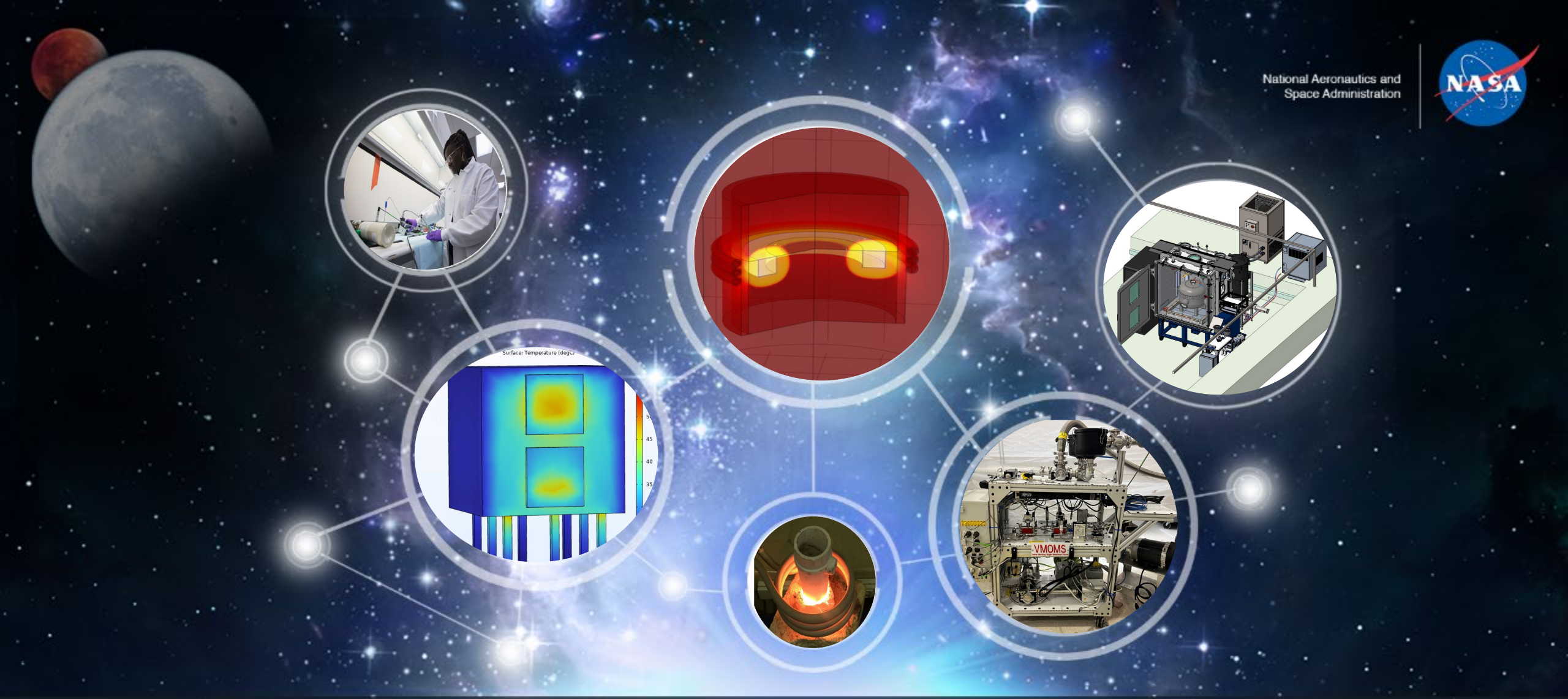


Space Technology Mission Directorate

Game Changing Development Program

Jaime Toro Medina (PI) | Annie Meier (PM) | Molten Regolith Electrolysis | Annual Program Review | September 10-12, 2024

MRE Project Overview

Timer

- Technology Product Capability
  - Molten Regolith Electrolysis (MRE) is currently the only technology tested with many regolith compositions that produces both O_2 and metals in a single-step process by performing direct electrolysis of molten regolith. MRE does not require consumables from Earth, using only electrical/thermal energy generated in-situ.
  - The goal of the project is to obtain critical experimental knowledge and retire risks associated with the development of a TRL4 integrated reactor test in the pursuit of a lunar demonstration.
- Technical Capabilities
  - The technology must mature through risk reduction testing of designs adapted to vacuum, thermal gradients, lunar G, and multiple production cycles, ensuring reliability of the technology.
  - Current knowledge gaps must be filled in terrestrial tests for design of ISRU plant in vacuum and lunar G.
- Exploration & Science Applicability
  - In-situ production of O_2 and metals on the lunar surface.
  - Provide first observations and data on molten regolith behavior on the lunar surface (lunar geophysics science)

Regolith melt formation by inductive heating
(Tests conducted by KSC and RDO Induction, Inc.)

MRE Tech Maturation
Goals

Timer

Needs Addressed by Project	
Stakeholder (e.g. HLS)	This project aims to demonstrate In-situ production of O2 and metals with lunar regolith. Shortfall ID: 1580; ISRU 564: Oxygen Extraction from lunar regolith; ISRU-575: Sensors to monitor ISRU process gases.
Stakeholder	ISRU STMD; ESDMD.

Project Goals	
Goal #1	Provide resources and technical support to the LUNAR commercial partner as they develop LR-1 to demonstrate an integrated capability to mature the technology readiness level (TRL) of Molten Regolith Electrolysis from TRL3 to TRL4.
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.

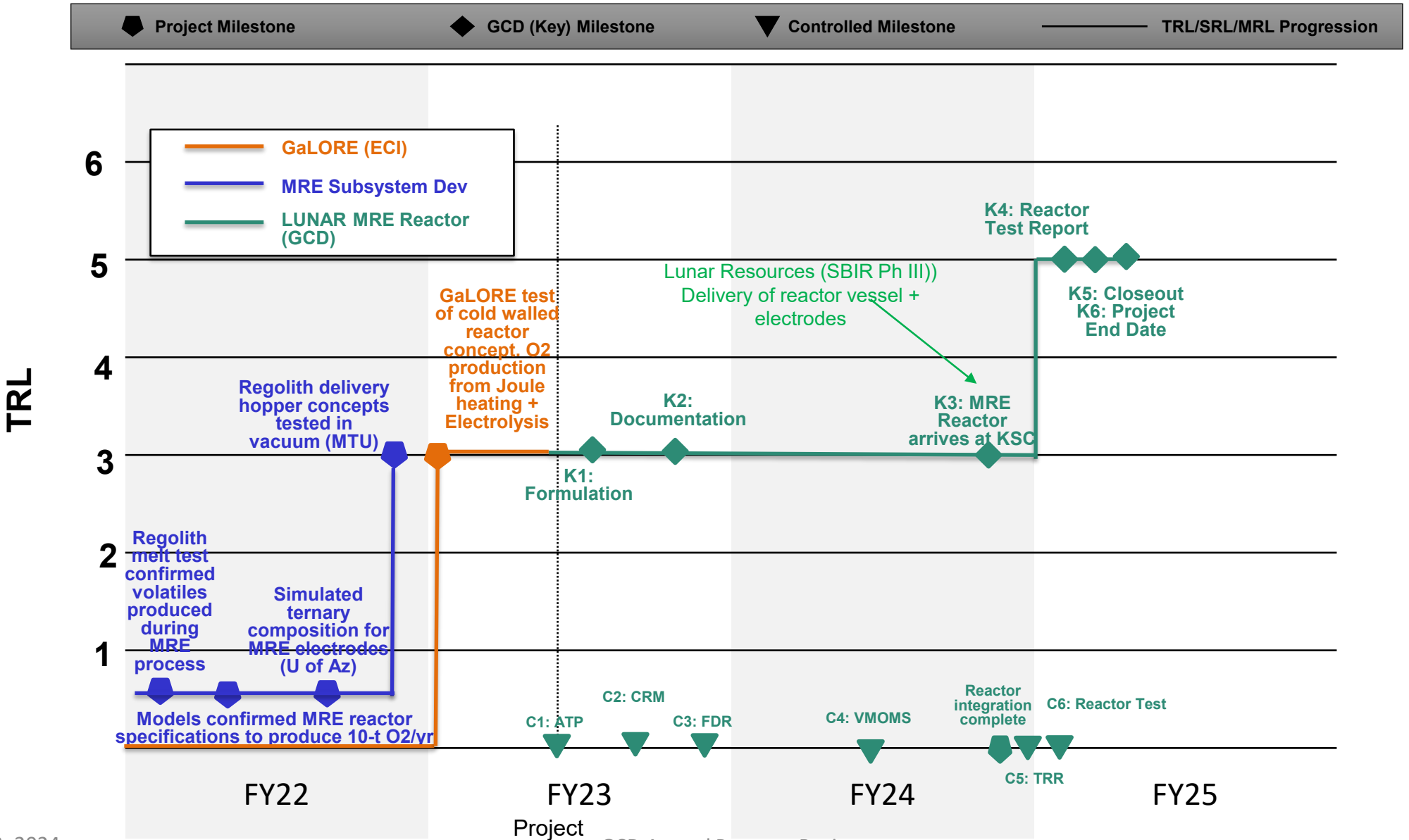
Project Objectives	
Objective #1	Define Concept of Operations (CONOPS) and requirements for an MRE ground demonstration reactor built by LUNAR and tested in the Atmospherically Sealed Simulator for In-Situ System Testing (ASSIST) chamber at KSC. (LUNAR & KSC)
Objective #2	Complete risk reduction actions on the heaters from LUNAR. (KSC)
Objective #3	Design and build the Volatile Monitoring and Oxygen Measurement System (VMOMS). (KSC)
Objective #4	Design and build MRE reactor, LR-1. (LUNAR)
Objective #5	Design process control system. (LUNAR)
Objective #6	Integrate and test MRE reactor, LR-1. (LUNAR & KSC)

Key Performance Parameters	
KPP #1	Produced Oxygen Mass (as percent of regolith melt mass). Test duration target of 14 hours at target current. **Threshold value**: 5.7 Weight %; **Goal**: 10%
KPP #2	Average Oxygen Production Rate; **Threshold value**: 0.1 kg/hr **Goal:** 0.2 kg/hr
KPP #3	Oxygen Production Energy Efficiency (During electrolysis): **Threshold value**: 0.6 Mols O2/kW-hr; **Goal:** 1.0 Mols O2/kW-hr
Objective #4	Energy Efficiency for Melt Phase (pre-electrolysis melt phase): **Threshold value**: 2000 kJ/kg; **Goal:** 1500 kJ/kg

MRE Tech Maturation

TRL

Timer

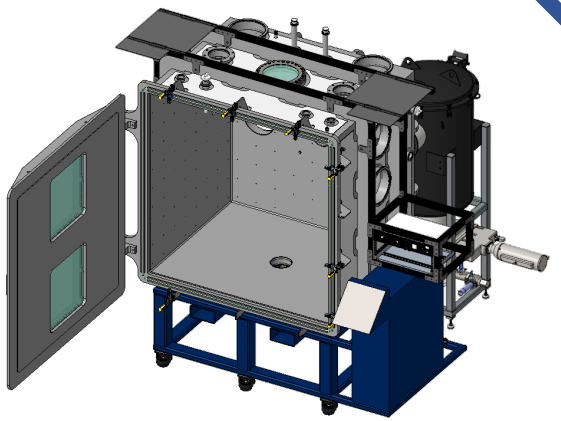


Technical Progress - Status

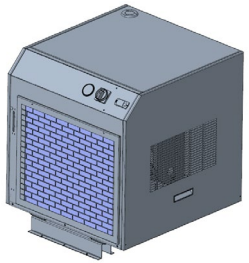
- KSC MRE team tested the current LR heater design in a configuration that is analogous to the reactor test in October 2023. The test was done in vacuum in KSC's ASSIST Chamber.
- KSC MRE team completed Final Design Review (C3-2, Feb 7, 2024) with NASA and Lunar Resources Systems for integration and test into the KSC ASSIST Chamber.
- The VMOMS (Volatile Monitoring and Oxygen Management System) Subsystem is built and ready for testing to detect and measure oxygen production.
- A comprehensive thermal analysis was completed on the ASSIST chamber that includes thermal analysis during reactor operation. The results are being published at the NASA Thermal & Fluids Analysis Workshop (TFAWS).
- The KSC team is expecting delivery of the reactor from Lunar Resources Inc in September 2024. After the Test Readiness Review the batch test of the MRE reactor integrated in the ASSIST environmental chamber will take place.

Hot Reactor Proving Grounds - ASSIST

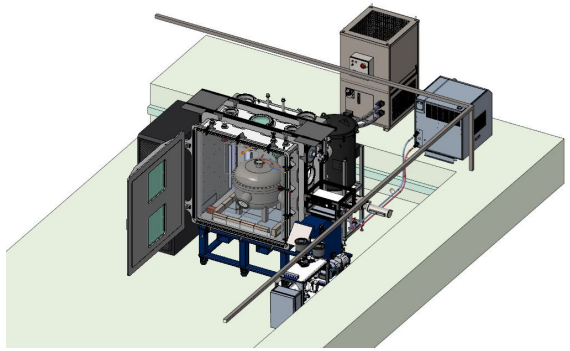
Timer

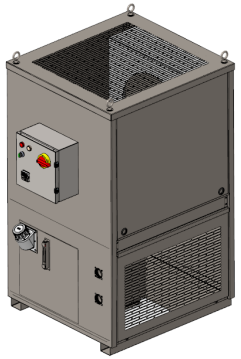


ASSIST Environment Chamber
3E-6 Torr Minimum Pressure
1.4 x 1.1 x 1.4 m test volume

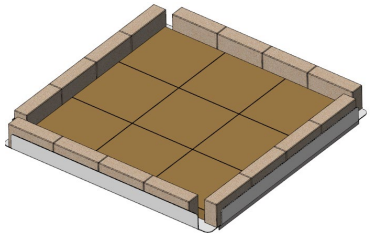


ASSIST Exterior Wall Cooling (7kw)





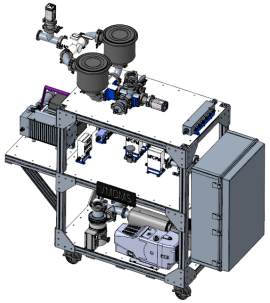
Reactor Interior Oil Cooling (10kw)



Ceramic Firebrick Pallet

3 Power Supplies 10-15kW ea.

DAQ Capabilities
- Temperature
- Cameras
- Pressure



O2 Monitoring

Technical Progress - Interface

- Control System Verification
  - Elements of the control system have been tested to ensure functionality.
  - Load testing of the reactor components have been performed under simulated environment.
  - Integrated system tests have been performed with procedure in simulated environment.
- Power and Control vacuum interfaces have been verified.
- Facility Power Modifications
  - Ready to support operations

Inside ASSIST chamber

Outside of ASSIST chamber

Technical Progress - Interface

- Vacuum Chamber Equipped
  - Thermal Protection
  - Electrical Interface
  - Pneumatic lines
  - Cooling lines
  - Camera
  - Mirrors
- Data Acquisition and Monitoring
  - Chamber temperatures
  - Modeling verification

View of inside ASSSIT chamber

Hot Reactor Proving Grounds - ASSIST

Timer

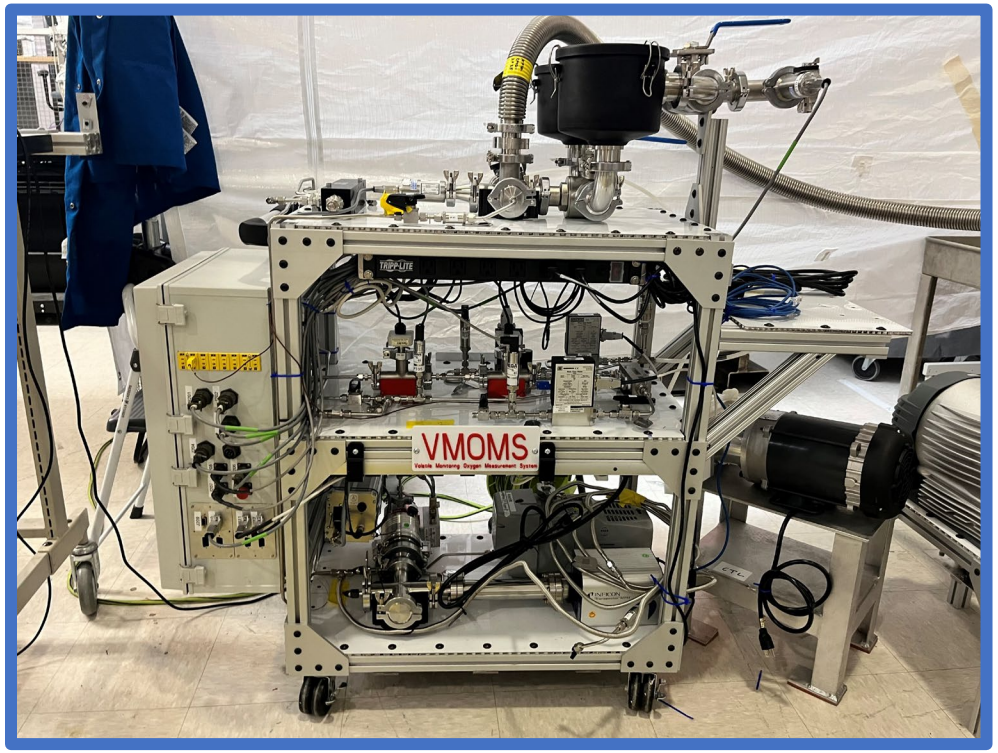
ASSIST Chamber Operations Area

Additional ASSIST Project Testing:

- CIF Metals Processing
  - Aug 1 to Aug 15
- GCD Vertical Lunar Regolith Conveyor (VLRC)
  - Aug 15 to Sep 1
- IRAD Modular Interface for CLPS Excavators (MICE)
  - Sep 1 to Sep 15
- IRAD Additive Construction Twin Screw Extruder (ACTSE)
  - Sep 15 to Oct 1
- Tipping Point Redwire Space Mason Compactor
  - FY25
- GCD ISRU Pilot Excavator (IPEx)
  - FY25
- FY25 CIFs and IRADS (pending award)

Technical Progress - Status

- **VMOMS** enables the identification and quantification of gases that evolve in molten regolith electrolysis (MRE) during high temperature melting and electrolysis phases.



VMOMS System

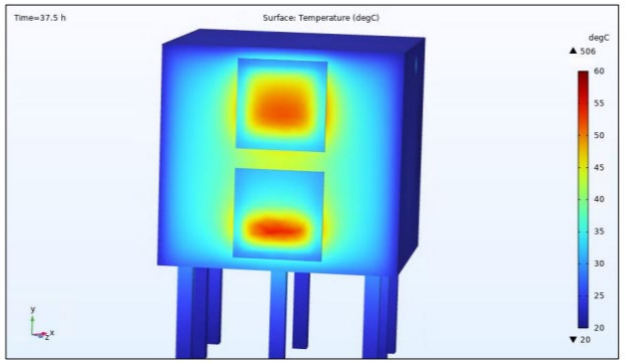


Figure 13. Internal temperature contour plot of ASSIST door elements.

The contour temperature plot in Figure 14 shows the temperatures on the aluminum sh protecting the front door of the ASSIST chamber. The two cut outs show the front windows.

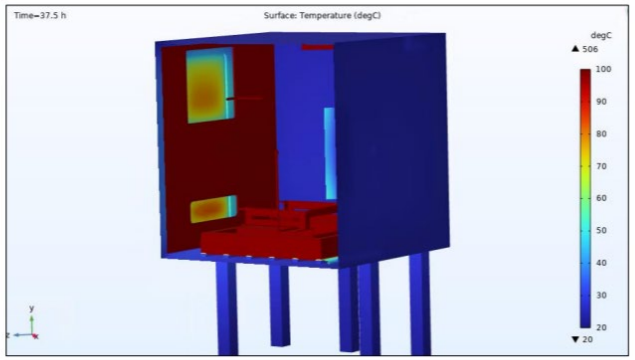


Figure 14. ASSIST chamber internal aluminum shield temperature contour plot.

- **TFAWS** – paper published August 2024: A Transient Multiphysics Thermal/CFD Simulation Analysis of a Molten Regolith Electrolysis Reactor within a Thermal Vacuum Chamber.

SBIR Phase 3 Tech Infusion

Lunar Resources, Inc. SBIR Ph 3 Reactor Development team

+

NASA KSC Molten Regolith Electrolysis team

MRE Tech Maturation
Transition/Infusion Status

Timer

- There are conversations taking place with external collaborators and potential partners for responding to NASA calls to infuse technology into higher TRL for potential flight demonstrations. i.e. LIFT-1
- There are multiple internal projects at KSC being funded in FY25 towards various areas of technology development needed for subsystem robustness including advanced materials and software controls.

- We are open to discussions if you'd like to work with us. Please reach out if interested:
  - Jaime Toro Medina (PI + MRE Avionics and Controls): jaime.a.toromedina@nasa.gov
  - Evan Bell (ASSIST Chamber / MRE Structures): evan.a.bell@nasa.gov
  - Annie Meier (GCD MRE Project Manager): anne.meier@nasa.gov

O2 Production from Regolith

Project Name	Performance				Comments
	C	S	T	P	
Annual	G	Y	Y	G	Technical – Partner's hardware still requires integration and successful checkouts to commence testing in ASSIST chamber. Cost – Change request was approved to continue testing in Q1 FY25 once reactor arrives at KSC. Schedule – Schedule is dependent on commercial partner delivering reactor to KSC. Programmatic – On track

	Oct	Nov	Dec	Jan	Feb	MYR	Apr	May	Jun	Jul	Aug	APR
C	G	G	G	G	G	G	G	G	G	Y	G	G
S	Y	Y	Y	Y	Y	Y	Y	Y	Y	R	G	G
T	G	G	G	G	G	G	G	G	G	Y	Y	Y
P	G	G	G	G	G	G	G	Y	G	Y	G	G

S = Yellow due to reactor manufacture/delivery delays. Once change request approved for extended schedule into Q1 FY 25, S=Green.
Technical remains yellow as wait to integrate and test in ASSIST chamber at KSC.