HEAF Modeling with Sierra

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Sierra Plasma Arc Modeling

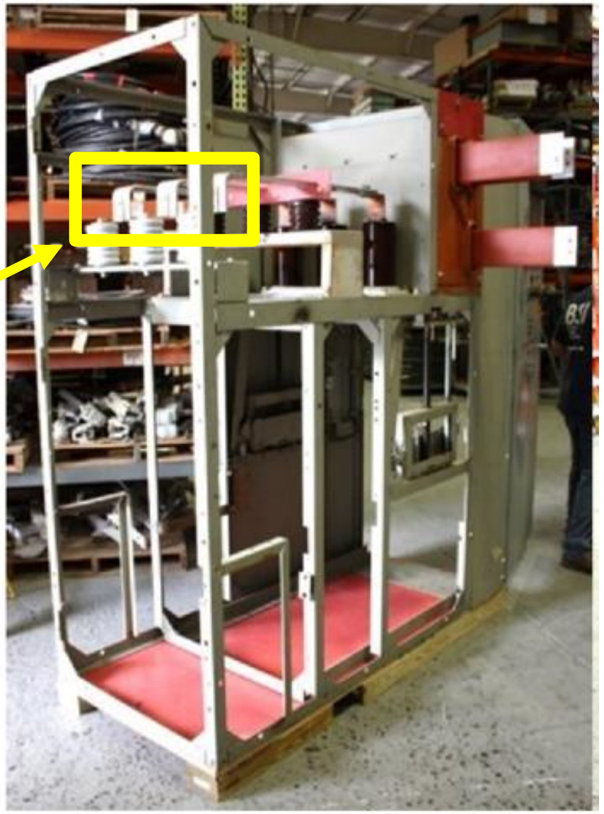
The conduction of current through the gas (arc) is the source of gas heating, melting and vaporization of metal, and radiation.

The NIST simulation software Fire Dynamics Simulator (FDS) has expertise in gas heating and transport mechanisms but does not have a capability for accurate modeling of the arc physics.

Sandia National Laboratories (SNL) has extensive capability and expertise in simulating arc physics. Scales for arc physics are micron (and smaller) and require accurate modeling of charged particle transport to capture localized heating effects.

The current approach is to use a Sierra model for the arc and local gas transport, then transfer results to FDS for the full domain transport problem.

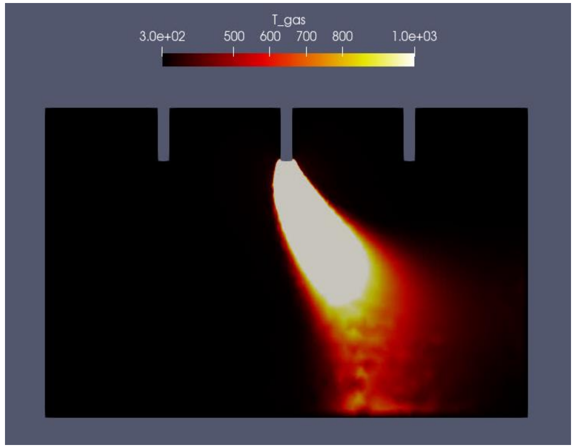
Arc domain



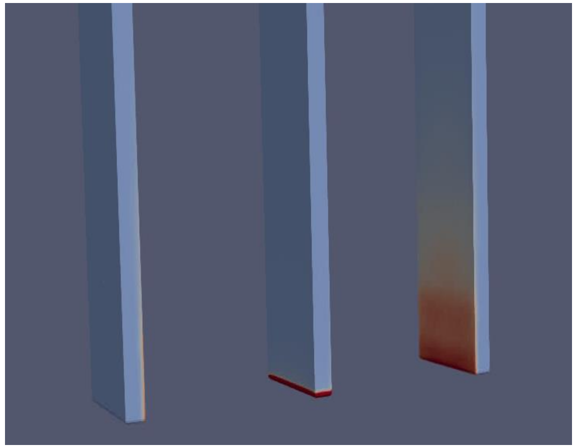
(walls removed for viewing cabinet internals)

HEAF – a Complex Multi-scale Coupled Physics Problem

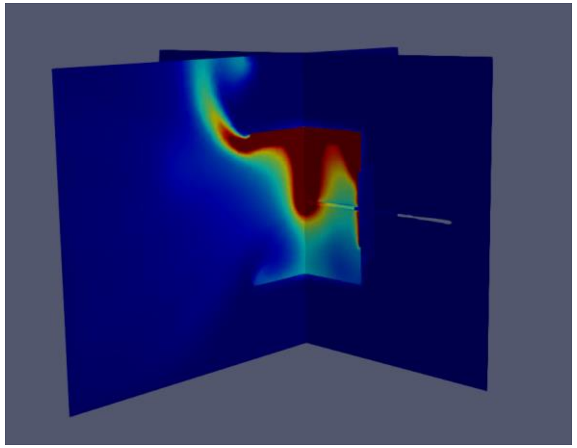
Arc Physics
(μm scale)



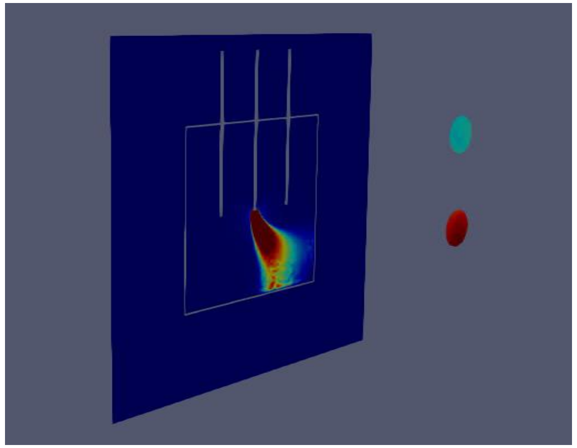
Electrode Melting/Vaporization
(mm scale)



Gas Heating
(cm-to-m scale)



Radiation
(m scale)



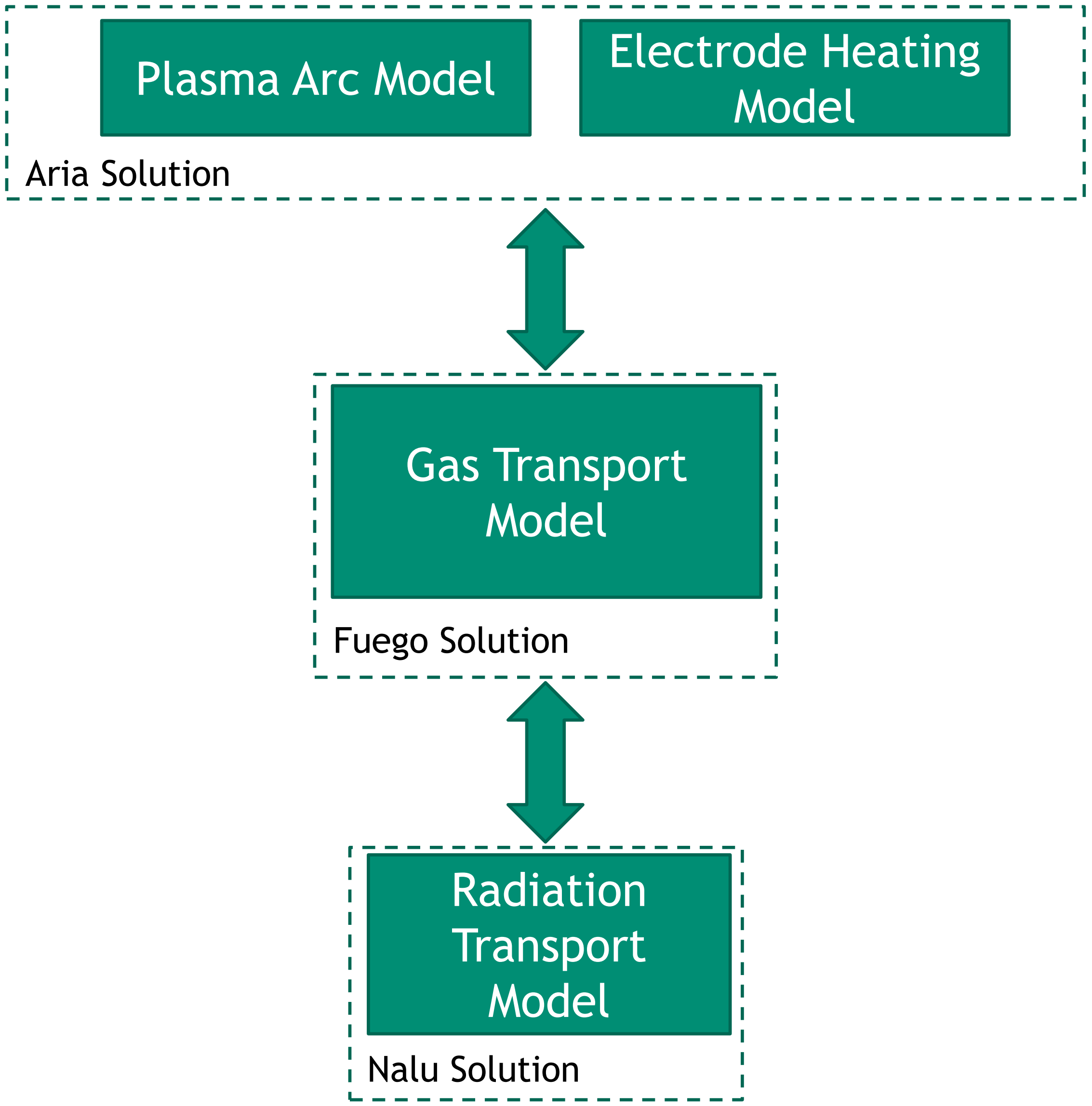
Feedback from different phenomena lead to a coupled physics problem

Arc Model Overview

The Sierra model couples together hydrodynamics (Fuego), plasma physics (Aria), and radiation transport (Nalu).

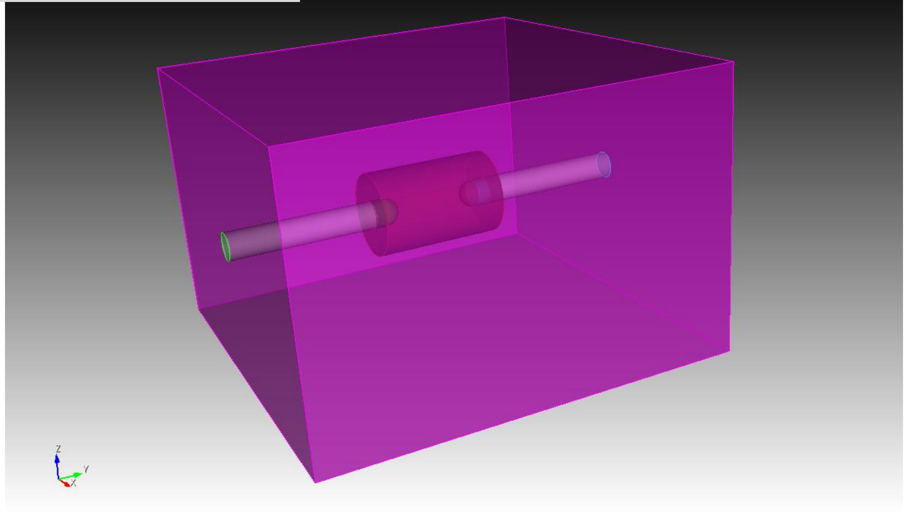
It is possible to investigate differences in electrode materials, gas composition, gas optical thickness, and other parameters, depending on resource allocation.

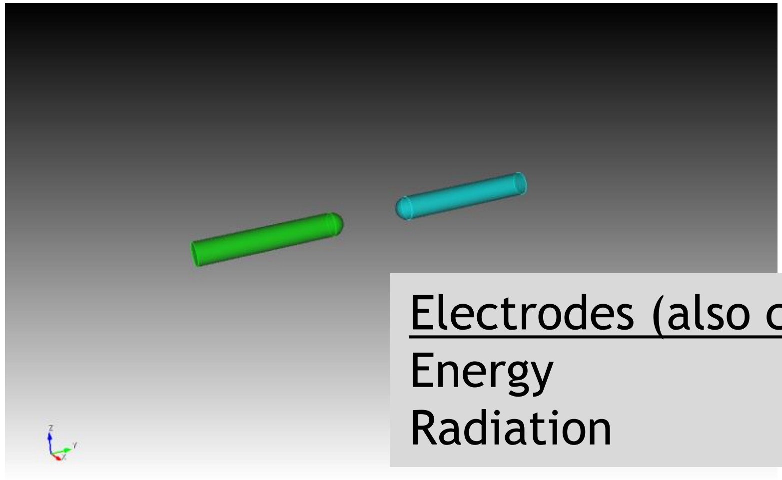
The model currently assumes a DC plasma discharge (providing time-averaged heating rates).



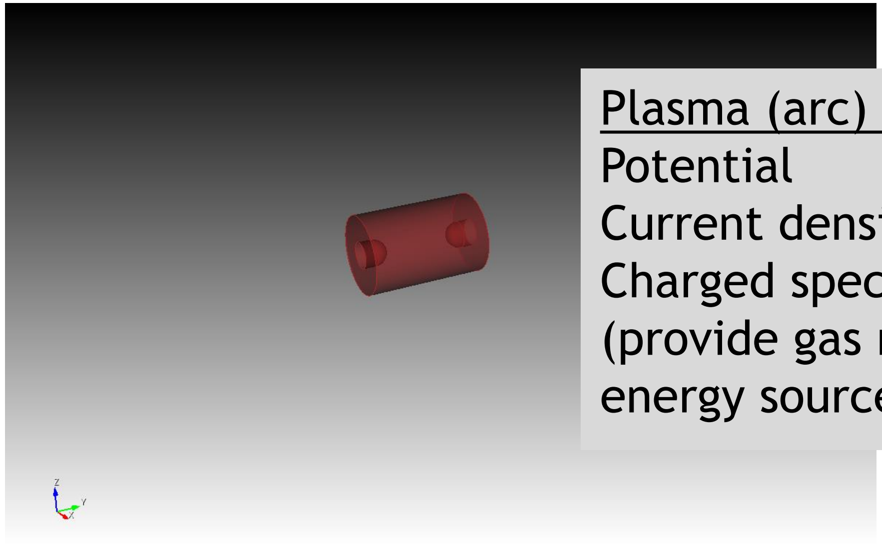
Example Coupled Problem

Entire domain



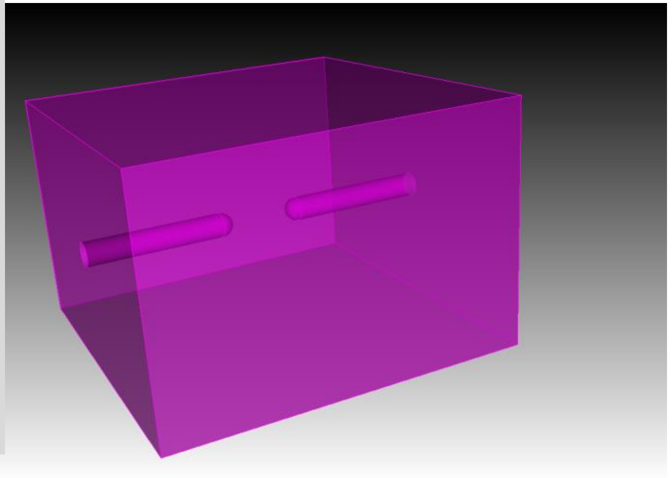


Electrodes (also calorimeters)
Energy
Radiation

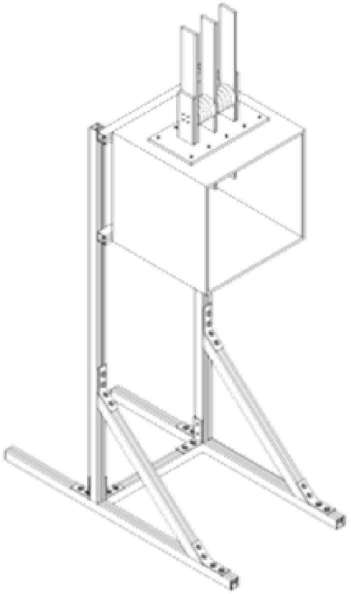


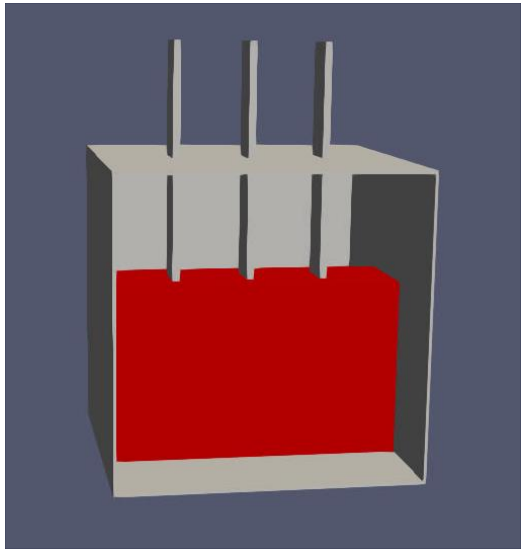
Plasma (arc) region
Potential
Current density
Charged species
(provide gas region energy source term)

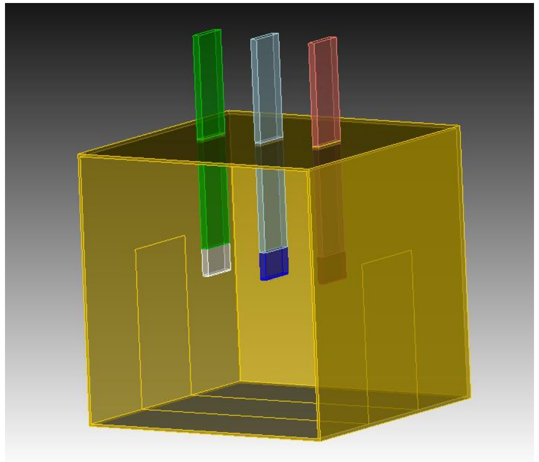
Gas region
Mass
Momentum
Turbulent kinetic energy
Energy
Radiation (Nalu)
(provide plasma region temperature)



Open Box OBMV4







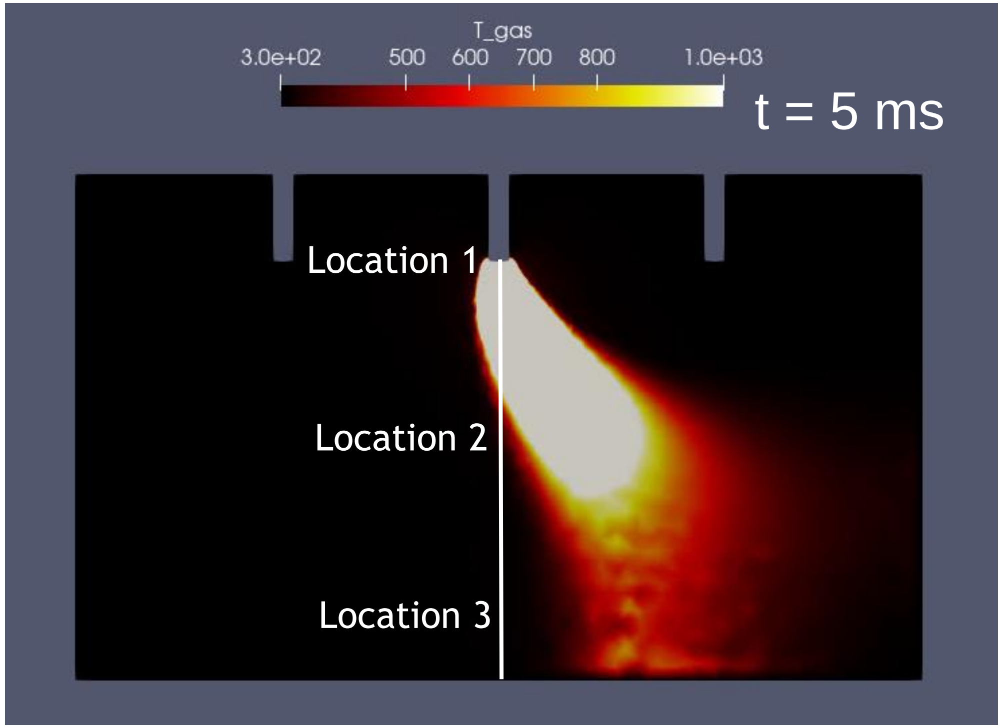
Nominal parameters:

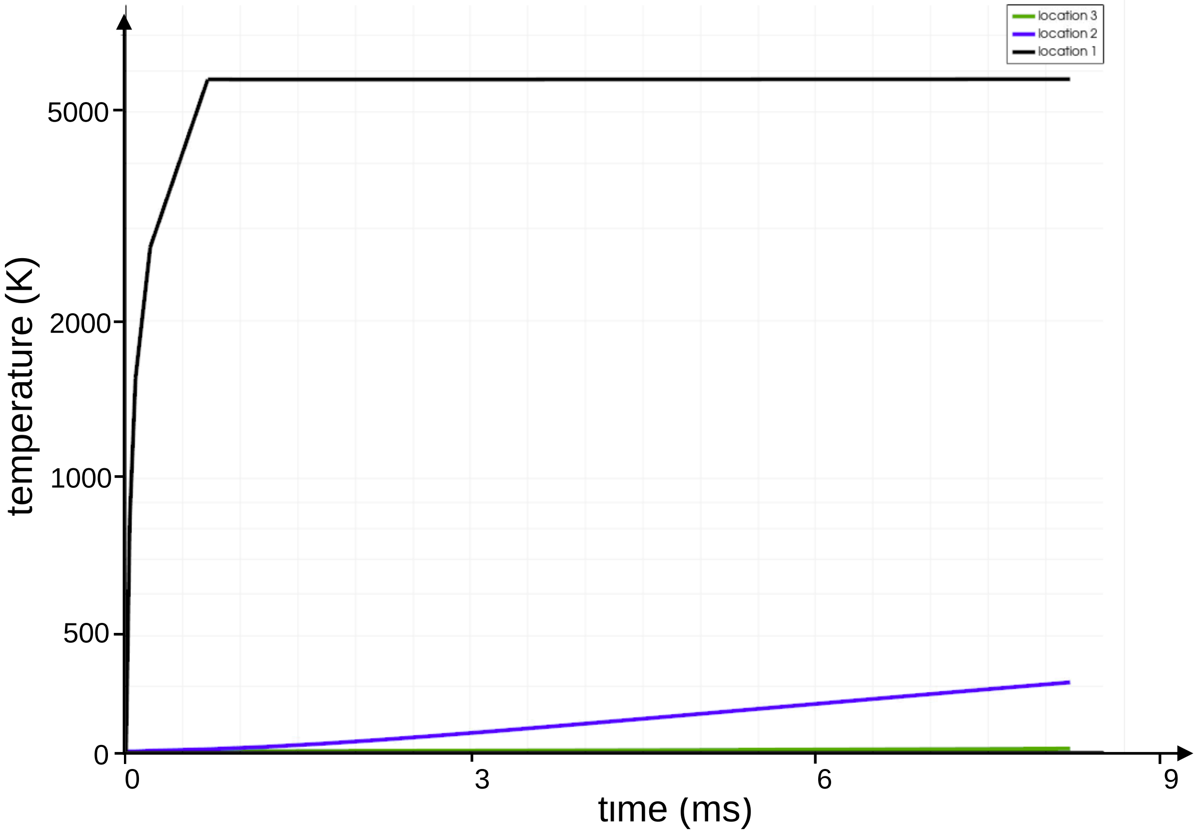
- 6900 V L-L system voltage
- 14.3 kA
- 264 V L-N arc voltage
- 5 s duration

Model Setup:

- Injection of 14.3 kA (electron current) from middle electrode.
- Middle and left electrode fixed at -264 V.
- Right electrode and walls held at ground.

Temperature Evolution (Al Mass Fraction = 0.3)

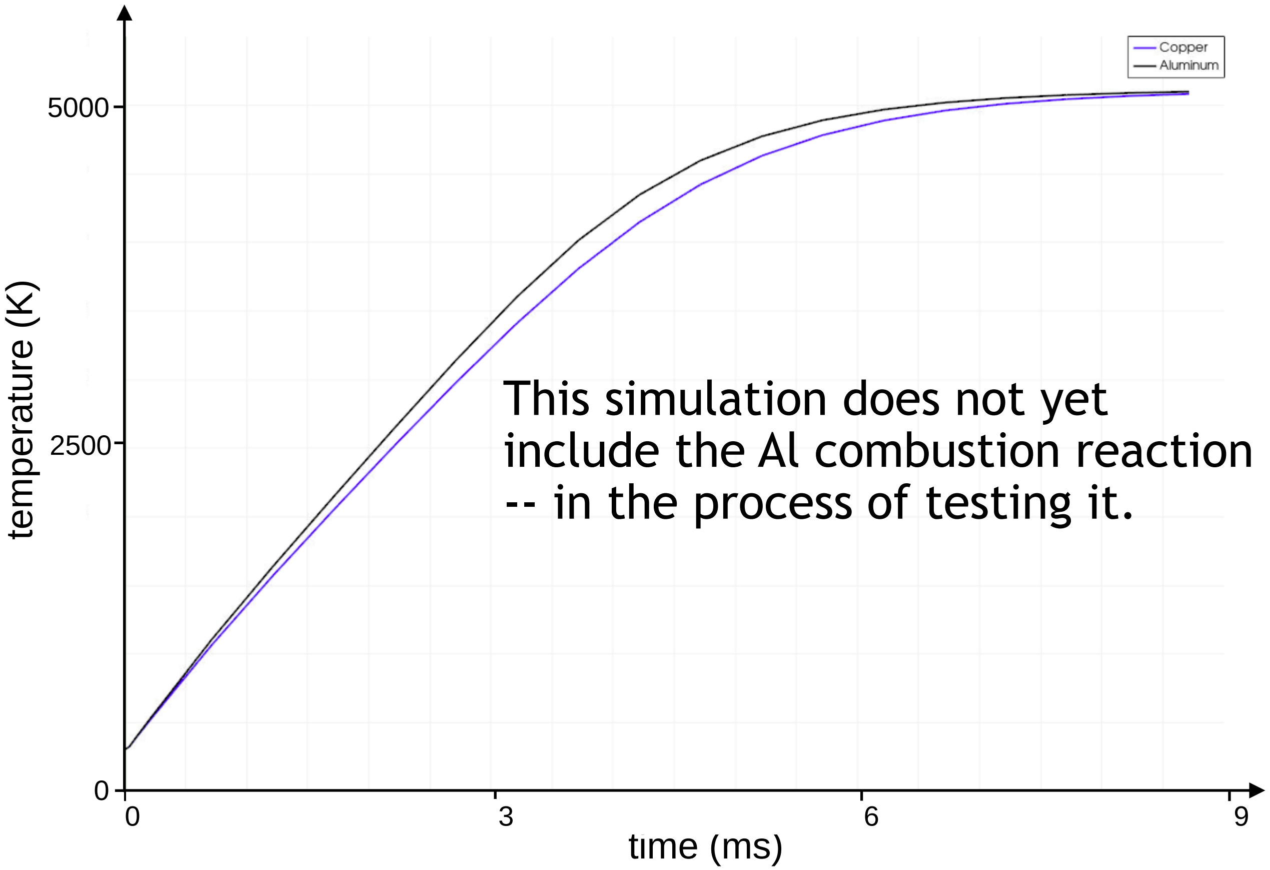




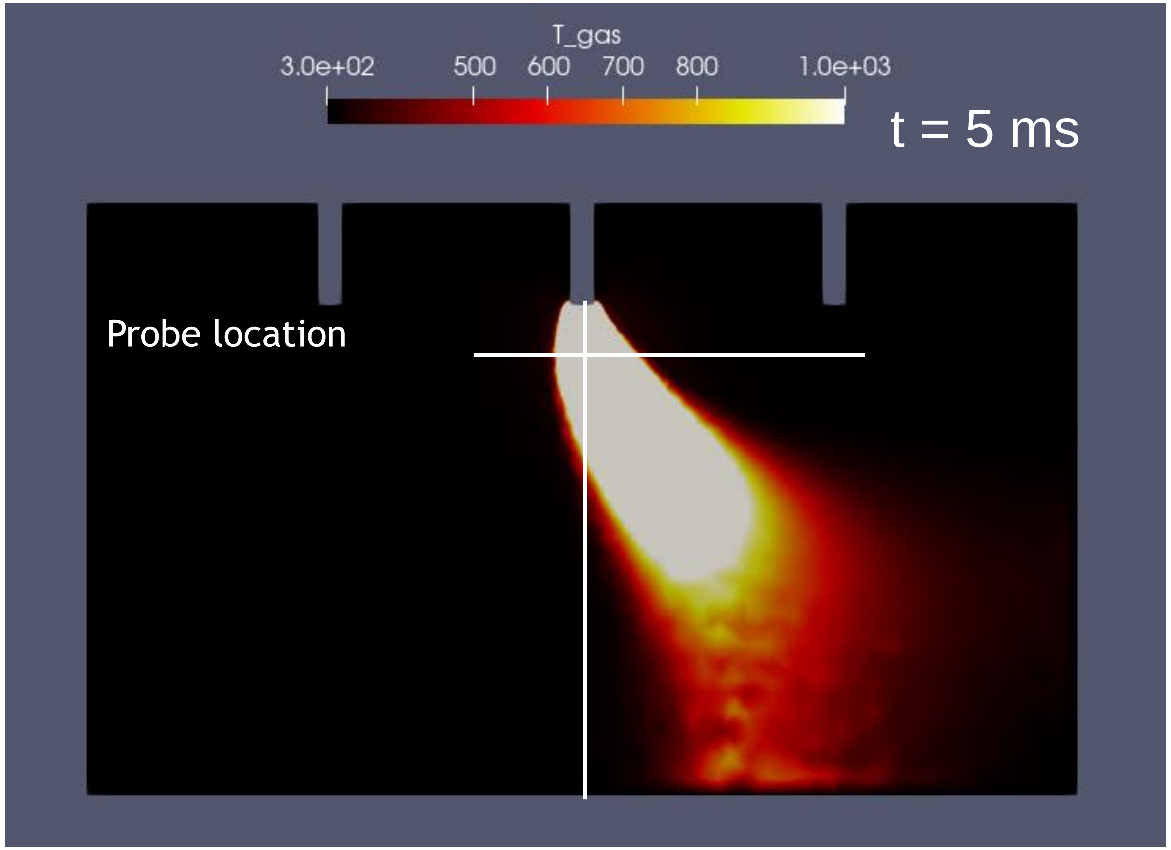
Have not yet reached a steady-state temperature in the plasma volume.
Heating term from arc has stabilized.

Open Box – OBMV4

Temperature Rise Difference in Cu vs. Al

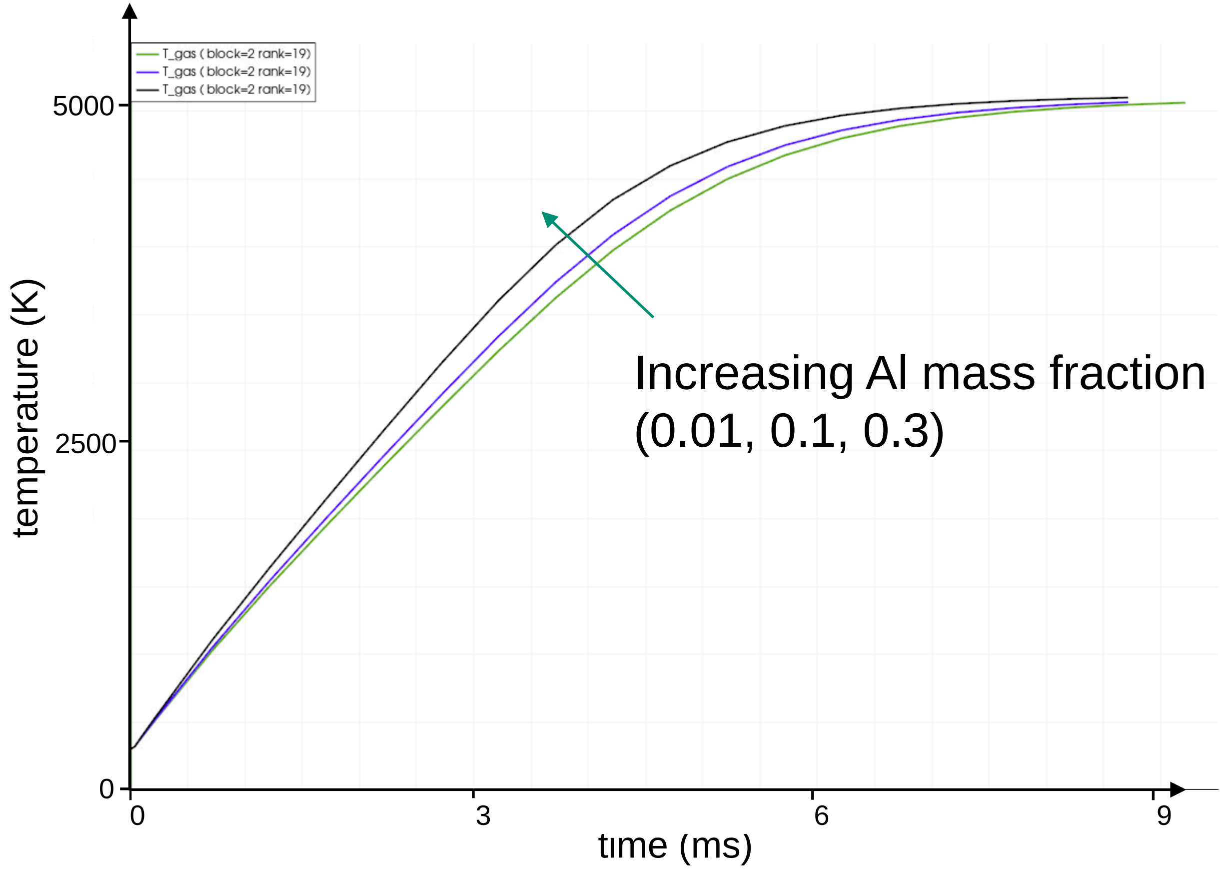


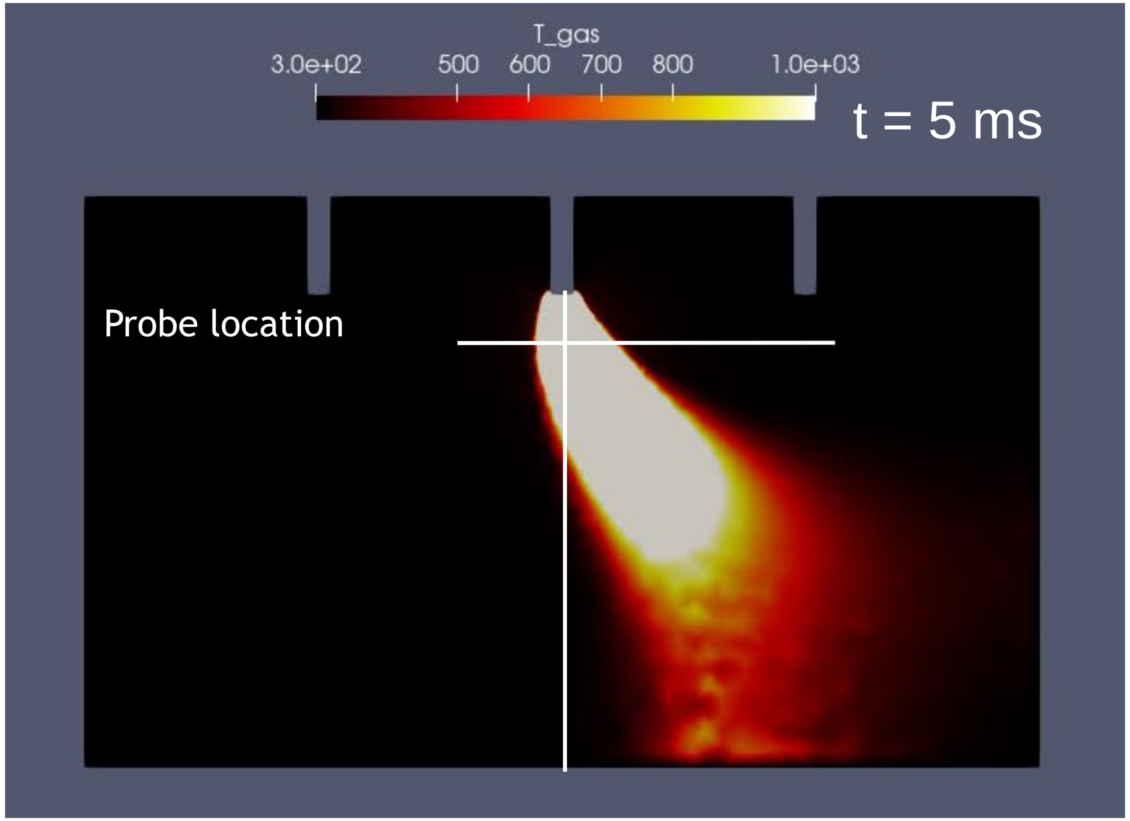
This simulation does not yet include the Al combustion reaction -- in the process of testing it.



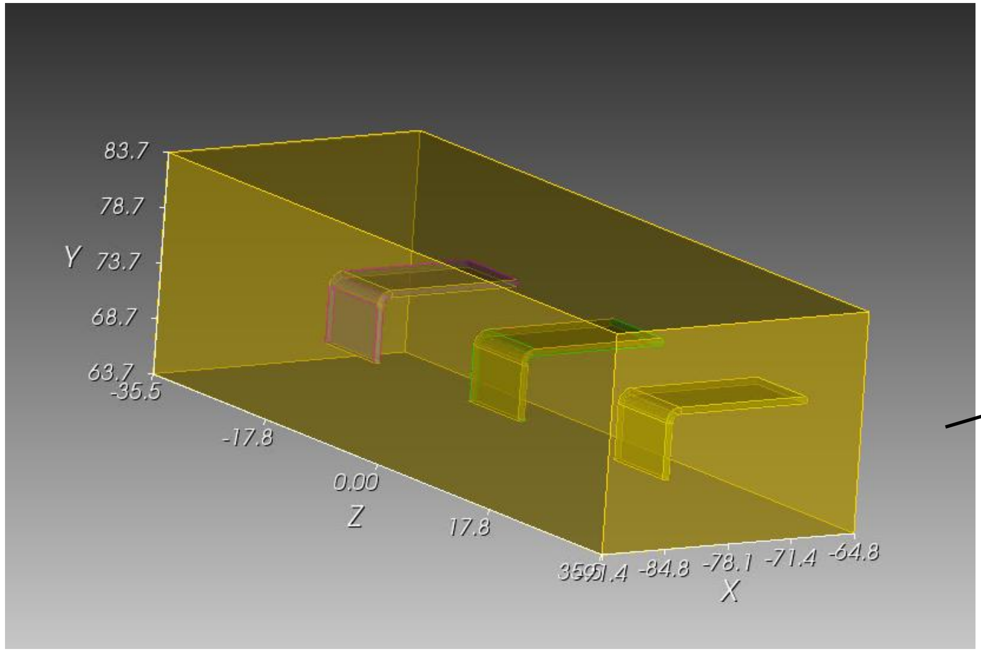
Open Box – OBMV4

Influence of Al Mass Fraction



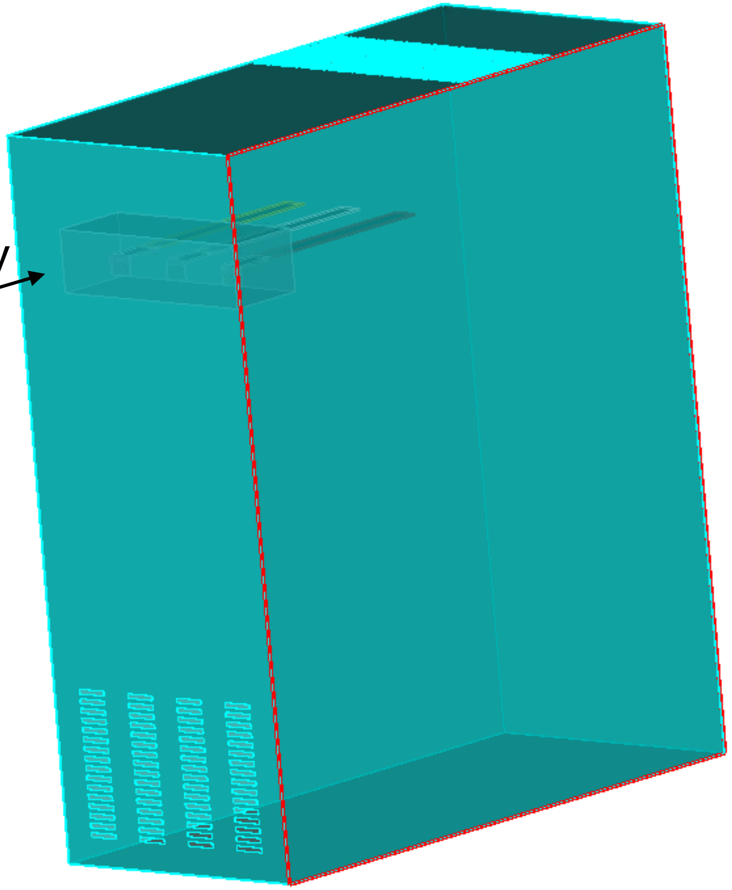


Medium Voltage Switchgear Simulations – 2018 KEMA Test



No metal or combustion reaction included

Focus on plasma region only



Nominal parameters:

- 6900 V L-L system voltage
- 25.76 kA
- 246 V L-N arc voltage
- 2 s duration

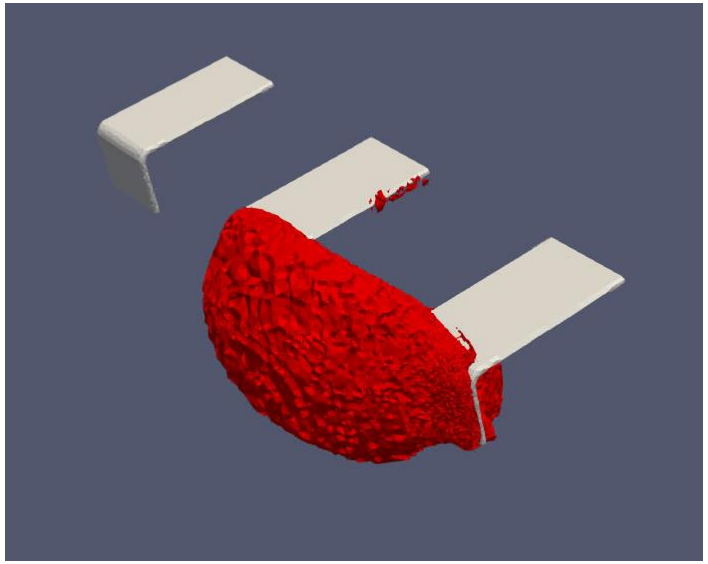
Model setup:

- Injection of 25.76 kA (electron current) from middle electrode to right electrode.
- Middle and left electrode fixed at -246 V.
- Other electrode and surfaces at ground.

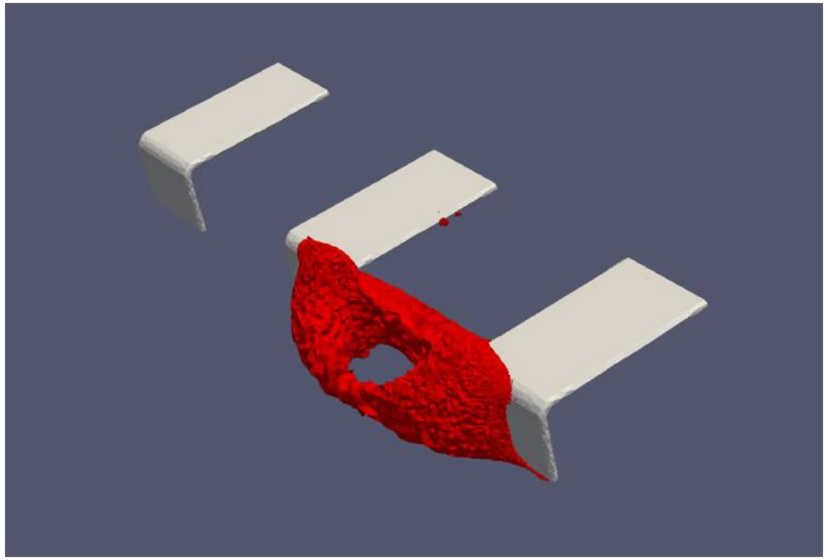
Localized Heating

Locations of gas heating due to arc (plasma) formation.

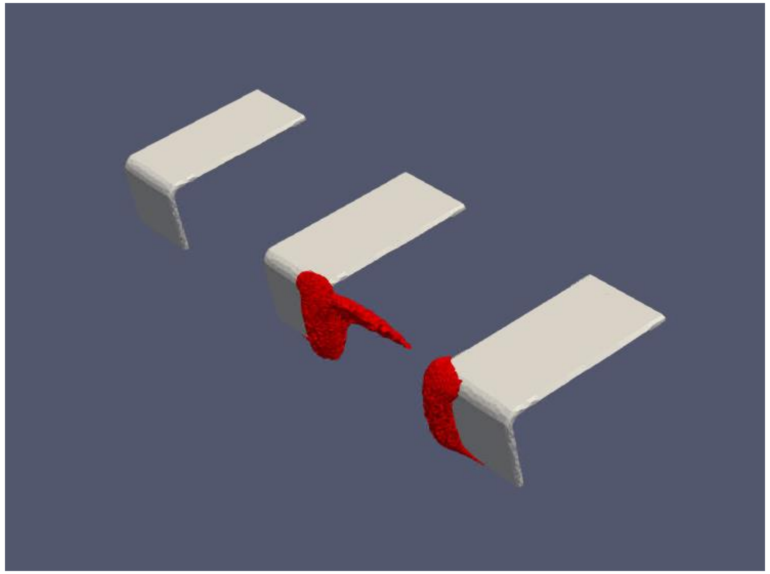
90% total

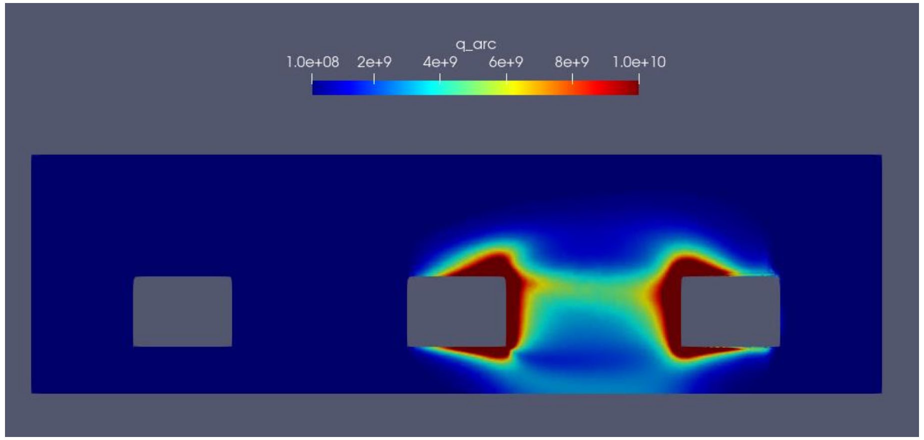


50% total



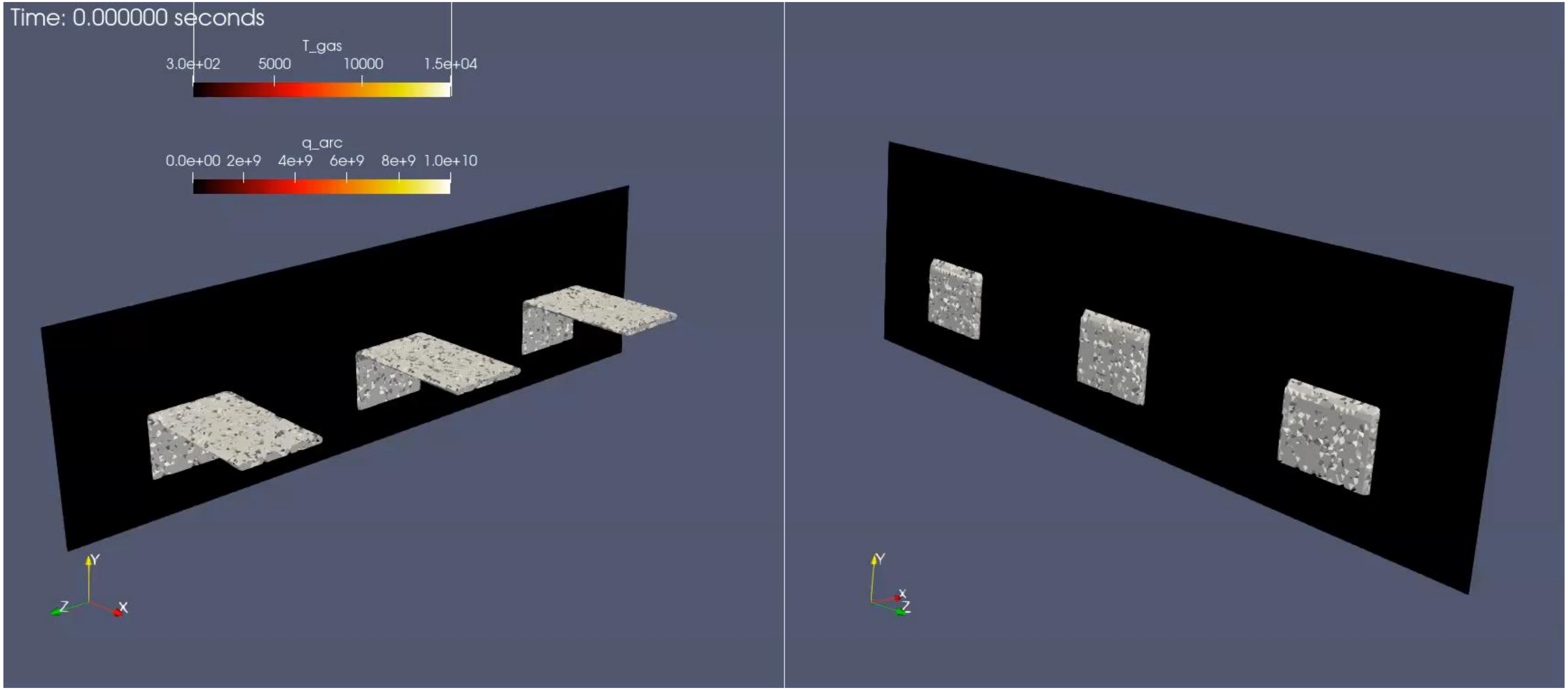
10% total





NRC 2018 KEMA Test

Evolution of gas temperature and heating source



NRC 2018 KEMA Test

Current Activity

Complete Al Oxidation Reaction

- Al + O2 → AlO + O

Continue definition of hand-off parameters for plasma arc source term to FDS model

- Power
- Radiation fraction
- Compare temperatures between FDS and Sierra

Develop other geometries and operating conditions for ZOI calculations

Backup Slides Follow

Fully-coupled Model Equations

Gas dynamics

$$\frac{\partial \rho}{\partial t} + \rho \nabla \cdot \boldsymbol{v} + \boldsymbol{v} \cdot \nabla \rho = q_m$$ (continuity)

$$\rho \frac{\partial \boldsymbol{v}}{\partial t} + \rho \boldsymbol{v} \nabla \cdot \boldsymbol{v} - \boldsymbol{g} - \nabla \mathbf{T} = 0$$ (momentum)

$$\frac{\partial (\rho C_p T)}{\partial t} + \rho C_p \boldsymbol{v} \cdot \nabla \mathrm{T} = -\nabla \cdot \mathbf{q} + H_v$$ (energy)

1-term turbulence model equation
Species transport (Al/Cu)

Plasma arc (drift-diffusion approximation)

$$\frac{\partial n_x}{\partial t} + \nabla \cdot \boldsymbol{\Gamma}_x = S_e$$ (charged species continuity)

$$\boldsymbol{\Gamma}_x = \pm \mu_x n_x \boldsymbol{E} - \nabla (n_x D_x)$$ (flux term)

$$\nabla^2 \varphi = \frac{-e(n_e - n_i)}{\varepsilon_o}^{\dagger} \qquad \boldsymbol{E} = -\nabla \varphi$$ (electrostatic voltage and electric field)

$$H_v = \boldsymbol{J} \cdot \boldsymbol{E} \qquad \boldsymbol{J} = \sigma \boldsymbol{E} \qquad \sigma = n_e \mu_e e$$

(Heating/Coupling between equations)

Radiation transport

$$s_i \frac{\partial}{\partial x_i} I(s) + \mu_a I(s) = \frac{\mu_a \sigma T^4}{\pi}$$ (transport)

$$I(s) = \frac{1}{\pi} \left[\tau \sigma T_\infty^4 + \epsilon \sigma T_w^4 + (1 - \epsilon - \tau) q_j^{r,inc} n_j \right]$$ (boundaries)

$$\frac{\partial q_i^r}{\partial x_i} = \mu_a \left[4 \sigma T^4 - G \right]$$ (energy source)

Metal Vapor Fraction

- We showed 30% but we include other fractions
- Literature shows that our guesses are reasonable
- There are no measurements of droplet vs. vapor distribution of electrode material