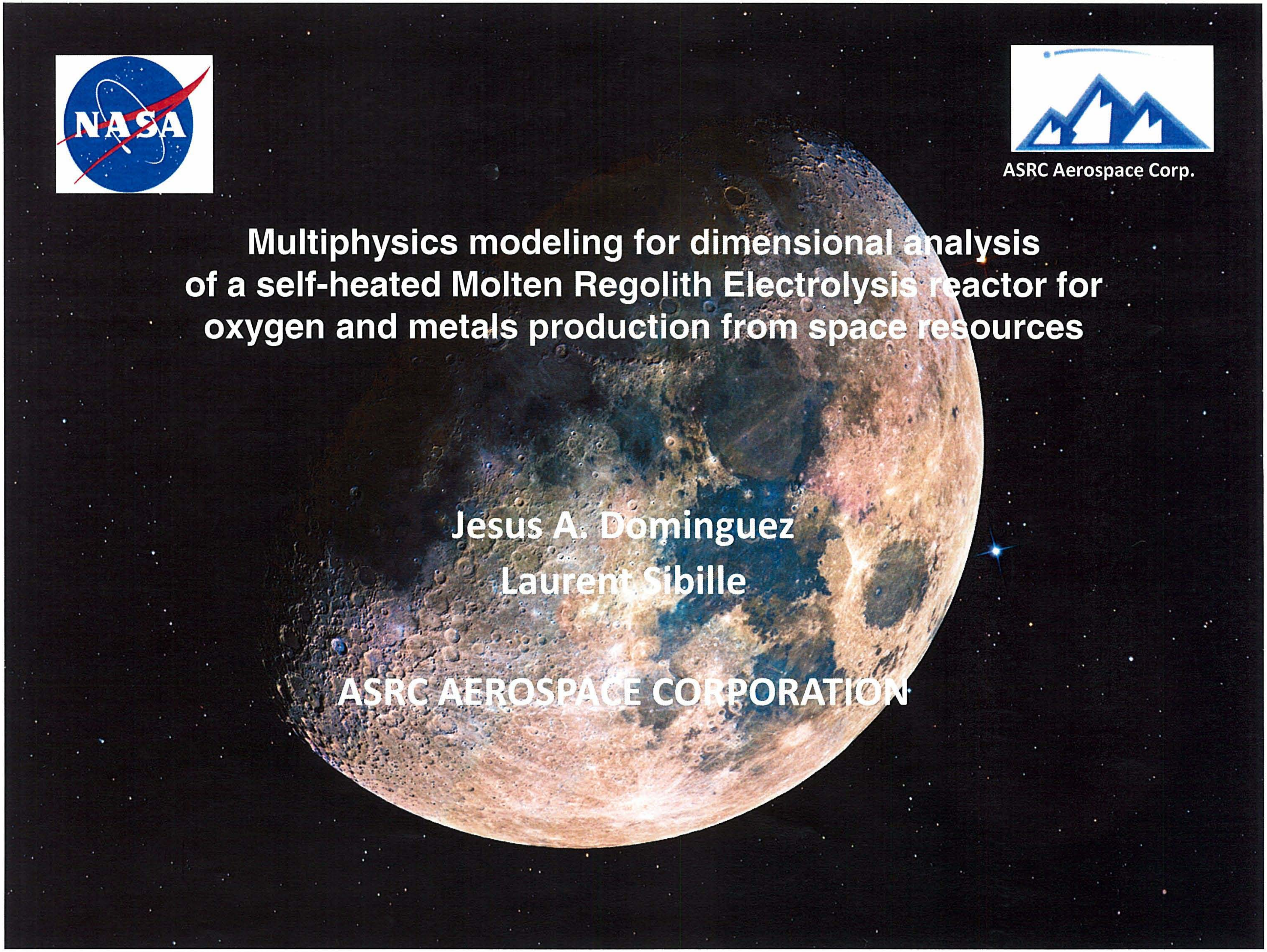

# Multiphysics modeling for dimensional analysis of a self-heated Molten Regolith Electrolysis reactor for oxygen and metals production from space resources


ASRC Aerospace Corp.

Jesus A. Dominguez

Laurent Sibille

ASRC AEROSPACE CORPORATION

# BACKGROUND

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- 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: it might make use of the regolith itself as a crucible material thus protecting the vessel walls and simplifying the engineering of the reactor by eliminating the need for high-temperature materials for containment.

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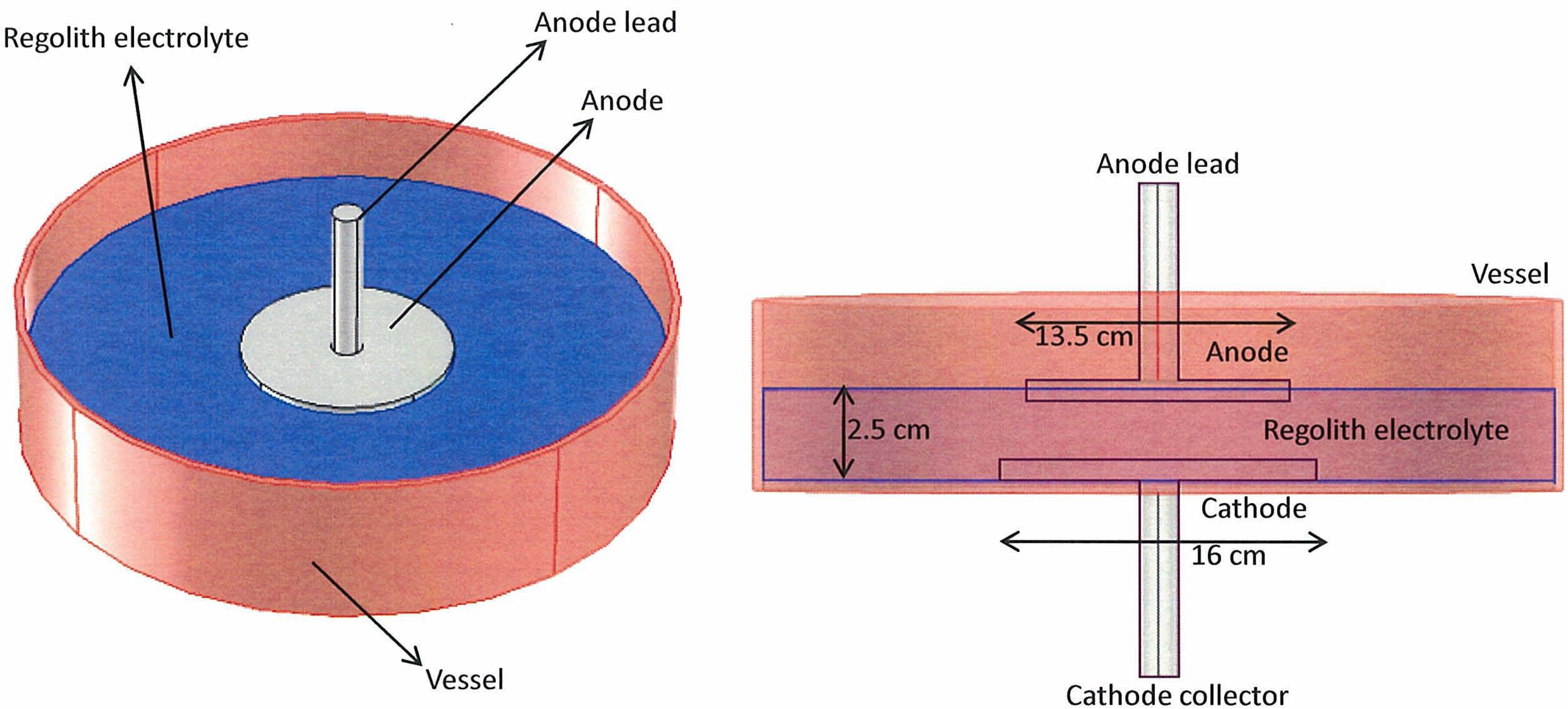
# REACTOR CELL



# PHYSICAL PROPERTIES

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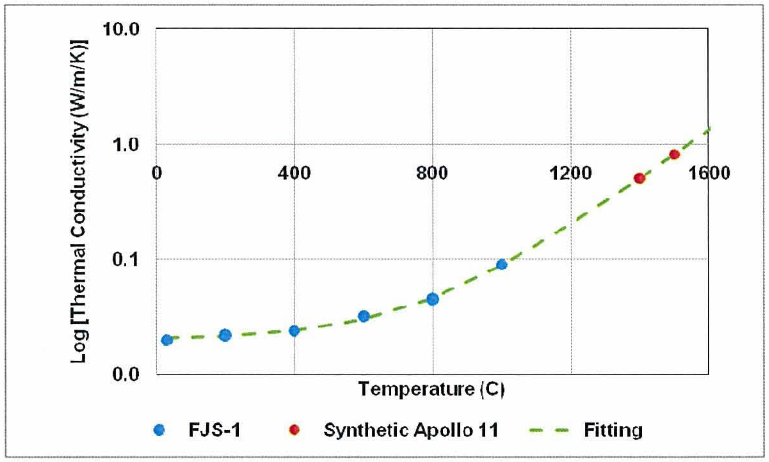
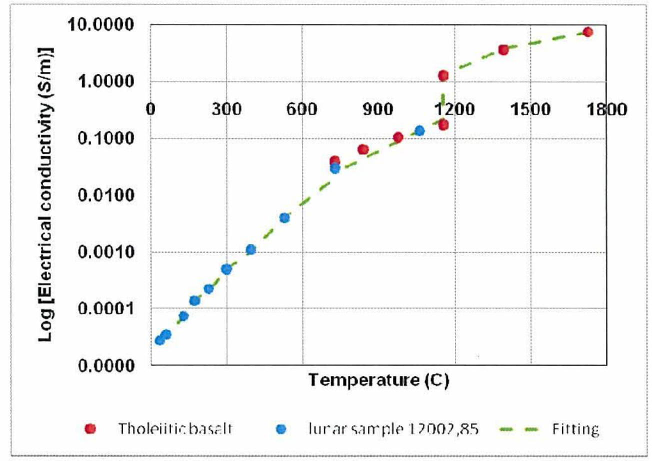
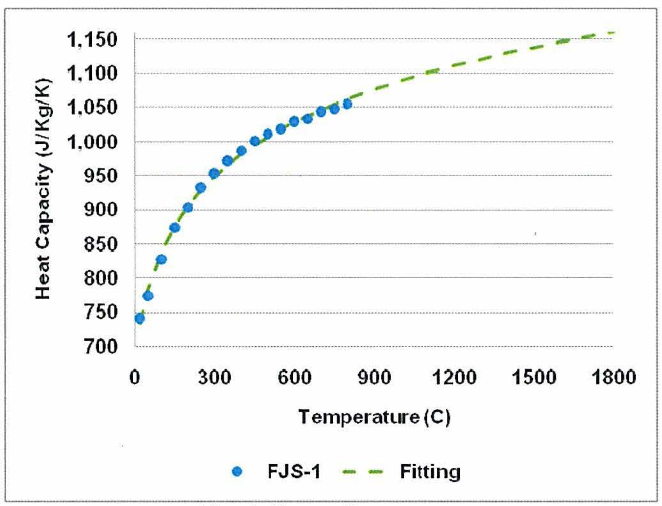


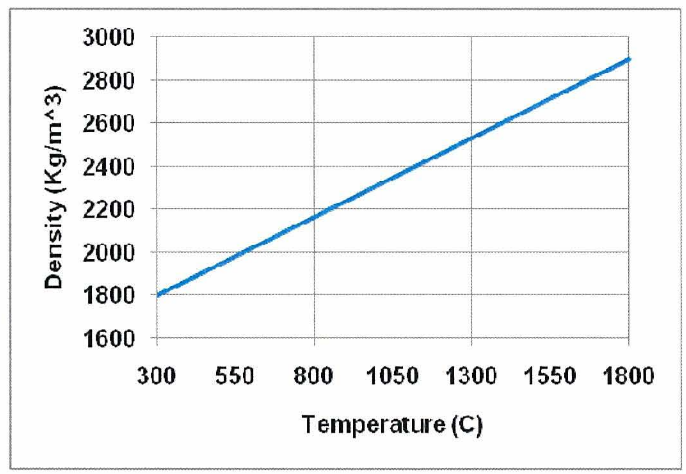

Thermal Conductivity




Electrical conductivity




Heat Capacity




Density

# PHYSICAL PROPERTIES: OPTICAL ABSORPTION

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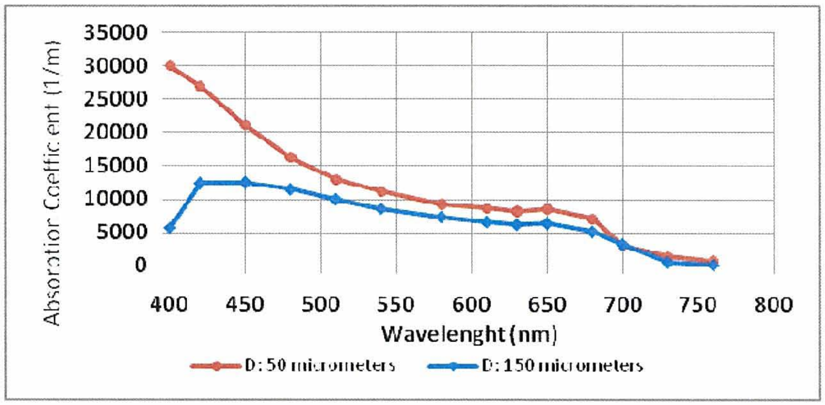
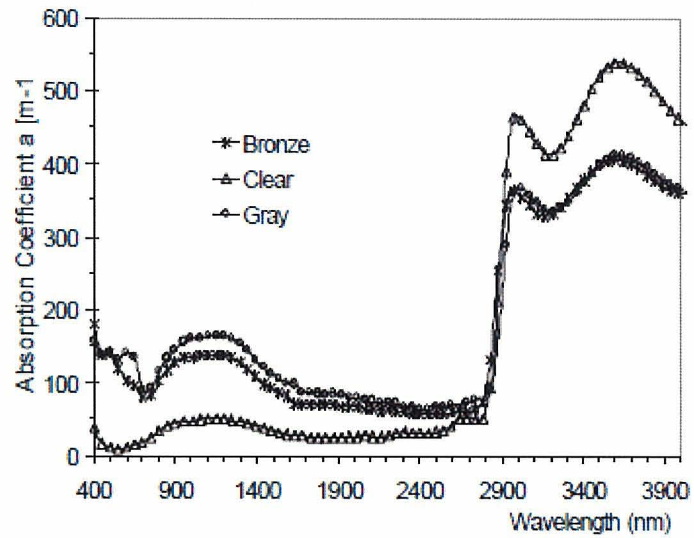
## Absorption coefficient




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




Commercial glass (clear and gray) and bronze

# MATHEMATICAL APPROACH

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**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*

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

**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*

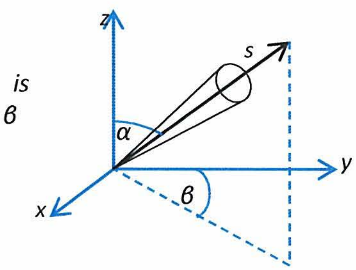
***Radiative Intensity for gray & isotropic medium***

$$\nabla I(r,s) = k_a I_b(T) - (k_a + \sigma_s) I(r,s) + \frac{\sigma_s}{4\pi} \int_0^{4\pi} I(r,s') \varphi(s',s) \partial\Omega'$$

*change in radiative intensity* | *emission* | *absorption* | *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*




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

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

| | | | |
|---|---|---|---|
| $\rho$ | = *density* | *s* | = *position vector* |
| $C_p$ | = *heat capacity* | *r* | = *direction vector* |
| *k* | = *thermal conductivity* | *Ω′* | = *variable for control angle direction* |
| *δ* | = *electrical conductivity* | *Φ* | = *scattering phase function* |
| *T* | = *temperature* | $k_a$ | = *adsorption coefficient* |
| *J* | = *current density* | $\sigma_s$ | = *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* |

# JOULE HEATING PERFORMANCE WITHOUT PREHEATING

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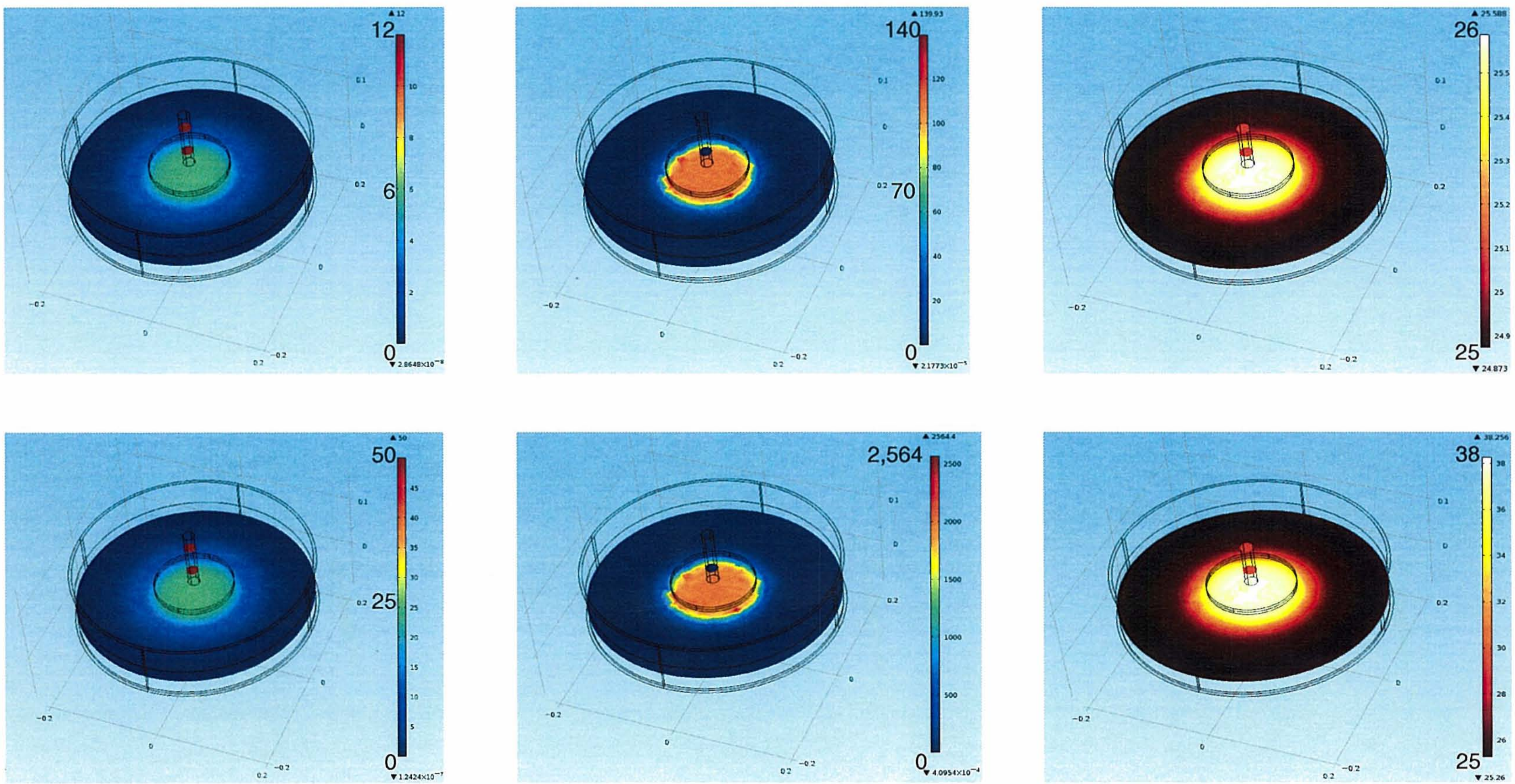
Initial temperature: 25 °C

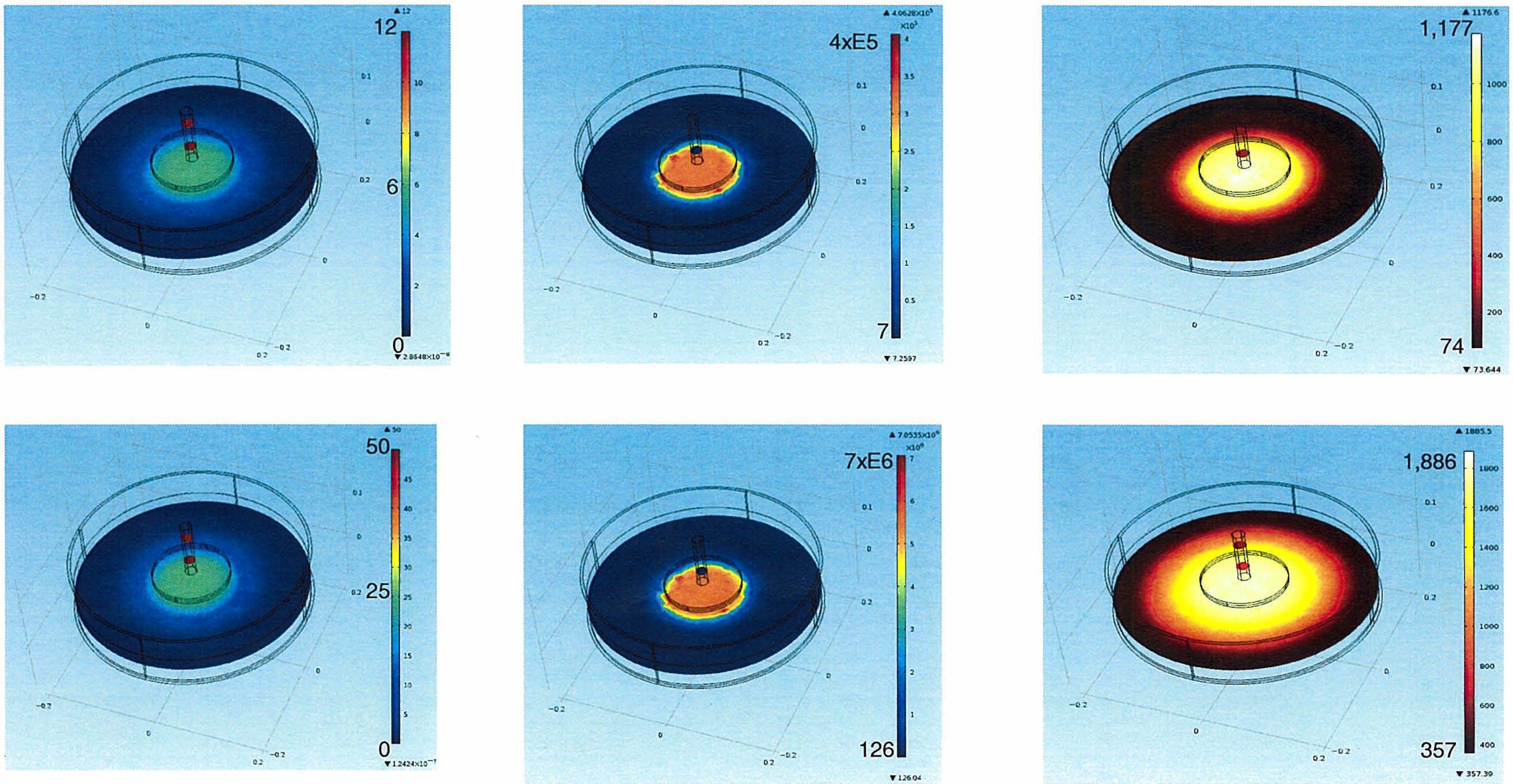
Potential (Volts) | Heat dissipation (W/m^3) | Temperature (°C)



# Joule heating Performance with Preheating

## Preheating temperature: 1,700 °C

Potential (Volts) | Heat dissipation (W/m$^3$) | Temperature (°C)



# RELEVANCE OF THERMAL RADIATION WITHIN PARTICIPATING MEDIA

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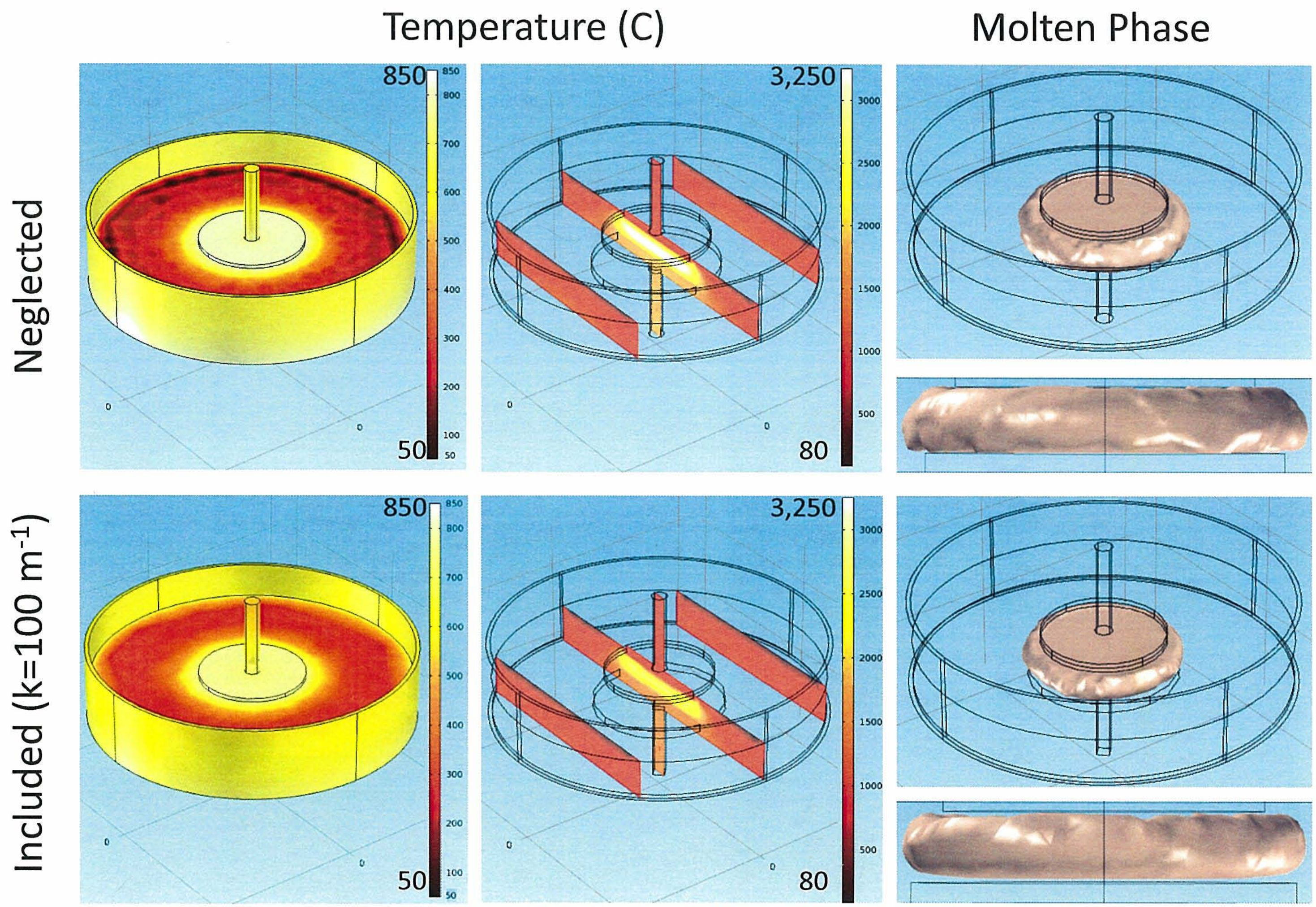
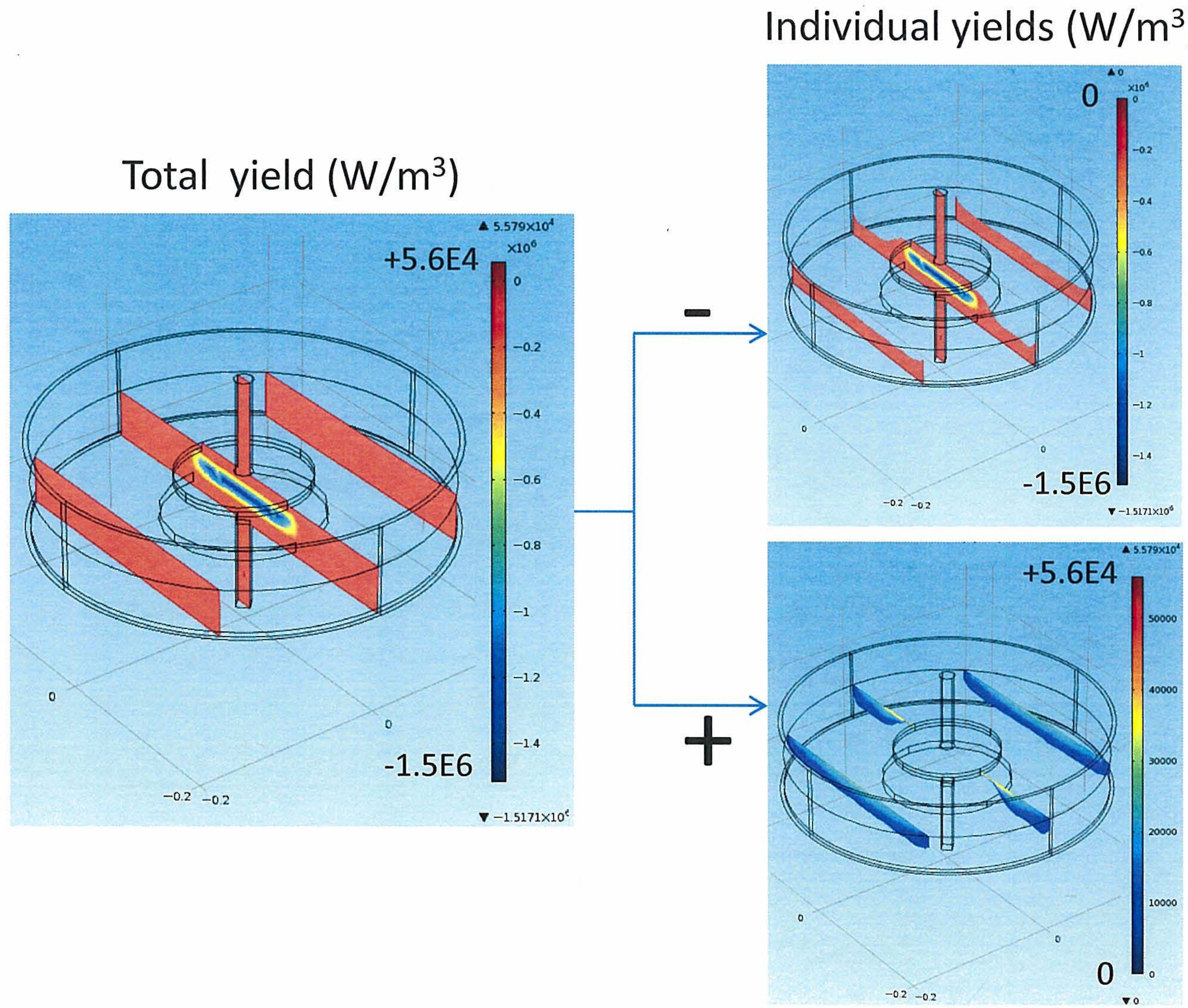



Applied Voltage: 34 V at the anode lead that yields 15 V at the molten phase.

# RADIATION HEAT SOURCE WITHIN PARTICIPATING MEDIA




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

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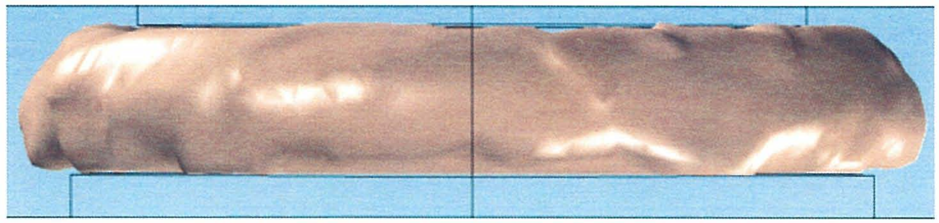
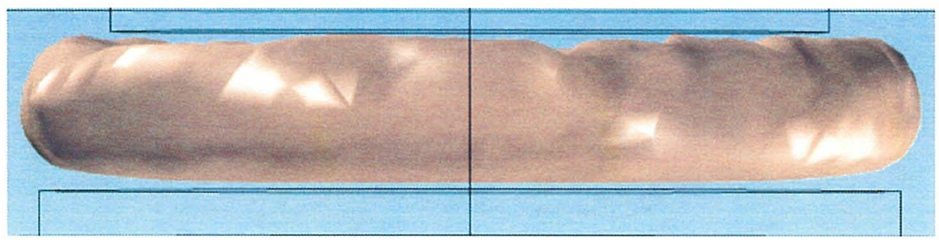
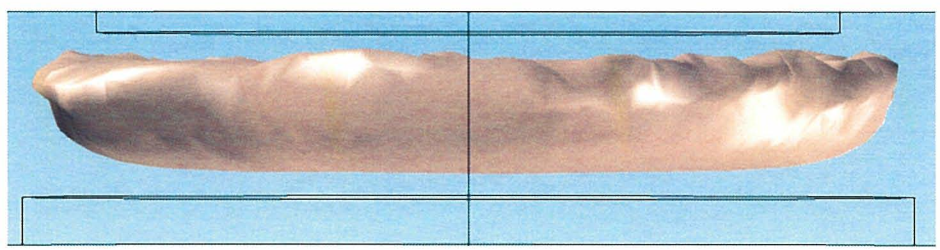
# OPTICAL ABSORPTION EFFECT ON MOLTEN PHASE FORMATION



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



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



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

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

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# 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 accuracy of the model is strongly dependent on important variables such as optical properties of the melt, which have yet to be measured for these complex oxide mixtures.

- 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

The authors wish to thank NASA Exploration Technology Development Program and the ISRU Project for funding this effort and NASA Kennedy Space Center.

QUESTIONS?

**Multiphysics modeling for dimensional analysis of a self-heated Molten Regolith Electrolysis reactor for oxygen and metals production on the moon and Mars**

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The technology of direct electrolysis of molten lunar regolith to produce oxygen and molten metal alloys has progressed greatly in the last few years The development of long-lasting inert anodes and cathode designs as well as techniques for the removal of molten products from the reactor has been demonstrated The containment of chemically aggressive oxide and metal melts is very difficult at the operating temperatures ca 1600°C Containing the molten oxides in a regolith shell can solve this technical issue and can be achieved by designing a self-heating reactor in which the electrolytic currents generate enough Joule heat to create a molten bath

In a first phase, a thermal analysis model was built to study the formation of a melt of lunar basaltic regolith irradiated by a focused solar beam This mode of heating was selected because it relies on radiative heat transfer, which is the dominant mode of transfer of energy in melts at 1600°C Knowing and setting the Gaussian-type heat flux from the concentrated solar beam and the phase and temperature dependent thermal properties, the model predicts the dimensions and temperature profile of the melt A validation of the model is presented in this paper through the experimental formation of a spherical cap melt realized by others The Orbitec/PSI experimental setup uses an 3 6-cm-diameter concentrated solar beam to create a hemispheric melt in a bed of lunar regolith simulant contained in a large pot Upon cooling, the dimensions of the vitrified melt are measured to validate the thermal model

In a second phase, the model is augmented by multiphysics components to compute the passage of electrical currents between electrodes inserted in the molten regolith The current through the melt generates Joule heating due to the high resistivity of the medium and this energy is transferred into the melt by conduction, convection and primarily by radiation
The model faces challenges in two major areas, the change of phase as temperature increases, and the dominance of radiative heat flux as heat transfer mechanism within the melt The change of phase concerns the regolith itself which is present in states ranging from a fine grain regolith with low thermal conductivity and low density to a vitrified melt with much higher thermal conductivity, and higher density As the regolith is heated, it starts to soften around 1300°C The melt is very viscous and evolving gas bubbles out in thick, lava-like fashion By 1600°C the regolith is completely melted and the viscosity is low The second challenge resides in the proper modeling of the radiative heat flux requiring the addition of the computing-demanding radiative-heat-transfer function to the general heat transfer equation The model includes temperature-dependent properties (density, thermal conductivity, heat capacity, and viscosity, and absorption coefficients) and solves the radiative heat flux equation assuming gray (fine grains) and semi-transparent (melt) media and using an absorption coefficient spectral found in the literature for terrestrial minerals similar in composition to those of lunar regolith simulant