

# Magnetohydrodynamic (MHD) arc flash model verification and validation



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# Introduction

## Problem

- As more data is urgently needed for dc arc flash model development, arc flash experiments remain costly and time consuming.
- Simulations can supplement experimental data for use in practical arc flash model development.
- But how do you know that these simulations reflect reality?

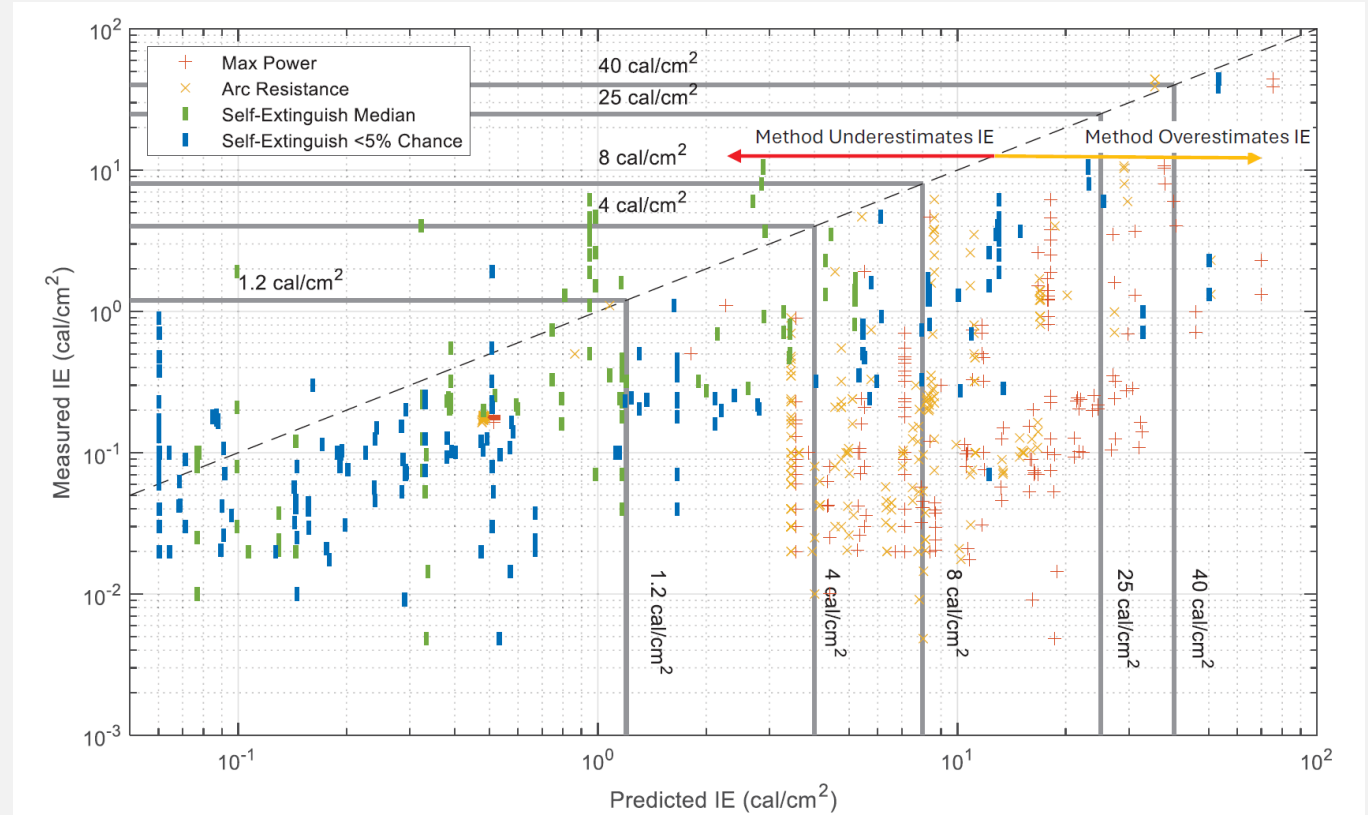
## Contributions

- We perform verification and validation of a developed MHD model using the methods described in the ASME V&V 20 standard.
- Verification involves testing each of the governing differential equations against analytical or benchmark solutions.
- Validation then compares simulated results using finite element analysis to experimental data.

Preliminary results are presented here, for full results see  
IEEE IAS ESW 2027 in Reno, NV

# Experimental Data Review

New dc arc flash models help. But they are fundamentally limited by the available data.



[20] D. Rosewater, L. Gordon and W. Cantor, "Practical Battery Arc Flash Models," in IEEE Transactions on Industry Applications, doi: 10.1109/TIA.2025.3637673.

# Overprescription of Arc Flash PPE

While over prescription of PPE may seem to be safer or more conservative when planning work, it often makes the worker less safe when performing the work by reducing manual dexterity and accelerating heat-induced exhaustion.

Battery workers have an intuition for the potential hazard and could lose trust in safety professionals if we drastically overestimate it.



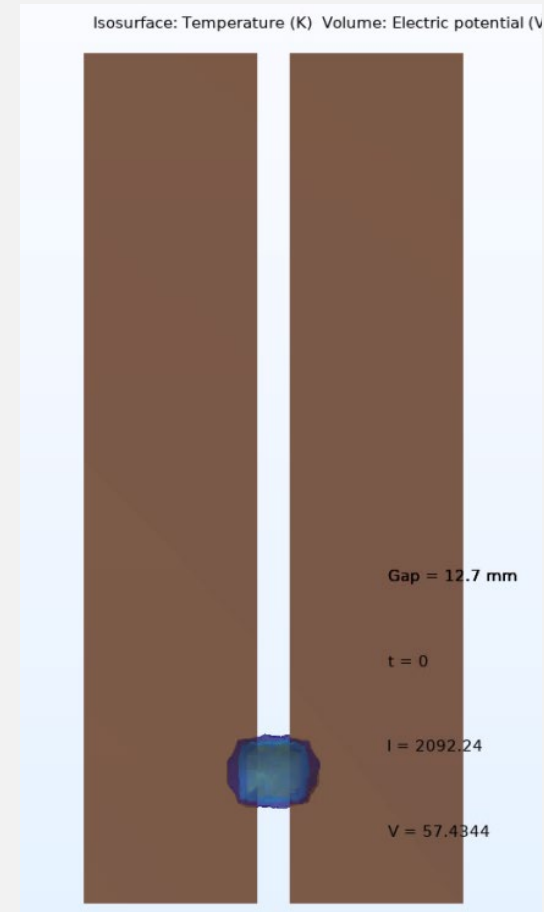
[https://newsreleases.sandia.gov/grid\\_saver/](https://newsreleases.sandia.gov/grid_saver/)



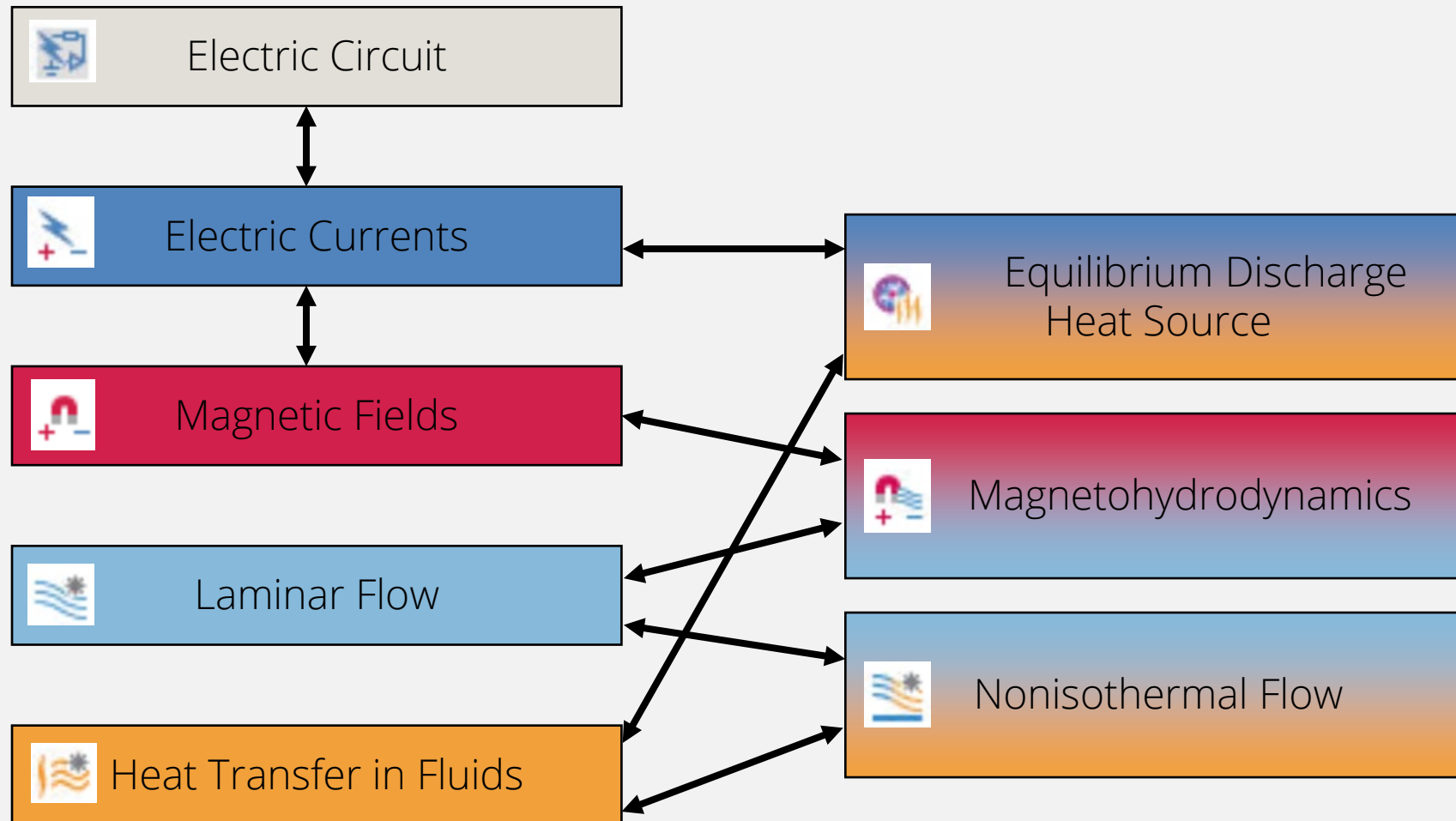
**Magnetohydrodynamic (MHD)  
arc flash model**

**Verification**

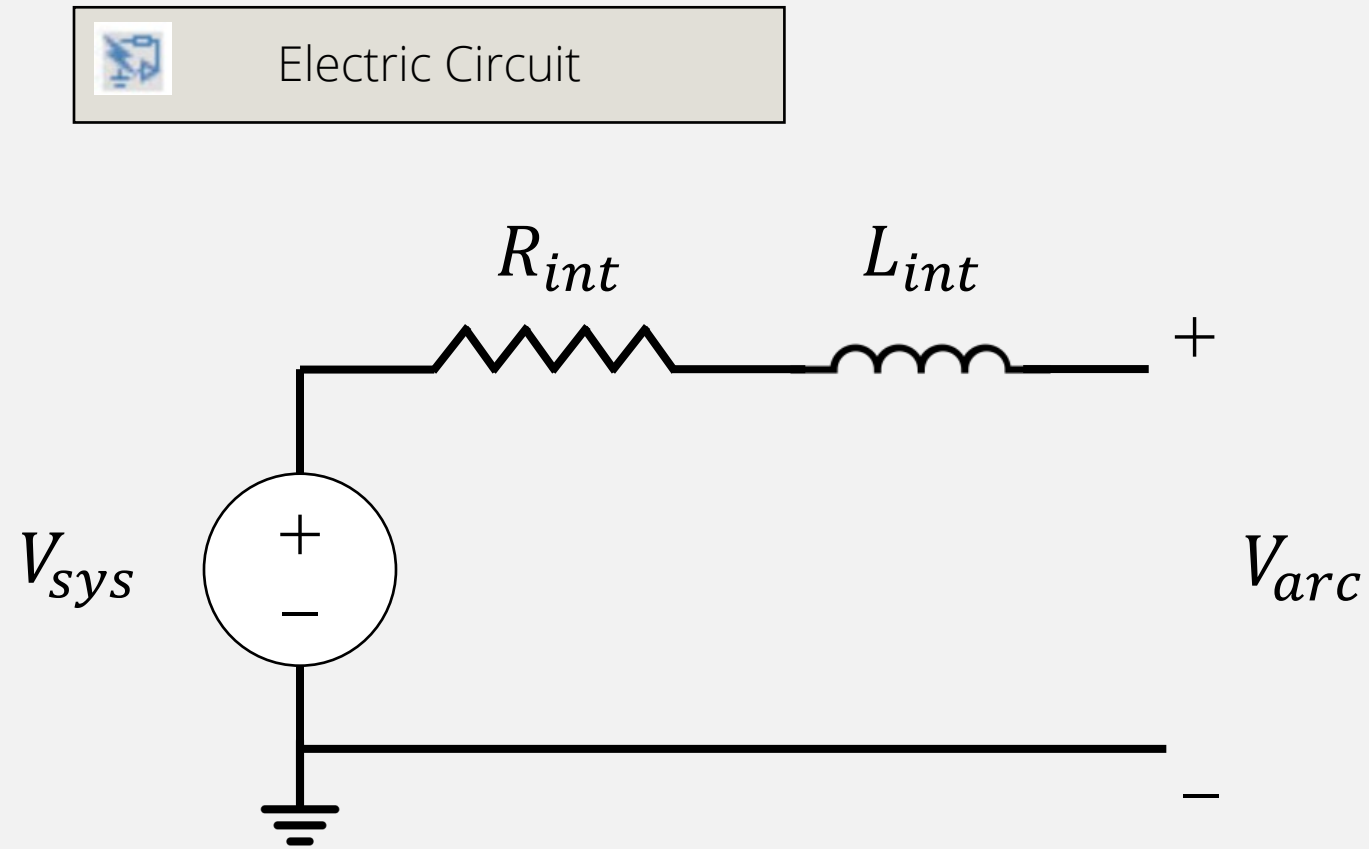
# Simulate arc flash



# Arc model in COMSOL Multiphysics



# Arc model in COMSOL



# Arc model in COMSOL



$$\nabla J = Q_{j,v}$$
$$J = \sigma E + \frac{\partial D}{\partial t} + J_e$$
$$B = -\nabla V$$

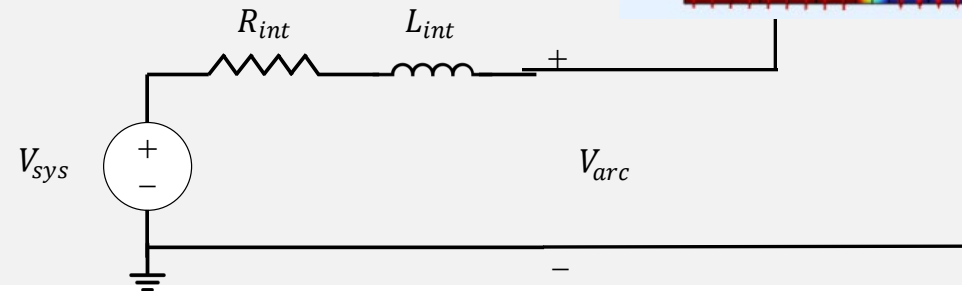
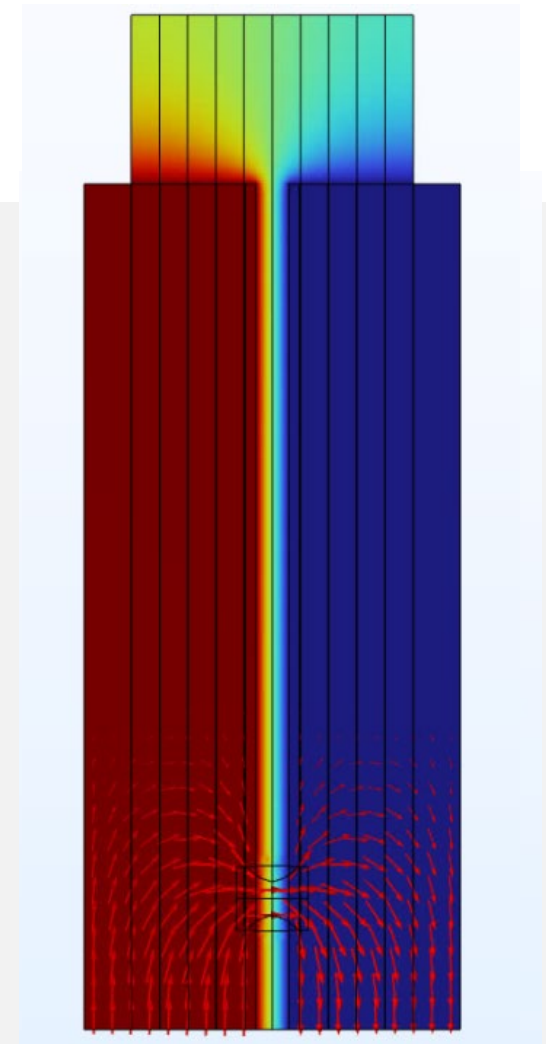
- Current
- Electric Field
- Magnetic Field
- Voltage

## Boundary Conditions

- Electric Insulation
- Terminal and Ground

## Verification Test Cases

- Magnetic Field from an Infinite Conductor [1]



# Arc model in COMSOL



## Magnetic Fields

$$\nabla \times \mathbf{H} = \mathbf{J}$$

$$\mathbf{B} = \nabla \times \mathbf{A}$$

$$\mathbf{J} = \sigma \mathbf{E} + \mathbf{J}_e$$

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t}$$

$$\nabla \times \frac{1}{\mu_0} \mathbf{B} = \mathbf{j}$$

## Boundary Conditions

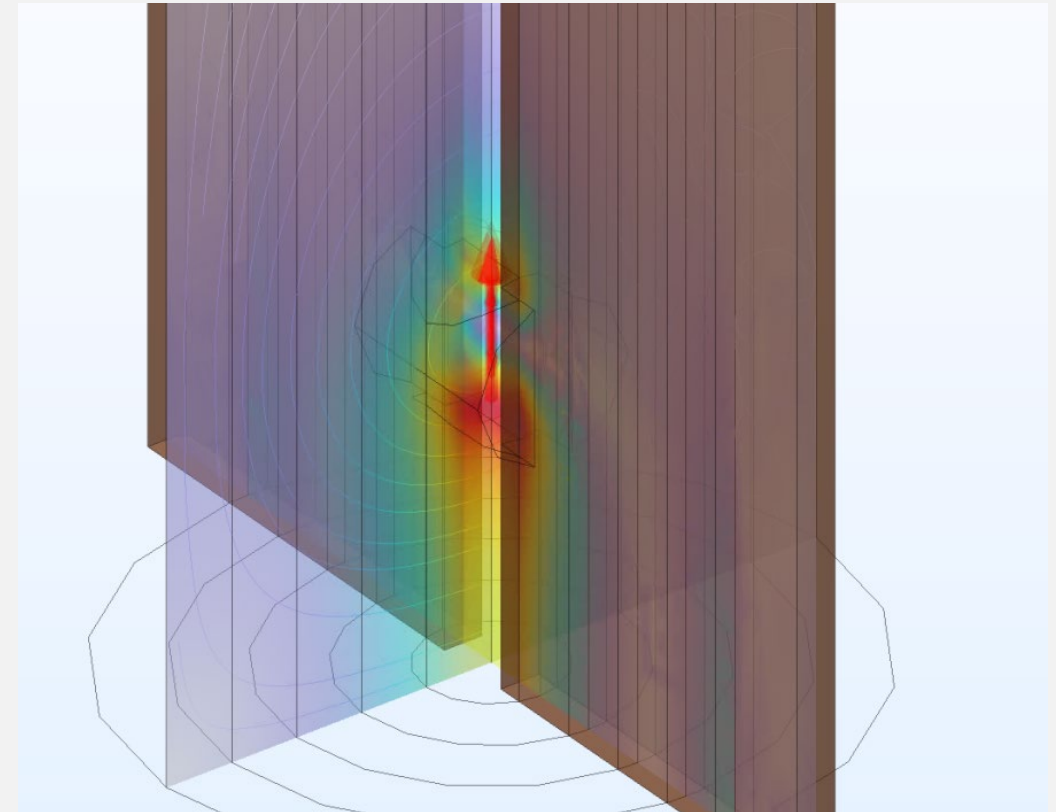
- Magnetic Insulation
- Ampère's Law in Solids and Fluids
- External Current Density (from Electric Currents)

## Verification Test Cases

- Verification Of COMSOL Multiphysics for Magneto-hydro-dynamics (MHD) Flows In Fusion Applications [2]



## Magnetohydrodynamics



# Arc model in COMSOL



Laminar Flow



Magnetohydrodynamics



Nonisothermal Flow

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u} \cdot \nabla)\mathbf{u} = \nabla p + \mathbf{F}$$

$$\rho \nabla u = 0$$

Density

Velocity Field

Pressure Gradient

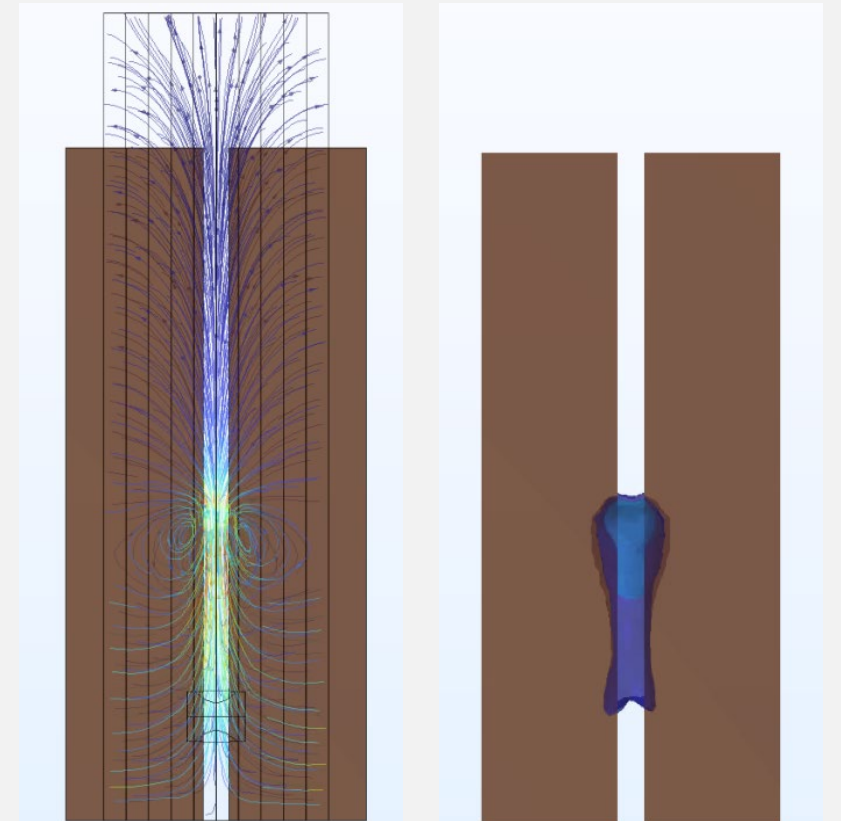
Force

## Boundary Conditions

- Walls (slip)
- Inlets/Outlets (constant pressure)

## Verification Test Cases

- Validation Of COMSOL Multiphysics® For Magneto-hydrodynamics (MHD) Flows In Fusion Applications [2]
- A Verification and Validation Approach for COMSOL Multiphysics to Support the High Flux Isotope Reactor (HFIR) [3]



# Arc model in COMSOL

 Heat Transfer in Fluids

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p \mathbf{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q$$

$$Q = \frac{\partial}{\partial t} \left( \frac{5k_b T}{2q} \right) (\nabla T \cdot \mathbf{J}) + \mathbf{E} \cdot \mathbf{J} + Q_{rad}$$

## Boundary Conditions

- Thermal Insulation

## Verification Test Cases

- A Verification and Validation Approach for COMSOL Multiphysics to Support the High Flux Isotope Reactor (HFIR) [3]
- Non-isothermal laminar flow in a circular tube [4]



Equilibrium Discharge  
Heat Source

Heat capacity

Mass Flow

Heat transfer

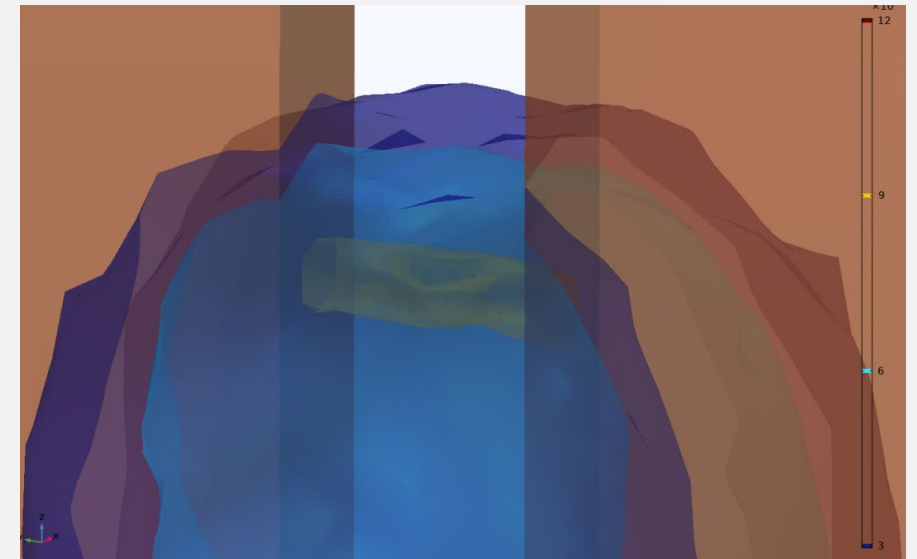
Enthalpy transport

Jule heating

Net radiation loss



Nonisothermal Flow



# Other Verification Sources

Transient Arc Discharge in Guided Copper Rails [6]

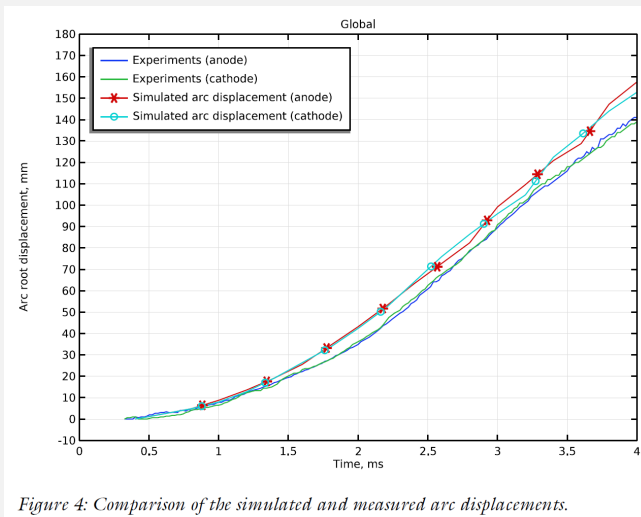
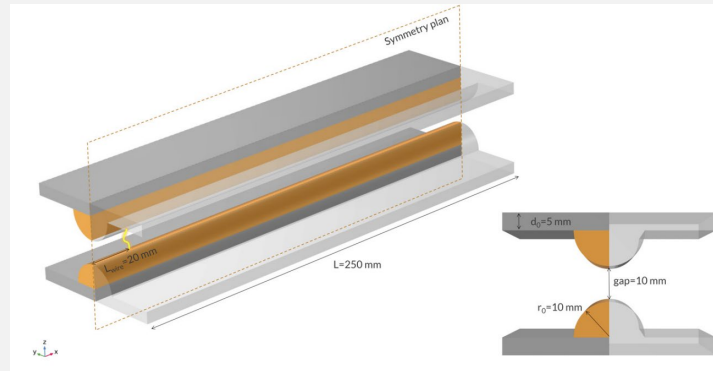
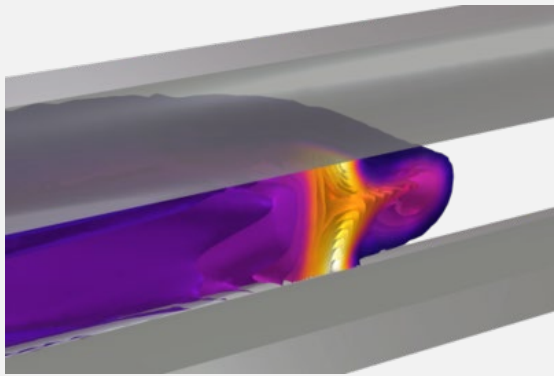
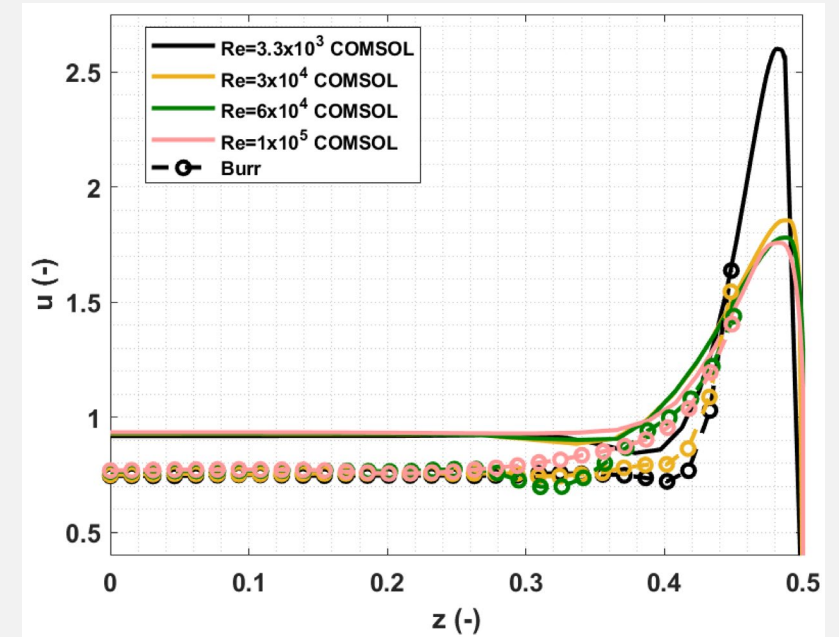


Figure 4: Comparison of the simulated and measured arc displacements.

Verification and Validation of COMSOL Magneto hydrodynamic Models for Liquid Metal Breeding Blankets Technologies [7]



An aerial photograph of a university campus, likely the University of Utah, showing various academic buildings and a central tower. The campus is set against a backdrop of large, arid mountains under a clear sky. The image has a blue tint and is used as a background for a presentation slide.

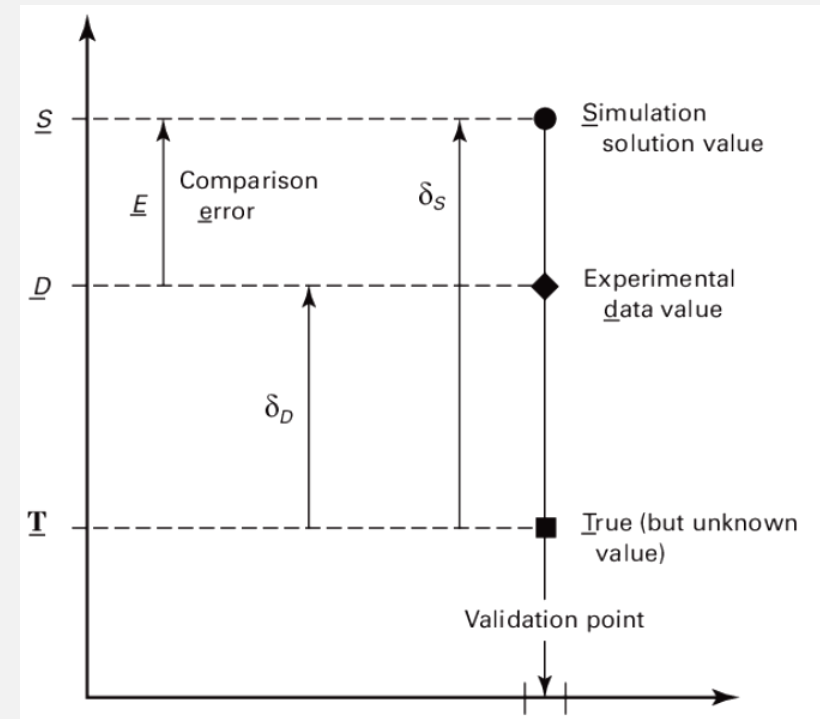
# Validation\*

\* Progress so far

# Validation

ASME V&V 20 [19]

“In the validation process, a simulation result (solution) is compared with an experimental result (data) for specific validation variables at a specified set of conditions (validation point).”



# Validation points

Voltage / Current over time

Arc Current (for protection settings)

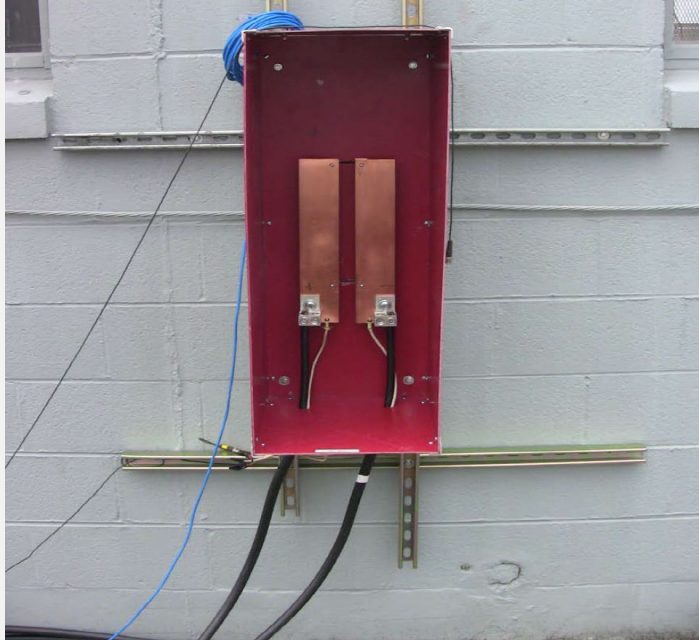
Arc Duration (for PPE selection)

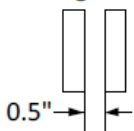
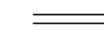
Arc Energy (for PPE selection)

Incident Energy (for PPE selection)

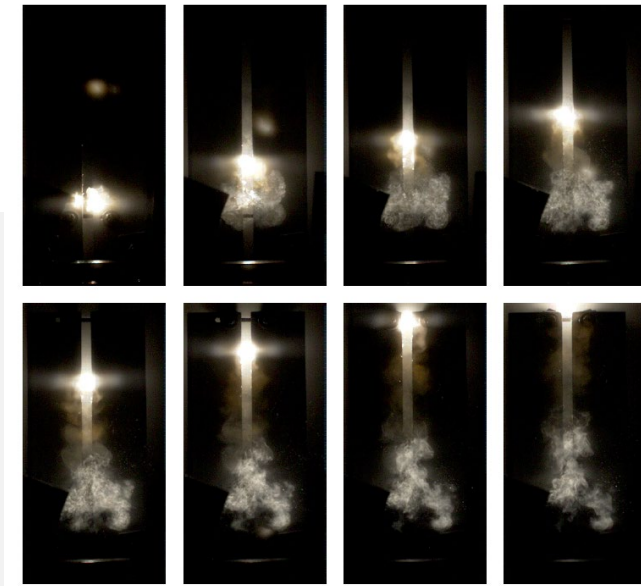
Speed of arc (where available)

# Experimental Data: Case 1

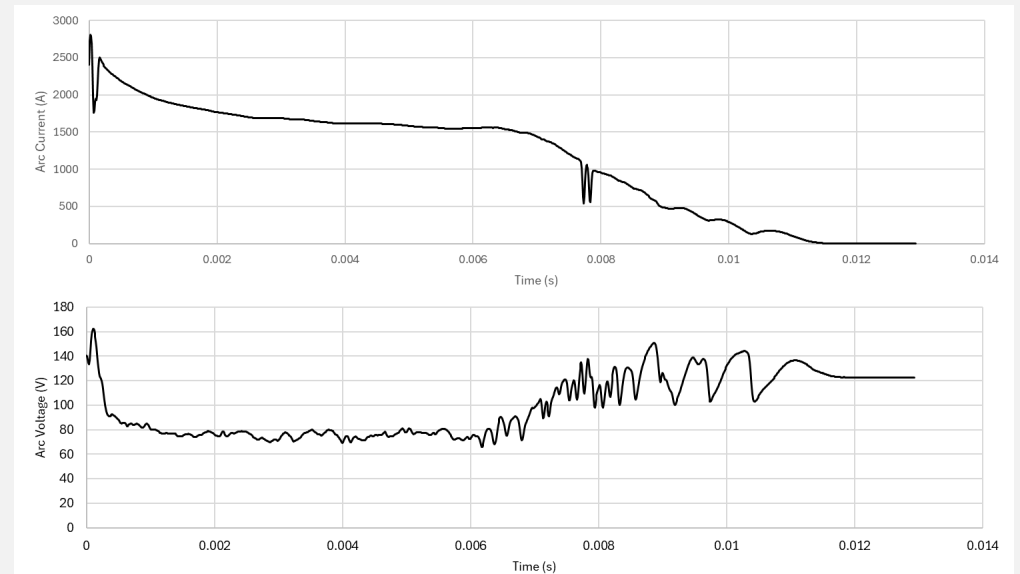


<b>Gap Configuration</b>  0.5"	<b>No-Ox Added?</b> NO	<b>Test # 1</b> <b>Energy</b> Not Measured	<b>Duration</b> 0.015 sec	<b>Charger</b> None
	<b>Fuse Wire</b>  Double #24		<b>Current</b> Peak Mean 2980 A 1415 A	<b>Added Inductance</b> None

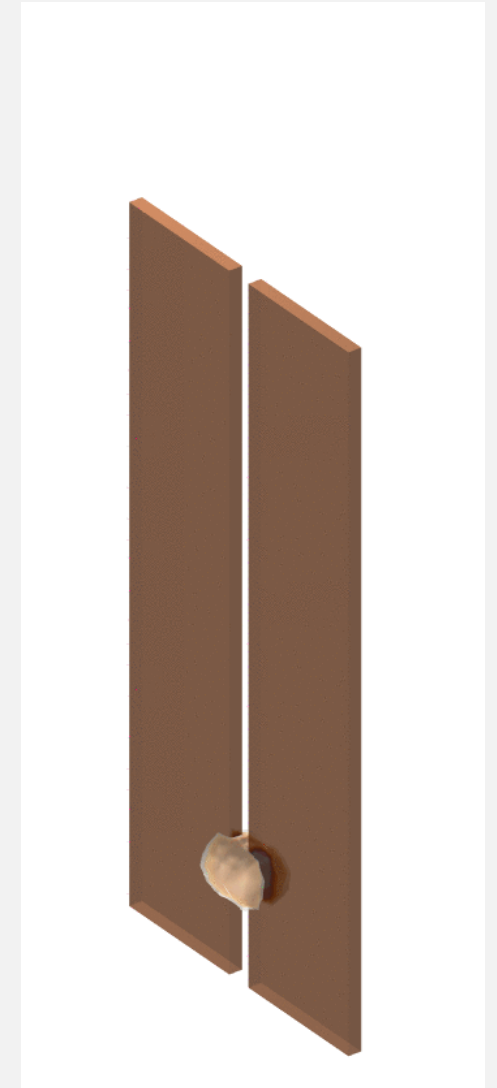
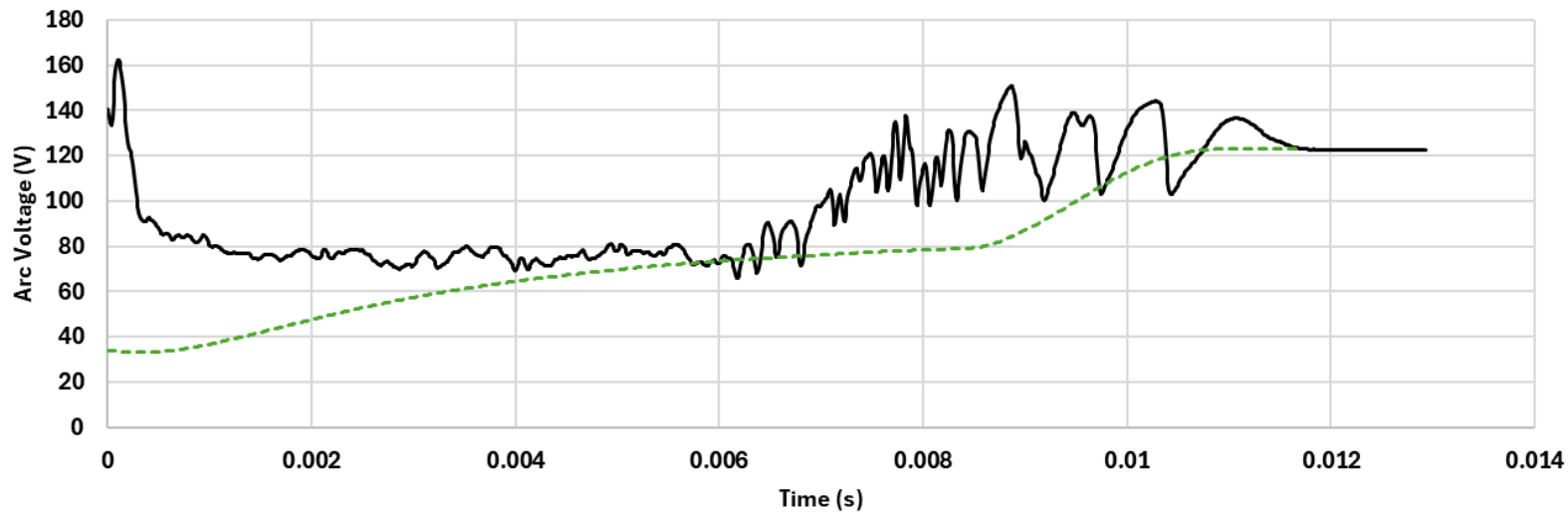
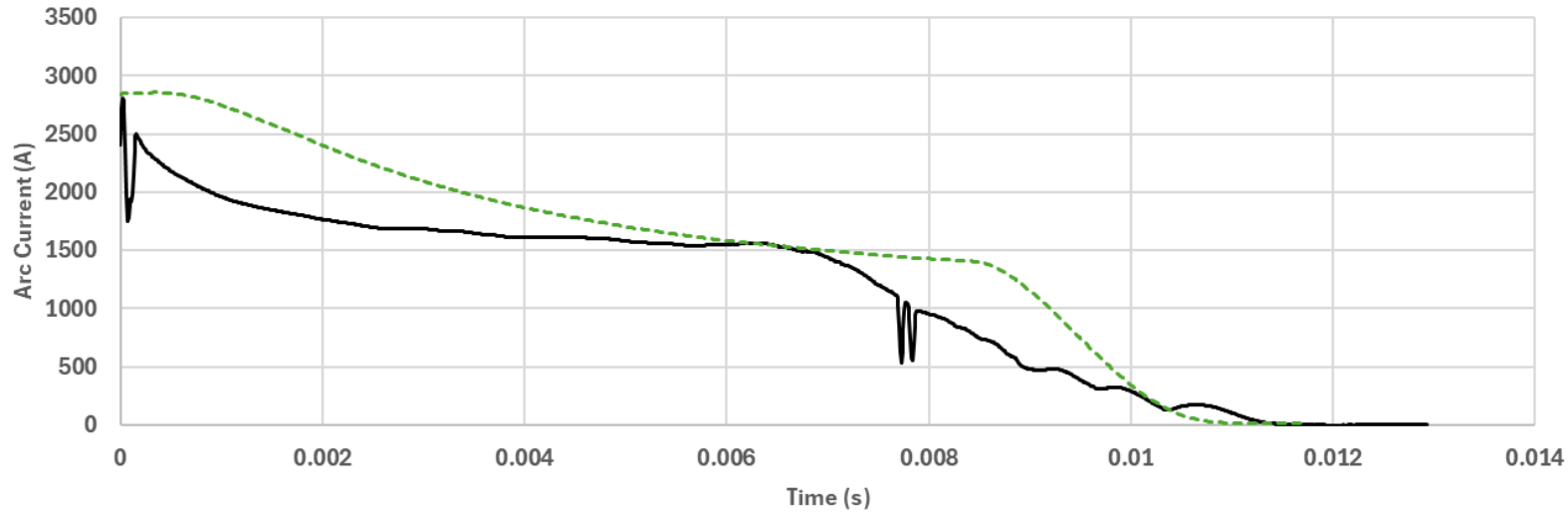
[12] J. G. Hildreth and K. Feeney, "Arc flash hazards of 125 vdc station battery systems," in *2018 IEEE Power Energy Society General Meeting (PESGM)*, 2018, pp. 1–5.



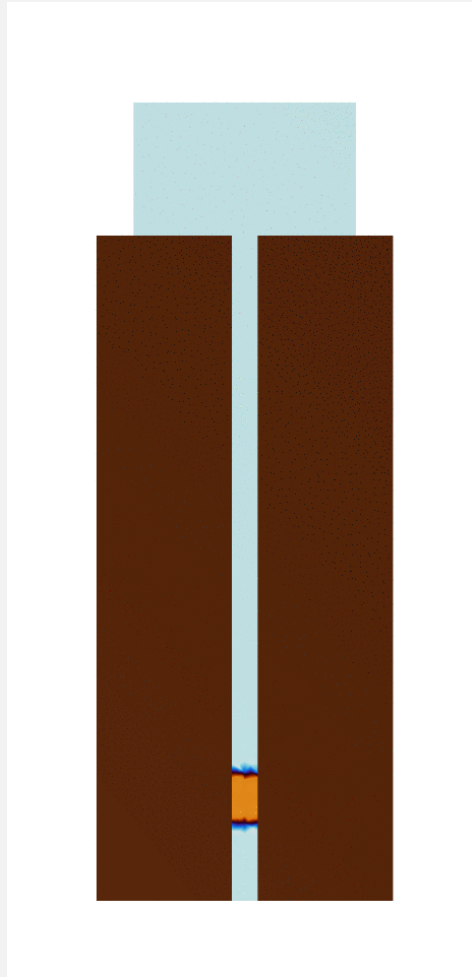
In the example given above the arc moves from where it is initiated to the top of the bus (a distance of ten inches) in approximately 6 msec. This corresponds to an arc velocity of 139 ft/sec (42.4 m/s).



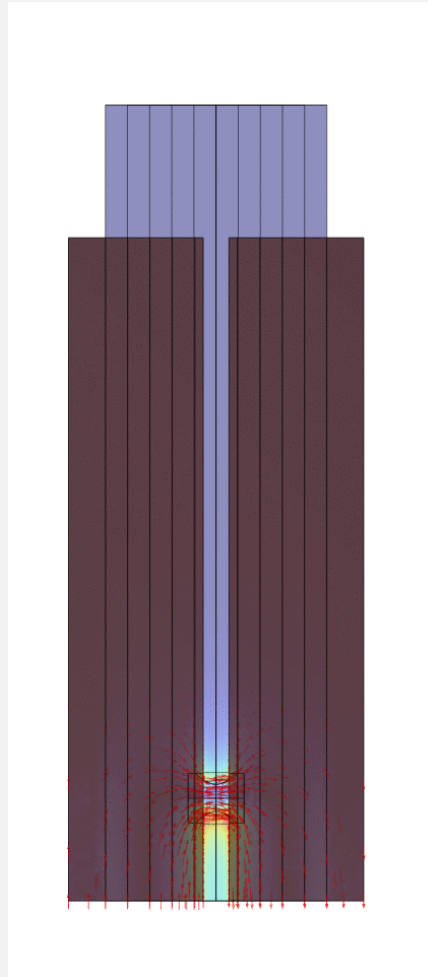
# Experimental Data: Case 1



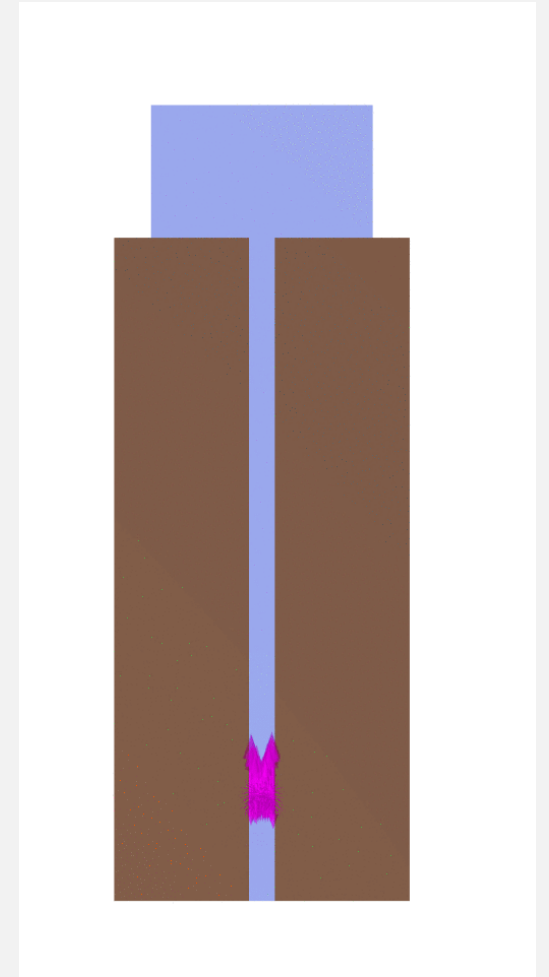
# Experimental Data: Case 1



Temperature

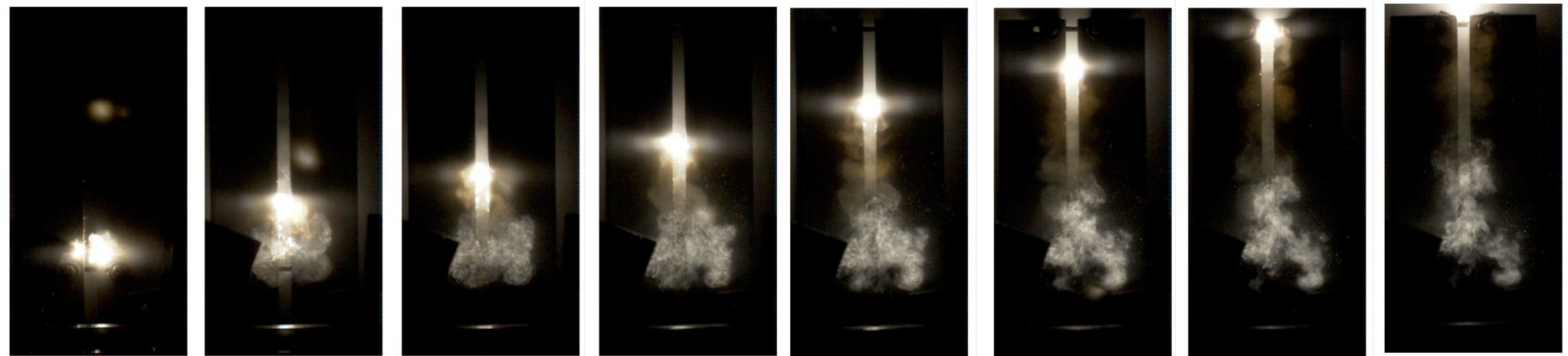
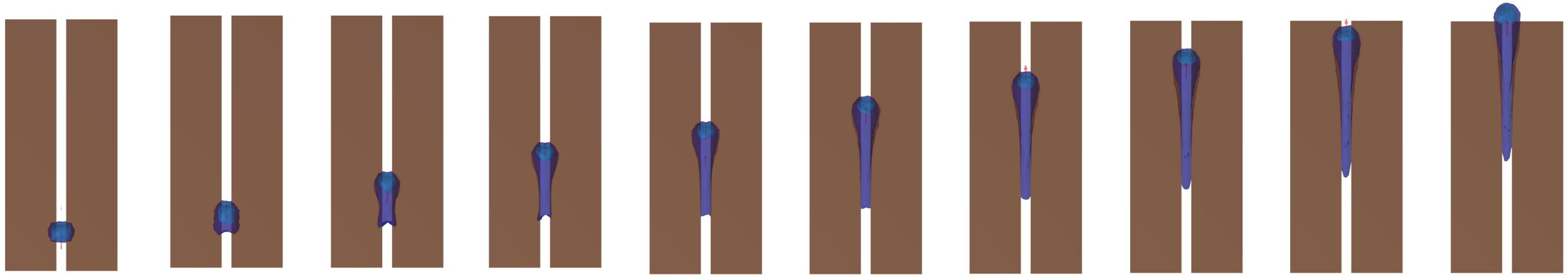


Current and Magnetic Field



Pressure and Flow Velocity

# Experimental Data: Case 1



0 ms

1 ms

2 ms

3 ms

4 ms

5 ms

6 ms

7 ms

8 ms

9 ms

# Discussion

What this model ignores:

- Conductor erosion
- Turbulent flow
- Dynamic gas chemical composition
- Fluid-surface friction
- Gas compression
- Air absorption and scattering
- Reflection of radiated heat



[16] W. Cantor, S. Marri, and L. Gordon, "NFPA 70E proposed dc arc flash updated guidance," in 2024 IEEE IAS Electrical Safety Workshop (ESW), 2024, pp. 160–211. [Online].

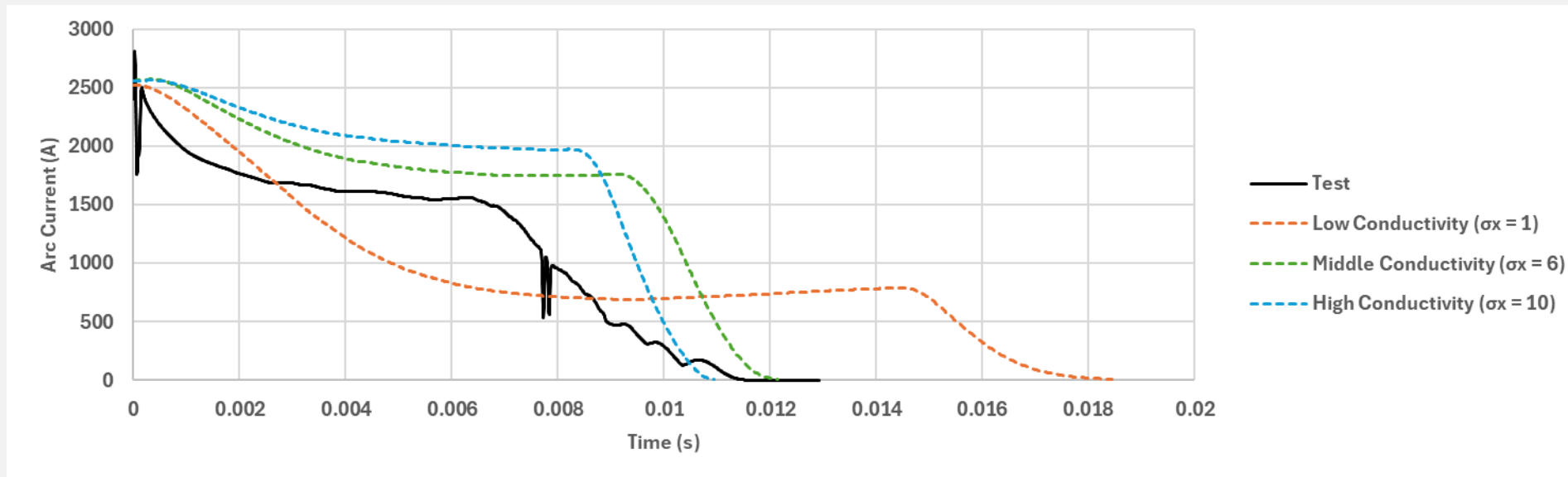


[8] K. Gray, S. Robert, and T. Gauthier, "Low voltage 100–500 vdc arc flash testing," in 2020 IEEE IAS Electrical Safety Workshop (ESW), 2020, pp.1–7.

# Discussion

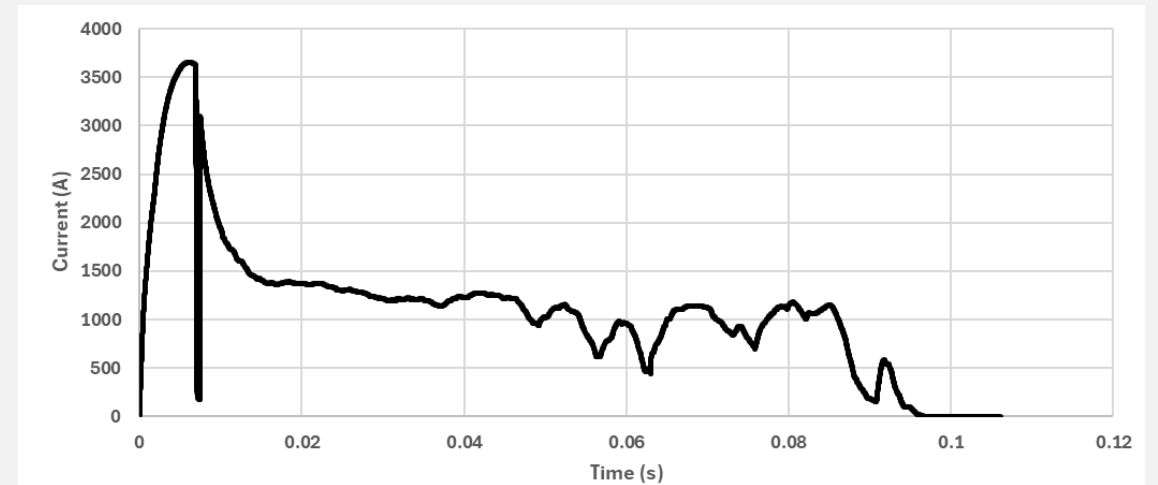
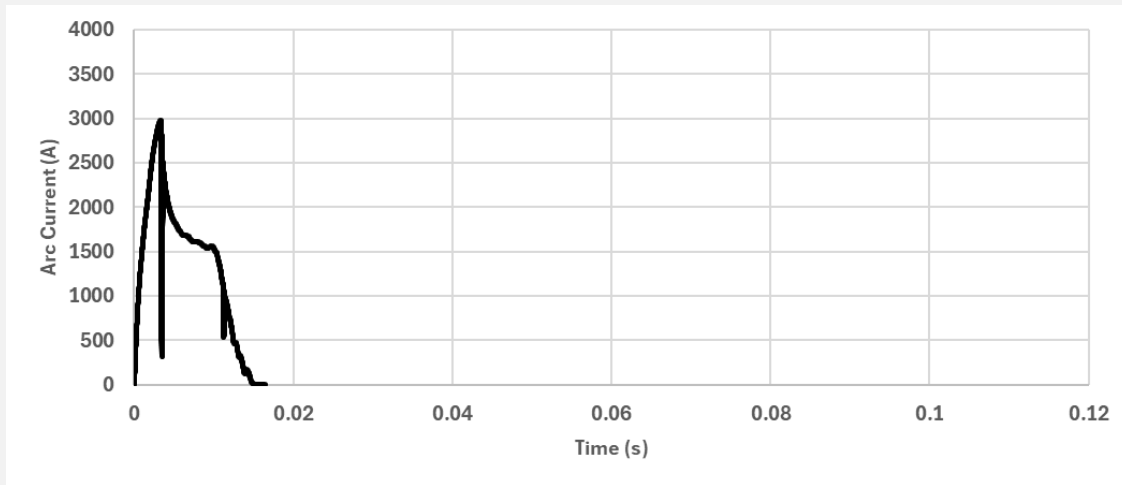
Fine tuning parameters:

- Smoke from vaporized copper conducts electricity better than pure air. This can be modeled by a factor that multiplies the conductivity of air.



# Discussion

Arc Flash is 'Complex' in that nearly identical test conditions can result in very different outputs.

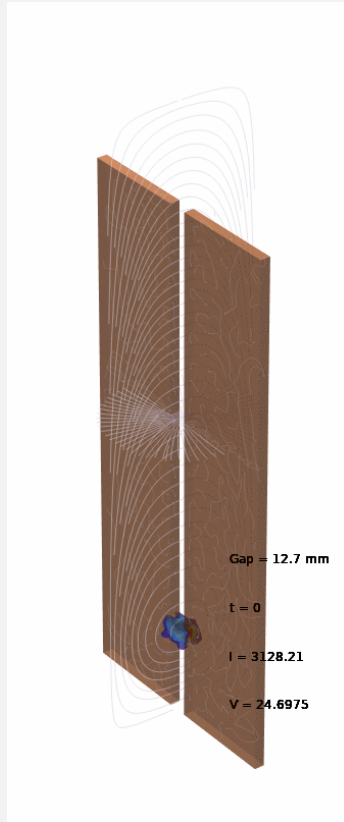


<b>Gap Configuration</b> 	<b>No-Ox Added?</b> NO	<b>Test # 1</b>	<b>Duration</b> 0.015 sec	<b>Charger</b> None
<b>Peak</b> 2980 A	<b>Mean</b> 1415 A			

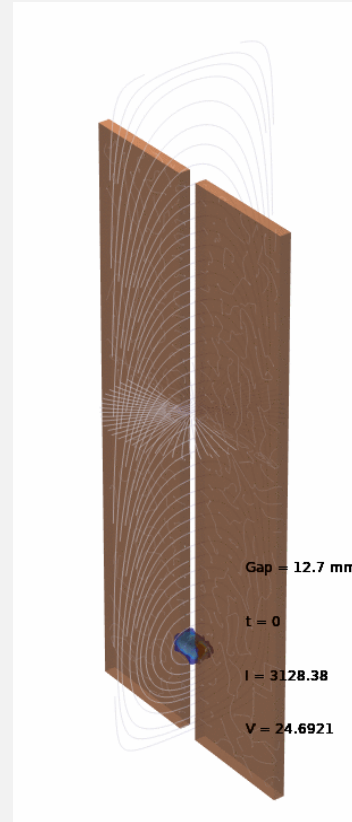
<b>Gap Configuration</b> 	<b>No-Ox Added?</b> NO	<b>Test # 6</b>	<b>Duration</b> 0.097 sec	<b>Charger</b> None
<b>Peak</b> 3656 A	<b>Mean</b> 1210 A			

# Discussion

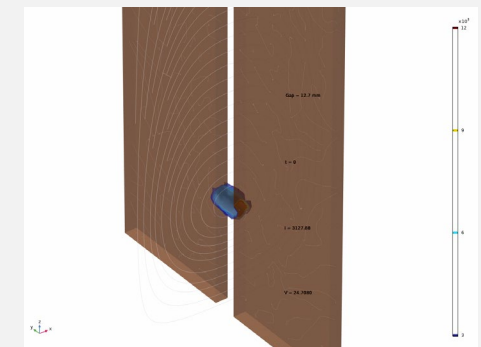
The same is true for MHD simulations



Mesh Size = 1



Mesh Size = 0.5



Mesh Size = 0.25

Small initial arcs are more subject to chaotic numerical effects than large initial arcs.

An aerial photograph of a university campus, likely the University of Utah, with a large mountain range in the background. The image is overlaid with a semi-transparent blue filter. The word "Conclusion" is centered in white text, with a thin blue horizontal line above it and a white horizontal line below it.

# Conclusion

# Takeaways and Next Steps

- Electric arcs are complex and have irreducible uncertainty.
- We have replicated many of the important properties of electric arcs in simulation.
- No one simulation will predict the outcome of a given arc flash test
- We hope to build toward a set of simulations whose results will predict the most likely outcomes of arc flash tests

## Next Steps

We will simulate arc flash tests at higher voltage and higher current

We hope to present a paper at the IEEE ESW conference next year

## **Acknowledgements:**

**I want to thank Jeffrey Hildreth, Sai Marri, and Kirk Gray for sharing the current and voltage data from their arc flash experiments with me.**

**This material is based upon work supported by the U.S. Department of Energy, Office of Electricity (OE), Energy Storage Division.**

# Questions

# References

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- [2] Yi Yan "Validation Of COMSOL Multiphysics for Magneto-hydro-dynamics (MHD) Flows In Fusion Applications" COMSOL Conference, Boston, MA, October, 2017, Available : <https://www.comsol.com/paper/validation-of-comsol-multiphysics-for-magneto-hydro-dynamics-mhd-flows-in-fusion-applications-50552>
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- [4] "Non-isothermal laminar flow in a circular tube " COMSOL Application Gallery, [Online] retrieved 05/01/26, Available : <https://www.comsol.com/model/nonisothermal-laminar-flow-in-a-circular-tube-55861>
- [6] Hengxin He, "Transient Arc Discharge in Guided Copper Rails" COMSOL Application Gallery, [Online] retrieved 05/01/26, Available: <https://www.comsol.com/model/transient-arc-discharge-in-guided-copper-rails-132161>
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