Large-scale Demonstration of Molten Regolith Electrolysis for Oxygen Production in a Relevant Environment

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Introduction and Vision

- *IN-SITU* production from lunar resources is the cornerstone for supporting a long-term sustainable presence on the moon.
- Oxygen from regolith technologies
- From laboratory scale and enviroment to large scale and relevant enviroment.
- Technology Maturation
- NASA’s vision

Molten Regolith Electrolysis Overview

THREE CRITICAL PHASES

1. Regolith heating to ≈1400˚C (1,673 K)
2. Electrolysis allowed the heaters to be reduce power, and Joule-heating (resistive heating) sustained melt mass of 1600˚C (1,873 K) + to release molecular oxygen from regolith.
3. Cool down

NOTE:

-Each oxygen molecule formed requires removal of 4 electrons.

-Total electrical current into the reactor limits the maximum oxygen production rate.

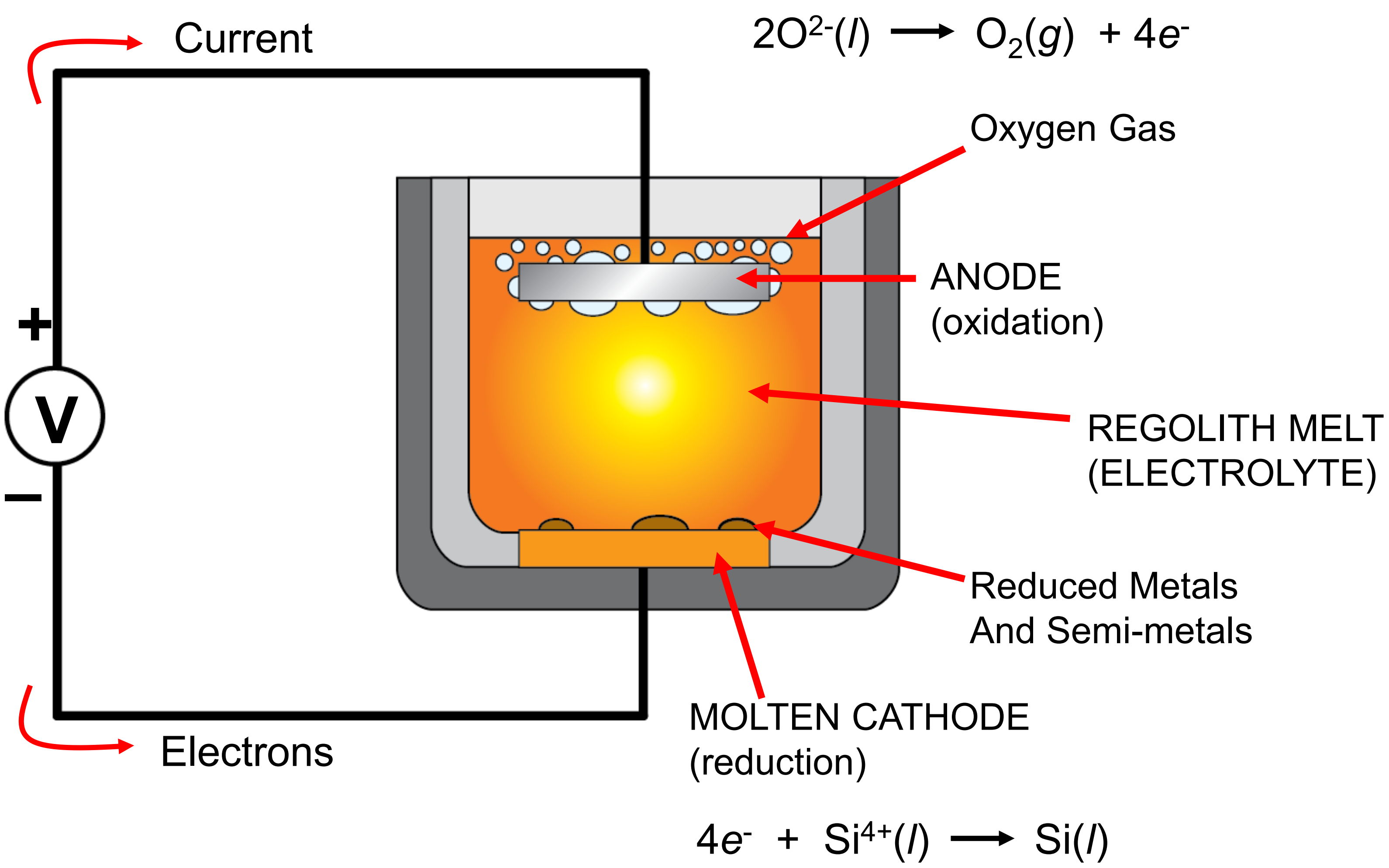


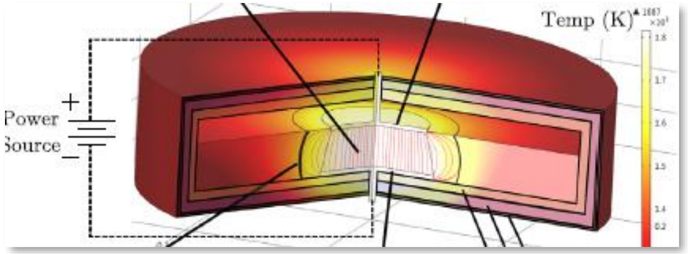
Image Credit: Joel Olson

Molten Regolith Electrolysis History

Laboratory Enviroment

1990: A case for MRE is reported [1]
2009: Electrode materials are demonstrated for MRE in a lab environment [2]

Parametric Sizing



2015: Parametric modeling investigations into MRE [3]

Relevant environment Melting technology & oxygen qualification

2023: GaLORE ECI develops 3 regolith melting methods and demonstrates cold-wall reactor at KSC

[1] Colson, Russell O., and Larry A. Haskin. "Lunar oxygen and metal for use in near-earth space: Magma electrolysis." *Arizona Univ., NASA Space Engineering Research Center for Utilization of Local Planetary Resources* (1990).
[2] Sibille, Laurent, et al. "Recent advances in scale-up development of molten regolith electrolysis for oxygen production in support of a lunar base." 47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition. 2009.
[3] Schreiner, Samuel Steven. Molten Regolith Electrolysis reactor modeling and optimization of in-situ resource utilization systems. Diss. Massachusetts Institute of Technology, 2015.

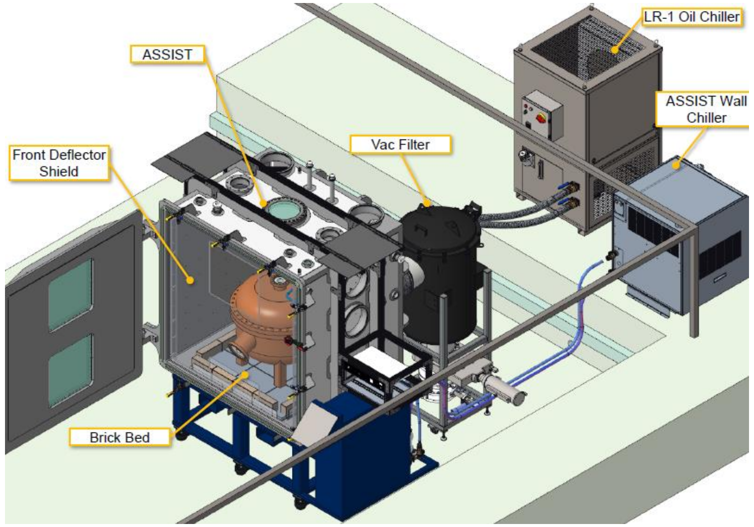
MRE Tech Maturation Project Overview

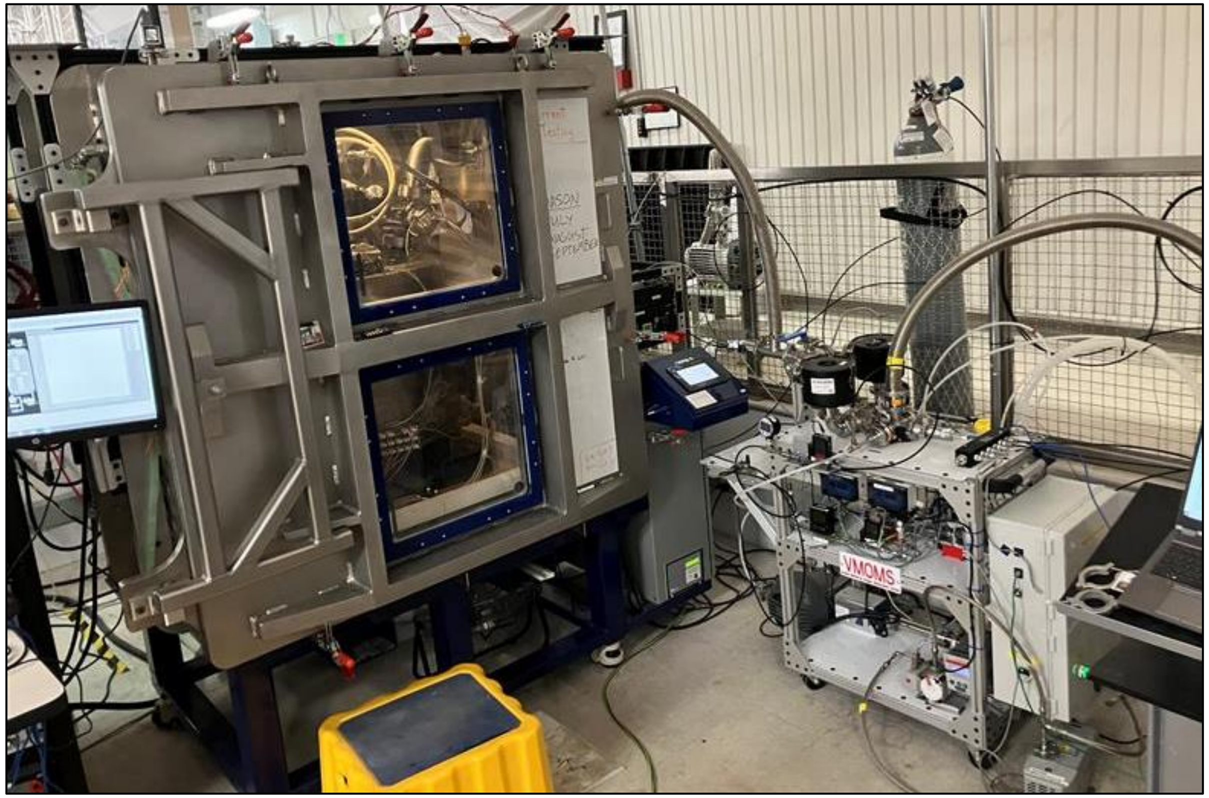
Project Goals	
Goal #1	Provide resources and technical support to Lunar Resources, Inc. as they develop a reactor to demonstrate an integrated capability to mature the technology readiness level (TRL) of Molten Regolith Electrolysis
Goal #2	Prepare the test environment at KSC for demonstration of the MRE reactor
Goal #3	Ground demonstration of a commercially developed MRE reactor to measure the performance of its ability to produce oxygen in a 1G vacuum environment
Goal #4	Capture test data and develop lessons learned to inform future maturation of this technology

Project Objectives	
Objective #1	Define Concept of Operations (CONOPS) and requirements for an MRE ground demonstration reactor built by Lunar Resources, Inc. and tested in the ASSIST chamber at KSC
Objective #2	Complete risk reduction actions on the heaters from Lunar Resources, Inc.
Objective #3	Design and build the Oxygen Monitoring and Measurement system
Objective #4	Design and build MRE reactor, LR-1
Objective #5	Design process control system
Objective #6	Integrate and test MRE reactor

Test Assembly

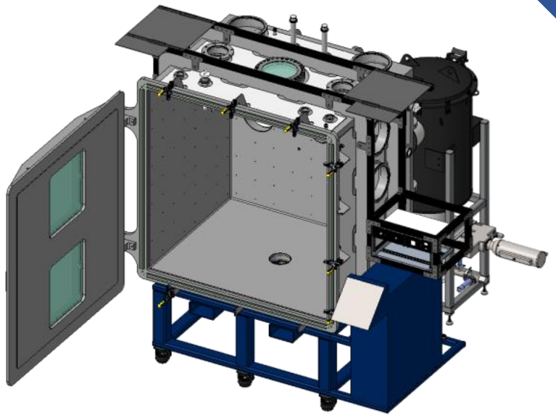
- KSC and Lunar Resources Inc. Collaboration
- KSC Test system & LR Reactor
- 2024: MRE GCD demonstrates a large-scale reactor in lunar like conditions.
- Large Scale: 25 kg of Regolith





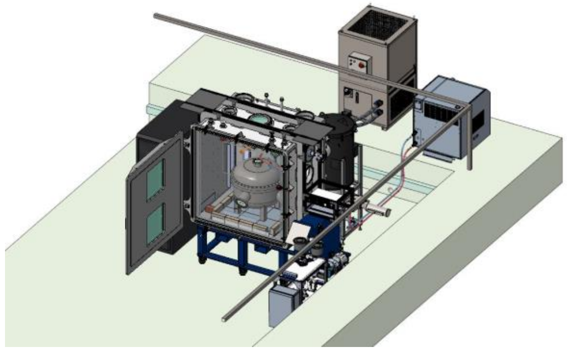
LR-1 in ASSIST under vacuum pressure (Front Deflector Shield excluded during this pump-down). System reached 9.84E-06 Torr on ASSIST and 0.8 torr on LR-1 during leak checks.

Hot Reactor Proving Grounds - ASSIST

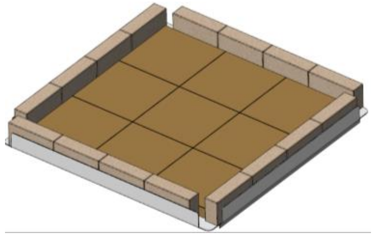


ASSIST Environment Chamber
3E-6 Torr Minimum Pressure
1.4 x 1.1 x 1.4 m test volume

ASSIST Exterior Wall Cooling (7kw)



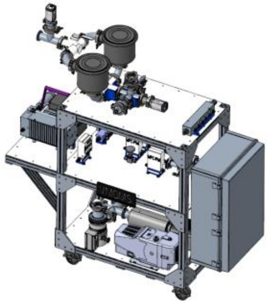
Reactor Interior Oil Cooling (10kw)



Ceramic Firebrick Pallet

3 Power Supplies 10-15kW ea.

DAQ Capabilities
- Temperature
- Cameras
- Pressure



O2 Monitoring

Volatile Monitoring and Oxygen Measurement

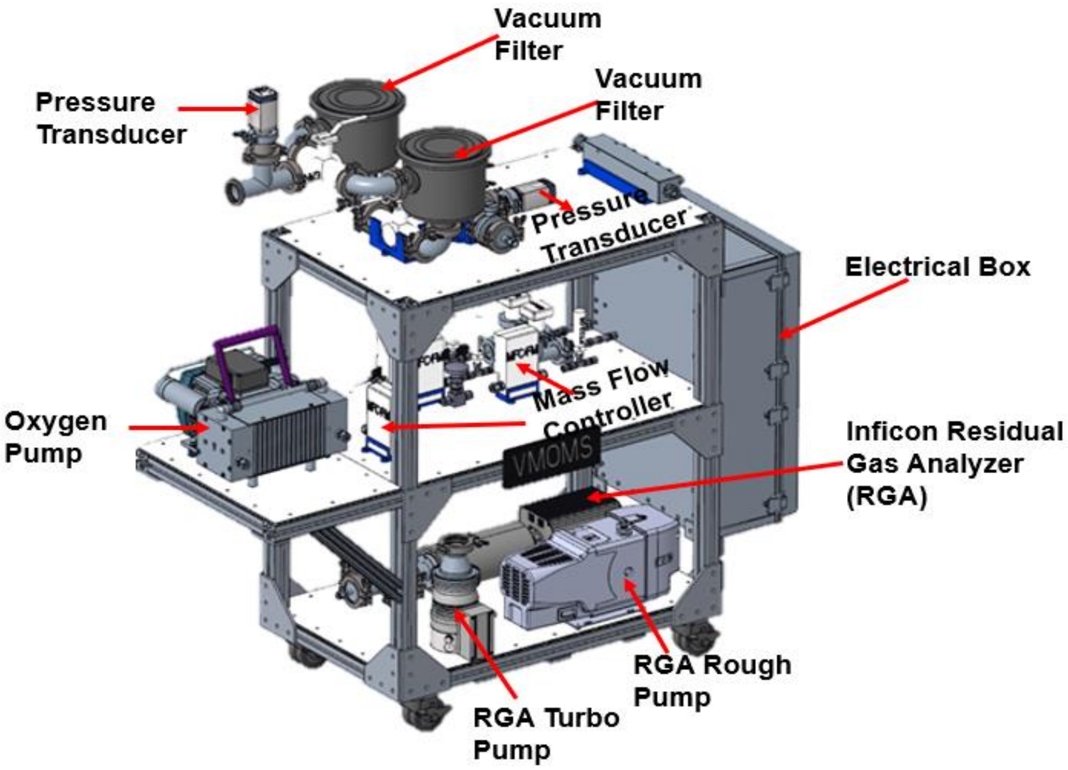
The aim of the system is to quantify the amount of oxygen produced in the reactor during electrolysis. It also identifies gases in the reactor during evacuation, heating, and electrolysis phase.

Original Technology Developed:

A	Oxygen Sensor – Trace O2 analyzer	(0-1000 ppm)
B	Oxygen Sensor – Oxygen monitor	(0-95%)
C	Residual Gas Analyzer (RGA)	(0-100 amu)
D	Gas Chromatograph (GC)	
E	Vacuum Pump – Oxygen compatible	
F	Vacuum Pump – Corrosive compatible	
G	Relief Valve	
H	Flow Meter	
I	Mass Flow Controller	
J	Thermocouple	
K	Pressure Transducer	
L	Power Control System	
M	DAS	

Oxygen Sensor with KF25 Flange

Residual Gas Analyzer

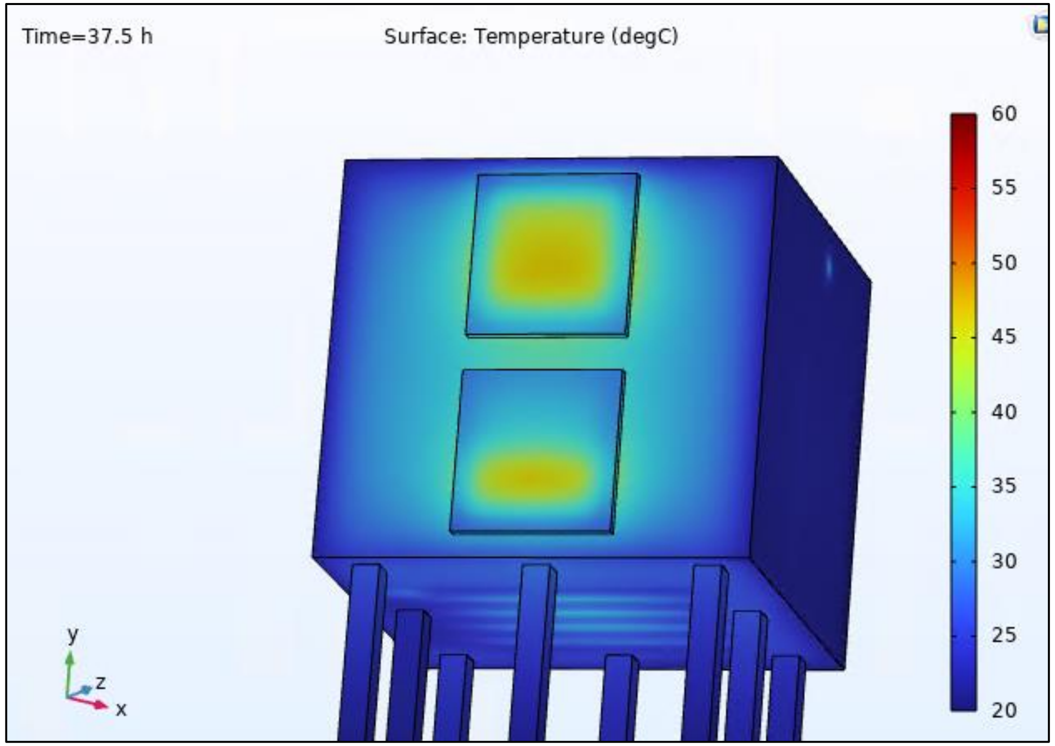


Thermal Modeling

- KSC developed both high and low-fidelity models to determine system thermal limits and nominal expected operation.

- Due to thermal modeling, the team determined the need for a “front deflector shield” on the front door to prevent damage to door seals and supplemental cooling fans were added to reduce temperatures to be “safe touch”.

- Thermal modeling was used to estimate peak melt temperature during operation when compared to thermocouple readings within the melt.

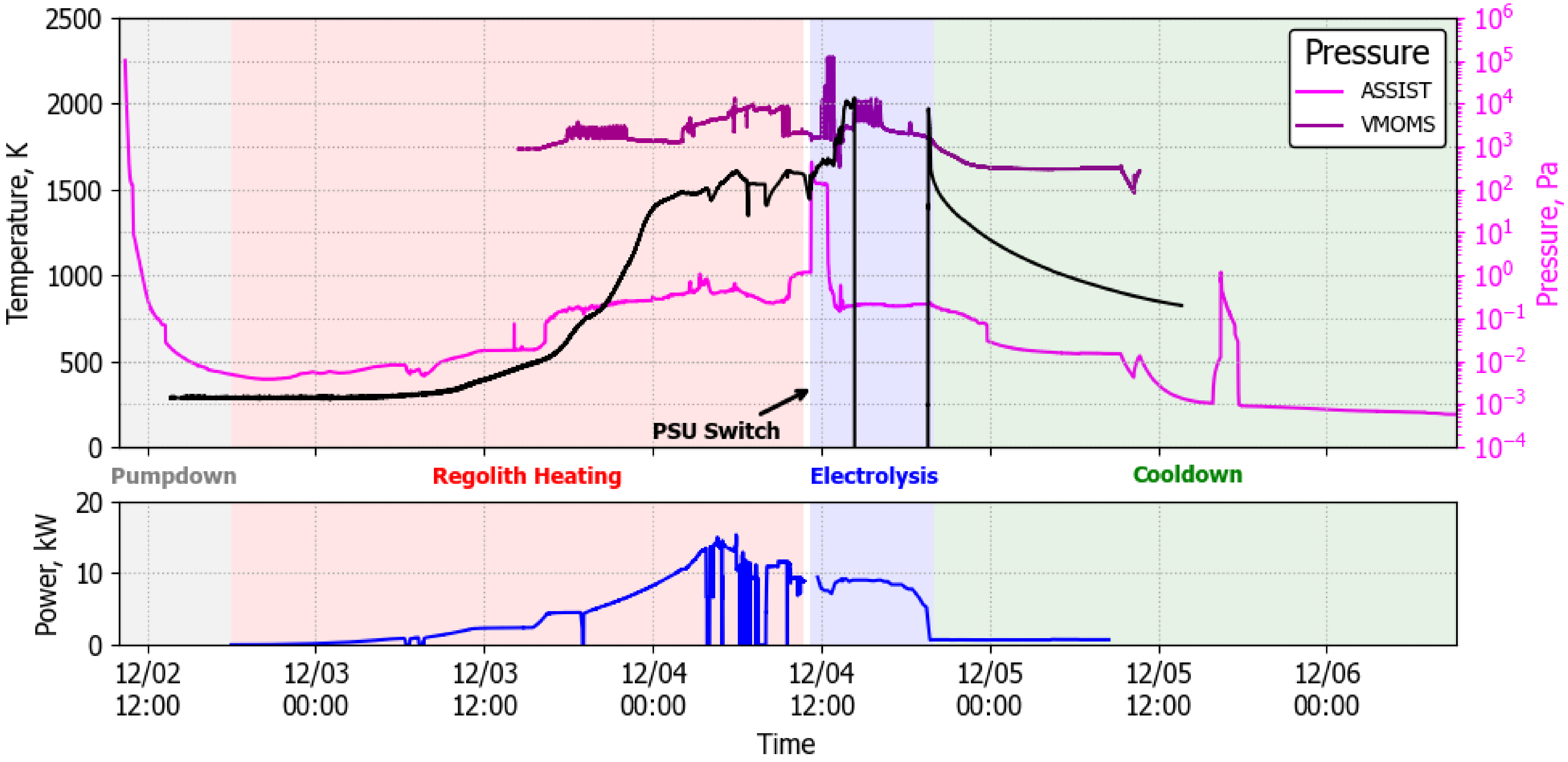


Test Layout

KSC Hardware was quality checked via an XE-6 torr vacuum test.

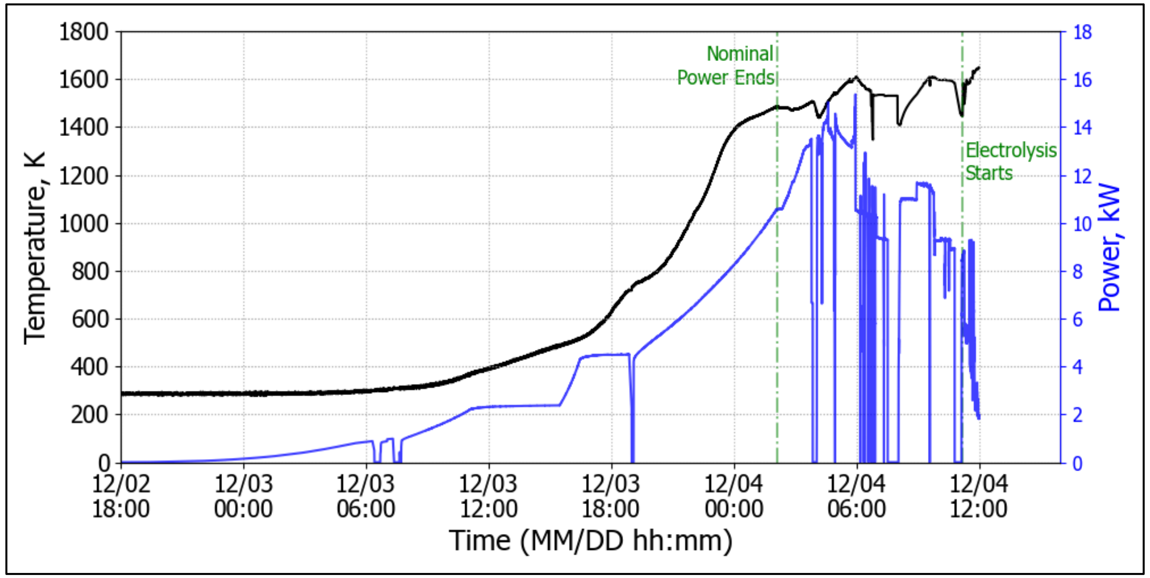
Loading reactor into ASSSIT chamber

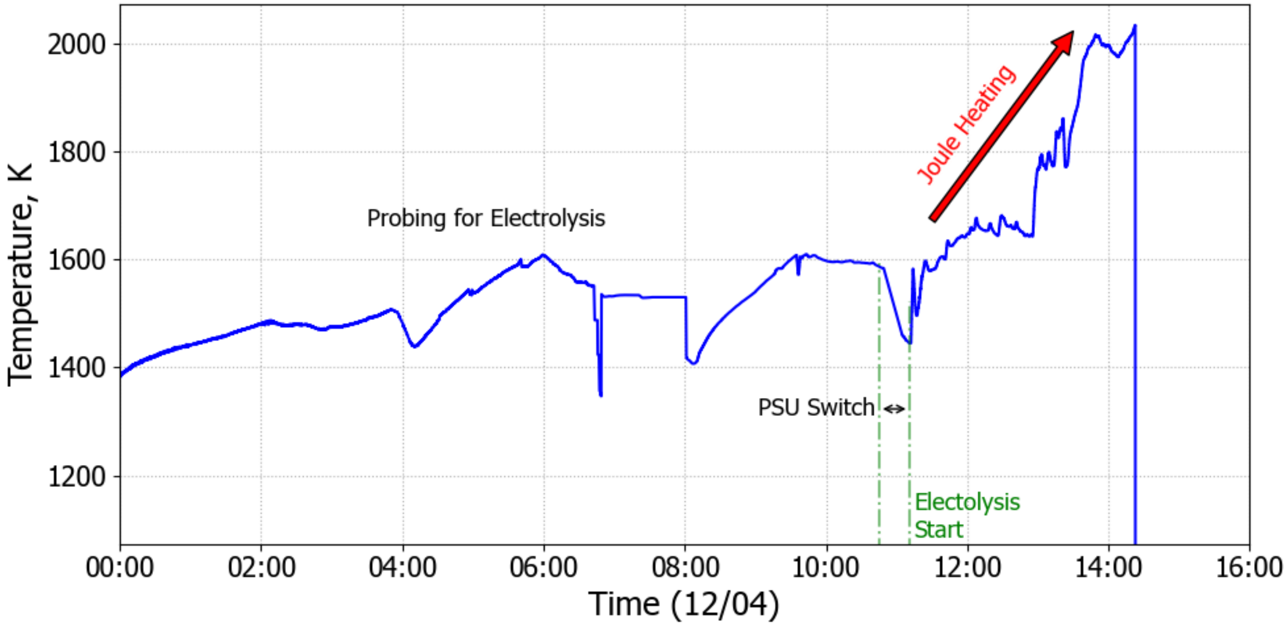
Test Campaign



Test Phases

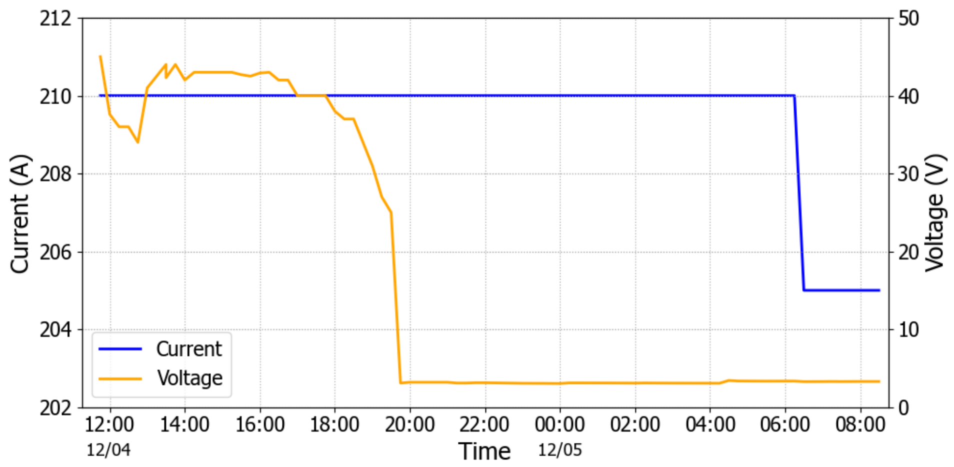
- Heating
  - Constant Ramp Rate of 3 to 5 A every 15 min
  - Slow increase until 1300°C
- Transition:
  - Thermal conditioning to 1200-1300°C
- Electrolysis
  - Electrolysis initiated at 45V
  - Joule Heating
  - Temperature increase beyond 1700 °C
- Cooldown

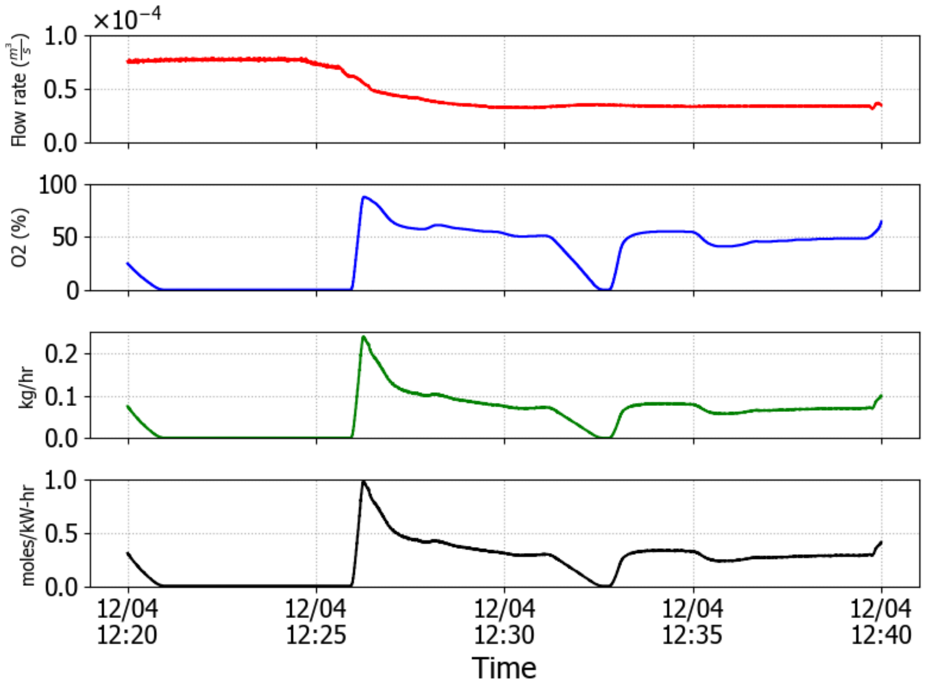




Electrolysis and Gas Production

- Joule heating: Electrolysis maintained.
- Electrolysis duration: 9 hrs.
- Power Characteristic
  - Overall: 45 V, 210 A.
- Key Performance Parameters
  - Produced Oxygen 2.3 Weight %
  - Average Production Rage: 0.07 kg/hr
  - Oxygen Production Efficiency: 0.3 Mols O2/kW-hr





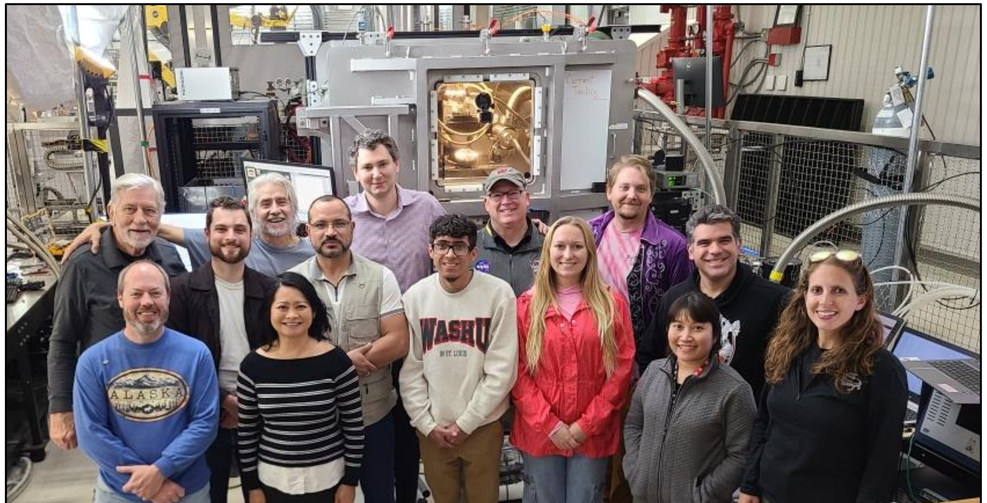
Core Sample

- A post-test sample of the reduced melt was retrieved from the core of the reactor.
- Several test where performed:
  - Computer tomography (CT) scan was performed to provide internal images of the core
  - X-Day Diffraction (XRD)
  - Scanning Electron Microscopy (SEM)
  - Elemental Dispersive Spectroscopy (EDS)




FY23-25 Accomplishments Summary

- Largest MRE experiment done with 25kg of regolith.
- Goals and objectives completed
- Hardware integration of LUNAR, ASSIST, VMOMS, power supplies, and DAC were successfully.
- ASSIST demonstrated its ability to operate an integrated MRE system.
- The LR-1 data acquisition and control system (DAC) collaboration successful.
- The LR-1 reactor was able to stabilize and sustain high temperatures for a period exceeding 12 hours.
- Joule heating was sustained by the electrolysis process. This allowed temperature beyond **1700°C** with a maximum power draw of about 9 kilowatts during vacuum chamber operations.
- Several datapoints provided results of up to **80%** by volume molecular oxygen concentration.
- Core sample retrieval for post-analysis



GCD Team Members & Stakeholders

KSC MRE Team

- Annie Meier, PM, Chemical Engineer, UB-E, Anne.Meier@nasa.gov
- Jaime Toro, PI, Data Acquisition, NE-L1
- Deborah (Dherby) Essumang, VMOMS, UB-E
- Evan Bell, Mechanical Design ASSIST, NE-L6
- Malay Shah, Thermal and Fluid Analysis, NE-L6
- Kenneth Engeling, Vacuum and Systems, UB-E
- Joel Olson, VMOMS Chemist, LASSO II
- Lucy Somervill, Chemical Engineer, LASSO II
- Beau Peacock, VMOMs Electrical, NE-L6
- Jackson Smith, NASA Pathways Intern, UB-E
- Ajchariya Harrison, VMOMs Oxygen Compatibility, LASSO II
- Rodolphe 'Gino' Carro, Pressure Vessel Systems, LASSO II
- Bill Dziedzic, Reactor Scale Modeling, NE-XY
- Tim Murphy, Safety Officer, SA-B
- Raeesah Dalal, Resource Manager, GG
- Eric Smith, SE, NE-TE*
- David Rinderknecht, NE-L3*
- Joyce Crum, Scheduling/Integration, JSC Barrios*
- Matthew Nugent, Test Support/Electrical, LASSO II*
- Kevin Grossman, PI, Materials Engineer, UB-E*
- Laurent Sibille, MRE Analysis & model assumptions, LASSO II*
- Toni Curate, PM UB-T*
- Elspeth Petersen, PM/Chemical Engineer, UB-E*

*(Supported prior years/retired/no longer @ KSC)

Lunar Resources, Inc. (LR/LUNAR)

- Elliot Carol, CEO, Lunar Resources, Inc.
- Alex Ignatiev, PI/CTO, Lunar Resources, Inc.
- Mark Hinkel, PM, Lunar Resources, Inc.
- Rabi Ebrahim, Lunar Resources, Inc.

Stakeholders

- Phillip Maloney, KSC STMD POC, UB-T
- QuynhGiao Nguyen, Program Element Manager, GCD, STMD
- Christopher Kuhl, Program Chief Engineer, GCD, STMD
- Duane Pettit, Program Safety Officer, GCD, STMD
- David Moore, Program Manager, GCD, STMD
- Gerald (Jerry) Sanders, ISRU System Capability Lead, STMD

KSC Chief Engineers/Review Board

- Marty Grashik, R&T Chief Engineer

Future Work

- Apply lessons learned for future MRE projects
- Include gas concentration characterization for future experiments
- MRE Reactor Improvement
  - Reusability
  - Batch or continuous production
- Subsystem development
  - Feed and removal
  - Gas cleanup
  - Compression
  - Accumulators and gas distribution
- Applications:
  - ELCSS – Multi Purpose Habitat (MPH)
  - Cryogenics – Propellant

Questions