# Molten Regolith Electrolysis Testing Performed in Vacuum at Kennedy Space Center: Analysis of the Retrieved Core Sample

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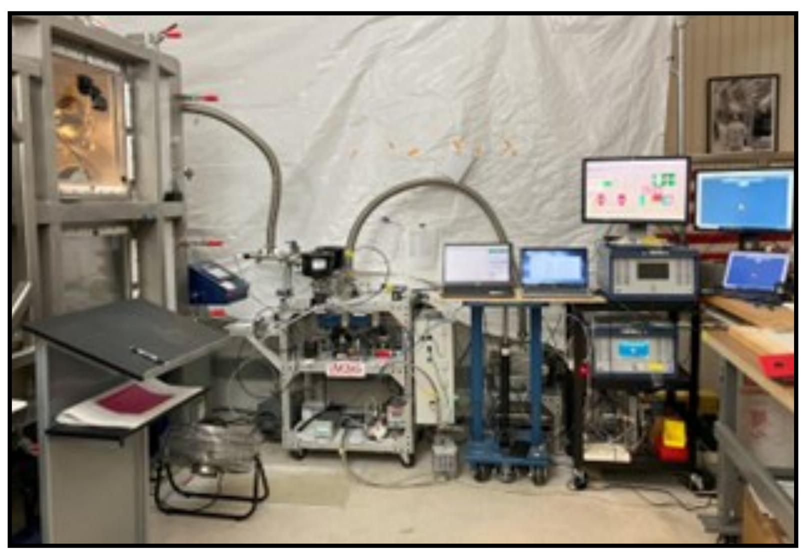
## Background

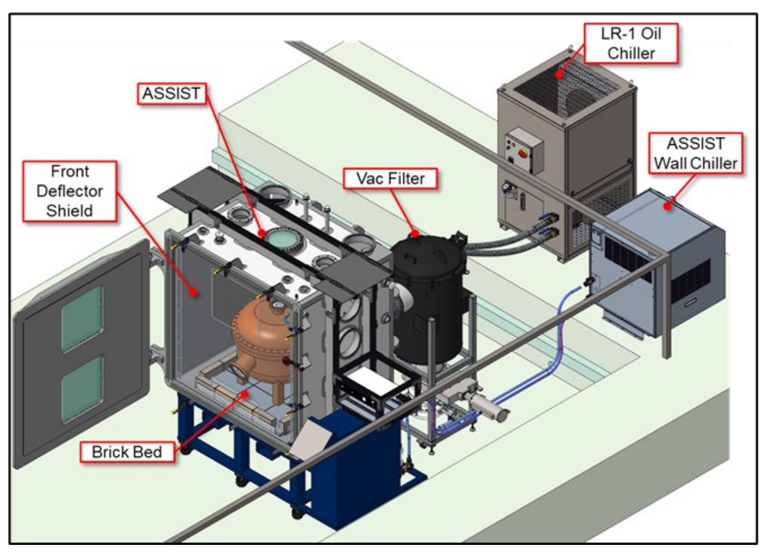
Molten Regolith Electrolysis (MRE) is a technology for oxygen ($O_2$) production from regolith on the lunar surface for life support and propellant supply, as well as production materials that can be retrieved from the molten metal slag [1] [2].

MRE testing concluded at Kennedy Space Center (KSC) in December of 2024 with a Lunar Resources, Inc. (LUNAR) reactor. The test summary included:

- 25 kg of ICN-LHT-1G lunar regolith simulant [3] processed in a LUNAR reactor under vacuum in the KSC Atmospherically Sealed Simulator for In-situ System Testing (ASSIST) chamber.
- Joule heating was sustained by electrolysis with temperatures ~1700°C and a maximum power draw of 9 kW during vacuum operations.
- Approximately 0.6 moles of $O_2$ per kW-hr measured, with an average rate of 0.1 kg/hr $O_2$ production.
- A core sample was retrieved after the molten regolith cooled down, post electrolysis.



ASSIST chamber with Volatile Monitoring Oxygen Measurement Subsystem (VMOMS) and data acquisition hardware.




MRE Test Set-up in ASSIST chamber at KSC.

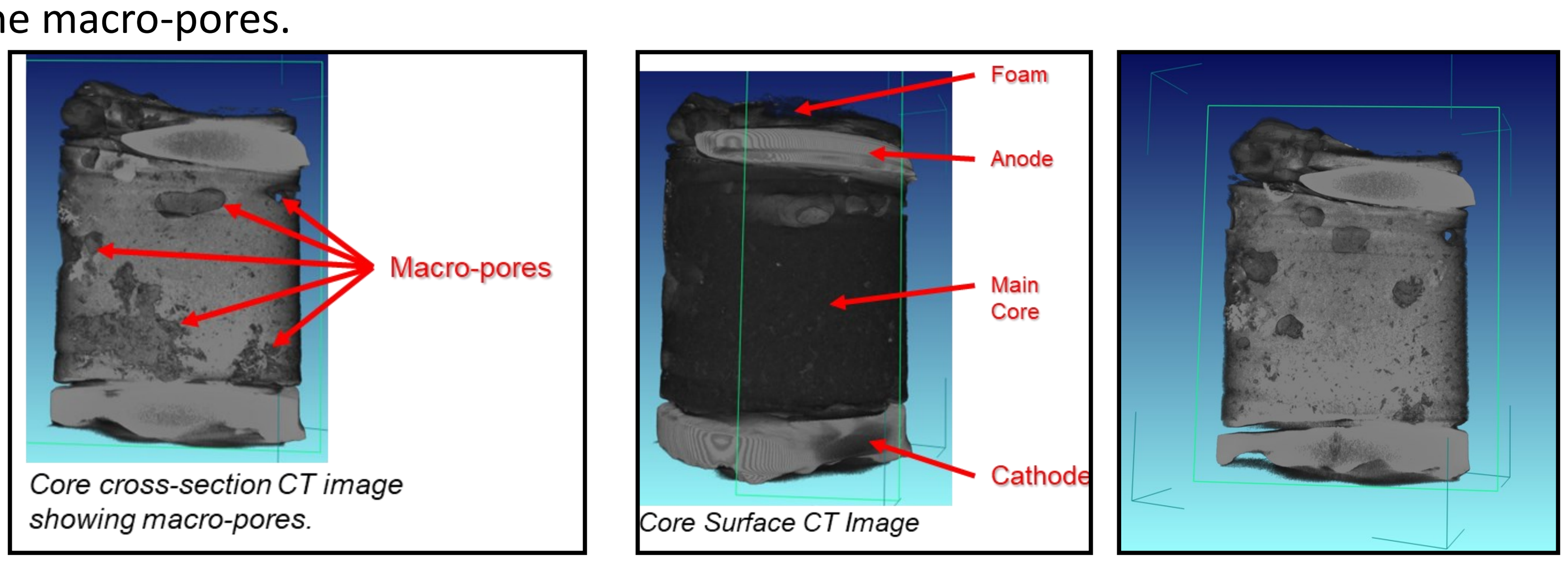
## Retrieved Core Sample

The core sample extracted was approximately 3-inch diameter, 4-inch tall specimen that include anode, magma melt, and metal cathode material. The coring equipment used was a Bluerock cutting 3-inch diamond coring bit for concrete coring.

## Computed Tomography (CT) Scan

A computed tomography (CT) scan was performed with a North Star Imaging unit with its Microfocus Digital Radiography and Computed Tomography System (NSI X5000 DR/CT). The x-ray source voltage was 195 kV, current 220 µA, and focal spot size 42.9 microns. The detector was a Perkin Elmer XRD with a gain of 2e/ADU and framerate of 6fps.

The CT slices were used to graphically estimate the macro-porosity by summing the void space for each slice. Similarly, the total density was determined graphically and includes the macro-pores.

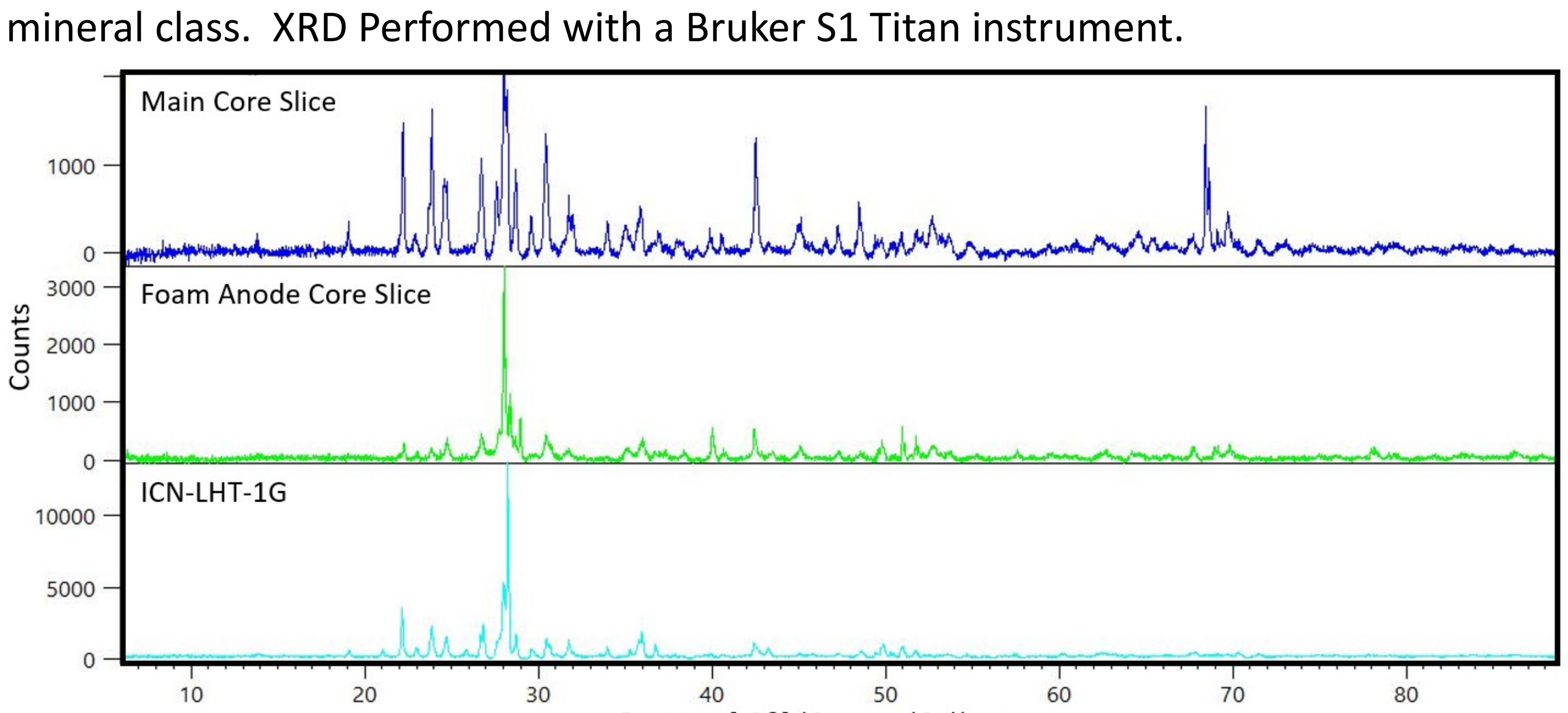



*Core cross-section CT image showing macro-pores.*

*Core Surface CT Image*

## X-Ray Diffraction (XRD)

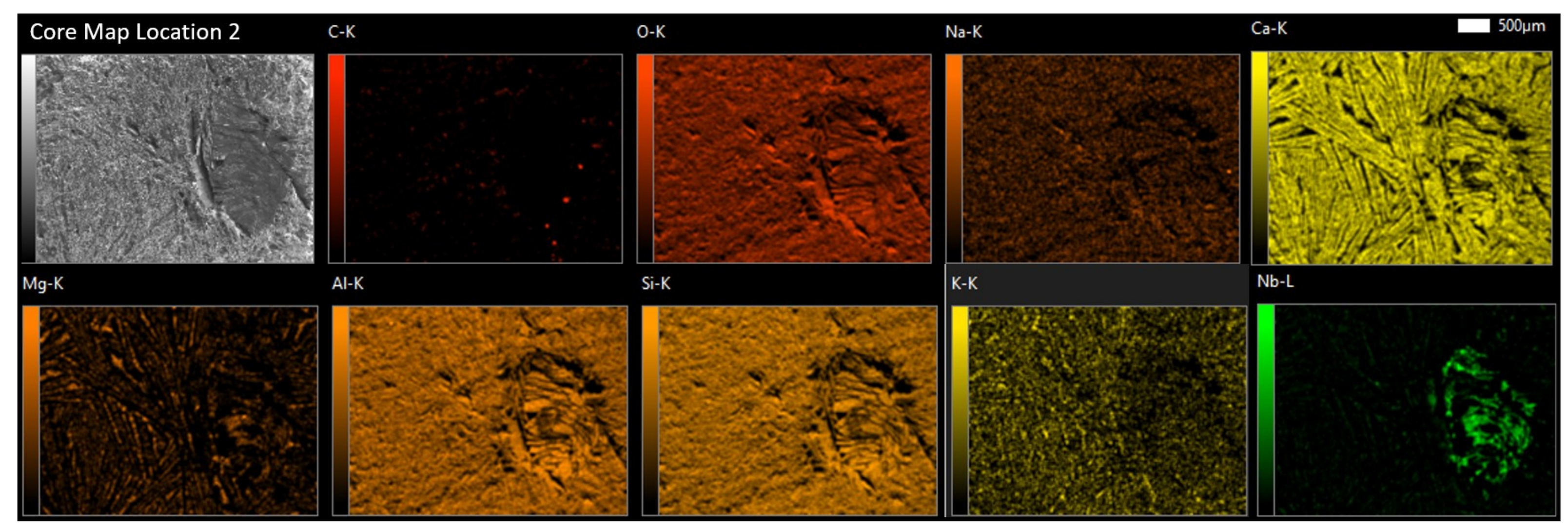
XRD was performed on bulk material with a Malvern Panalytical Empyrean instrument. The main core slice displayed more crystalline formations with predominant sodium calcium aluminum silicate peaks, dominating in the anorthic crystal structure of the feldspar mineral class. XRD Performed with a Bruker S1 Titan instrument.



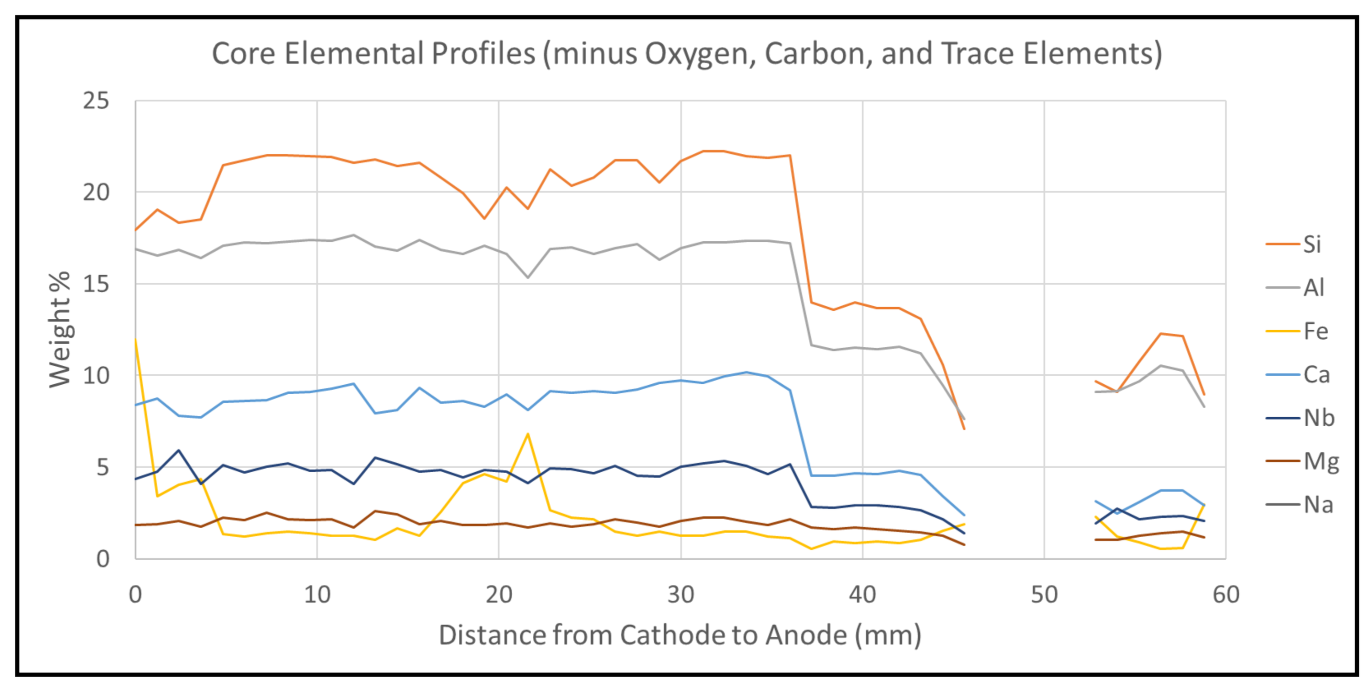

## Scanning Electron Microscopy (SEM) and Elemental Dispersive Spectroscopy (EDS)

SEM was performed using a TESCAN and JEOL JSM-IT800 SEM/EDS.

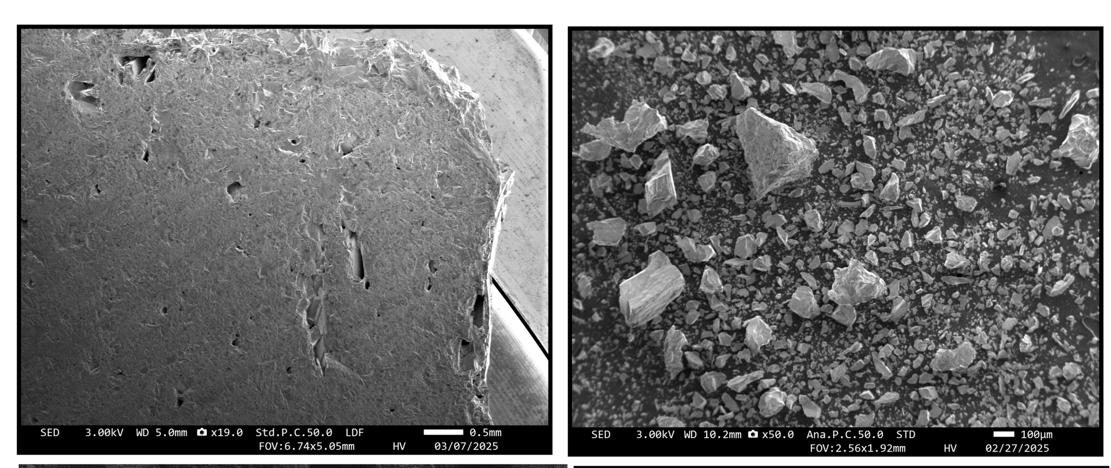
| Atom/Mol% | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Core Slice | O | C | Na | Mg | Al | Si | K | Ca | Ti | Fe | Nb | P | Mn |
| Average | 54.89 | 0 | 2.15 | 2.19 | 12.43 | 14.81 | 0.42 | 5.1 | 0.63 | 0.46 | 10.09 | 0 | 0 |
| Std. Dev. | 3.18 | 0 | 0.6 | 2.09 | 3.02 | 3.95 | 0.07 | 2.72 | 0.35 | 0.13 | 7.32 | 0 | 0 |
| ICN-LHT-1G Control | O | C | Na | Mg | Al | Si | K | Ca | Ti | Fe | Nb | P | Mn |
| Average | 47.95 | 21.49 | 1.89 | 2.52 | 8.22 | 11.98 | 1.31 | 4.53 | 0.8 | 5.59 | 0 | 0.16 | 0.08 |
| Std. Dev. | 6.85 | 15.54 | 1.11 | 1.32 | 3.53 | 5 | 0.99 | 2.13 | 0.2 | 1.99 | 0 | 0.05 | 0 |



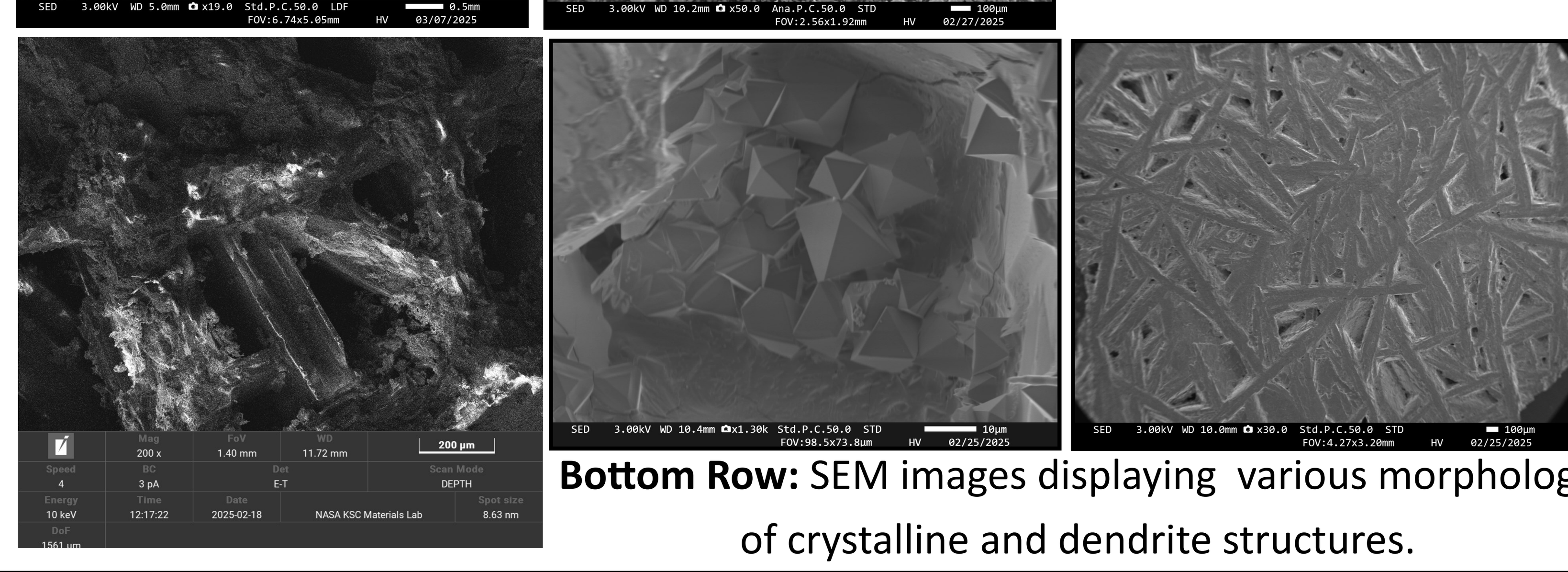

Elemental maps of core slice, showing dendrites and also mixed amorphous material with anode material mixed in.




Line profile of elemental composition (without oxygen, carbon, or trace elements). The line that was analyzed is shown as a red line in the image of the core above. Here the bottom (cathode) corresponds to zero. The blank portion represents the large vacancy toward the anode.



**Left**: SEM image example of core slice segment used in area mapping and EDS collection. **Right**: ICN-LHT-1G



**Bottom Row:** SEM images displaying various morphology of crystalline and dendrite structures.

## Summary

- Large scale electrolysis was achieved for MRE operations in a vacuum environment using 25 kg of ICN-LHT-1G regolith simulant. The core was successful removed after cool-down phase.
- Voids are present throughout with crystal structures formed in the voids. EDS used to determine macro-porosity of approximately 14.84%
- EDS observations: Non-homogeneous properties with mixed elemental composition. Anode degradation was observed throughout regolith magma in core slice.
- XRD observations: The main core slice became more crystalline, possibly due to regolith solidification effects.
- XPS was performed with a Thermo Scientific NEXSA G2. Due to Nb presence in the core from the anode material, it is believe that x-rays were absorbed and the scans were inconclusive.

## Acknowledgements / References

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**[1]** Standish (2010) Design of a Molten Materials Handling Device for Support of Molten Regolith Electrolysis. **[2]** S. S. Schreiner, (2015) Molten Regolith Electrolysis reactor modeling and optimization of in-situ resource utilization systems. **[3]** A. Slabic et al., (2024) Lunar Regolith Simulant User's Guide Revision A.