CHARACTERIZATION OF VOLATILES FROM SIMULATED LUNAR HIGHLAND MELTS UNDER VACUUM

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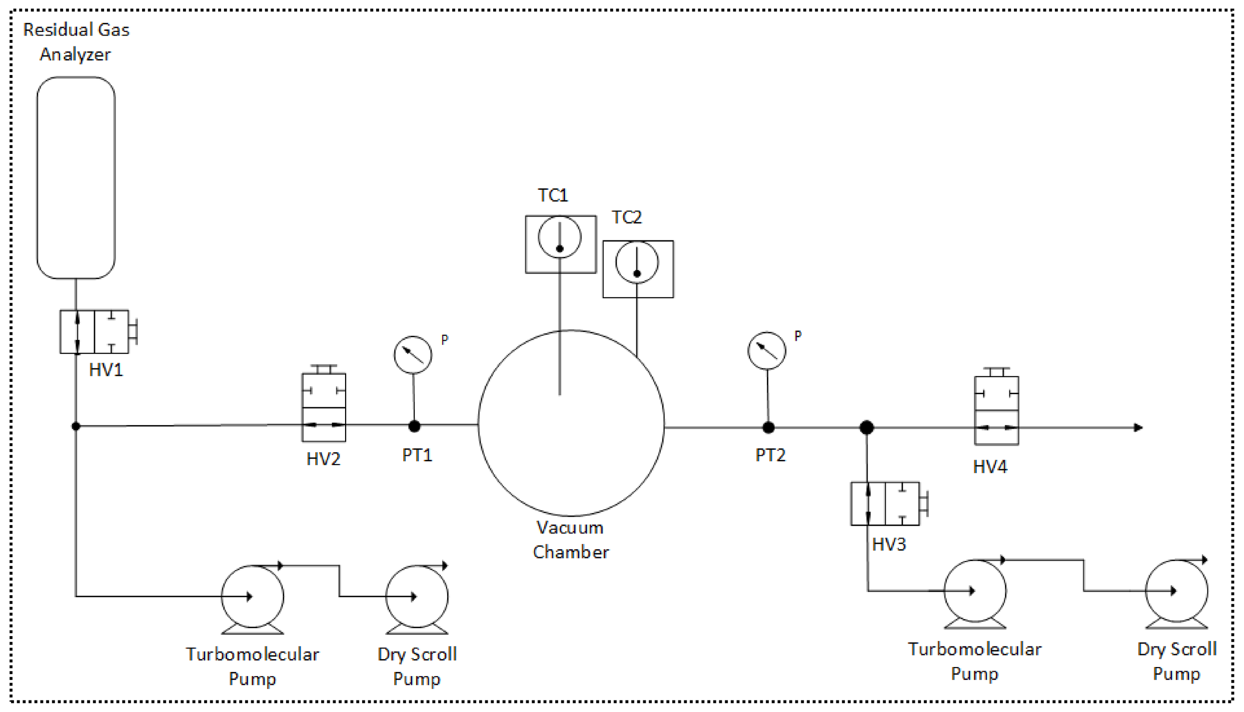
Background

For long duration crewed lunar missions, in-situ resource extraction of oxygen is essential. NASA is pursuing a variety of technologies in order to glean oxygen from lunar soil in the upcoming architecture of a lunar base. Molten Regolith Electrolysis or MRE is one of these technologies. MRE technology is based upon heating regolith into a molten state and then performing electrolysis on the liquid pool in order to release oxygen as a gaseous product. The work presented herein utilizes Lunar Highland Simulant-1 (LHS-1) for study as it is chemically comparable in soil composition to the proposed Artemis mission landing sites.

Benefits

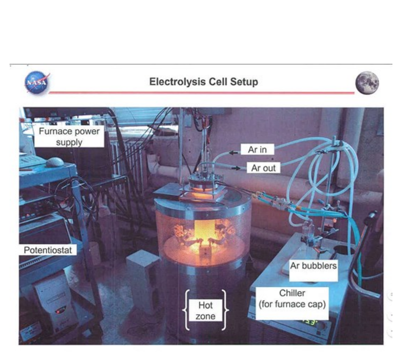
- Resource production of oxygen for propulsion, human metabolic processes, and chemical processes
- Molten oxide recovery (low purity metals from by-products)
- Reduce overall launch mass
- Progress towards true spaceflight sustainability, extracting resources from lunar/martian regolith

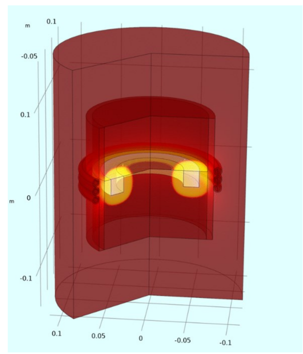
System Development & Overview

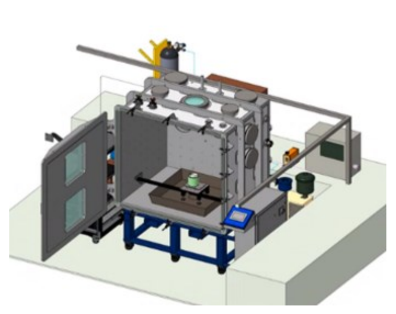


The resistive heating tests were performed at NASA Kennedy Space Center's Applied Chemistry Laboratory within a 50.8 cm height by 45.7 diameter cylindrical vacuum chamber with 18-gauge, Kanthal A-1 wire with 13 cm leads and a 4 cm wound coil with a total length of 30.5 cm (unwound). Up to 320 watts were applied to the coil with a ramp rate of an average of 13 watts per minute (≈1 Amp every 3 minutes) until a maximum suppliable current of 18 amps was reached. The chamber had two sets of turbomolecular and roughing pump combinations in order to allow for differential pumping to enable residual gas analysis. Current was supplied up to 18 A for the duration of 1-hour or until heater coil failure, whichever happened first. Thermocouples and pressure transducers monitored temperature and pressure at various locations, respectively. After testing, the re-hardened regolith was examined visually and set aside for surface and material analysis.

Project Timeline







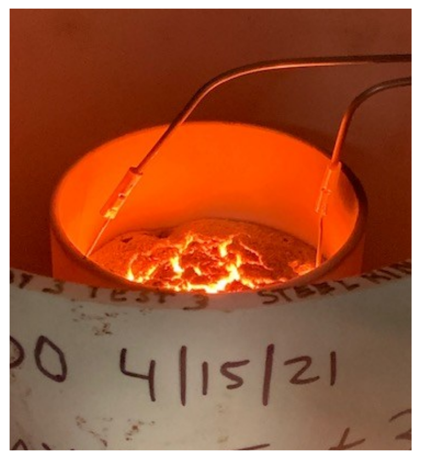
FY 16: Hot-walled MRE | FY 20-21: GaLORE STMD- | FY 21: MRE GCD

MRE: Molten Regolith Electrolysis GaLORE: Gaseous Lunar Oxygen from Regolith Electrolysis
GCD: Game Changing Development STMD: Space technology Mission Directorate
ECI: Early Career Initiative FY: Fiscal Year

High Vacuum Testing Campaign

Void formation under vacuum (Test 1)

- High vacuum conditions cause drastically different material properties
- Voids were present in atmospheric and vacuum melting, causing operational concerns for electrolysis and scaling
- High vacuum leads to radiative and conductive heat transfer verses convection
- Designs need to assist in eliminating voids



Off-gassing of molten processing (Test 2)

- Need to characterize gases produced for collection, separation, and reutilization
- Produced gases resulted in material compatibility considerations and impacts to human health
- Off-gassing during testing provides insight to operating conditions such as pressure
- Characterization of produced species provides production rate estimates

Void Formation Under High Vacuum Melt Conditions

Hardened sphere of LHS-1 after testing

Hardened sphere split in half with diamond saw to show void formation consistent with atmospheric testing. Cross-sectional view.

Chemistry of the Lunar Highlands Simulant from Exolith Laboratories (Univ. of Central Florida)[2]

Oxide	Wt.%
SiO_2	51.2
Al_2O_3	26.6
CaO	12.8
Na_2O	2.9
FeO	2.7
MgO	1.6
TiO_2	0.6
Loss during analysis	0.4
P_2O_5	0.1
MnO	0.1

Void Formation under High Vacuum Melt Conditions

- Resistive heating with 2.54 cm diameter coil winding (≈3x winding diameter used in off-gassing tests)
- 18 Amps of current applied for up to 1-hour or until wire failed
- Gaseous void formations and trapped volatiles clearly present in the hardened sphere
- Highlights the need for molten pool gas extraction considerations if produced oxygen from electrolysis is trapped within the molten regolith
- High vacuum conditions did not lead to decreased void formation when compared to atmospheric tests
- Gravity impacts and the viscosity of true lunar soil may present some differences.

Volatiles Produced from Regolith Simulant in a Molten, Vacuum Environment

Off-gassing of molten processing (Test 2)

- High vacuum base pressure of $\approx 2.5 \times 10^{-5}$ Torr
- Before heat, common air constituents
- Startup of heating highlights multi-fragmentation of species
- Some products associated with heating of wire, components
- Continued operation shows high peaks (m/z) at 44, 28, 18, 12
- Detection of CO_2, SO_2, Cl, CO in concentrated output

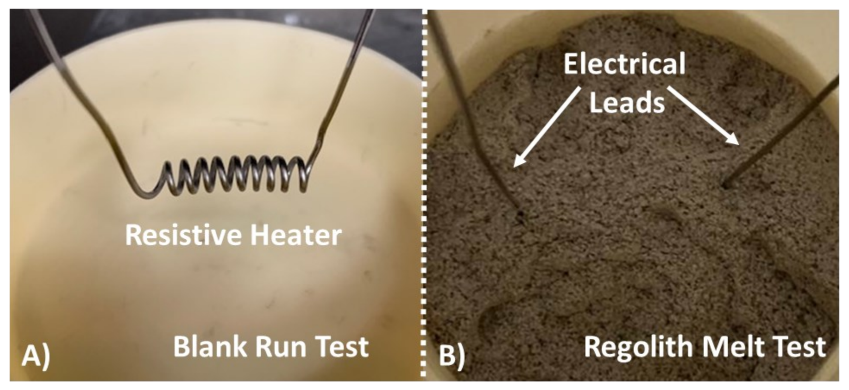
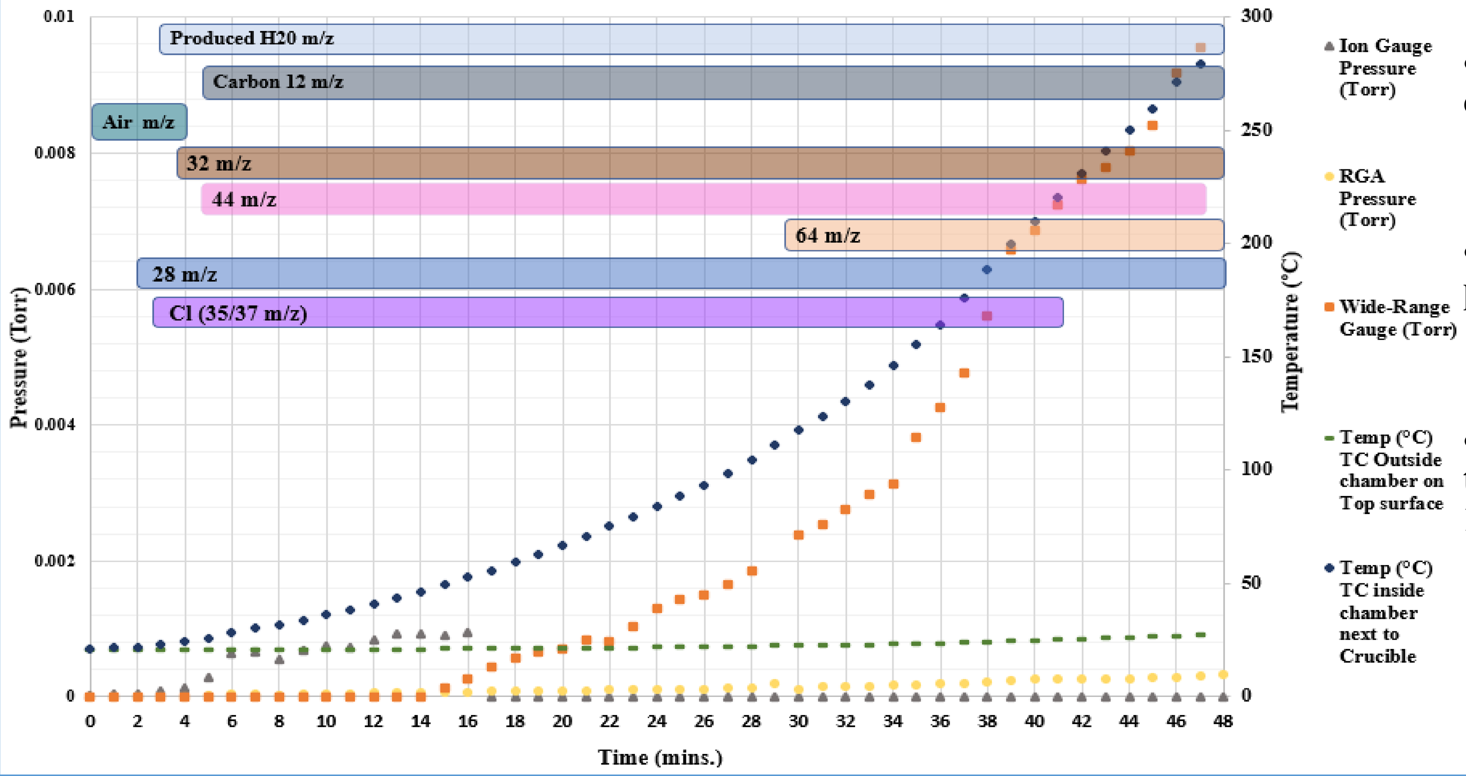


Image of the resistive heater. | Image of the resistive heater buried within the regolith.

Pressure and Temperature vs. Time



- Quick, drastic increase in pressure
- Different species produced over time
- Molten temperature greater than 1000 °C

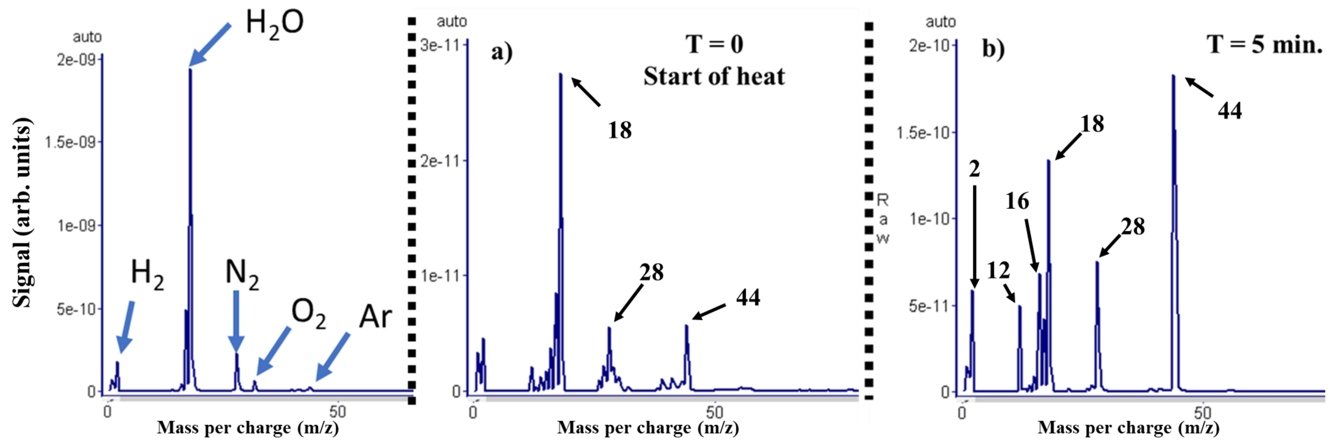
Conclusions

1. Thermal processing of regolith generates large increases in vessel pressure and will affect containment and collection
2. Vacuum processing of regolith follows radiative and conductive heat transfer laws based on collected temperature data and thermodynamics under vacuum environments
3. Produced gaseous species require proper ventilation during terrestrial operations
4. Material compatibility considerations are needed for the high temperature and corrosive environment
5. Gases produced and measured by the residual gas analyzer are complex and require carefully prepared systems for analysis
6. Scale-up considerations for pressure management and corrosive environments must be considered for system operations and maintainability
7. Void formation under a high vacuum environment traps the produced gaseous species and may interfere with electrolysis processing, requiring removal of molten volume
8. A complex mixture of gases is released during regolith melting. Downstream gas cleanup and/or separation will likely be required

Future Work

***Mission:** Develop flight-forward, critically-scaled MRE system for extraction and production of oxygen.*

- Resource recovery (Environmental Control and Life Support System consumables, fuel) from regolith is substantial and must be prioritized
- Molten material removal required to sustain continuous operation is required as well as a controlled regolith feed system
- Ability to capture extracted oxygen from molten regolith operations
- Volatile gas production analysis and mitigation strategies for increased molten volumes
- Collaboration with commercial companies for development and scale-up for eventual 10 ton per year of O_2 production



Baseline data from residual gas analyzer. Components detected are of air and the desorption of water vapor from the chamber. Hydrogen is a relic of an alternative experiment.

Data from residual gas analyzer at the start of applied power to the resistive heater that is buried within the LHS-1 simulant.

Data from residual gas analyzer after 5 minutes of applied power to the resistive heater. One can see an increase in peaks at 44, 28, 18, 12, and 2.

Infusion Paths

MRE is applicable for various scenarios during crewed exploration missions including:

- Mars Habitat
- Gateway Deep Space Logistics
- Lunar/Martian Surface Operations
- Artemis Base Camp (ABC)

Acknowledgements

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References

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[3] S.S. Schreiner, J.A. Dominguez, L. Sibille, and J.A. Hoffman. "Thermophysical property models for lunar regolith," Advances in Space Research. 57 (2016) 1209-12222

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