Team QinetiQ North America

Joule-heated Molten Regolith Electrolysis Reactor Concepts for Oxygen and Metals Production on the Moon and Mars

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BACKGROUND

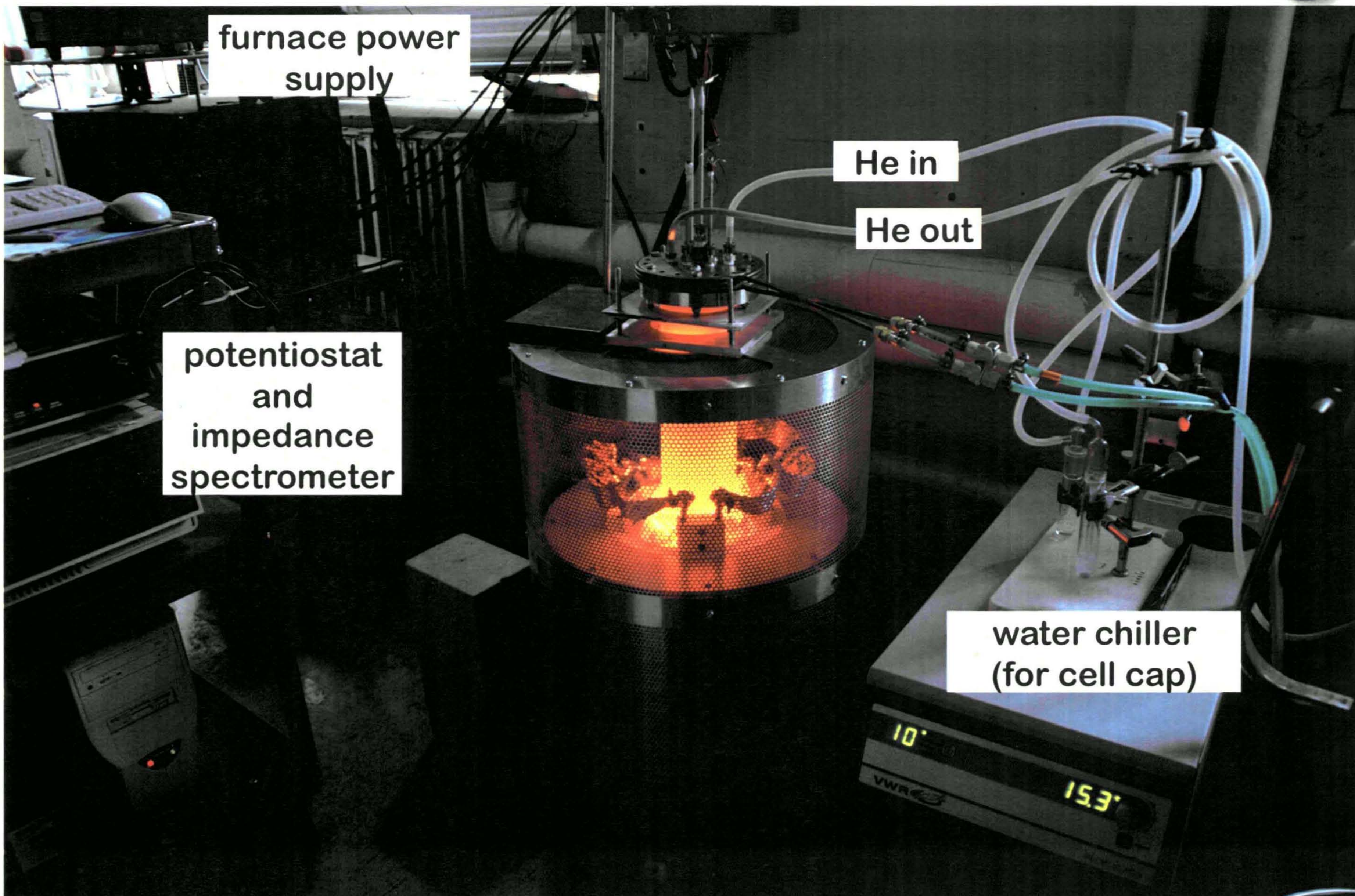
- The maturation of Molten Regolith Electrolysis (MRE) as a viable technology for oxygen and metals production on explored planets relies on the realization of the self-heating mode for the reactor.

- Joule heat generated during regolith electrolysis creates thermal energy that should be able to maintain the molten phase (similar to electrolytic Hall-Héroult process for aluminum production).

- **Self-heating via Joule heating offers many advantages**:
  - The regolith itself is the crucible material → protects the vessel walls
  - Simplifies the engineering of the reactor
  - Reduces power consumption (no external heating)
  - Extends the longevity of the reactor

- Predictive modeling is a tool chosen to perform dimensional analysis of a self-heating reactor:
  - Multiphysics modeling (COMSOL) was selected for Joule heat generation and heat transfer
  - Objective is to identify critical dimensions for first reactor prototype

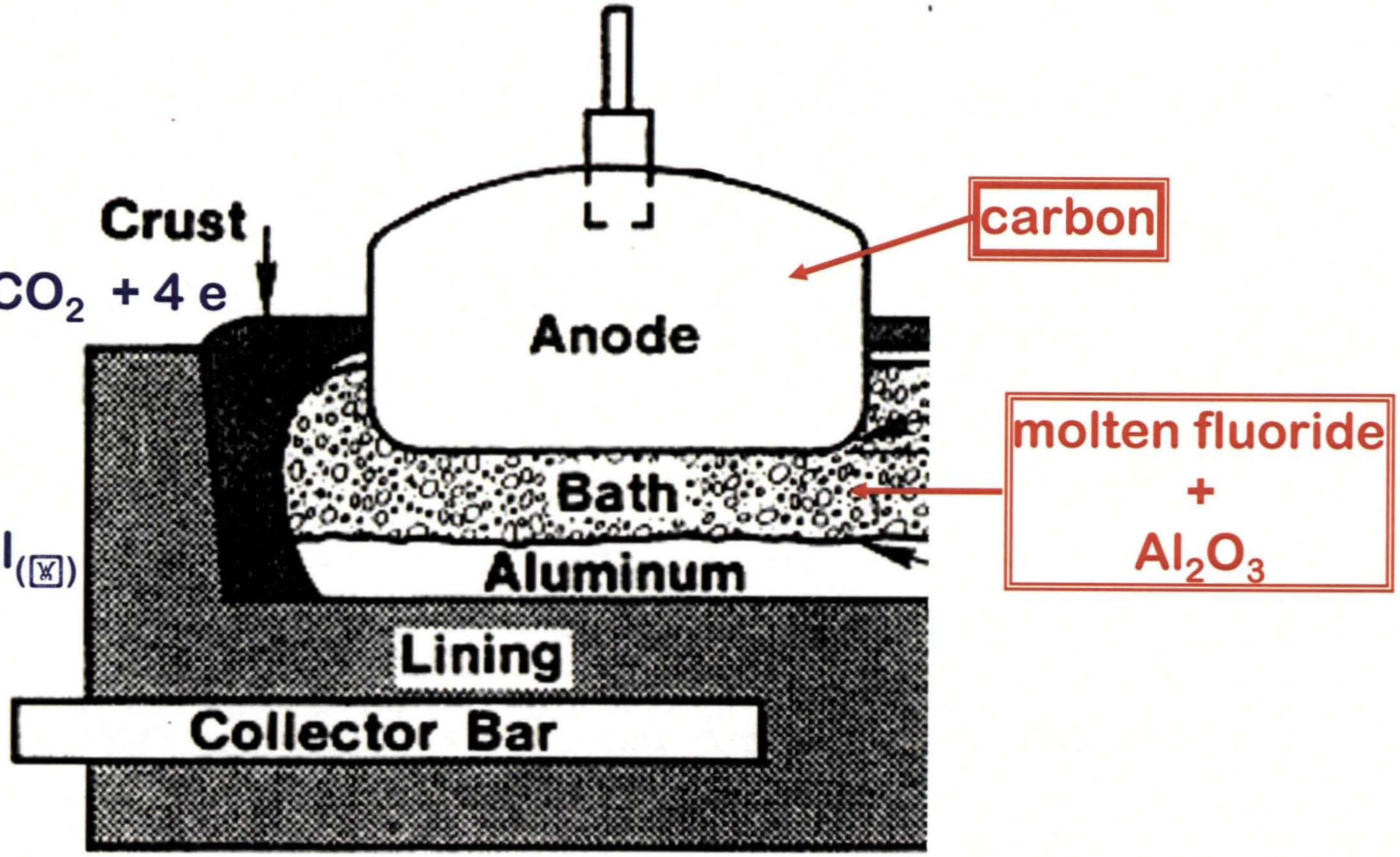
Lab Scale Cell for Molten Regolith Electrolysis



Self-heating Hall-Héroult reactor (Aluminum)

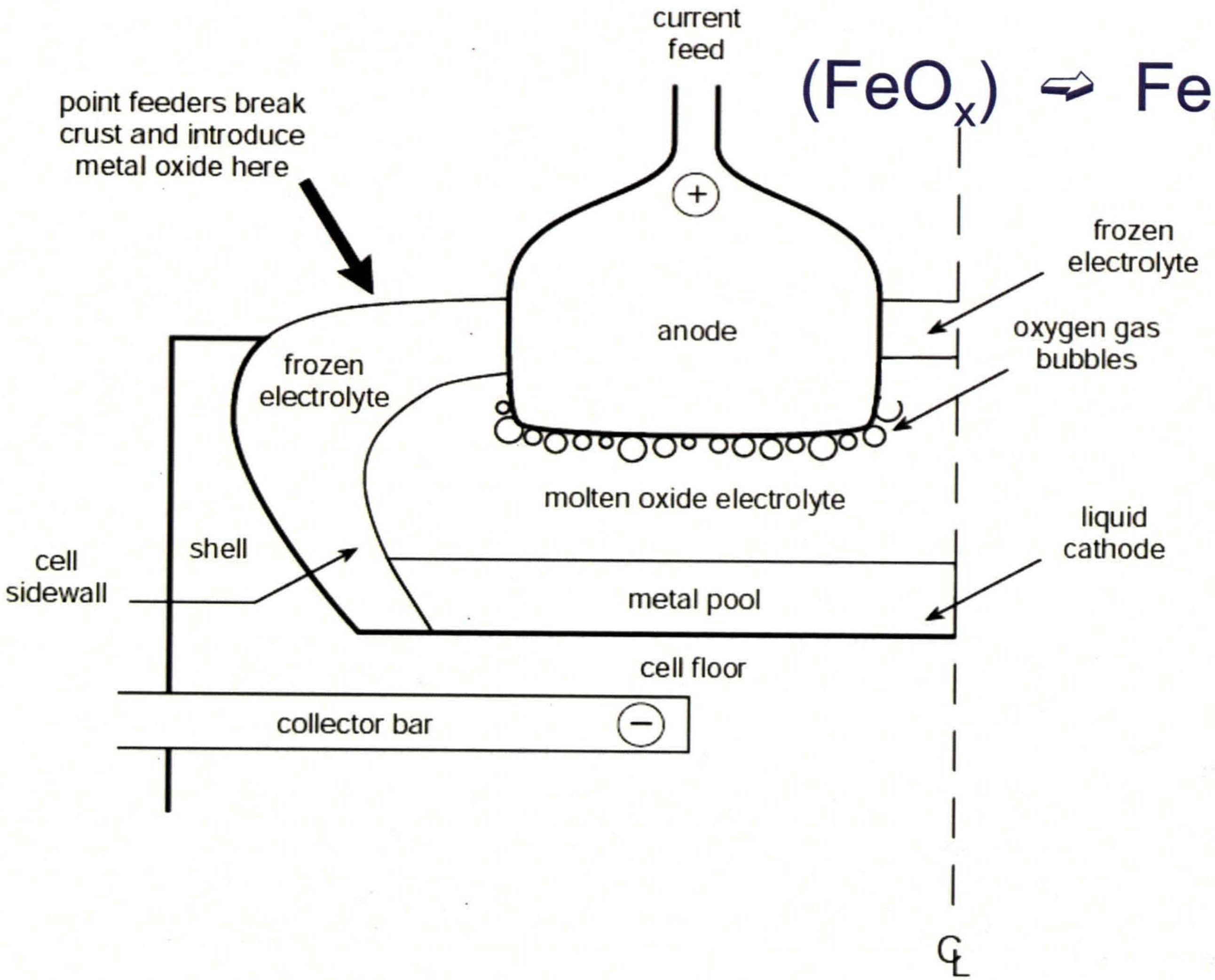
$$2\,O^{2-} + C \rightarrow CO_2 + 4\,e$$

$$Al^{3+} + 3\,e \rightarrow Al_{(\ell)}$$



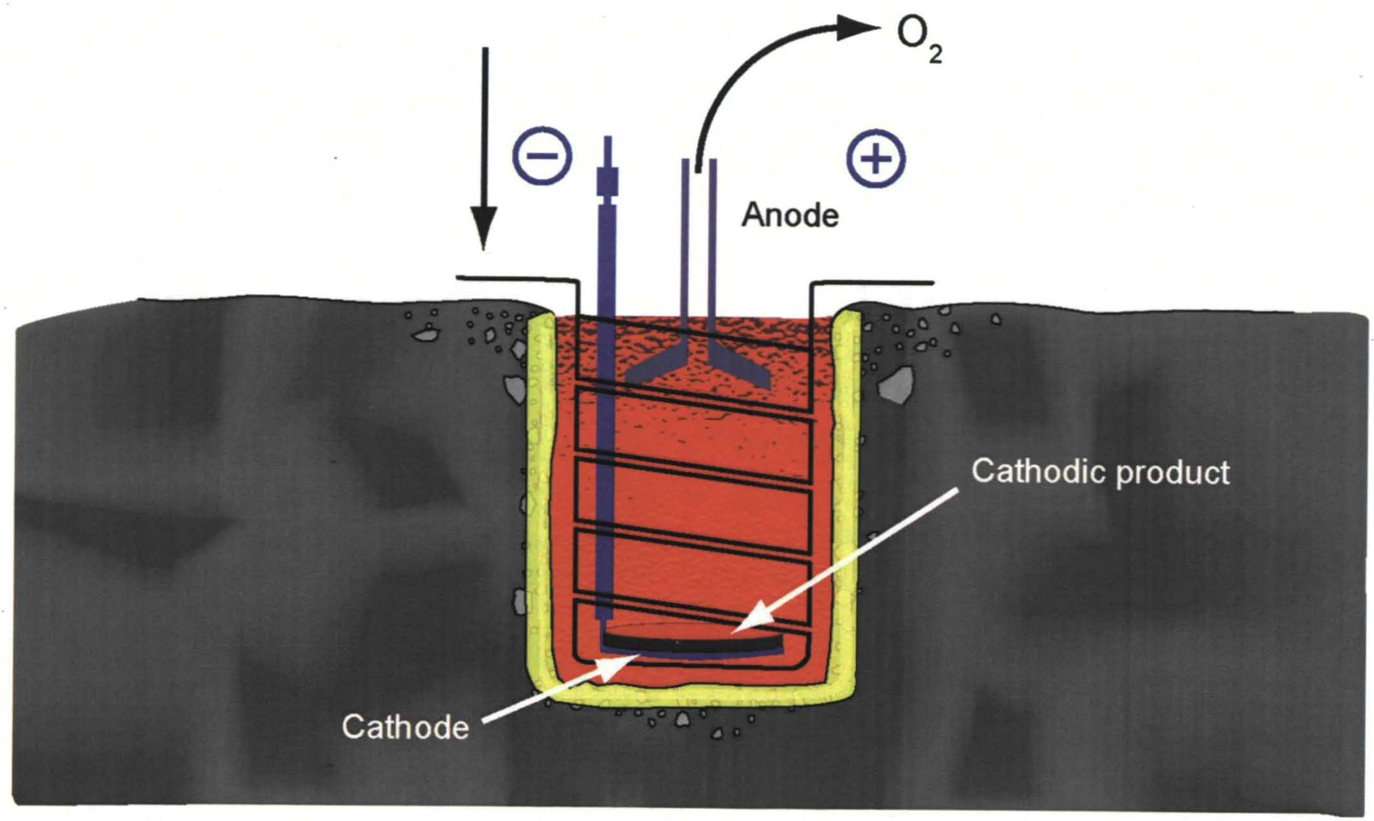
Self-heating Molten Regolith Electrolysis

$$(FeO_x) \Rightarrow Fe_{(\square)} + x/2\ O_2$$



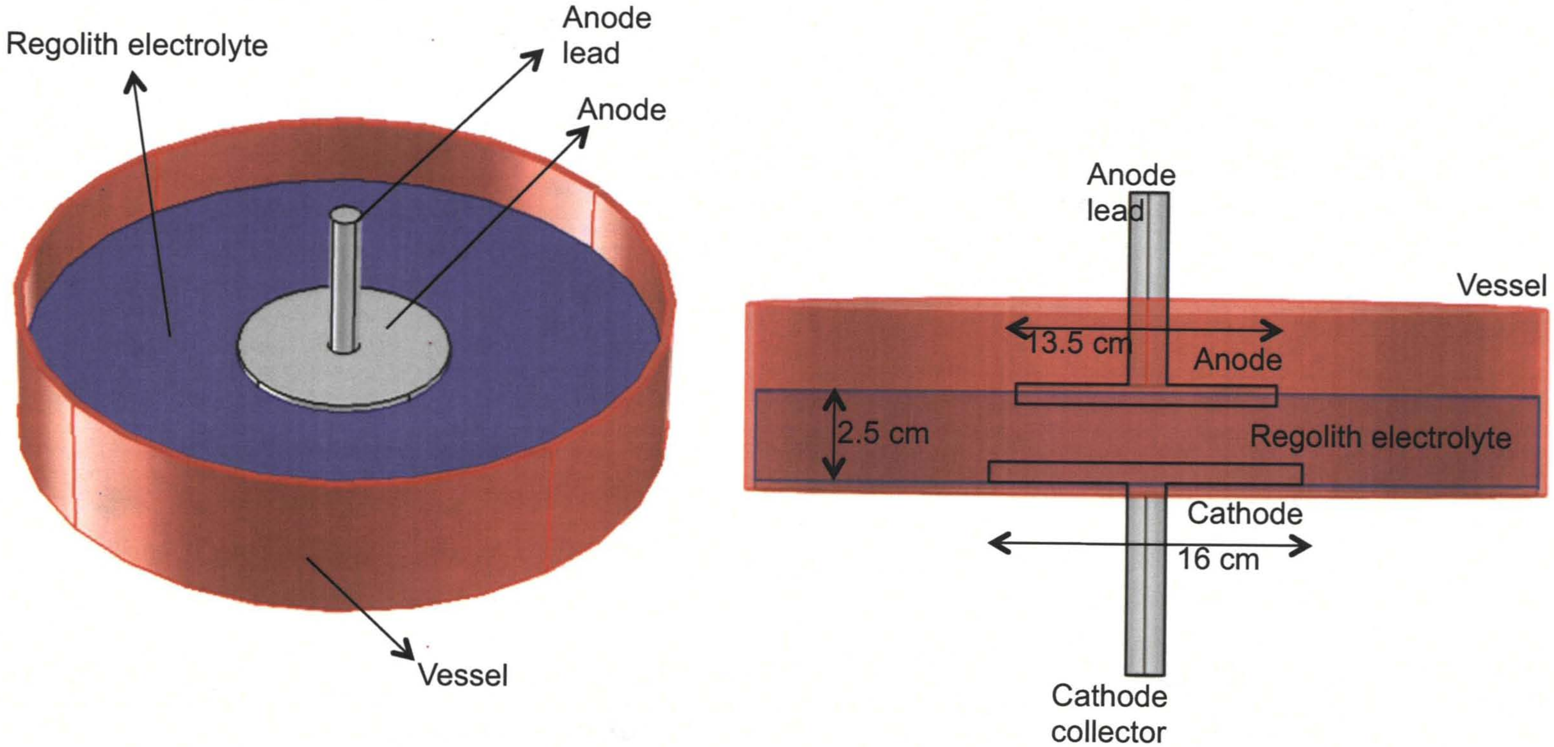
In-Regolith Concept for Lunar Electrowinning

Electrowinning



Self-heating Molten Regolith Electrolysis

REACTOR MODEL



Heat Transfer Modeling

General Energy Equation for solids

$$\rho C_p \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = Q$$

Heat Sources

$$Q = Q_j + Q_r$$

Thermal radiation in participating media

Joule heating

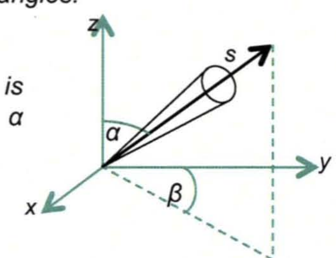
$$Q_j = \frac{1}{\delta} J^2$$

Radiative Intensity for gray & isotropic medium

$$\underbrace{\nabla I(r,s)}_{\text{change in radiative intensity}} = \underbrace{k_a I_b(T)}_{\text{emission}} - \underbrace{(k_a + \sigma_s) I(r,s)}_{\text{absorption}} + \underbrace{\frac{\sigma_s}{4\pi}\int_0^{4\pi} I(r,s')\varphi(s',s)\, d\Omega'}_{\text{scattering}}$$

This equation needs to be integrated over the spatial as well as the angular domain. Spatial discretization is done by dividing spatial domain into discrete control volumes or cells. The angular discretization is done using control angles.

The radiation direction vector s is defined in terms of two angles α and β



$$G = \sum I(r,s)$$

$$Q_r = k_a \left(G - 4\sigma T^4\right)$$

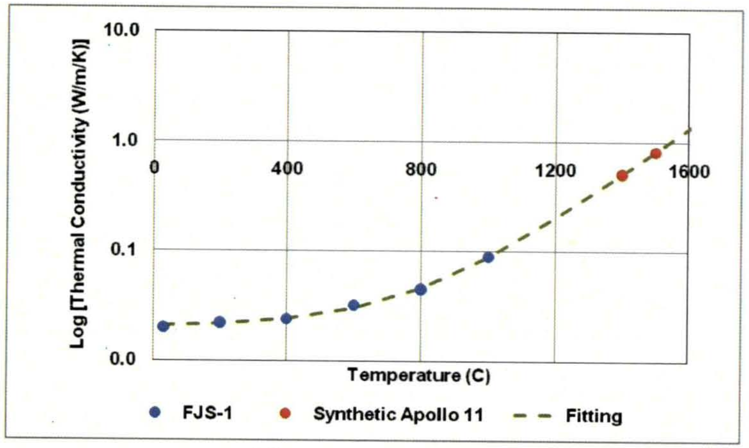
Boundary Conditions

- *Radiative heat transfer between outer surfaces and ambient.*
- *Radiative heat transfer between outer surfaces*
- *Free convective heat transfer with ambient*
- *Constant voltage at the top of anode lead*
- *Electrical ground at the top of cathode collector*
- *Thermal insulation at the outer bottom of the cell*
- *All surfaces electrically insulated*

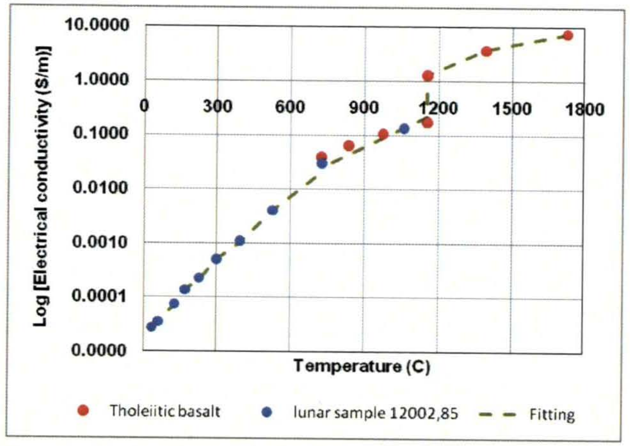
ρ = density
C_p = heat capacity
k = thermal conductivity
δ = electrical conductivity
T = temperature
J = current density

s = position vector
r = direction vector
Ω' = variable for control angle direction
Φ = scattering phase function
k_a = adsorption coefficient
σ_s = scattering coefficient
$I(r, s)$ = radiative intensity at r position and s direction
I_b = black body intensity
G = incident radiation within the participating media

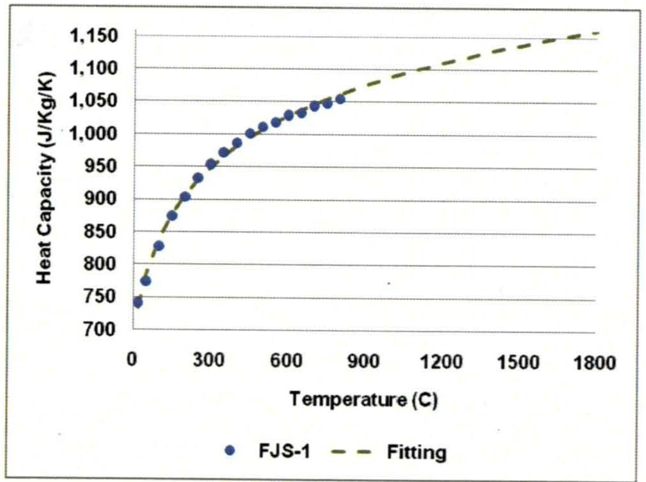
Thermophysical Properties of regolith



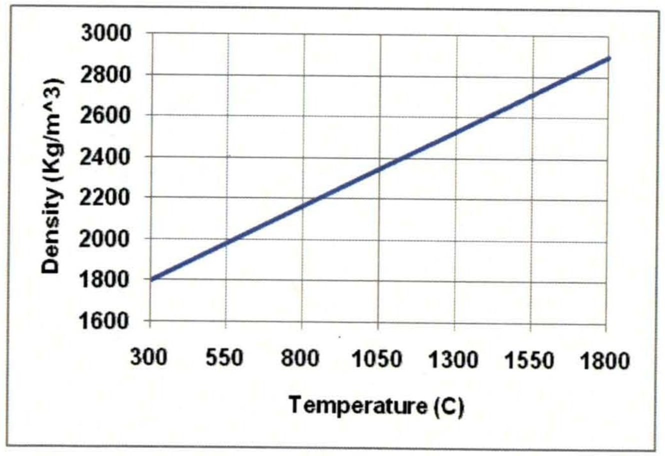
Thermal Conductivity



Electrical conductivity



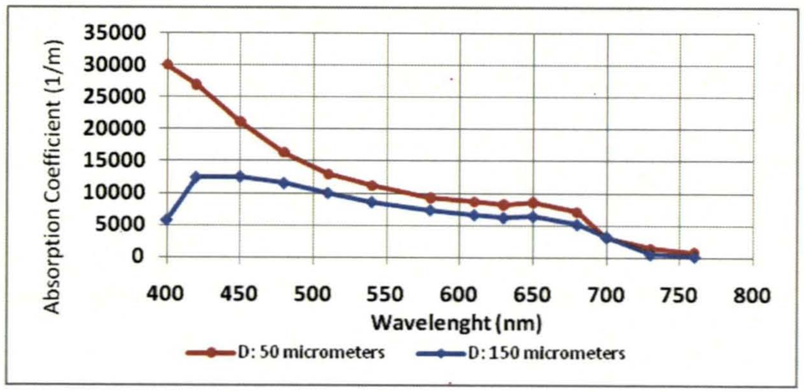
Heat Capacity



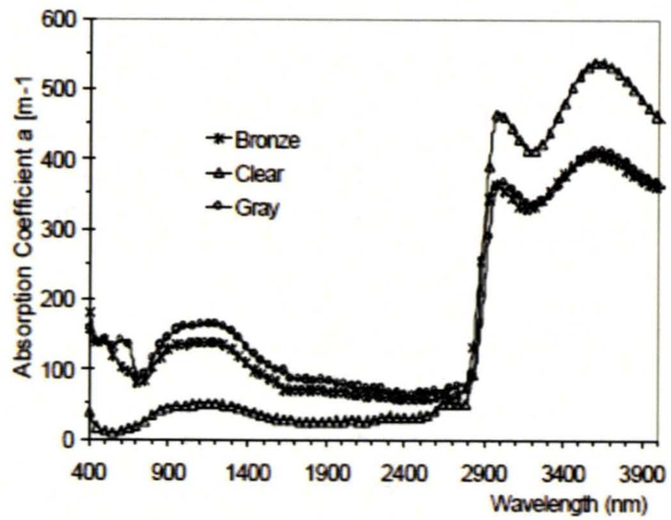
Density

Optical Absorption

Absorption coefficient



Lunar glassy spherules obtained from lunar dust brought to earth by Apollo 14 mission

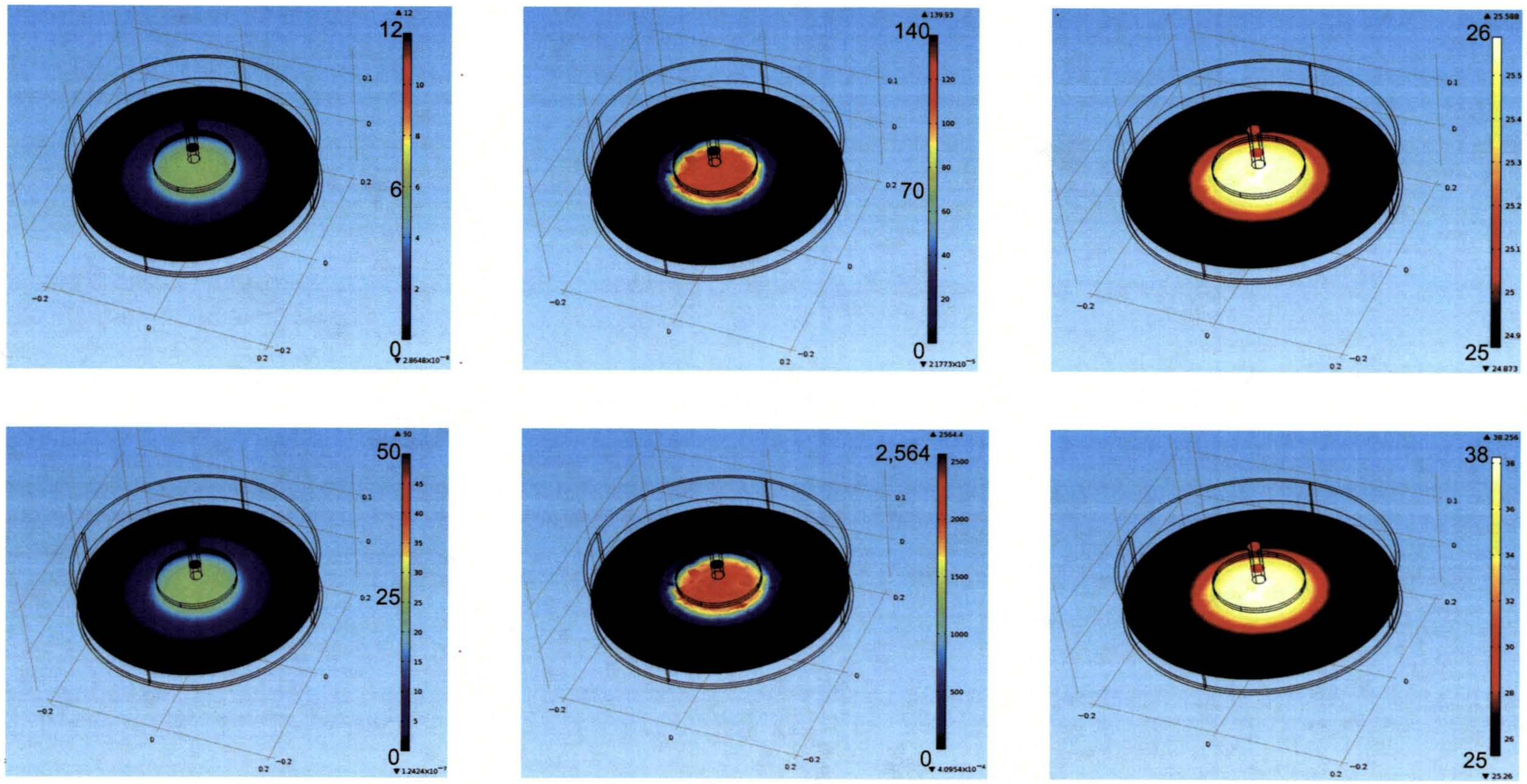


Commercial glass (clear and gray) and bronze

JOULE HEATING PERFORMANCE WITHOUT PREHEATING

Initial temperature: 25 °C

Potential (Volts) | Heat dissipation (W/m³) | Temperature (°C)



JOULE HEATING PERFORMANCE WITH PREHEATING

Engineering Services Contract
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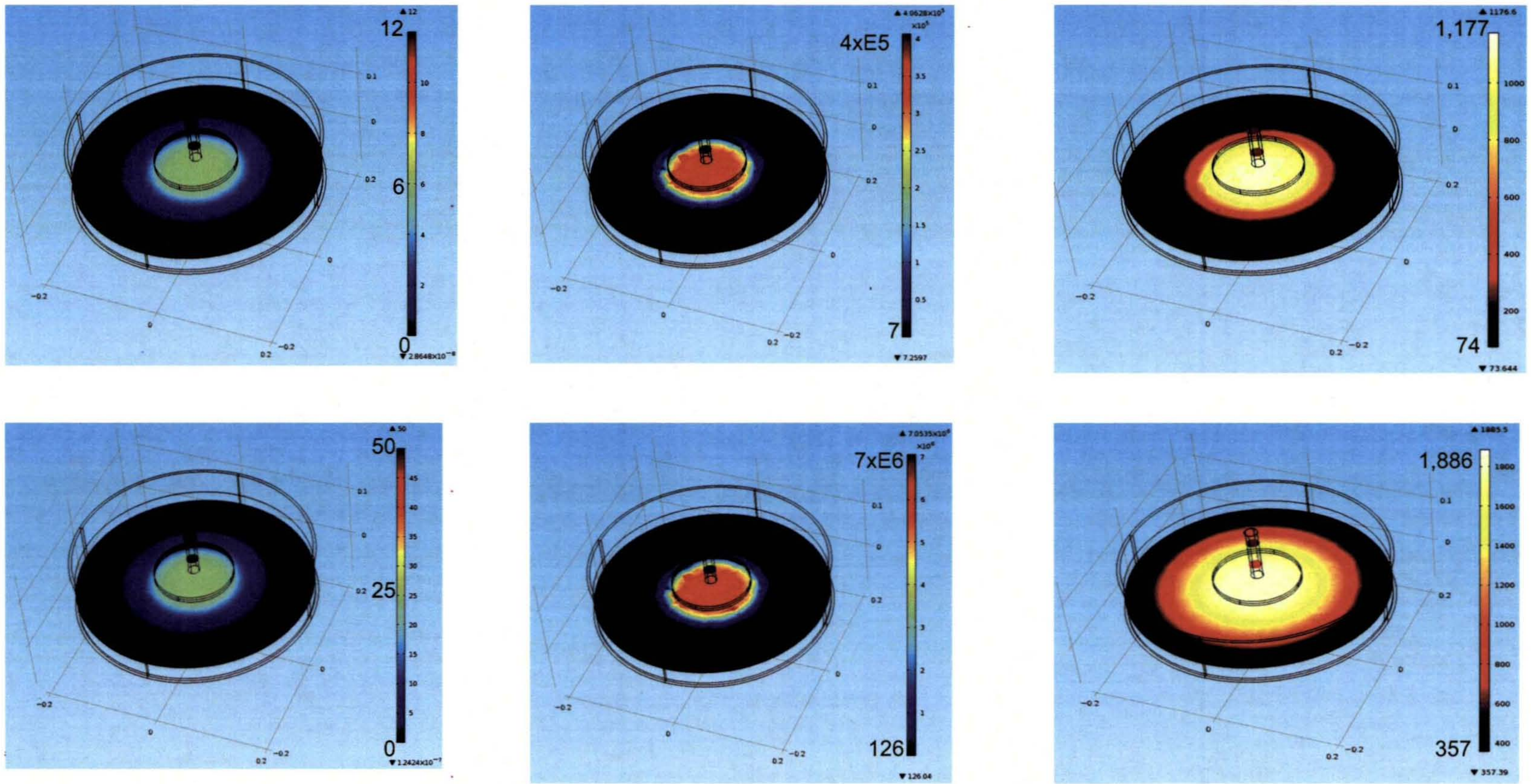
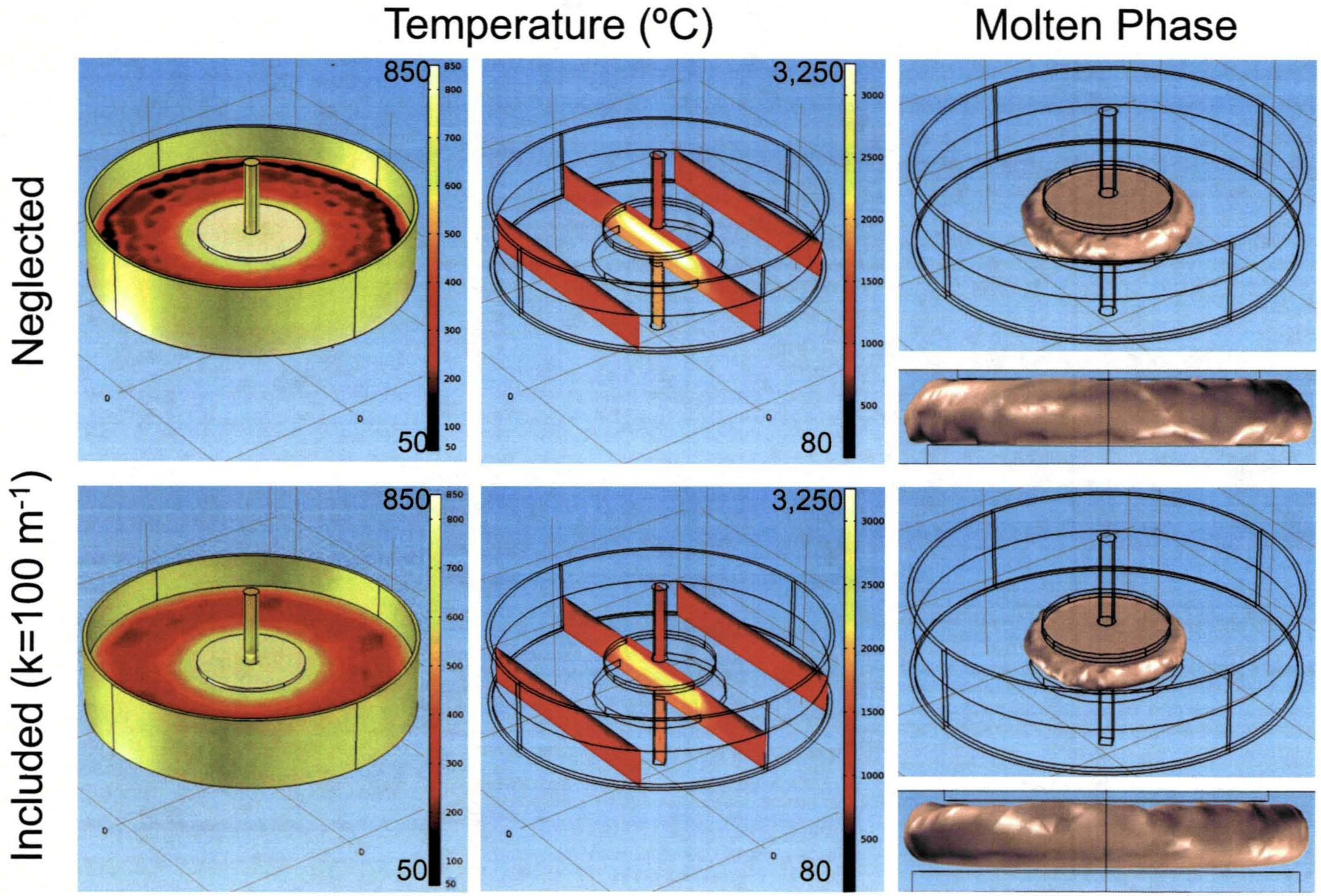
Preheating temperature: 1,700 °C

Potential (Volts) | Heat dissipation (W/m³) | Temperature (°C)



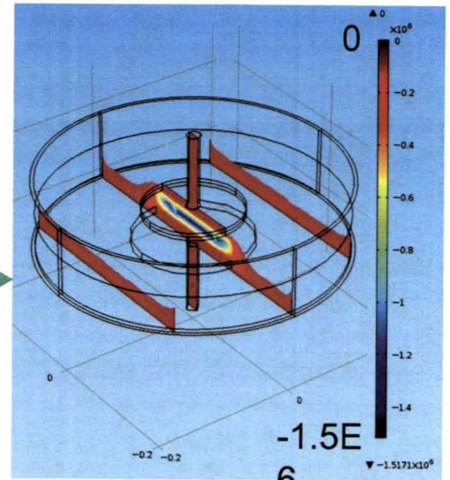
Relevance of Thermal Radiation within Participating Media



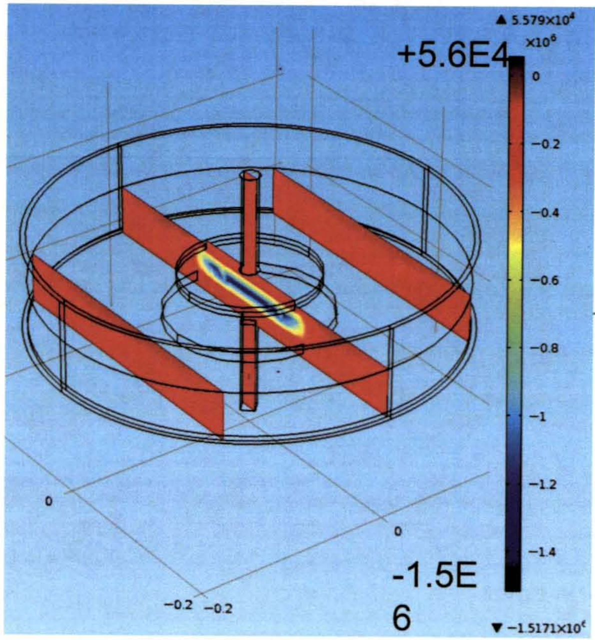
Applied Voltage: 34 V at the anode lead that yields 15 V at the molten phase.

RADIATION HEAT SOURCE WITHIN PARTICIPATING MEDIA

Absorption yields (W/m³)



Total yield (W/m³)



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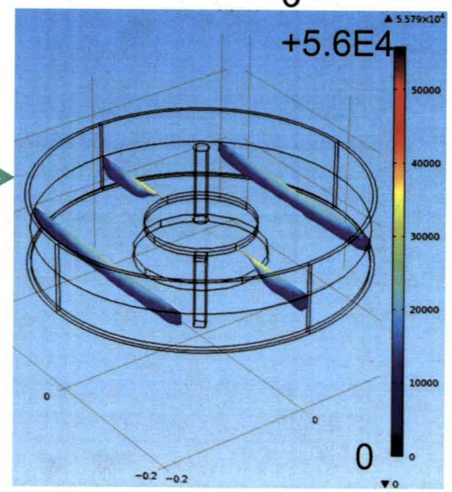
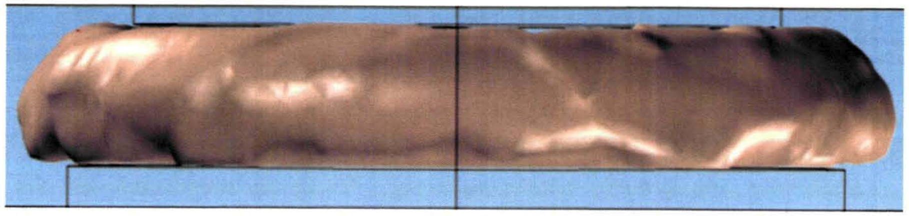


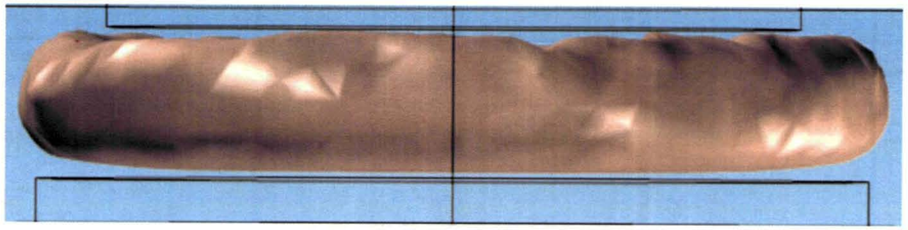
Emission yields (W/m³)

Applied Voltage: 34 V at the anode lead that yields 15 V at the molten phase.

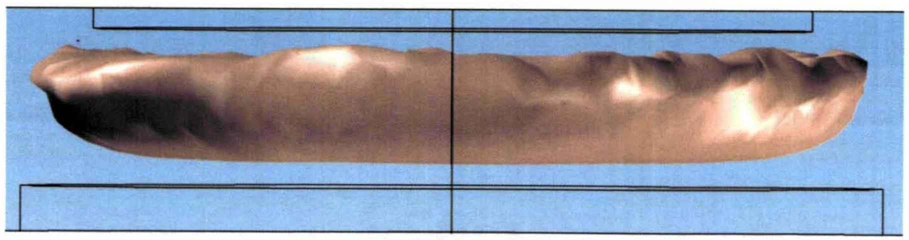
OPTICAL ABSORPTION EFFECT ON MOLTEN PHASE FORMATION



$k = 0\ m^{-1}$



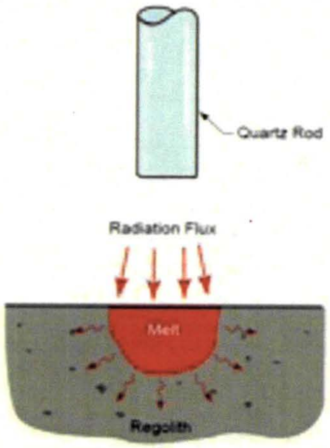
$k = 100\ m^{-1}$

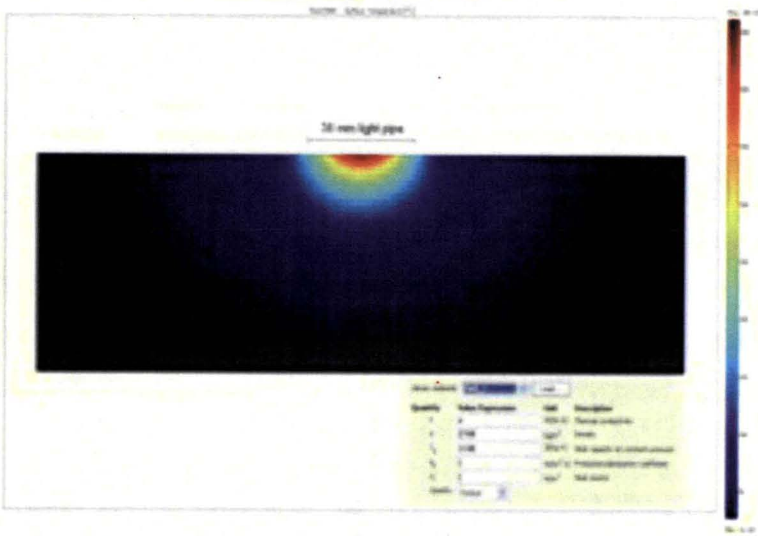


$k = 300\ m^{-1}$

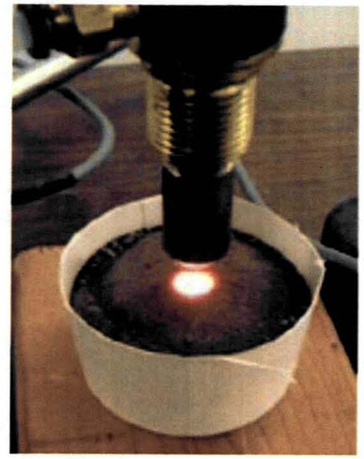
Applied Voltage: 34 V at the anode lead that yields 15 V at the molten phase.

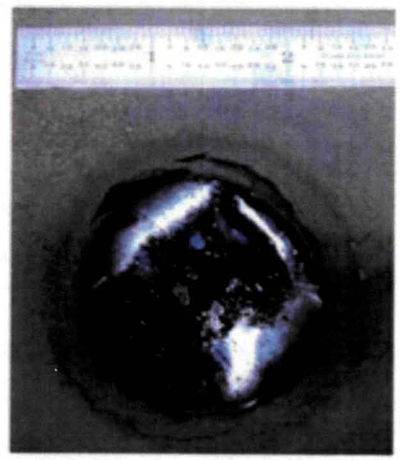
MODEL VALIDATION





Temperature profile of irradiated JSC-1A melts predicted by the model using Orbitec experimental conditions.





Solidified half-sphere produced by focused solar beam (Orbitec/PSI Corp.)

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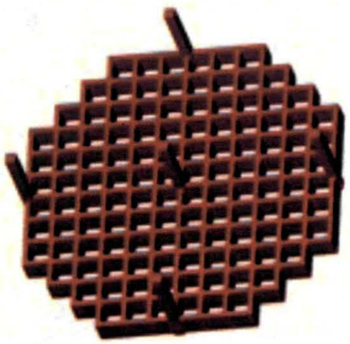
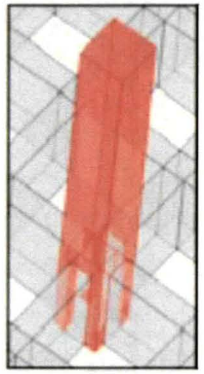
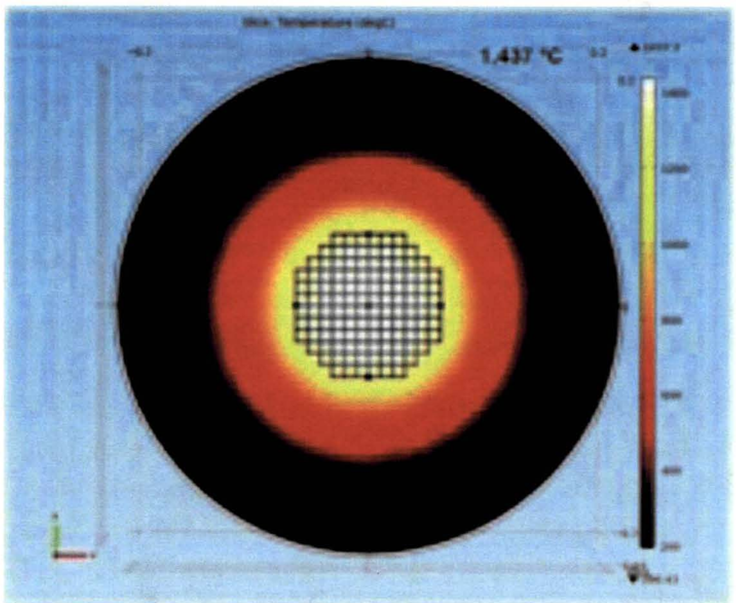
EFFECT OF ANODE GEOMETRY

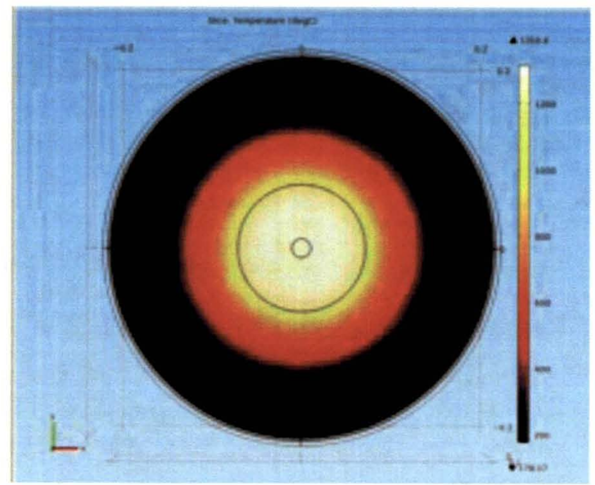






Regolith Temperature profile under a waffle anode at 34 V

Max. melt temperature: 1,437 °C



Regolith Temperature profile under a flat anode at 34 V.

Max. melt temperature: 1,437 °C

CONCLUSIONS

- The modeling of all modes of heat transfer within a self-heating Molten Regolith Electrolysis reactor can be useful tool to investigate the parameters driving its design.

- The heat transfer modeling performed so far confirms the feasibility of self-heating MRE reactors for electrolytic reduction of lunar oxides from their own melt.

- It also confirms that another technique is required to achieve the formation of the melt from the regolith at ambient conditions before activating the electrolysis and the self-heat mode.

- The combination of high surface area geometries for anodes, distributed electrical connections and adjustments of inter-electrode gaps were found to have strong effects on the overall power efficiency performance and thermal performance of Joule-heated MRE reactors for electrolytic reduction of lunar oxides from their own melt. Preliminary findings suggest that the minimum critical size of such reactor may be on the order of a cubic foot in volume with a power requirement of less than 5 kW.

- The engineering of prototype reactors designed to process regolith in space at melting temperatures will require the knowledge of these and other fundamental properties of the various mineral resources

Acknowledgements

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QUESTIONS?