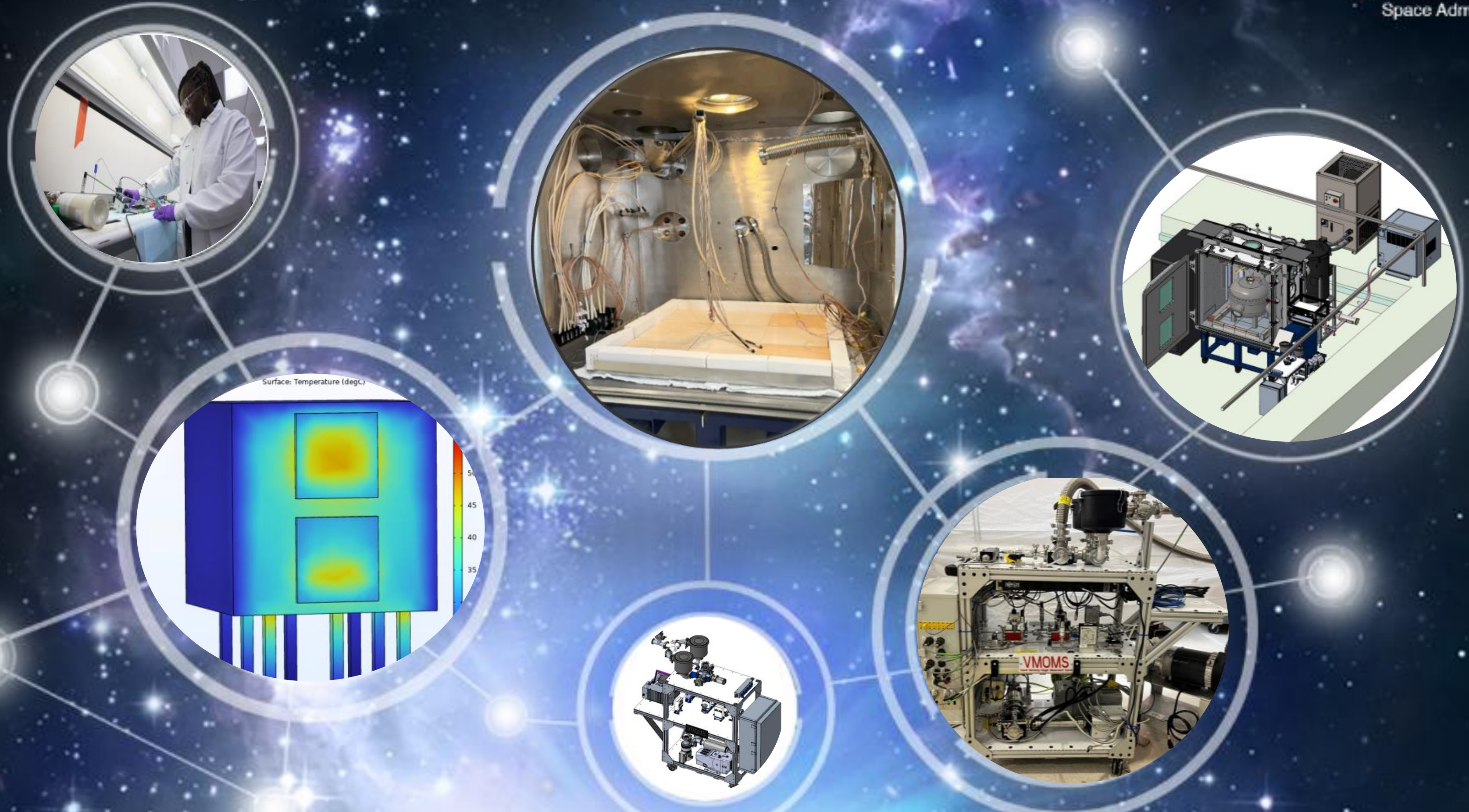
National Aeronautics and
Space Administration



Space Technology Mission Directorate

Game Changing Development Program

Jaime Toro Medina (PI) | Annie Meier (PM), Molten Regolith Electrolysis Public Release Document

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**

MRE Tech Maturation Project Overview

Technology Development Needs Addressed by Project
This project aims to demonstrate In-situ production of O2 and metals with lunar regolith.

STMD Civil Shortfalls Addressed by MRE GCD:

- ✓ **1580:** Extraction and separation of oxygen from extraterrestrial minerals (Ranked 68)
- ✓ **1581**: Extraction and separation of extraterrestrial atmospheric resources and gaseous products/reactants (Ranked 107)
- ✓ **1582**: Extraction and separation of metals/metalloids from extraterrestrial minerals (Ranked 110)
- ✓ **1583**: Produce propellants and mission consumables from extract In-Situ Resources (Ranked 79)
- ✓ **1593**: Lunar surface power generation from ISRU derived resources (Ranked 178)

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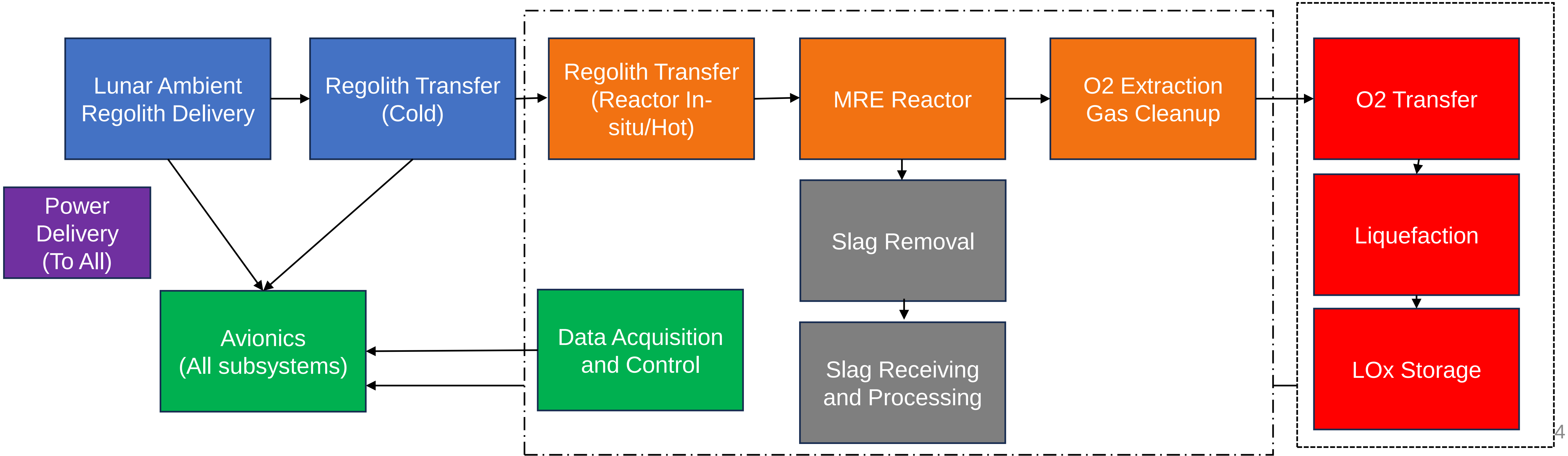
MRE PM/SE Approach & TRL Discussion

- The MRE reactor demonstration in the ASSIST chamber was governed by “KSC KDP-P-2723 Streamlined Design Process”.
  - The technical authority in this process is the KSC Chief Engineer and the review forum will be the Engineering Review Board (ERB) as defined in KDP-P-2761, Engineering Directorate Boards, Panels, and Reviews, Structure and Process Document, although streamlined reviews may be held at the discretion of the Technical Authority.
  - GCD Program Technical Authority was present at the KDP-P-2723 Gate Reviews and KSC Systems Engineering Review Boards
  - Lunar Resources, Inc. participated in a Formulation Review, Concept Review, and Final Design Review

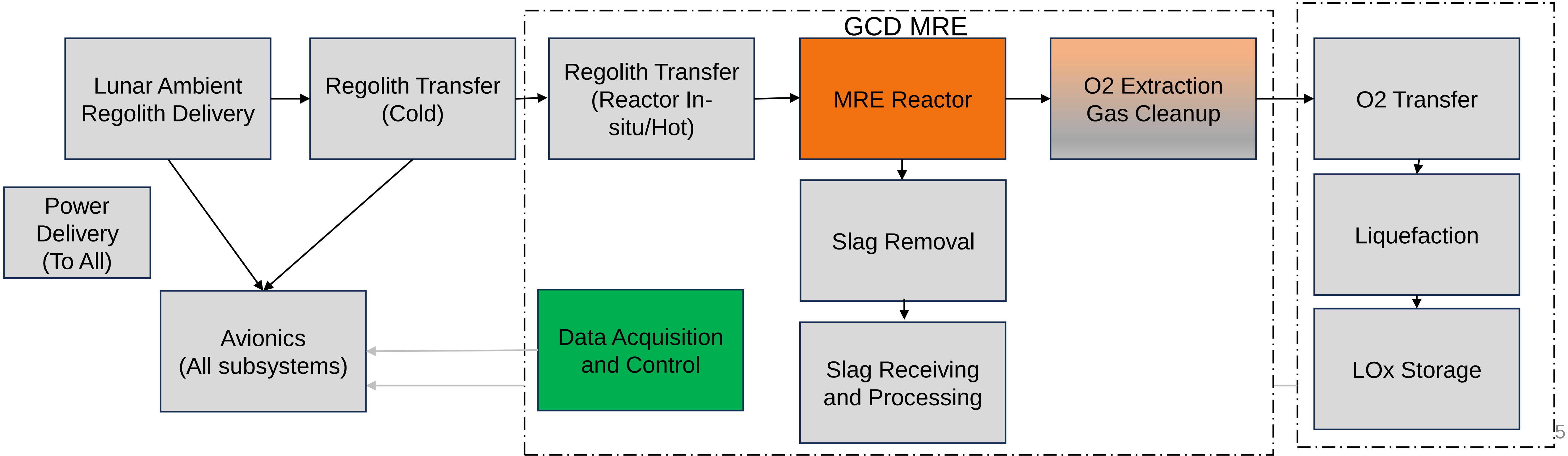
- For the entire MRE System (including reactor, other subsystems and components), development is required under NPR 7120.8A Research and Technology Program and Project Management Requirements
- To move to flight, the entire MRE System must advance to 7120.5 (with process tailoring to increase risk posture).



MRE PM/SE Approach & TRL Discussion

- This SBIR Phase III collaboration demonstrated:
  - MRE reactor in a vacuum environment
  - Data Acquisition and Control
  - Oxygen Extraction & Quantification

- MRE Tech Demo is classified as TRL 4, demonstration of component and or breadboard validation in a relevant environment.



MRE Tech Maturation Project Overview

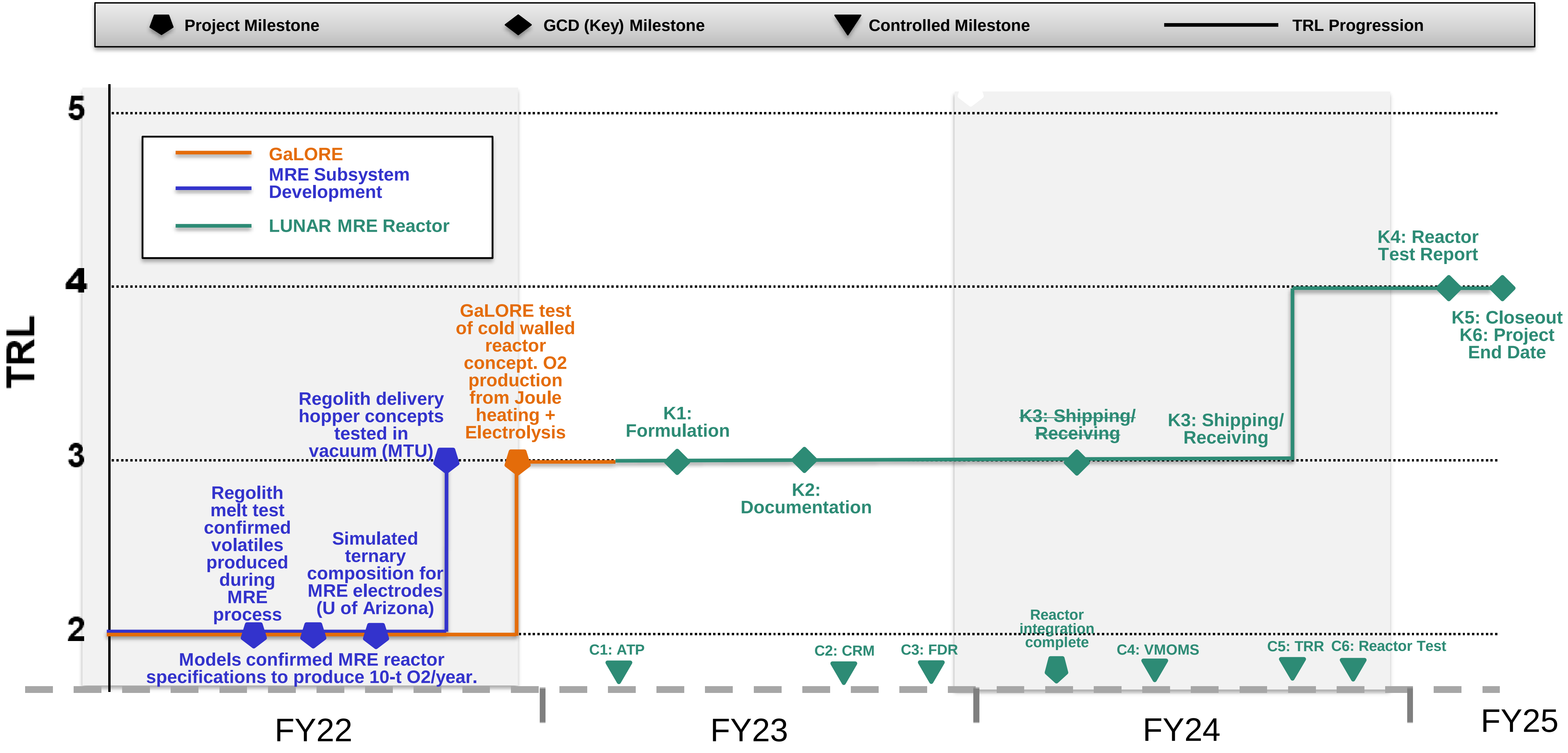
Project Goals	
Goal #1	Provide resources and technical support to Lunar Resources, Inc. as they develop a reactor to demonstrate an integrated capability to mature the technology readiness level (TRL) of Molten Regolith Electrolysis
Goal #2	Prepare the test environment at KSC for demonstration of the 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

Collaborations & Partnerships

- Contributing partners and/or stakeholders
  - Lunar Resources, Inc. – Hardware development
  - Jet Propulsion Lab (JPL) – Modeling and Simulations (FY22, FY23)
- Target applications within NASA, OGA, Academia or Industry. (Indicate whether these applications are planned or potential)
  - SBIR Phase III with Lunar Resources Inc. awarded on 01/2023. Ended November 2024.

MRE Tech Maturation
O2 Production from Regolith – Timeline Overview



Test Layout

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

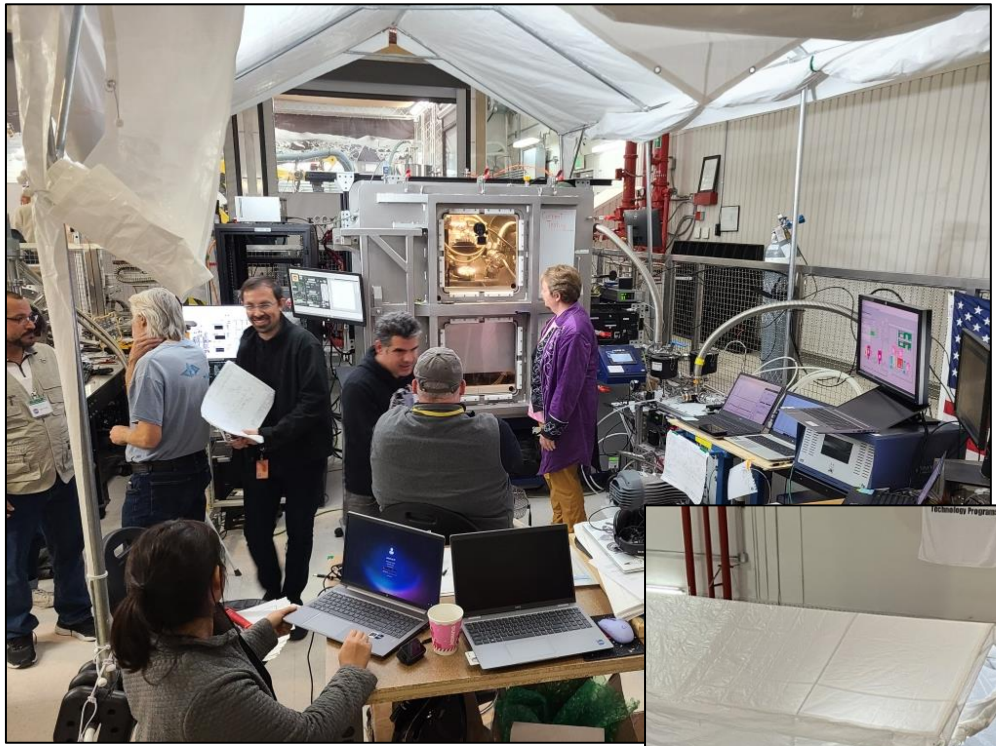
Loading reactor into ASSSIT chamber

Assembly Considerations

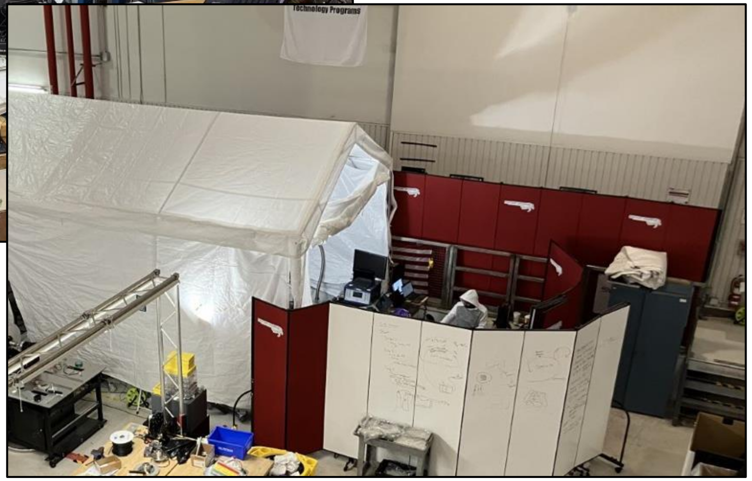
- MRE assembly occurred while GMRO was supporting external customer in testing within our BP-1 regolith bin.

- To protect LR intellectual property, the team developed means to separate the lab physically via a tent over ASSIST and the operational area.

- Tent walls lifted after reactor was in-ASSIST and external customer vacated premises.



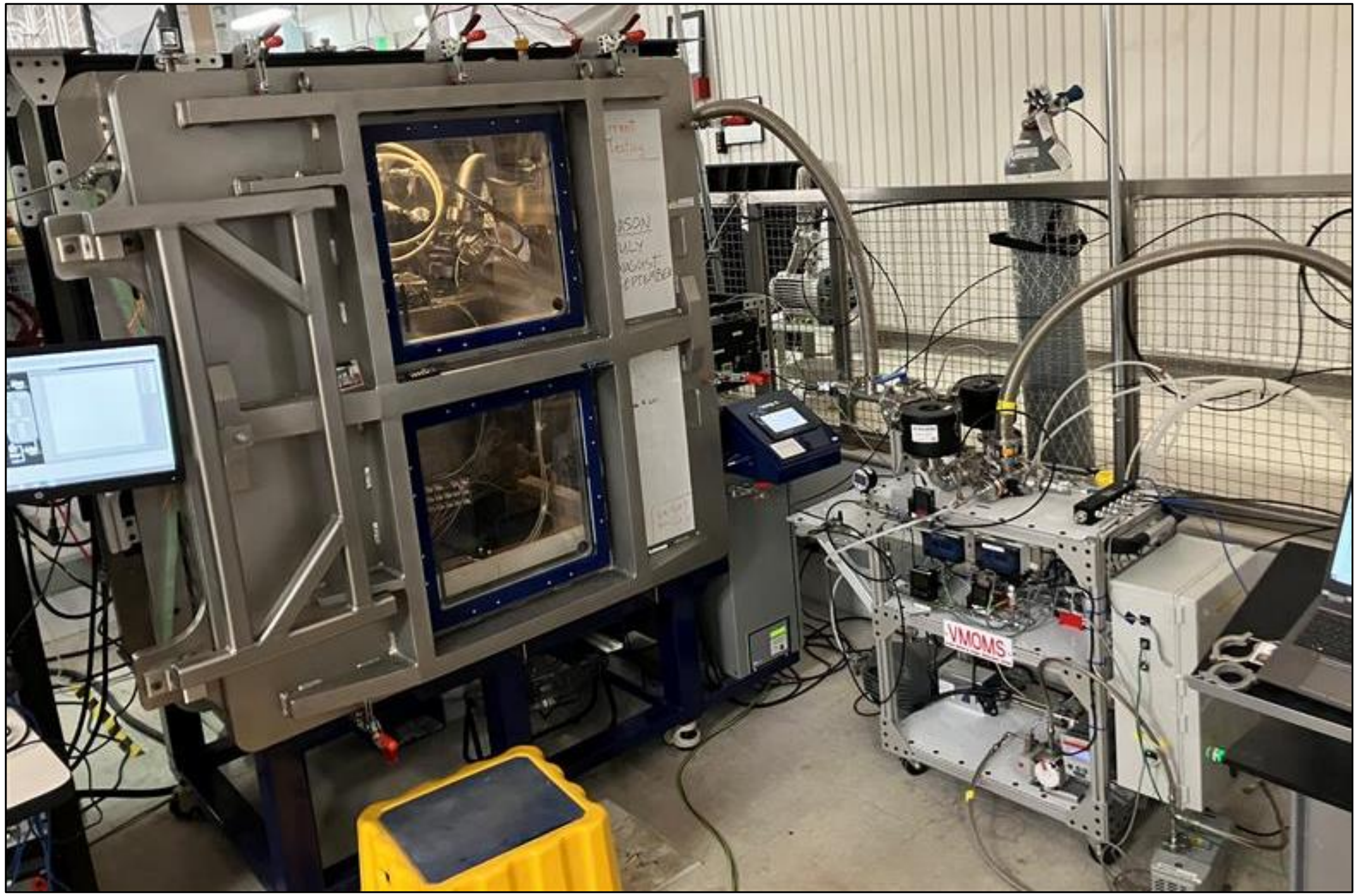
LR-1 in ASSIST during heating of regolith.



Physical barriers in GMRO lab.

Test Assembly

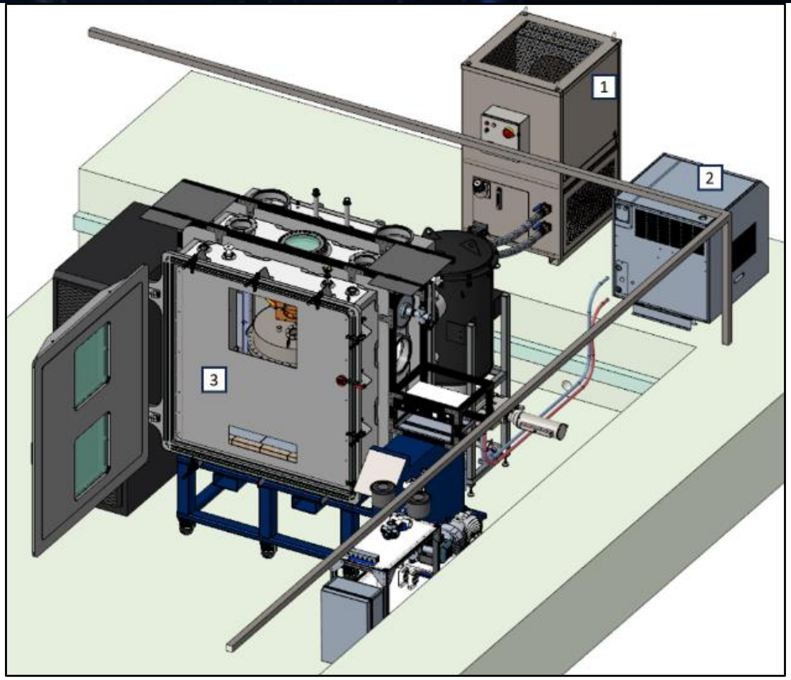
- KSC developed assembly and operation procedures with LR input.
- Assembly started 10/14/2024 but paused due to heater assembly leaks.
- Assembly and final leak checks ended on 12/02/24 after heaters were repaired at LR's facility.
- Through assembly LR was on-site to advise and assist with LR-1 assembly.



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.

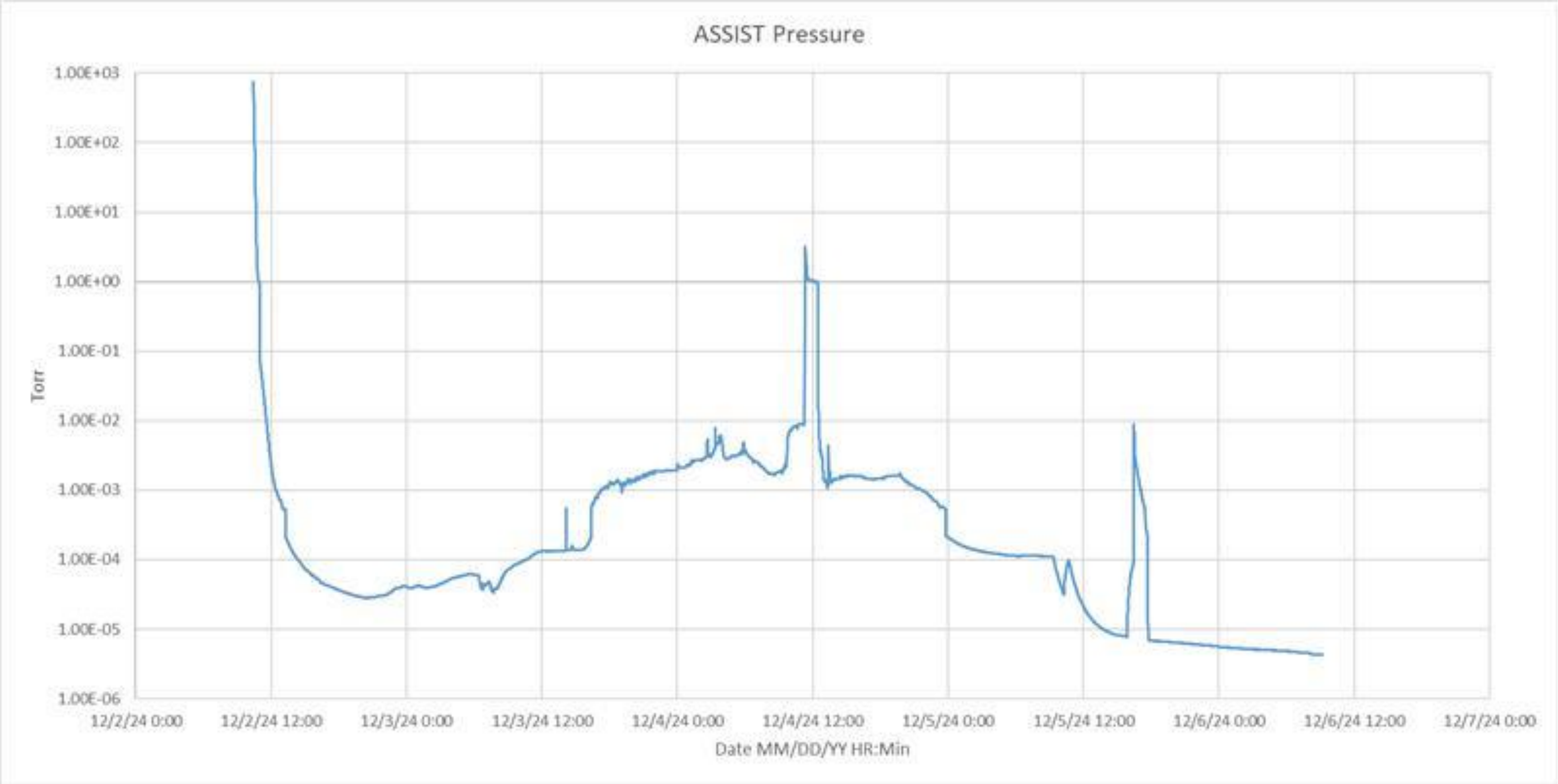
FY23-25 Accomplishments Summary

- Goals 1-4 and objectives 1-6 were achieved during this project. The team has recommended KPPs , which were achieved based on system available hardware.
- Hardware integration of LUNAR, ASSIST, VMOMS, power supplies, and DAC were successfully integrated and passed leak checks to begin heating and electrolysis of the reactor.
- ASSIST demonstrated its ability to operate an integrated MRE system. Several additional capabilities were added for thermal protection.
- The LUNAR data acquisition and control system (DAC) was able to provide critical monitoring, logging, and control capabilities during the experiments.
- The LUANR 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.
- During the electrolysis phase, VMOMS was able to collect and identify oxygen production concentrations. Several datapoints provided results of up to 80% by volume molecular oxygen concentration.

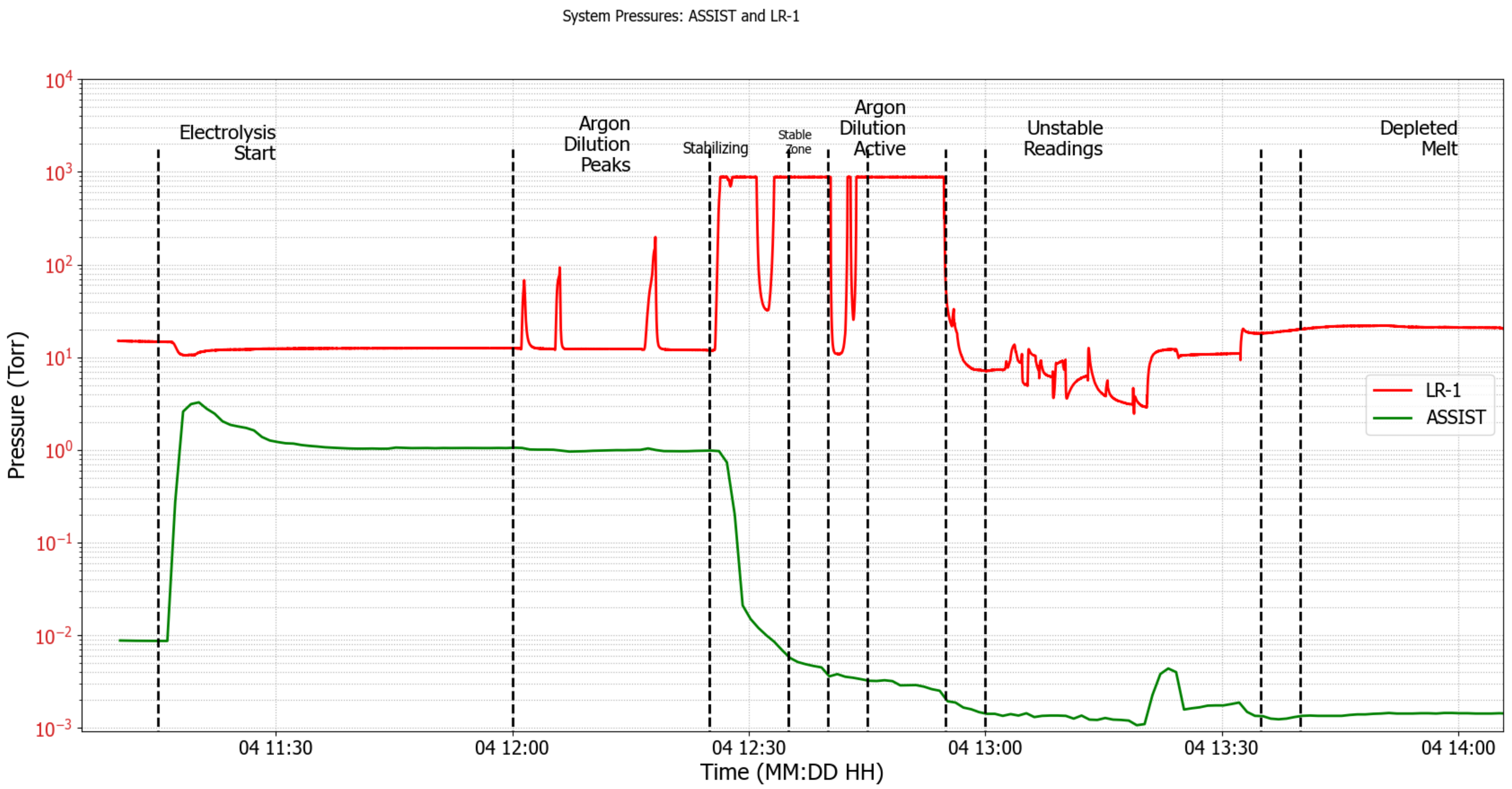


ASSIST chamber layout with Oil Chiller (1), Water Chiller (2), and Front Deflector Shield (3).

ASSIST Pressure Profile



ASSIST Pressure and PT Interface Pressure



Heating Phase

- Pumpdown during serval days: 4.07 E-5 Torr.
- Heating phase performed nominally.
- Constant Ramp Rate:
  - Variations over time.
  - 12hr periods (target 60 A and 80 A).
  - Increased 3 to 5 A every 15 min.
  - Several pauses.
- Heating rate up to 1200°C.
- Heater system reach its maximum operating parameter.
- Heaters were pushed to higher power.
  - Temperature increase to 1300°C.
  - Several filament degradations and failures.
  - Risk behavior was reduced through testing.
- Power system reconfigured to enter transition phase.

Electrolysis Phase

- Thermal conditioning to 1200-1300°C.
- Probing for electrolysis at 20 V, 5 A.
  - Melt not conductive enough.
  - Resistance was too high.
  - Anode manipulator non-responsive.
- Original electrolysis parameter: 12-15 V, 500 A.
  - System was pushed to 20 V with no response.
- Power system modified to 45 V, 210 A.
- Joule heating:
  - Electrolysis maintained.
  - Joule heating observed.
  - Temperature increase beyond 1700°C.
- Electrolysis duration: 9 hrs.

Technical Performance

Project Plan KPPs

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

Renormalized KPPs

Performance Parameter	Units	Threshold Value	Goal	Measured
KPP 1: Produced Oxygen Mass (as percent of regolith melt mass). Test duration target **of 9 hours at 210 Amps.**	Weight %	1.54	3.15	2.3
KPP 2: Average Oxygen Production Rate.	kg/h	0.04	0.08	0.07
KPP 3: Oxygen Production Energy Efficiency (During electrolysis).	Mols O2/kW-hr	0.6	1.0	0.3
KPP 4: Energy Efficiency for Melt Phase (pre-electrolysis melt phase of regolith). "Goal" = theoretical energy required to raise temperature from 25C to 1400C and change phase of solid regolith phase to molten phase at ambient pressure.	kJ/kg	-	3,100	11,877@1200C 24,692@1300C

Renormalized KPPs are called 'Recommended KPPs in GCD closeout report.

KPP4: Energy Efficiency for Melt Phase (pre-electrolysis melt phase)

- Original Methodology:
  - Based on LR Previous reactors and internal calculation.
- KSC Theoretical Calculations:
  - Based on Latent Heat of melting
- As run:
  - Energy to 1200°C
  - Energy to 1300°C
- Accounting for off-nominal:
  - Heater filament decay and break.
  - Anode manipulator not responding.
  - Power modifications during the test.

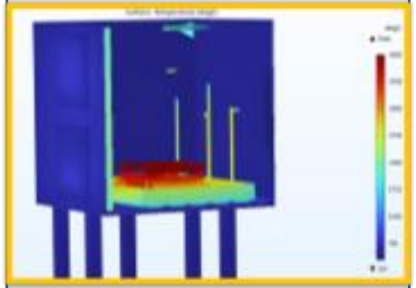
Backup

MRE Annotated Cover Pictures

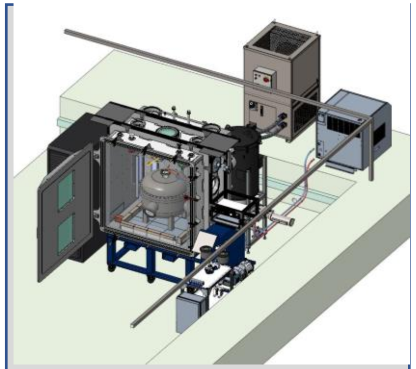
Annotated Cover Slide Images

ASSIST Environment Chamber Outfitted for Reactor Integration

Deborah Efua Adu Essumang, system lead scientist, conducts testing of the Volatile Monitoring Oxygen Measurement Subsystem (VMOMS) for Molten Regolith Electrolysis (MRE) inside a laboratory



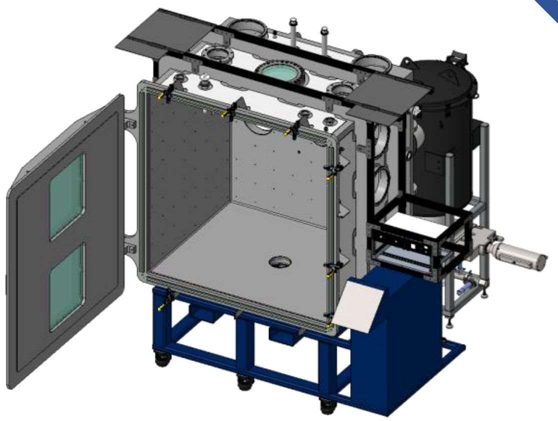
COMSOL thermal modeling of KSC ASSIST chamber (front door shown as closed).



KSC ASSIST chamber with VMOMs, chiller and power supply CAD with approved rendition of Lunar Resource MRE reactor. (Reactor is inside ASSIST chamber.)

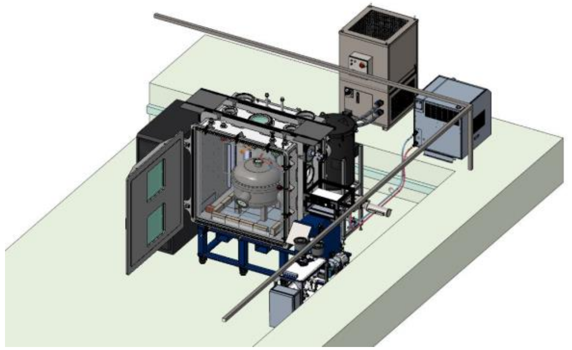
ASSIST chamber with Volatile Monitoring Oxygen Measurement Subsystem (VMOMS) and data acquisition hardware

Hot Reactor Proving Grounds - ASSIST

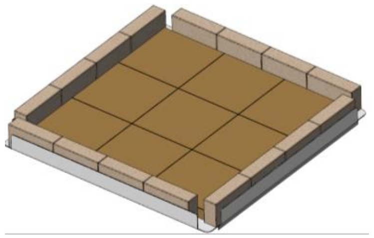


ASSIST Environment Chamber
3E-6 Torr Minimum Pressure
1.4 x 1.1 x 1.4 m test volume

ASSIST Exterior Wall Cooling (7kw)



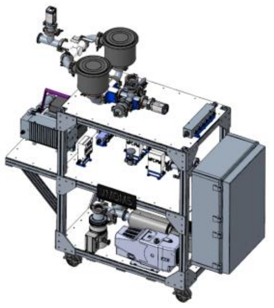
Reactor Interior Oil Cooling (10kw)



Ceramic Firebrick Pallet

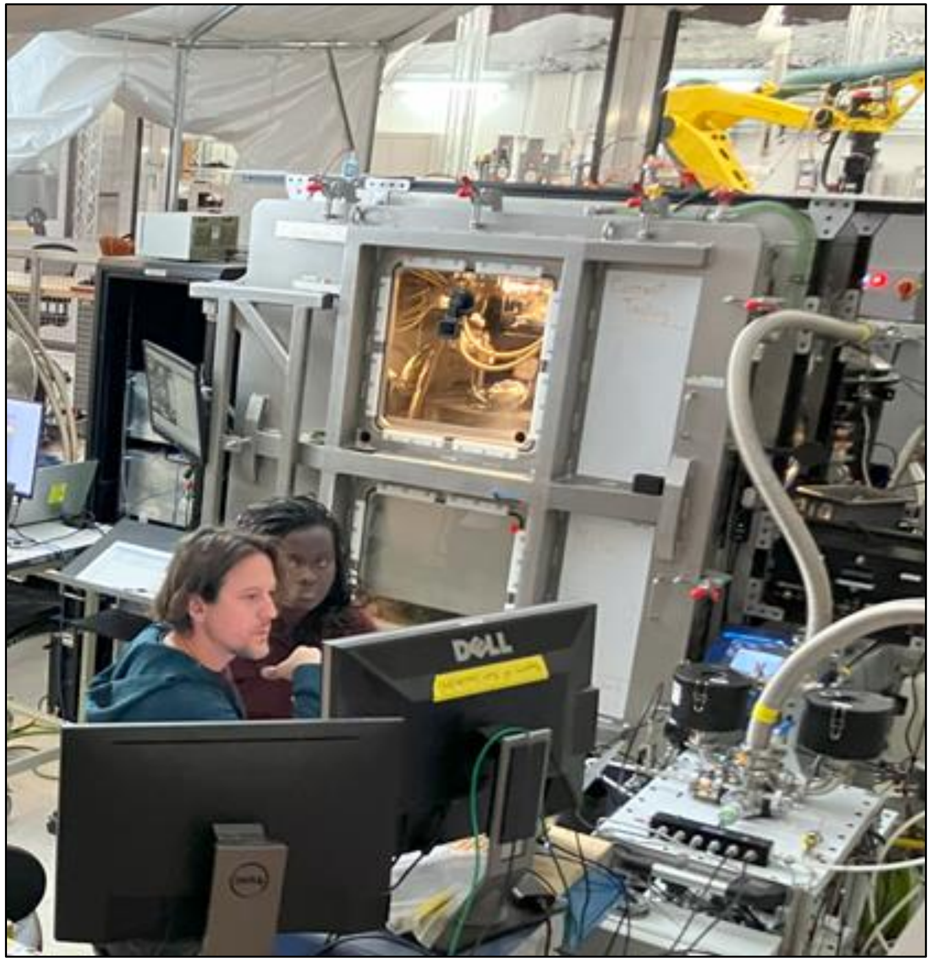
3 Power Supplies 10-15kW ea.

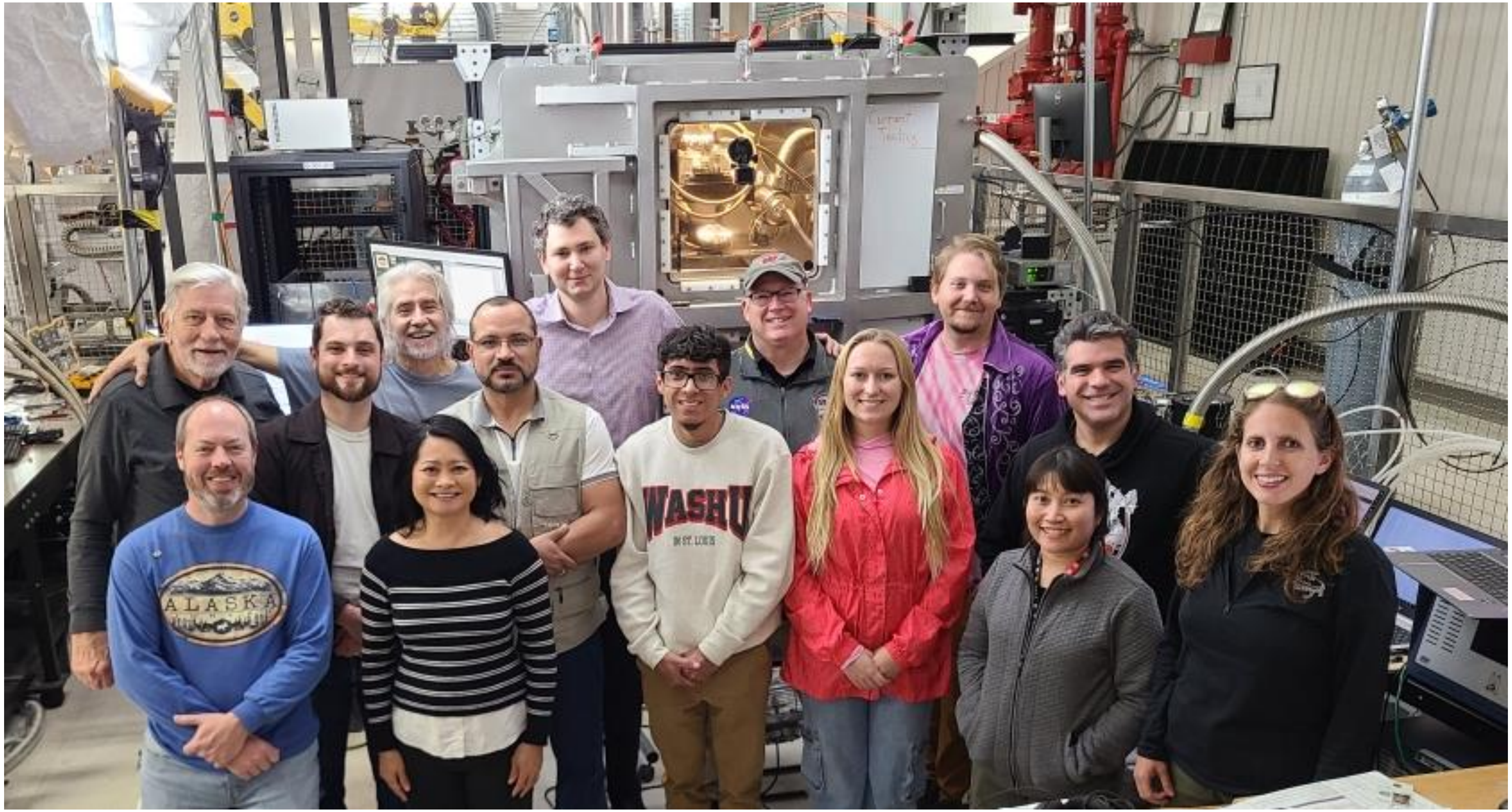
DAQ Capabilities
- Temperature
- Cameras
- Pressure



O2 Monitoring

Test Setup Photos

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