Gaseous Lunar Oxygen from Regolith Electrolysis (GaLORE): Recent Technology Advances for a Cold-Walled Molten Regolith Electrolysis Reactor

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MRE Technology Overview

The MRE reactor design enables **one-step electrolysis of regolith into metal and oxygen** without the need for fluxing agent, and without catalyst or consumable reagents.

$$Regolith\ + e^{-} \rightarrow Metal + \ O_2$$

Produces oxygen and a ferrosilicon alloy, with other inclusions, that can be further processed.

Operating temperature for MRE is set at (or above) 1600°C to keep regolith and metal products (ferrous alloys) in molten state.

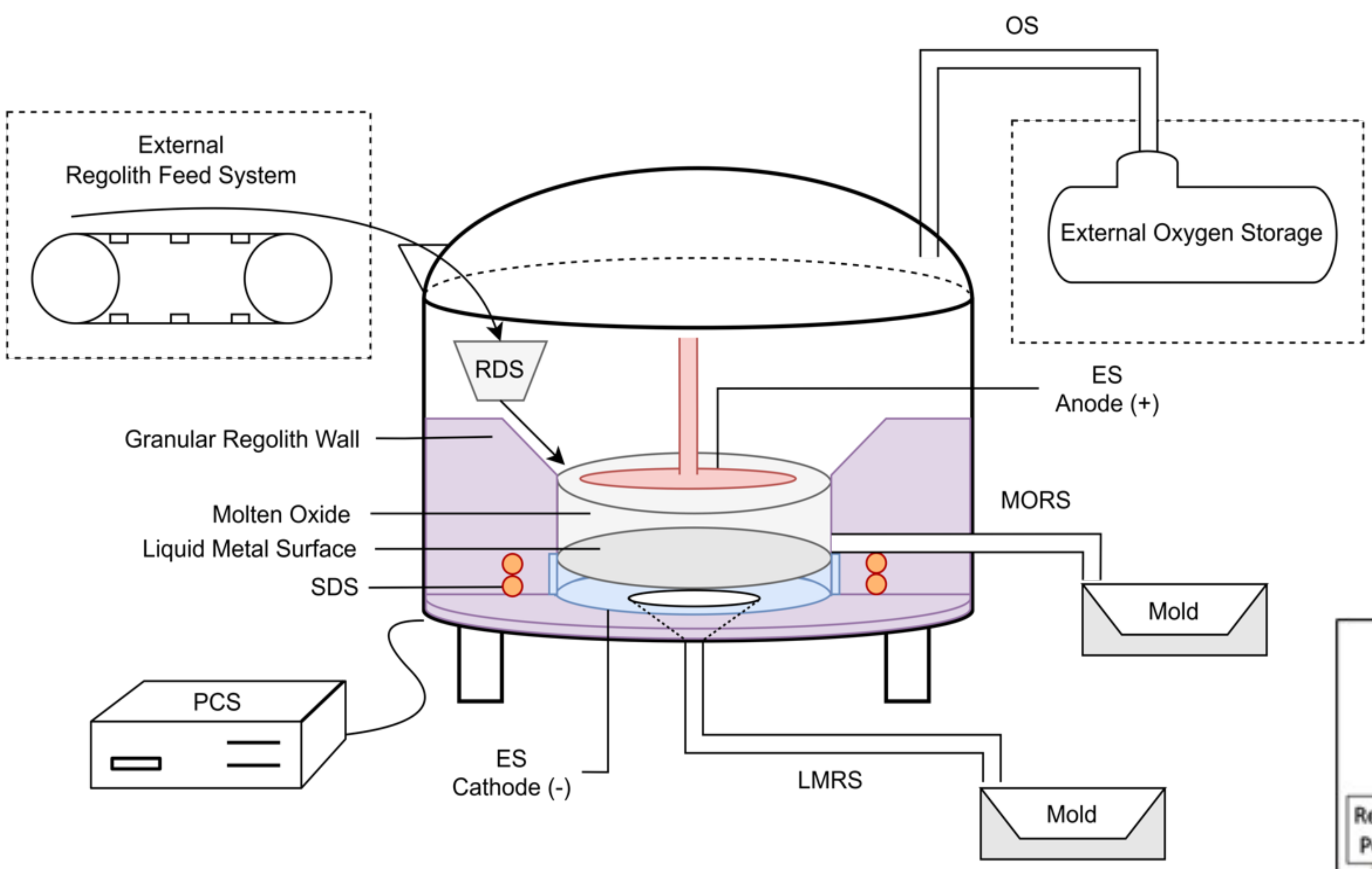
GaLORE Project Goals:

- **Phase I (year 1):** Design, build and test heater devices to melt regolith in a localized region between electrodes.
- **Phase II (year 2):** Integrate heater device(s) into reactor prototype to melt regolith and then electrolyze the produced melt.
  - ***Demonstrate a Cold-Walled Reactor design***

Challenge: Containment materials fail in corrosive environment of molten metals, regolith and high temperature oxygen

MRE Technology Overview

MRE Reactor Systems Concept

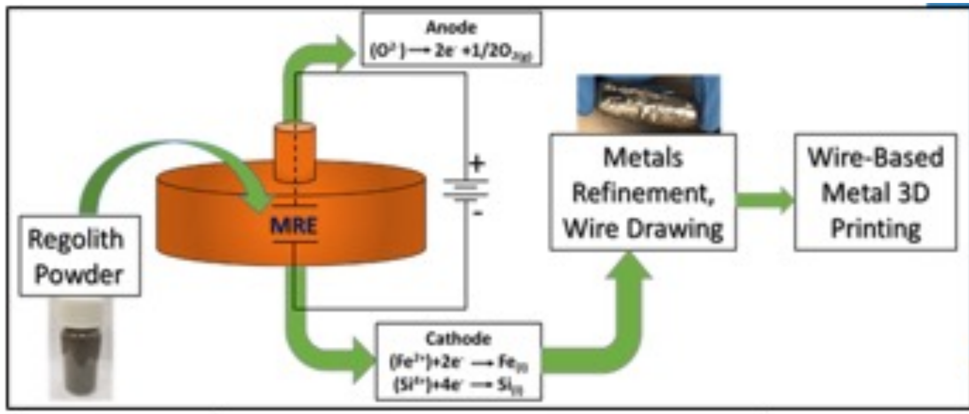


Operational Temp: 1500-1600 C

Voltage: 2-5 Volts

Oxygen Production rate based on current

Cycles require periodic removal of molten metals and molten oxide from reactor to allow for fresh regolith introduction.



Resistive Heating
- Vacuum Testing -

Two resistive heater concepts:

Permanent: remains in MRE rector during electrolysis

- Tantalum, tungsten, titanium

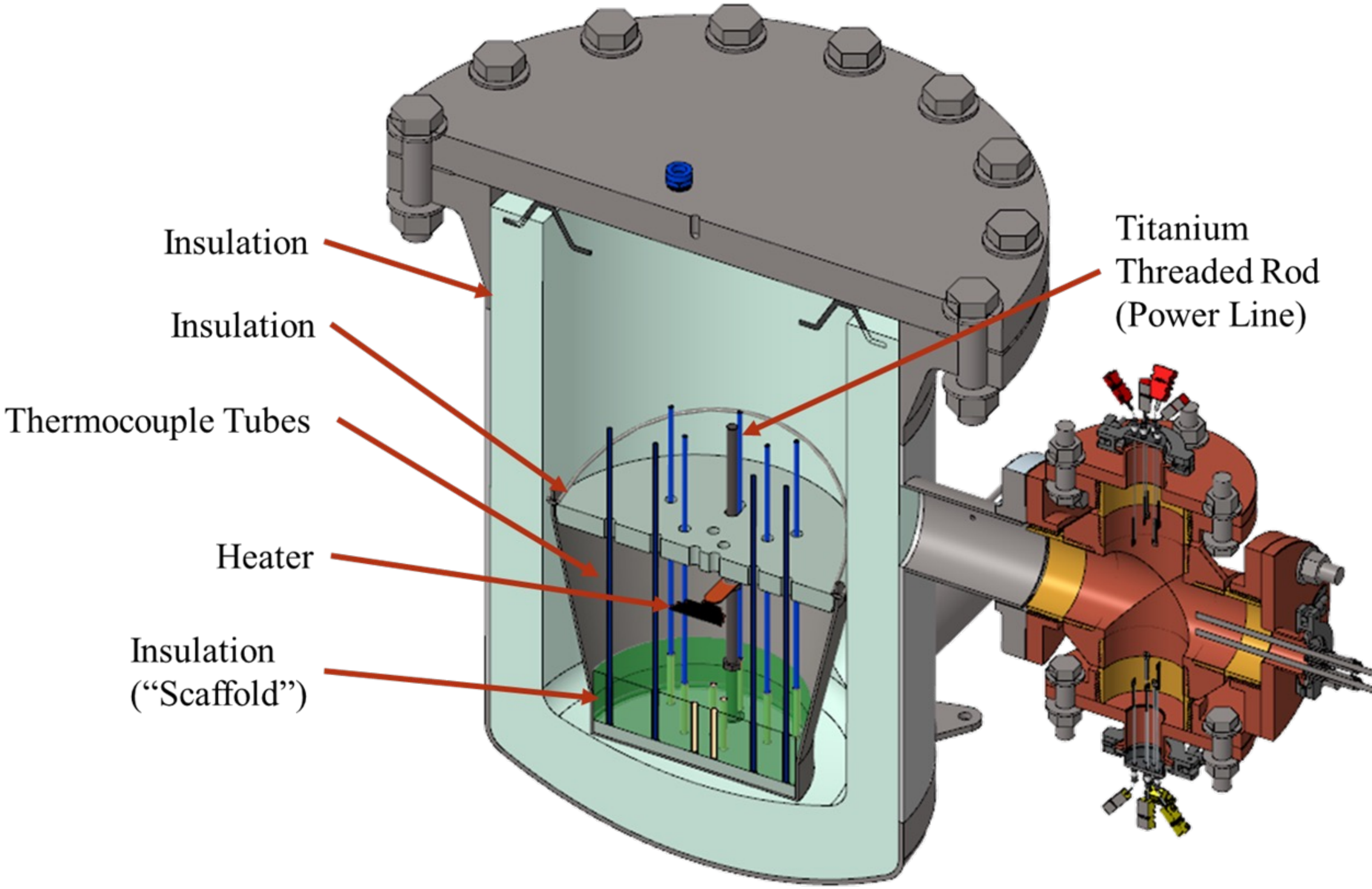
Sacrificial: designed to be melted after single use

- Materials must be ISRU products
- Iron, Kanthal

Experimental setup capable of applying 1 kW

Wires of selected material wound into 2 cm diameter coils and heated to failure

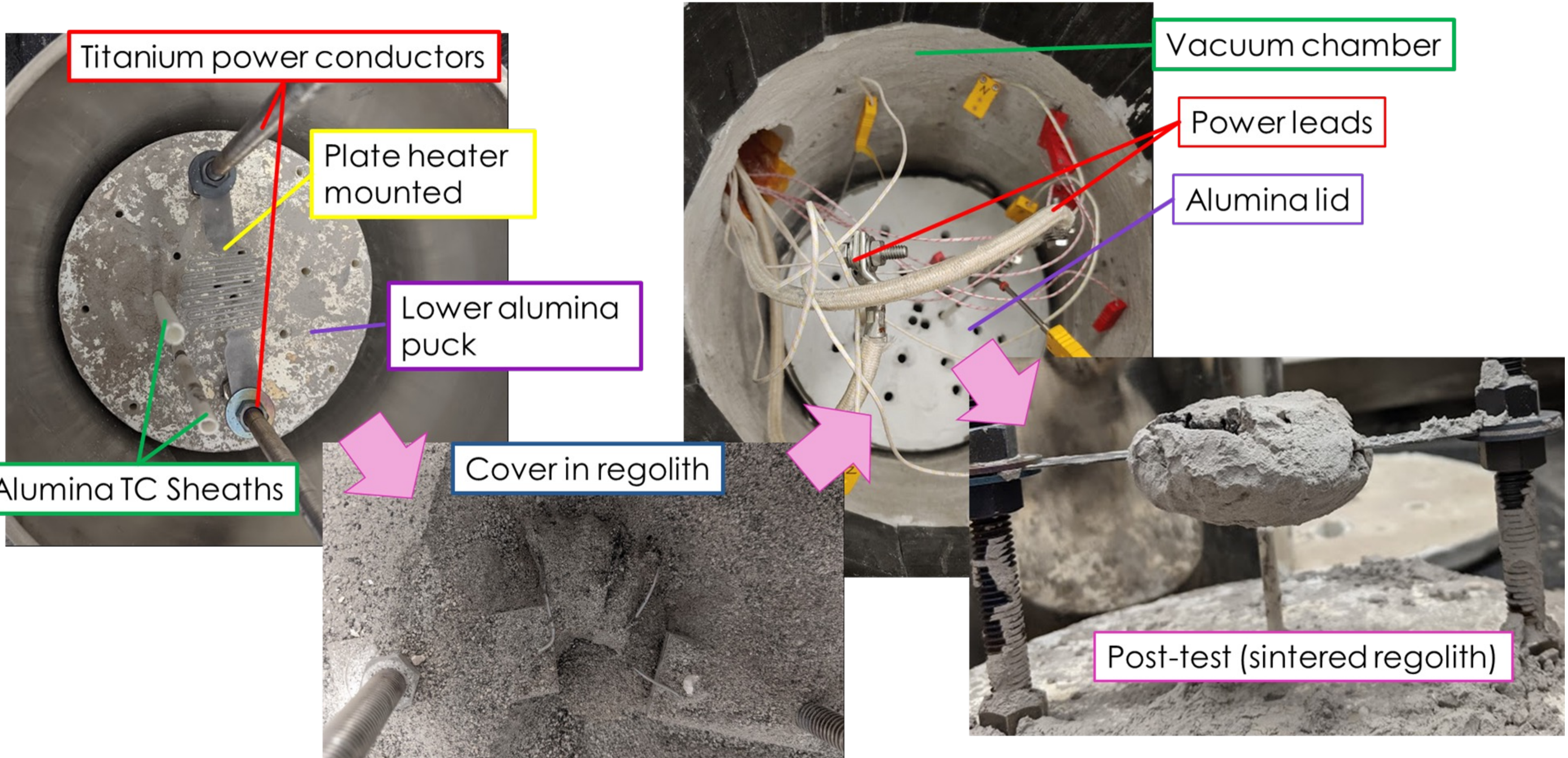
Testing done with LHS-1 (Exolith)



Vacuum test enclosure for melt heater tests

14

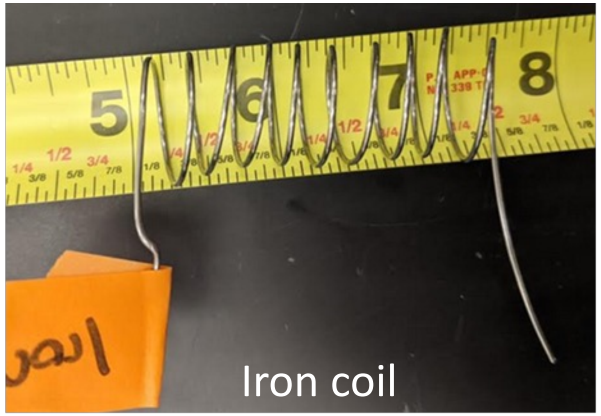
Resistive Heating
- Vacuum Testing -



Resistive Heating
- Vacuum Testing -

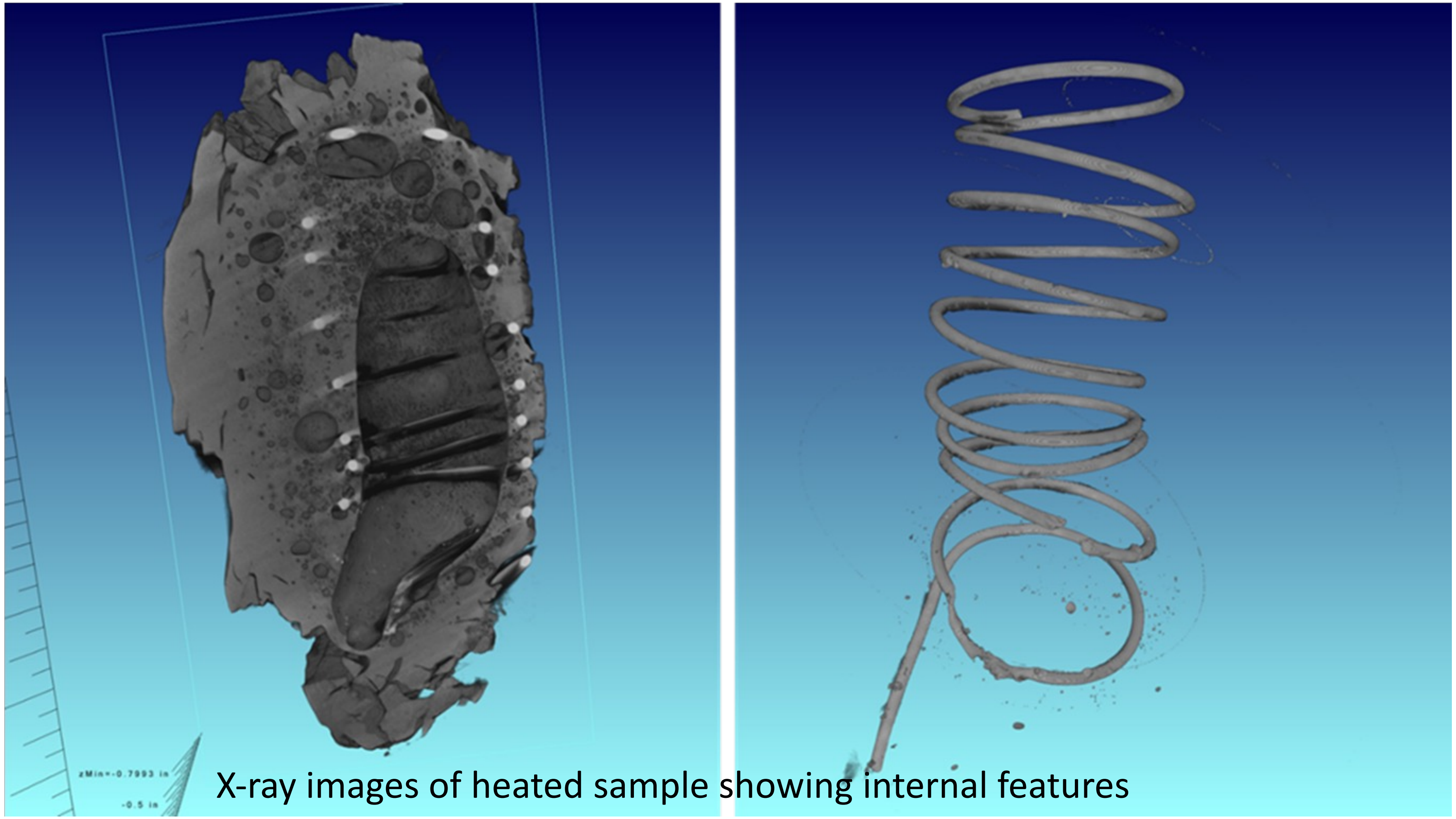
Regolith melt formation from tantalum plate heaters

Resistive Heating
- Vacuum Testing -


Iron coil


Heated LHS-1

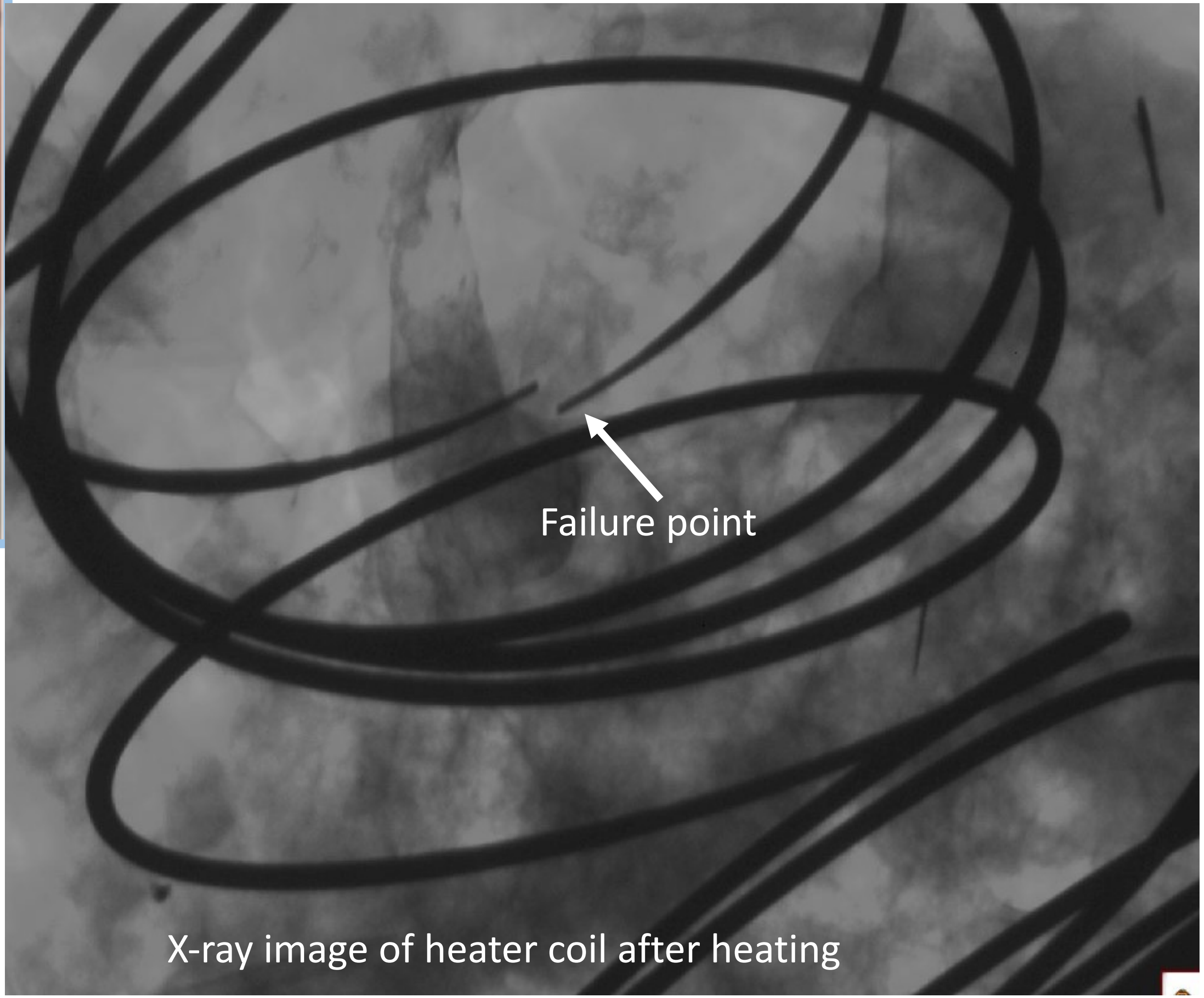
Heated samples typically had large sintered region encapsulating melted section with very large pores present.


X-ray images of heated sample showing internal features

Resistive Heating
- Vacuum Testing -

Crucible holding bed of regolith during heating

Heated LHS-1



X-ray image of heater coil after heating

Resistive Heating
- Vacuum Testing -

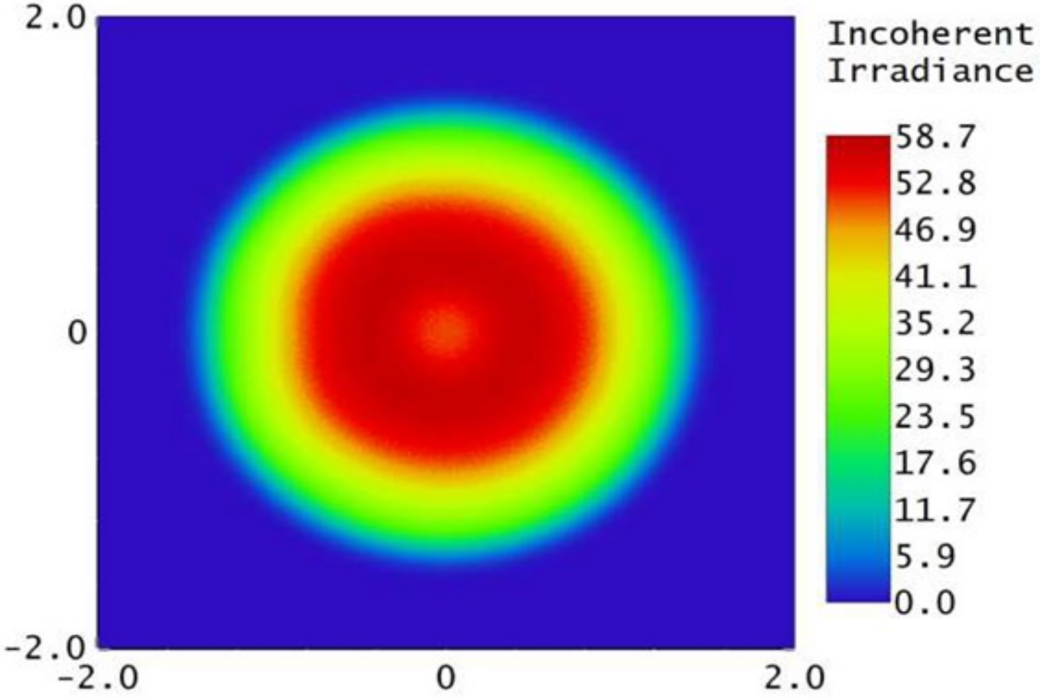
Material	Melting Point (°C)	Observations
Kanthal (FeCrAl)	1500	Lasts a long time and produces large sintered area. Seems like melting point is too low for effective regolith melt.
Tungsten (W)	3422	Lasts a long time. Some difficulty with breaking during molding thicker wire. Produces melt.
Titanium (Ti)	1668	Lasts a long time and produces large sintered area. Seems like melting point is too low for effective regolith melt.
Tantalum (Ta)	3017	Wire of same thickness as water-jetted plate seems to last longer than plate. Oxidizes pretty quickly but can form melt before failing.
Iron (Fe)	1538	Does not last very long before failing. Can produce sinter with some melt. (potential ISRU material)

9

Solar Heating
- Simulator System -

- System designed and fabricated by Honeybee Robotics

- 6.5 kW bulb (Xenotech Britelite), elliptical mirror
- Zemax Optic Studio simulation
  - 32.2 cm focal length to achieve 5 cm spot size
  - 1.3 kW reaches surface of regolith.



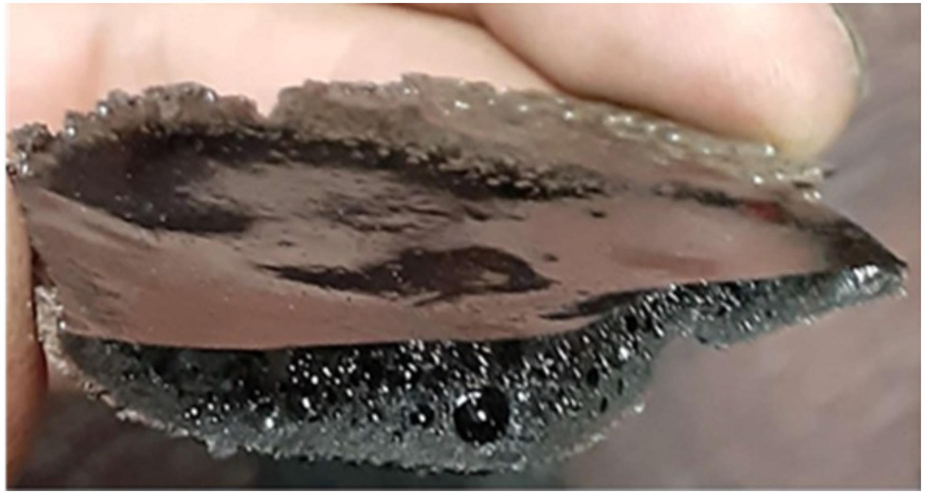
10

Solar Heating
- Vacuum Testing -

JSC-1A was heated for 10 minutes under solar simulator system.

Top Pictures: Heating done under vacuum

- Large pores formed



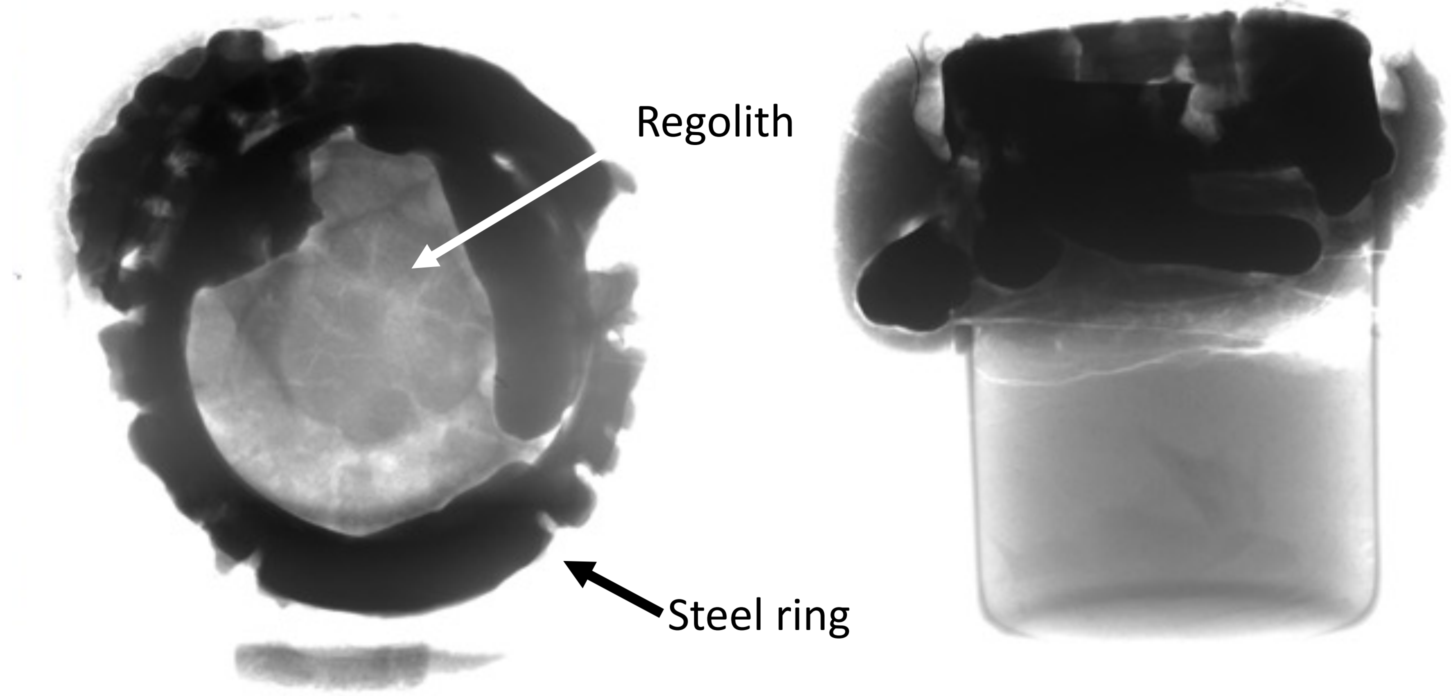
Bottom Pictures: Heating in open air

- Small pores.

Induction Heating
- Atmospheric testing -

Induction heating using 17.7 cm coil
- Up to 8 kW of power
- Steel ring susceptor (10cm OD, 7.5 cm ID and 3 cm height
- Buried 1 cm deep in LHS-1 (Exolith labs, UCF)

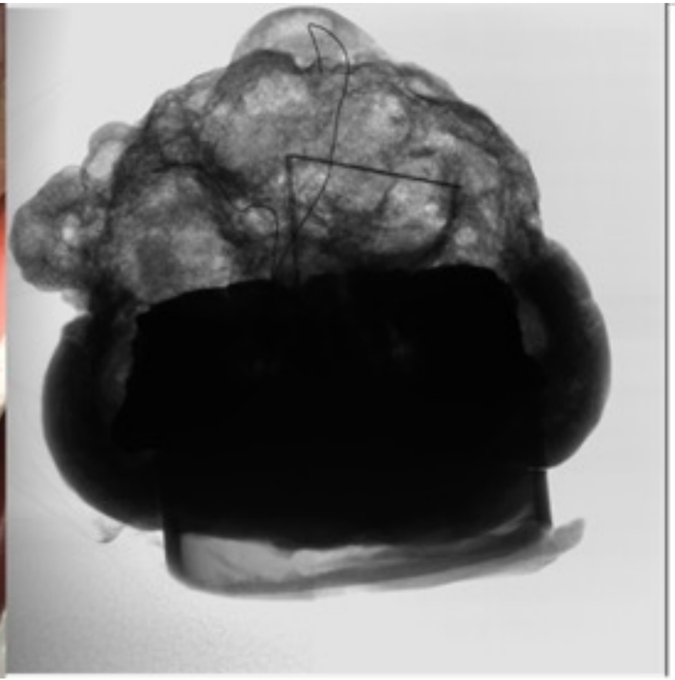
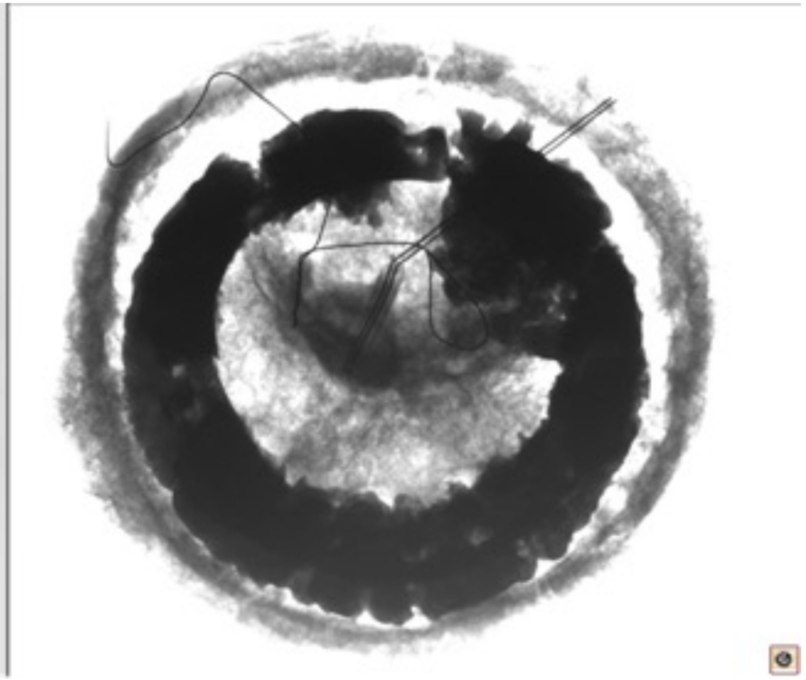
Temperature set point: 1400°C
Total Test runtime: 1 hour, roughly 30 minutes until melt
X-ray images (below)



Ambient Induction Melting Test

Induction Heating
- Atmospheric testing -

Steel ring susceptor was reheated to 1400 °C
Trapped gases expanded and were unable to escape

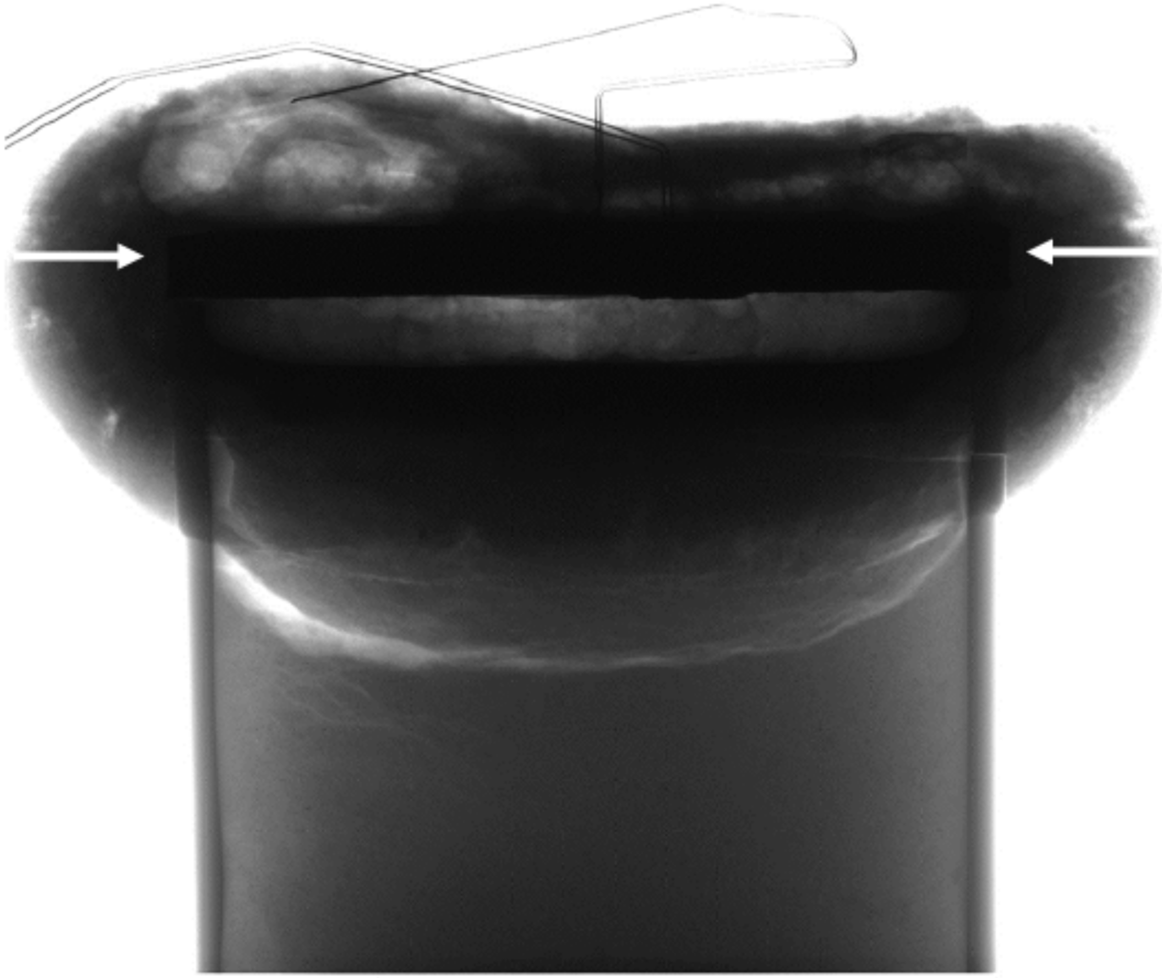



Induction Heating

- Atmospheric testing -

Repeated the same induction heating test with a tantalum disk instead of a ring.

Tantalum withstood the melting process much better.



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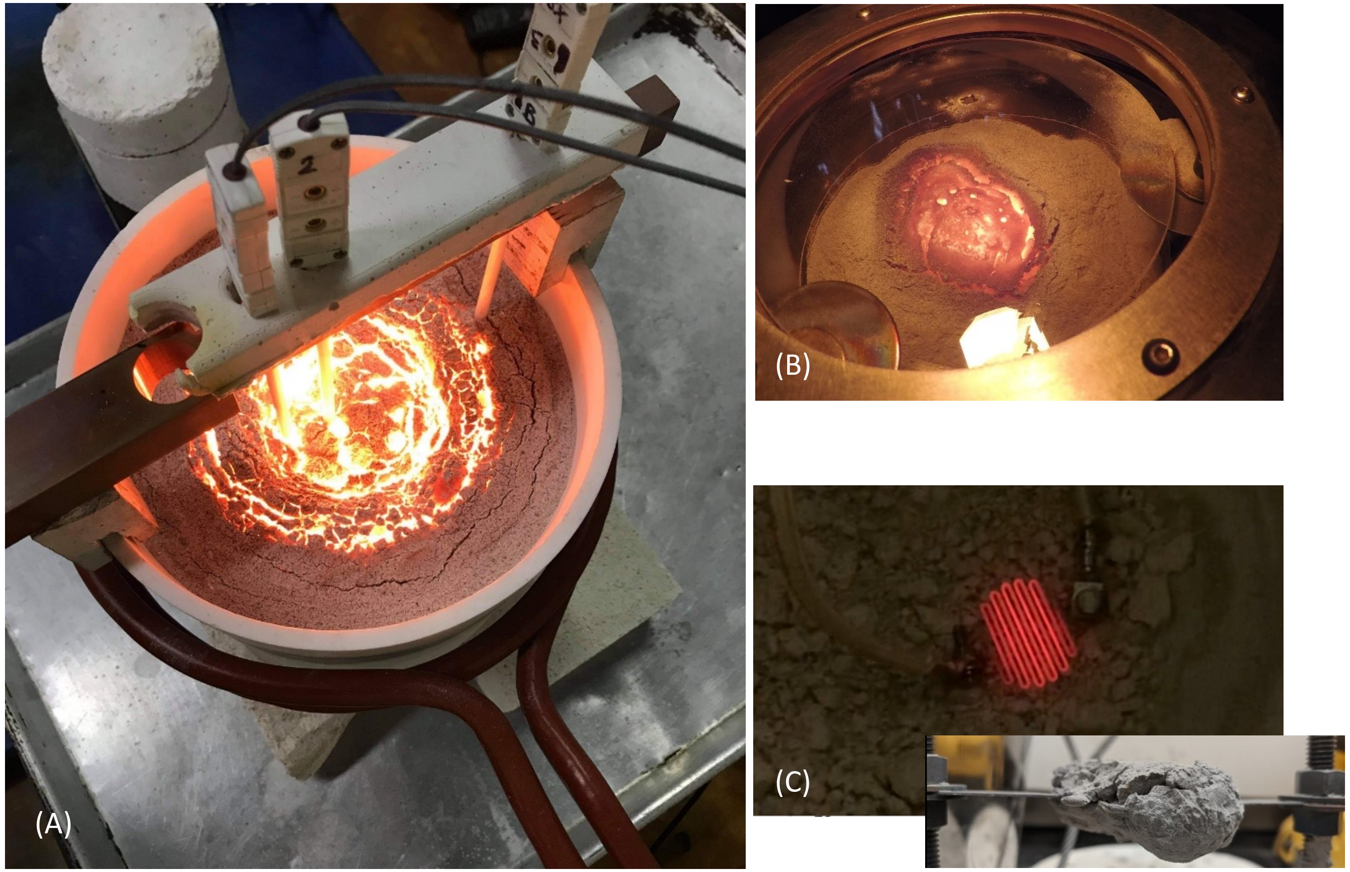
Melt Heater Trade Study

Large melt formation (1G) for MRE reactor start

- Trade of options completed for 3 methods: concentrated solar light, resistive heater, induction heater

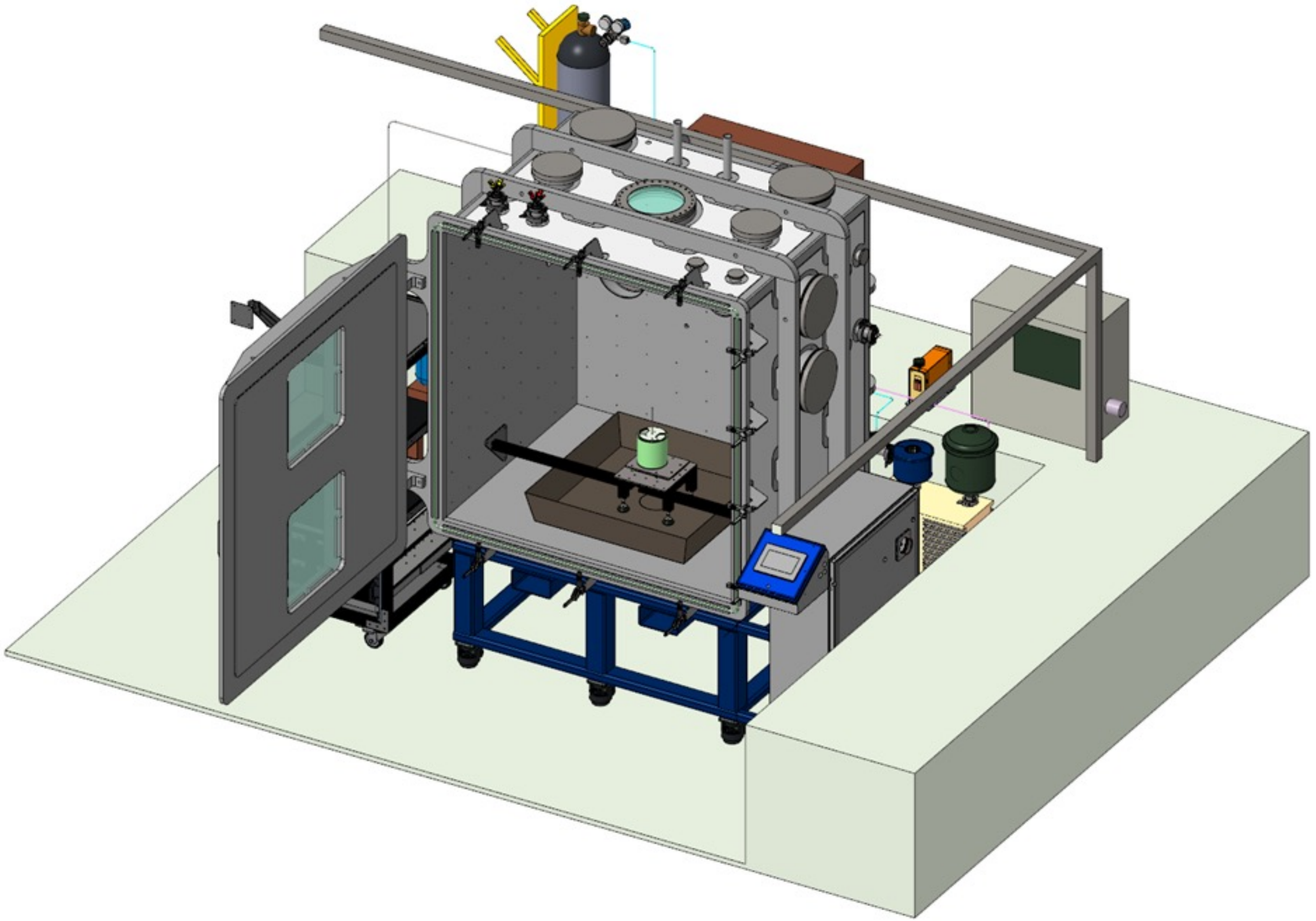
- Induction heating of embedded metal mass in regolith
    - Achieves large melt size at depth, scalable
    - Melt formation with cathode heating demonstrated
    - Challenges: integration with electrodes
- Concentrated Solar light (light simulator)
    - Shallow depth heating, scaling limitations
    - Vacuum melt demonstrated
    - Challenges: depth control, scaling
- Resistive heating of embedded metallic filament in regolith
    - Difficult to reproduce shapes, scaling limitations
    - Vacuum melt demonstrated
    - Challenges: integration with electrodes



Regolith melt formation by inductive heating in air (A), solar heating in vacuum (B), and resistive heating (C) – KSC, RDO Induction, Inc., Honeybee Robotics)

15

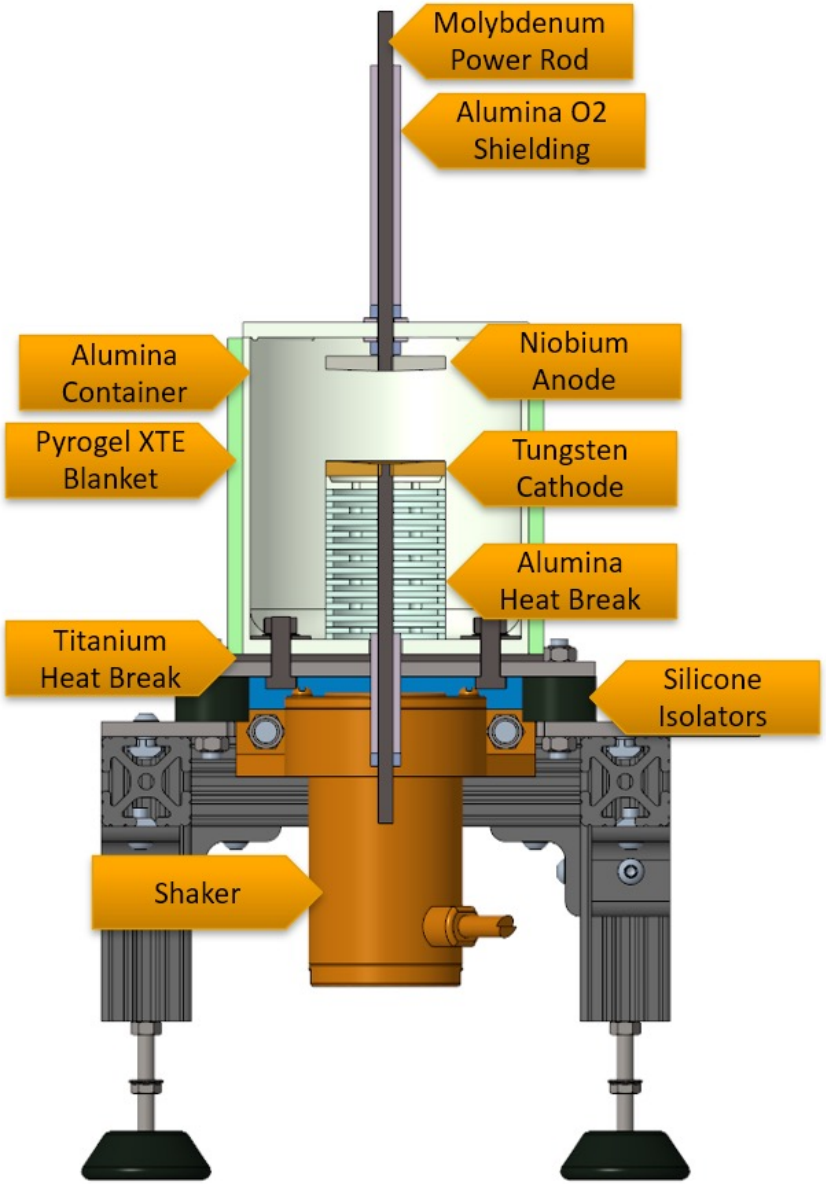
ASSIST Chamber at KSC



Electrolysis Test Cell

A test cell has been developed at KSC for a cold-walled reactor concept demonstration using an induction heating system directly on a 4 cm diameter electrode.

- Capable of producing a melt by applying induction heating directly on cathode
- Capable of applying up to 510 A to regolith melt to produce oxygen at a rate of up to 0.0012 mol/s of gaseous oxygen.
- Capable of sustaining melt size throughout electrolysis without the use of induction heater due to joule-heating of regolith



Areas for collaboration

Simulation and modeling Input:
Experimental Validation of thermophysical properties of various regolith simulants over temperature range

- Viscosity (above melt point)
- Electrical conductivity
- Thermal Conductivity
- Specific heat

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MRE Subsystem development support:

- Molten material handling
- Gas capture/storage
- Electrode design (mechanical and materials)