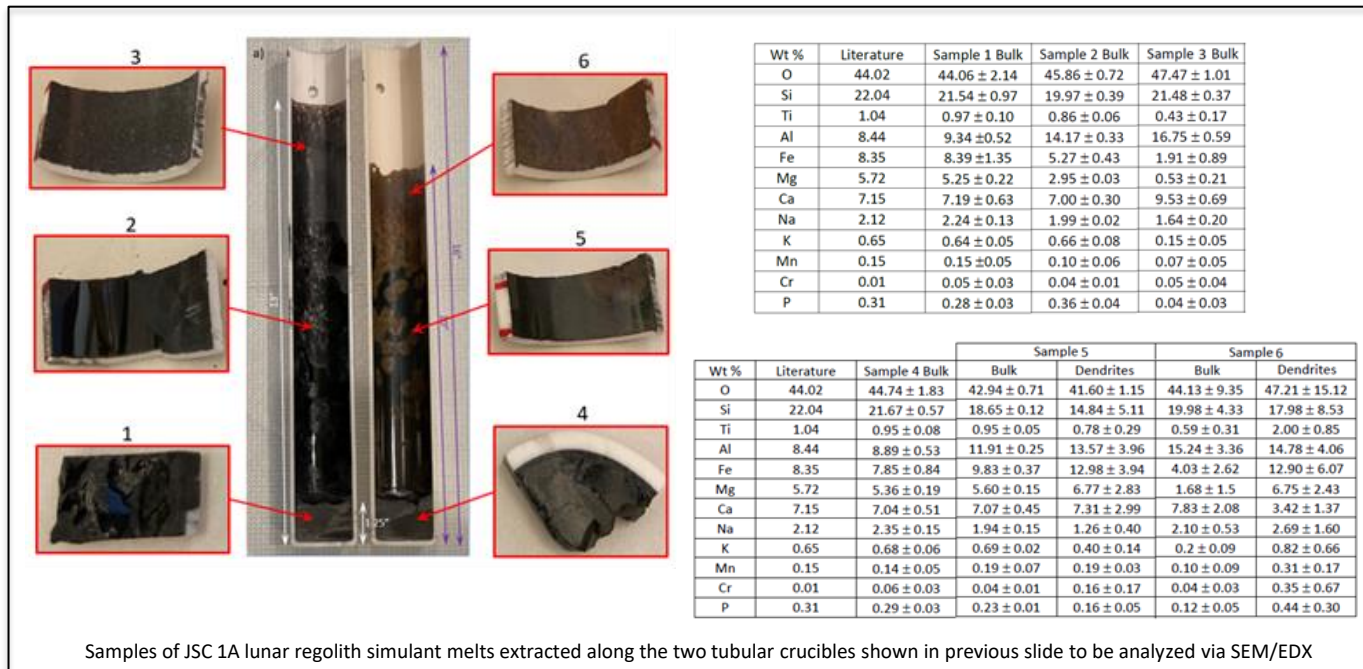


Image of the melt taken by the camera mounted on the top of the HVTC under blue-laser illumination at 1,400 C.

Test Outcome (Cont.)

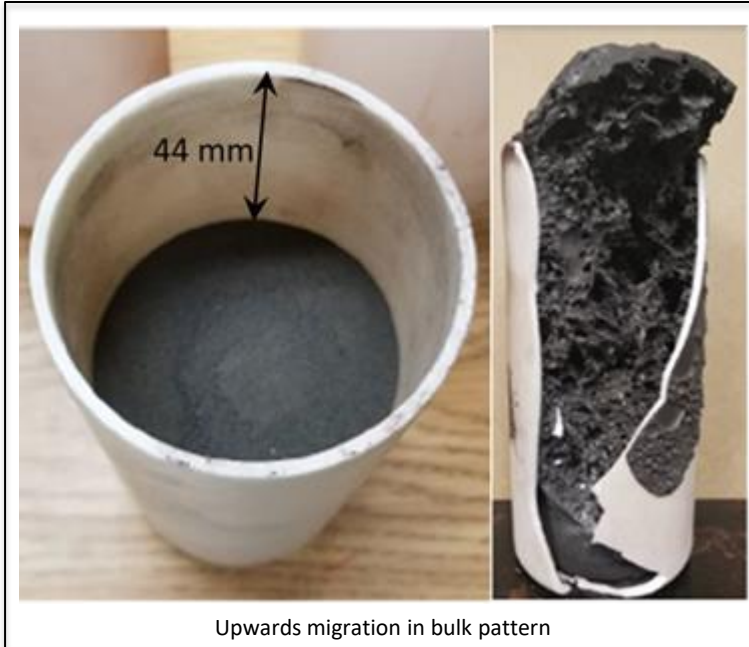


O₂ and O partial pressure peaks detected by the RGA at 1,400 C and 1.2E-3 torr vacuum

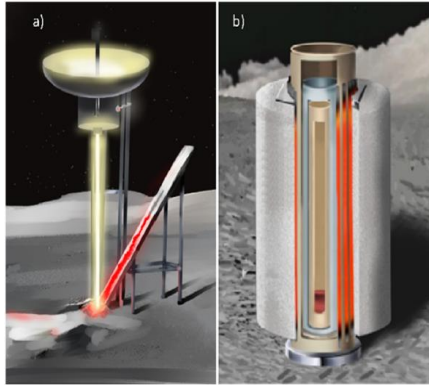


Samples of JSC 1A lunar regolith simulant melts extracted along the two tubular crucibles shown in previous slide to be analyzed via SEM/EDX

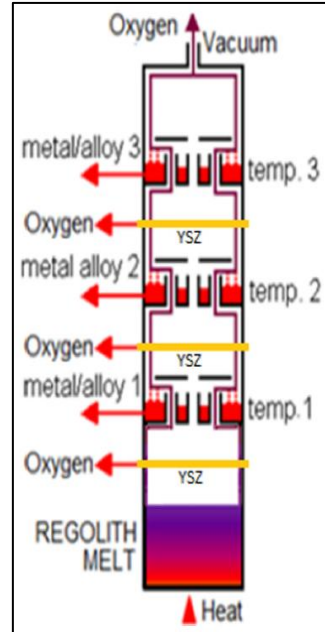
Thermal-driven Bulk and Film Flow Patterns



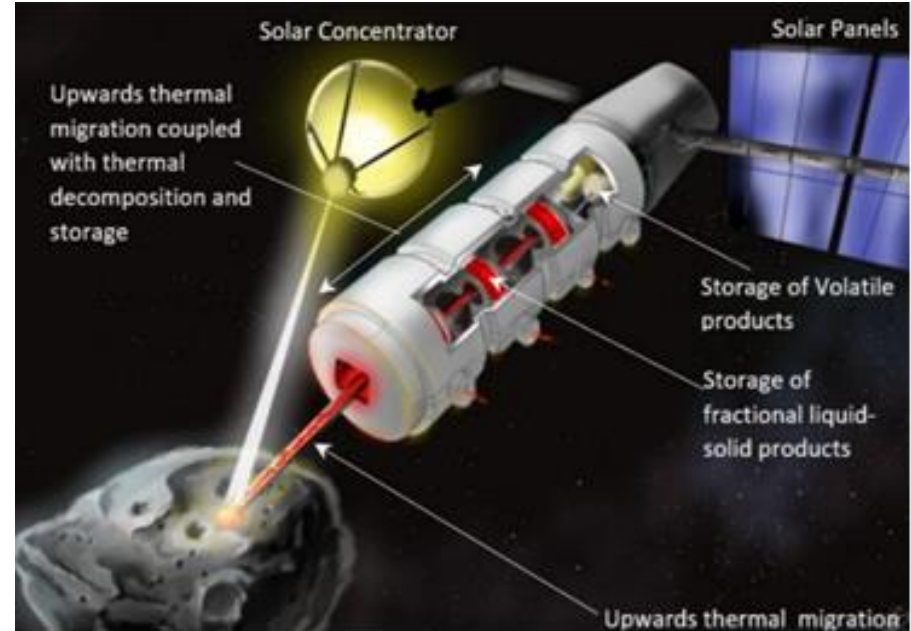
Extraterrestrial Mining



Conceptual rendering of key lunar experimental setups for a) corroboration and b) assessment of the Marangoni's effect science.

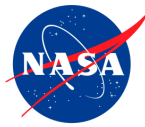


Conceptual rendering of a fractional O_2 /metal/alloy extraction thermal chamber.



Conceptual extraterrestrial mining coupled with in-situ processing and storage via thermal migration and decomposition

Summary and Conclusions



- Thermal-driven Marangoni effect alone and fractional decomposition/depletion of metal oxides releasing O_2 have been corroborated on molten JSC-1A lunar regolith simulant through long upwards migration paths, 10 and 13 inches, respectively, validating further the proposed approach for extraterrestrial mining. These two coupled phenomena, the thermal Marangoni effect and fractional decomposition, will be more prominent on extraterrestrial surfaces under much higher vacuum and reduced gravity.
- The decrement/increment of the JSC-1A elements observed through SEM/EDX analysis might be due to the decomposition and depletion of their corresponding oxides as they migrate upwards; this decrement/increment of particular elements might also be due to uneven/multidirectional migration of these component oxides leading to fractional depletion/accumulation of the corresponding oxides.
- Due to the Marangoni effect, self-transportation without fractional decomposition that would be required in the non-mechanical extraterrestrial mining approach was witnessed along 13 inches in the first case. Self-transportation coupled with fractional decomposition/segregation of the melt at a higher temperature required for sustainable extraction/refinery and an all-in-one extraterrestrial mining approach was also witnessed (and quantified via SEM/EDX analysis) along 10 inches in the second case.
- A comprehensive 3D model demonstrated to be a crucial tool to determine the proper location of the sample to optimize the gradient temperature along the wall of a long tubular crucible enhancing the Marangoni effect as surface tension (the driving force for the thermal Marangoni effect) depends on the temperature gradient.

Future Work



- NASA has granted discretionary funding to continue research work on the thermal-driven separation of metals from carbothermal/MRE slags generated at the moon to extract oxygen.
- A partnership has been established between NASA and other partners to process reduced, deoxygenated, carbothermal slag produced from MRE processes to separate aluminum from iron, calcium, and silicon. Success at this endeavor would close a process waste stream gap for potential Lunar surface life support systems while laying the groundwork to close gaps in NASA ISRU technologies for in-space welding, manufacturing, structural fabrication, and additive manufacturing.

Questions?

Thank you for your time!

