Multiphysics Modeling of the Graphite Electrode Joint in Electric Arc Furnaces for Scrap Steel Recycling

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Problem Statement

- The Electric Arc Furnace (EAF) uses graphite rods as electrodes to strike a powerful arc to melt scrap steel
- GrafTech International is a world leader in supplying graphite electrodes for the EAF process

Problem Statement

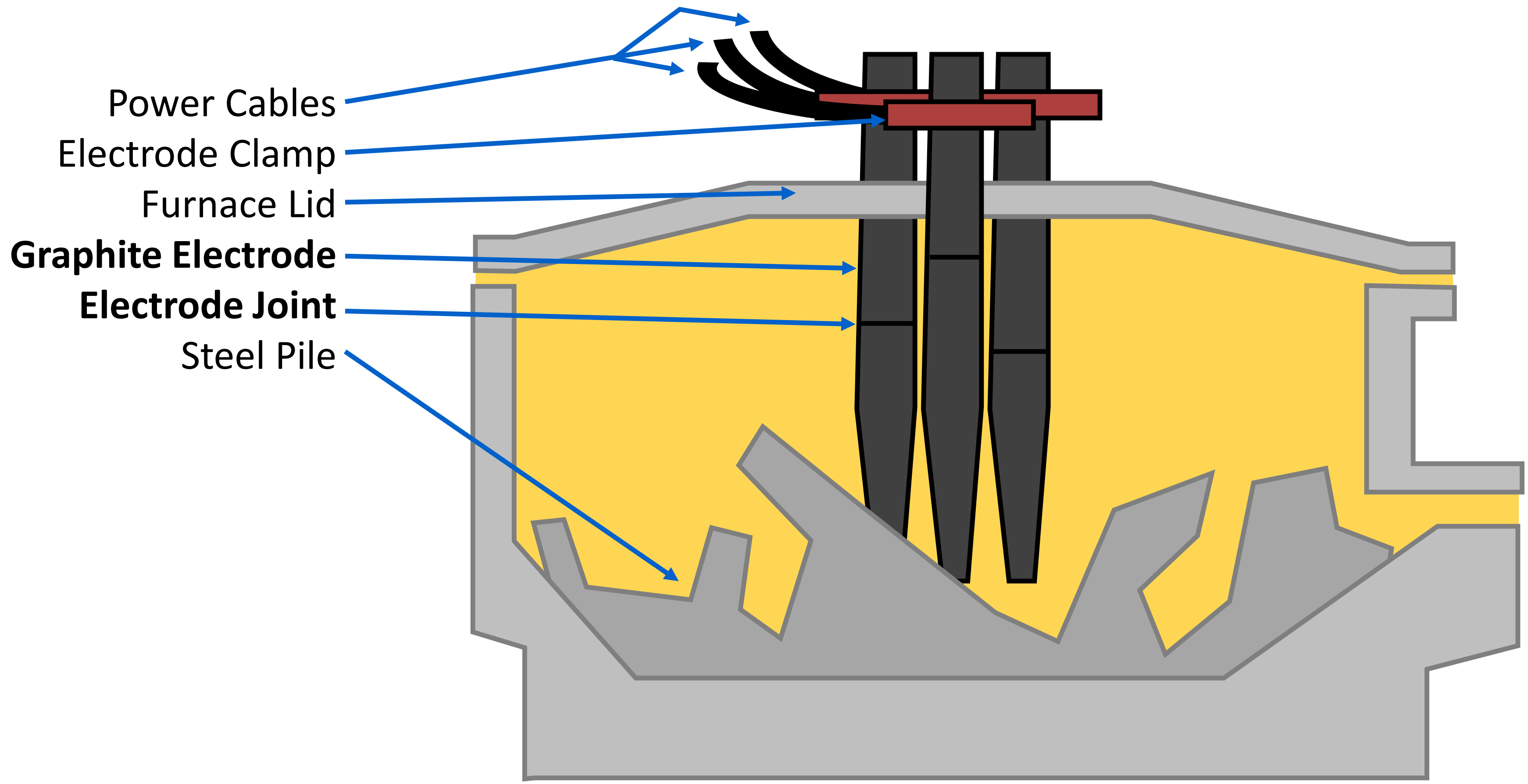
- The Electric Arc Furnace (EAF) is a massive industrial process, converting scrap steel into new raw material (millions of tons per year worldwide)
- Less greenhouse gas emissions versus Basic Oxygen Furnace steelmaking process (BOF, “Blast Furnace”) [1]
  - BOF: 1.6 tonnes CO_2/tonne steel
  - EAF: 1.08 tonnes CO_2/tonne steel

[1] US EPA, AVAILABLE AND EMERGING TECHNOLOGIES FOR REDUCING GREENHOUSE GAS EMISSIONS FROM THE IRON AND STEEL INDUSTRY, Sept 2012, https://www.epa.gov/sites/production/files/2015-12/documents/ironsteel.pdf

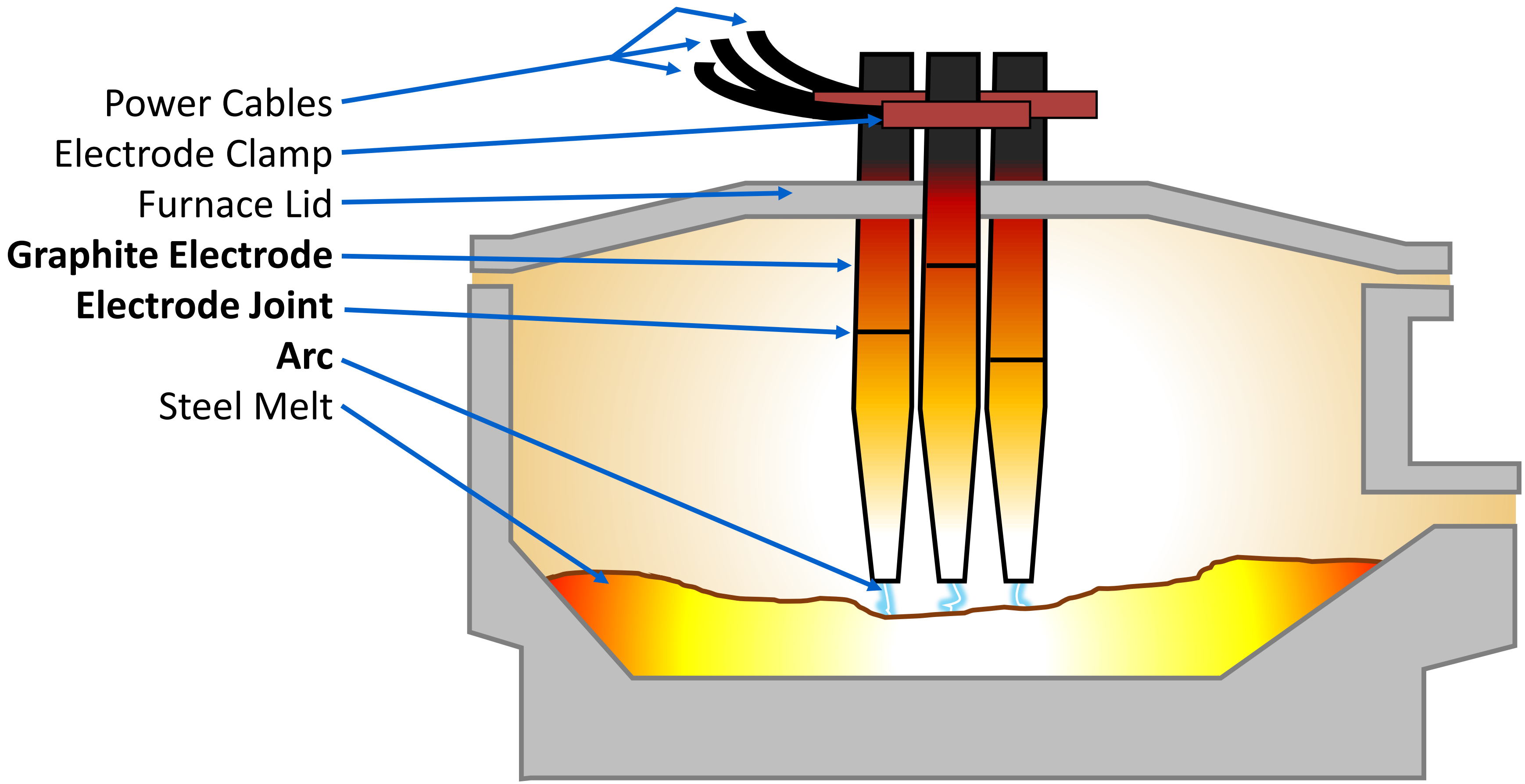
Problem Statement

- Previous finite element models have been very valuable to GrafTech's electrode business
- Previous models were relatively simple and coarse; new software and hardware enable next-generation of FEM
- Develop a multiphysics model of the electrode joint, including:
  - Structural mechanics and contact physics
  - Heat transfer
  - Electric currents
- Validate model through comparison with real data
- Better understand process/performance relationships
- Reduce design cycle time

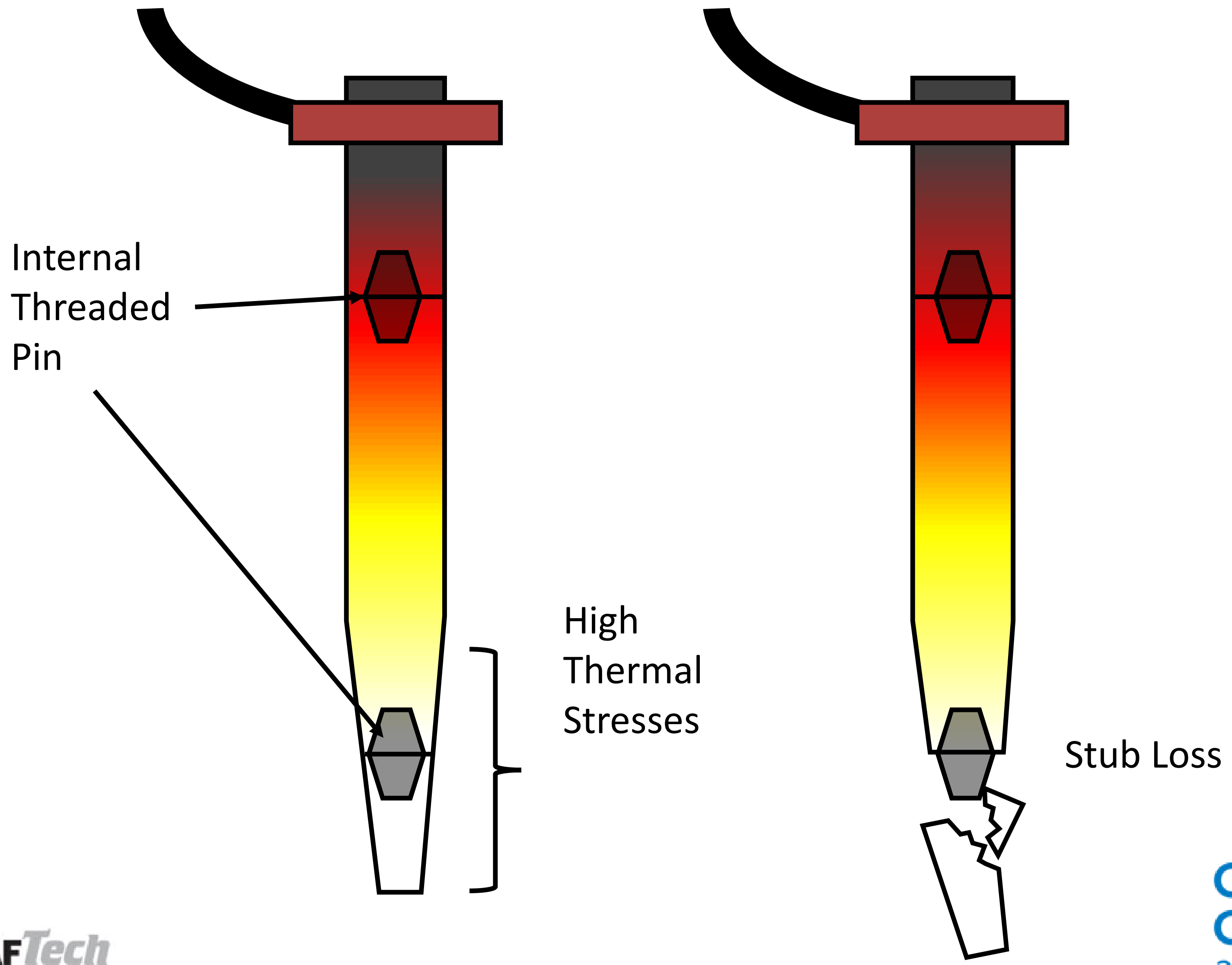
Problem Statement



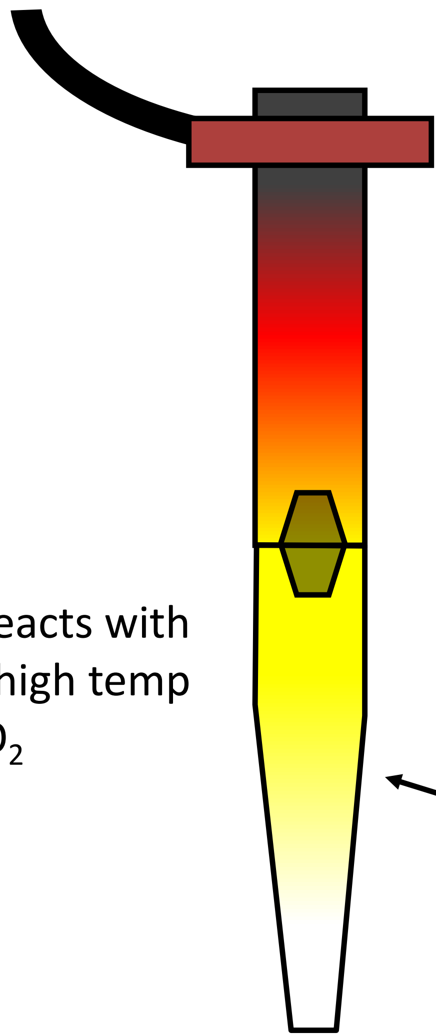
Problem Statement

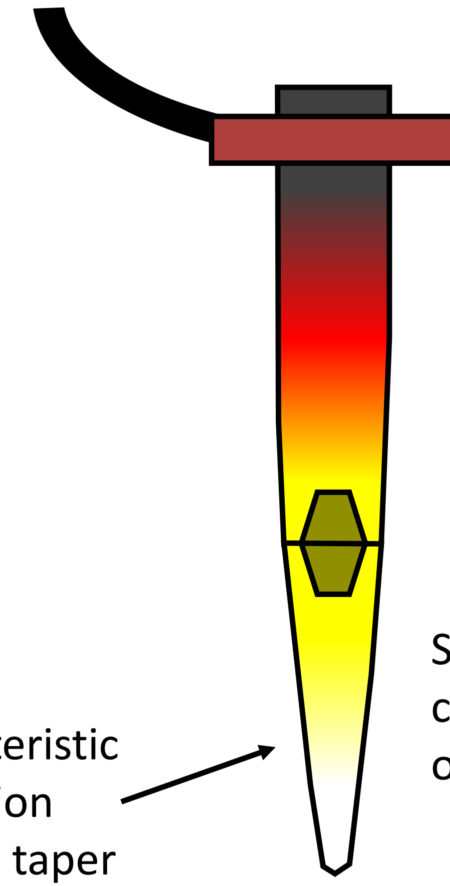


Failure Mechanism: Stub Loss



Failure Mechanism: Oxidation



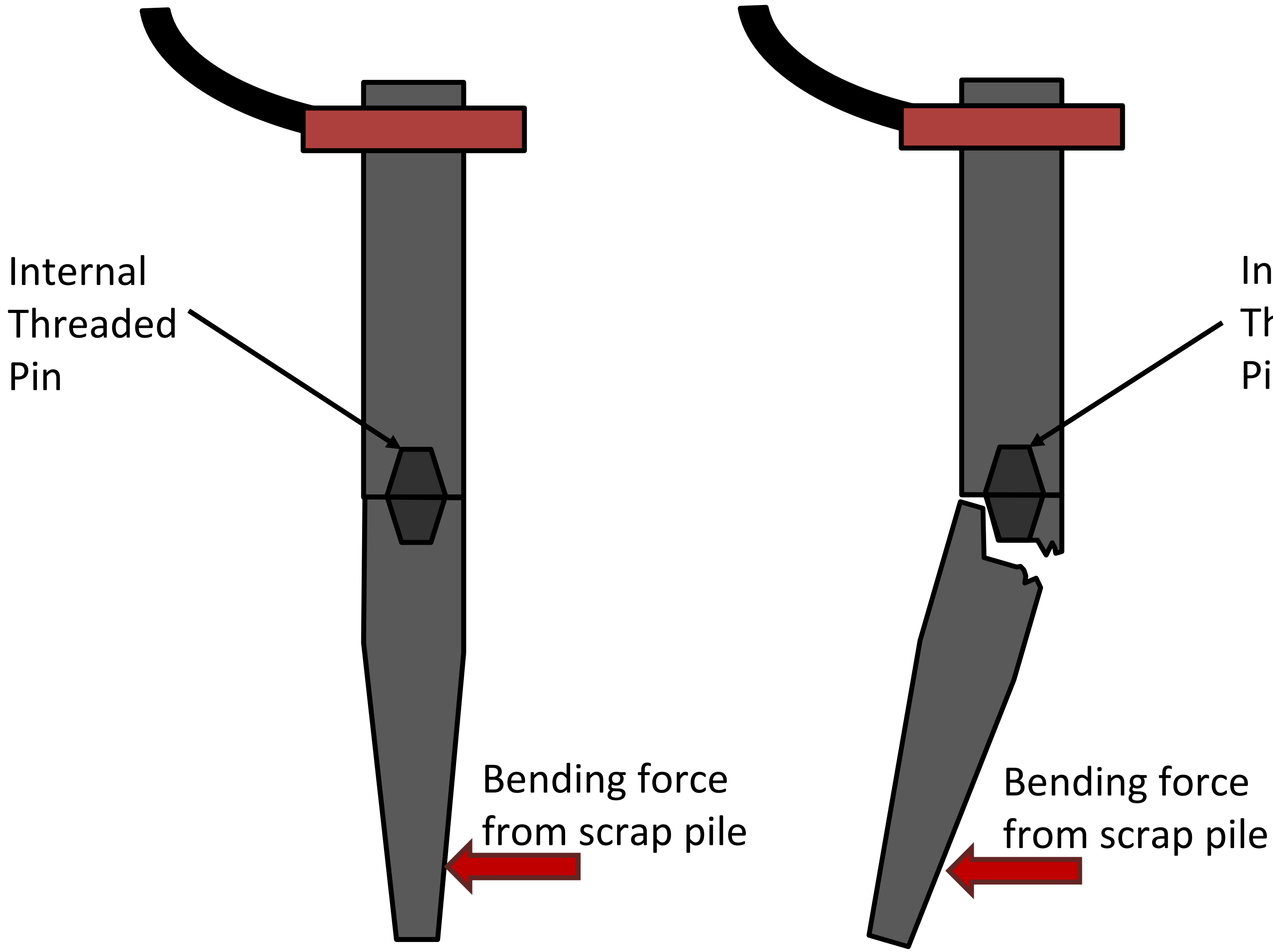


Graphite reacts with oxygen at high temp to form CO_2

Characteristic "oxidation profile" taper

Some materials/furnace conditions cause faster oxidation

Failure Mechanism: Column Break

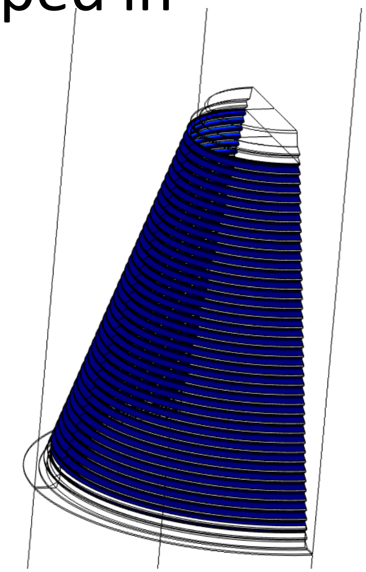


Problem Statement

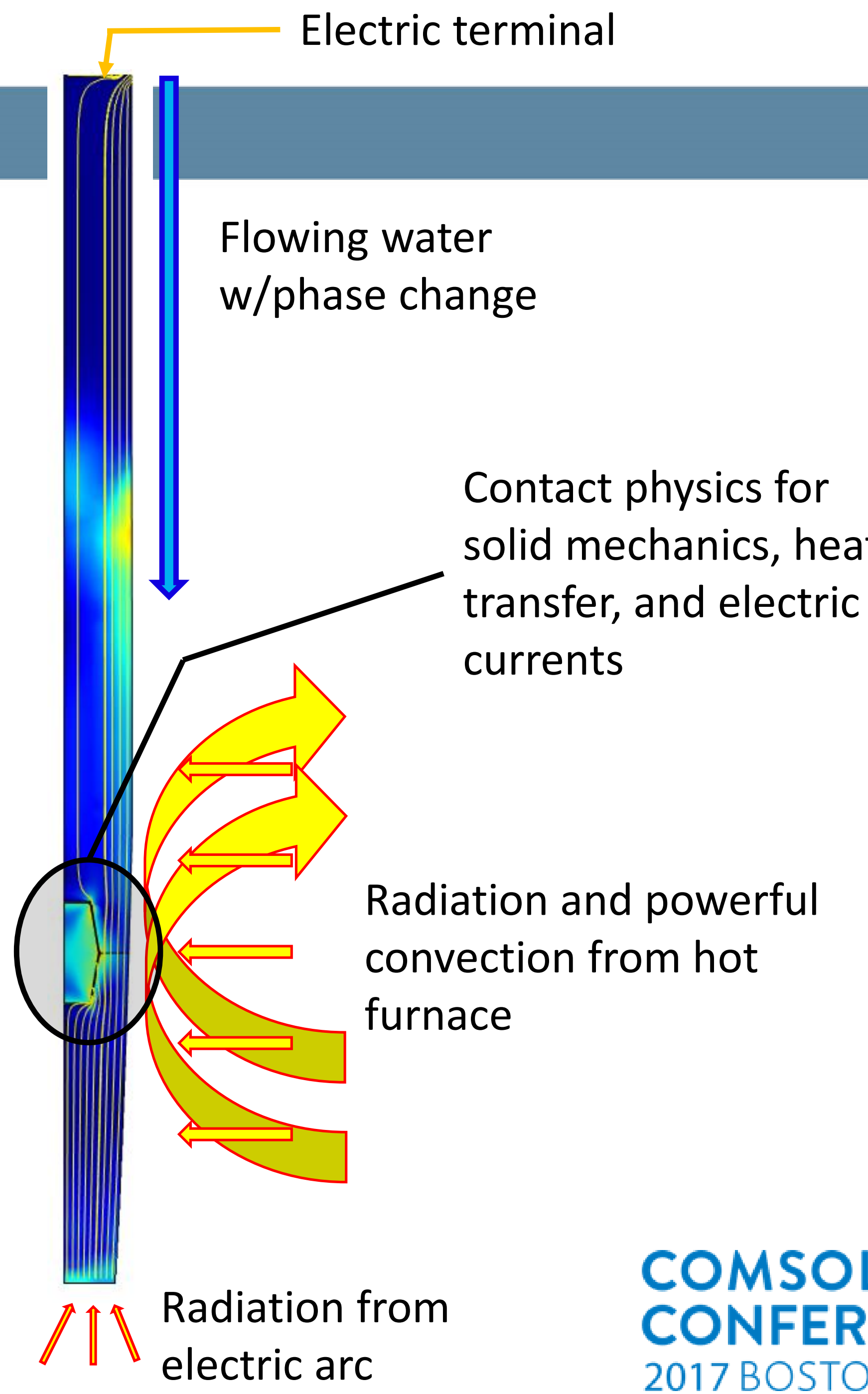
- Graphite Electrode consumption is a significant cost driver of EAF, *in particular:*
  - Stub loss: the tip of the electrode can crack and cause chunks of electrode to fall into the melt
  - Oxidation: furnace temperature is well over 1000 degC, and graphite oxidizes into CO_2 rapidly at this temperature
  - Column breaks: “scrap cave-ins” or poor electrode addition exert bending stress on column, leading to breaks high up and major process disruption
- Successive electrodes are connected at a “joint,” which becomes a critical point for reducing failure
- Because of the extreme environment, direct measurements are often difficult or impossible
- Graphite is a non-homogenous, anisotropic material
- Multiscale (>8 meters electrode and <10 microns defects) and multiphysics situation

Approach

- **Make a model that considers all three failure mechanisms!**
- Used COMSOL Multiphysics v5.3 (model developed in v5.0)
  - Structural Mechanics module
  - Heat Transfer module
  - Electric Current module
  - Moving Mesh module
- 2D Axisymmetric model:
  - Stationary pre-tensioning simulation
  - Transient multiphysics simulation of firing cycle
- 3D model:
  - Bending stress simulation
  - Transient multiphysics simulation of non-axisymmetric modes



Model Scheme



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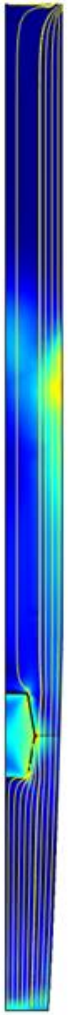
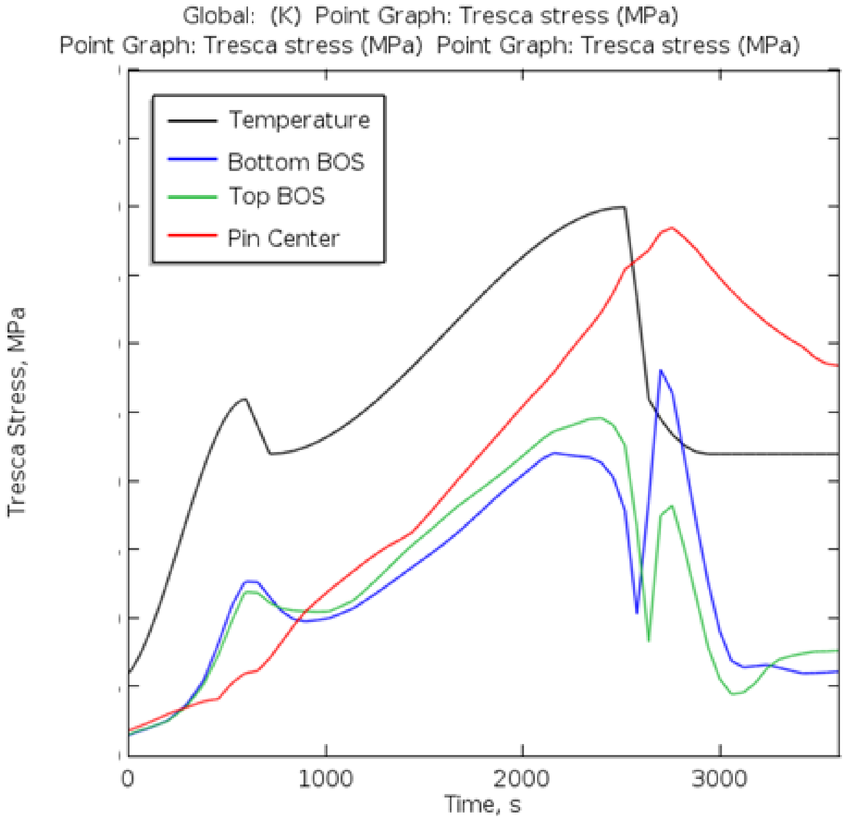
Model Validation

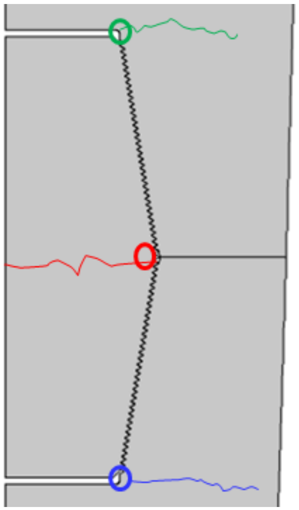
- Results were used on a comparative basis, in particular comparing the stress states of known failure location across different cases
- Used a variety of stress metrics, focusing on tresca and maximum principle stress criteria
- Focus on joint area as most common failure location
- Completed hundreds of simulations of different cases, grouped into about ten study areas



Stub Loss versus Firing Cycle



- EAF process has a characteristic firing cycle
- Involves heating and cooling segments
- Causes significant thermal stresses from temperature and material gradients



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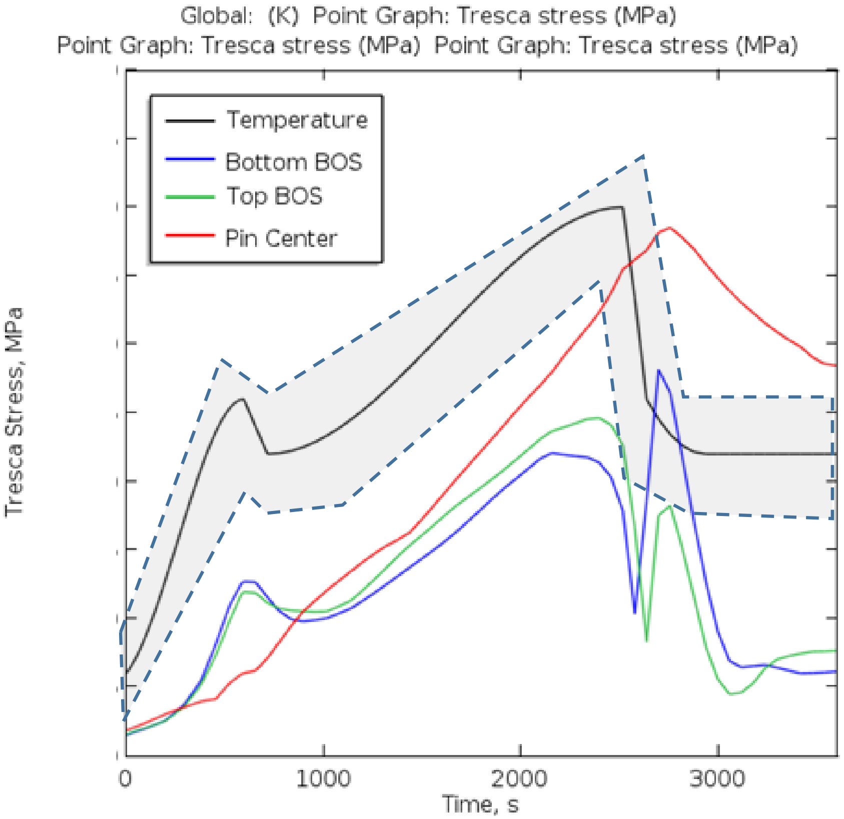
Stub Loss versus Firing Cycle



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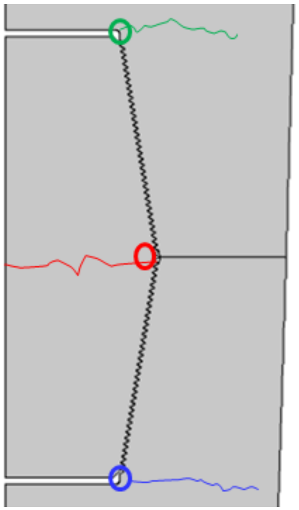

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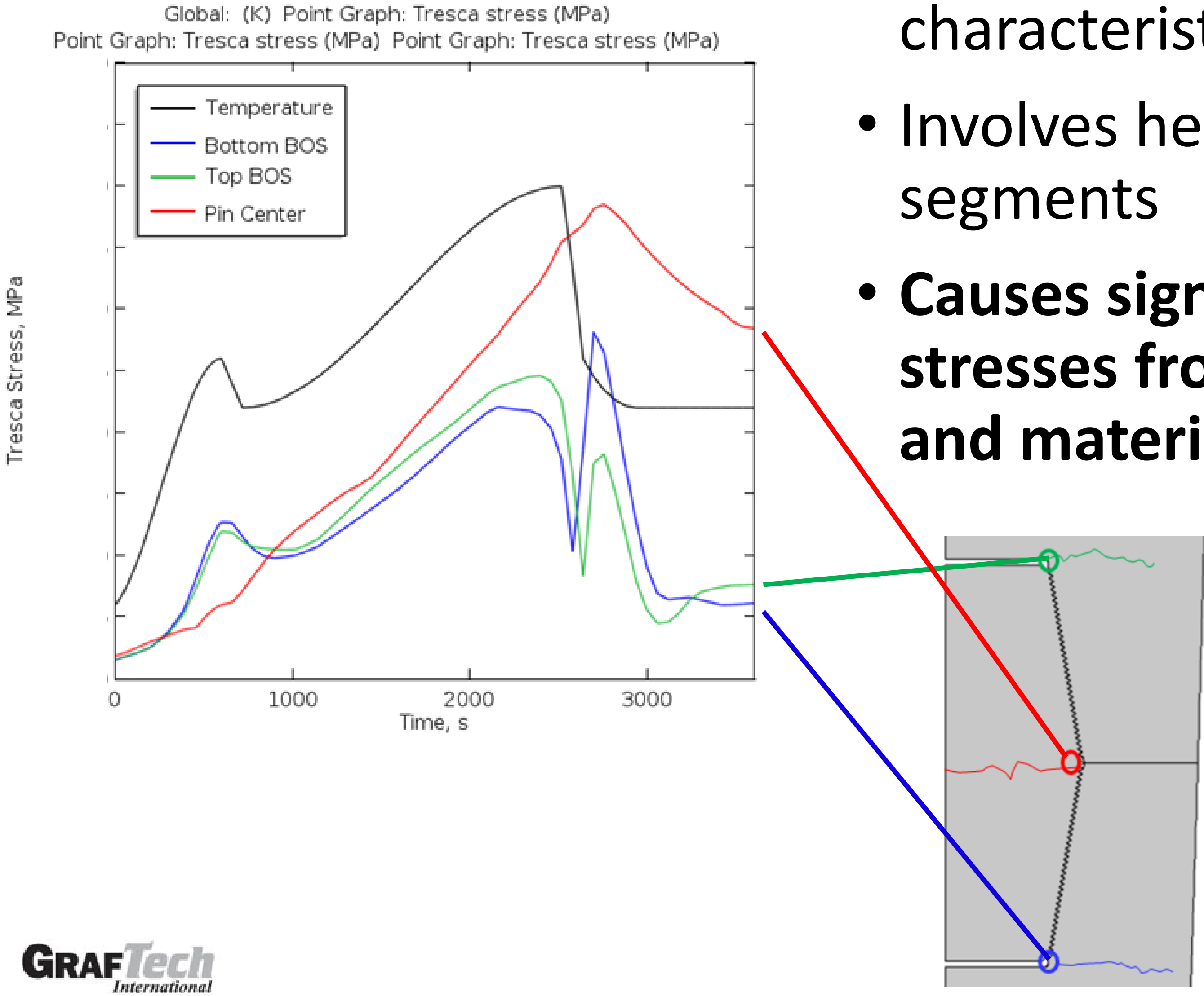

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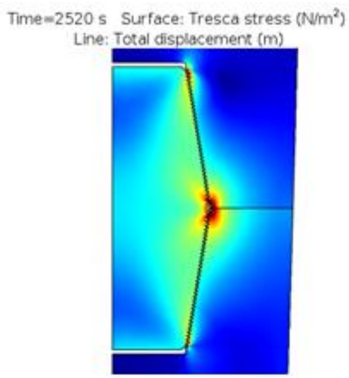
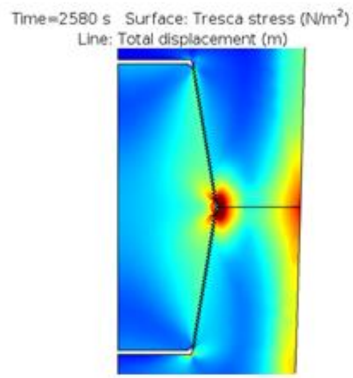
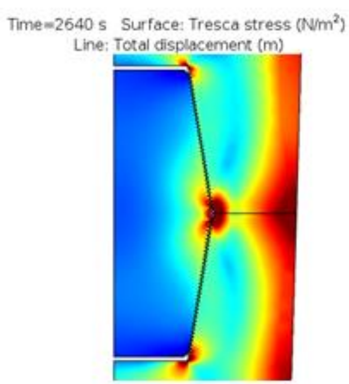
Stub Loss versus Firing Cycle



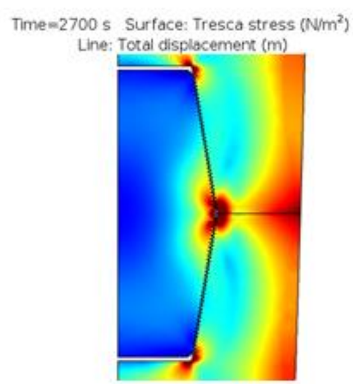
Power on,
highest temp



Power off,
cooling begins



Power off,
fastest cooling



Power off,
cooling slows

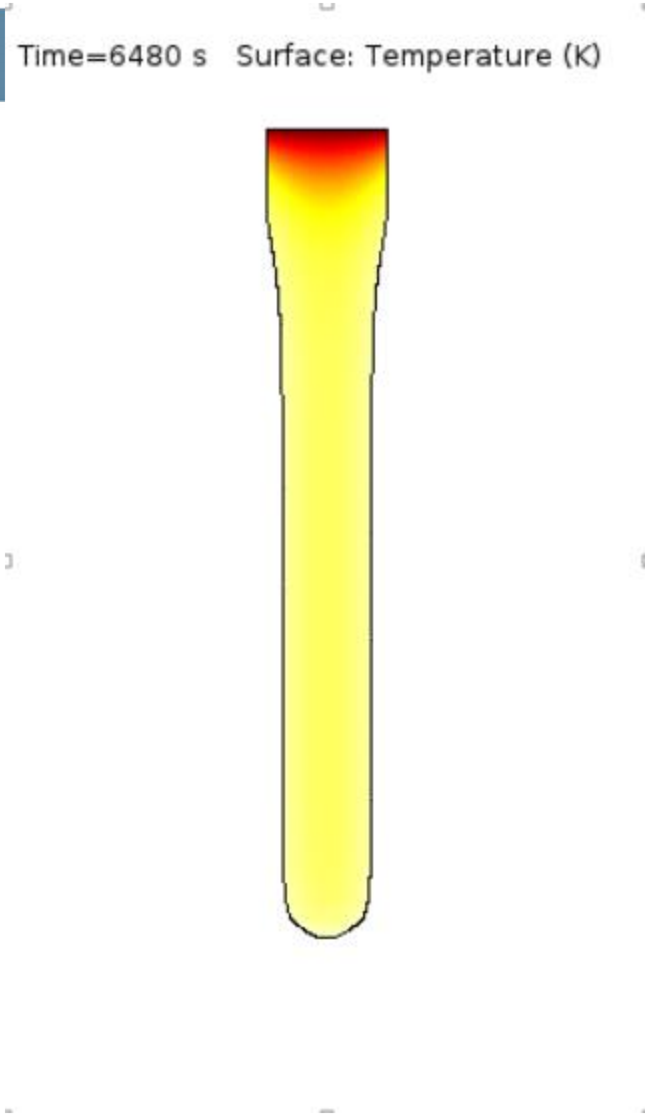
- EAF process has a characteristic firing cycle
- Involves heating and cooling segments
- Causes significant thermal stresses from temperature and material gradients
- **Our analysis involves comparing these stresses at different times and places**

Oxidation

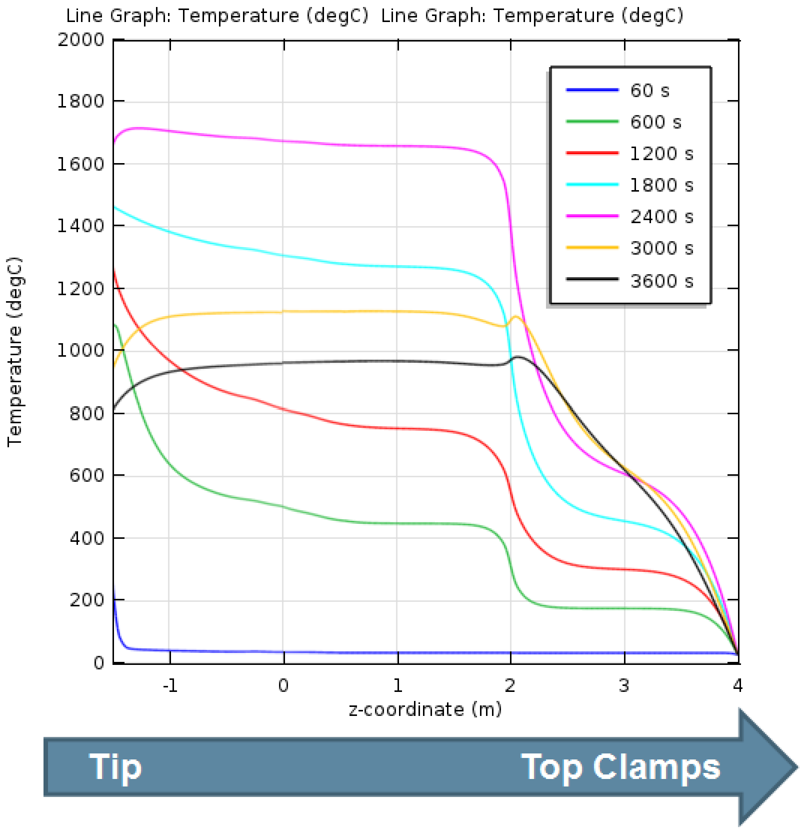
- Water flows from clamps down the exterior of the electrode
- Reduces temperature
- Provides barrier to oxygen migration
- Too much water flow can shift energy balance unfavorably

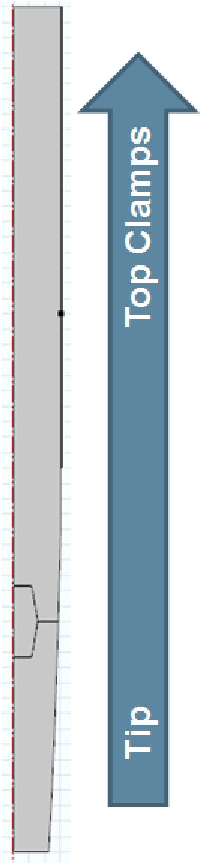
Oxidation

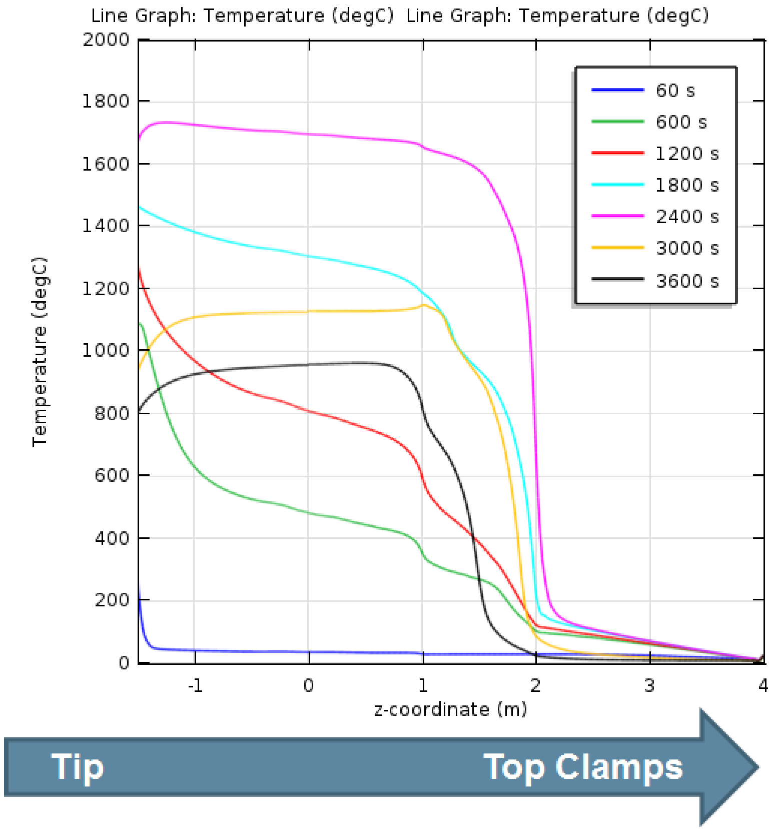
- Dependent on several factors:
  - Furnace type
  - Furnace oxygen/inert gas usage
  - Furnace power settings
  - Water cooling
- Deep multiphysics coupling is required
- Simulate water as a phase-change domain (built-in to COMSOL), but with constant velocity field



Oxidation







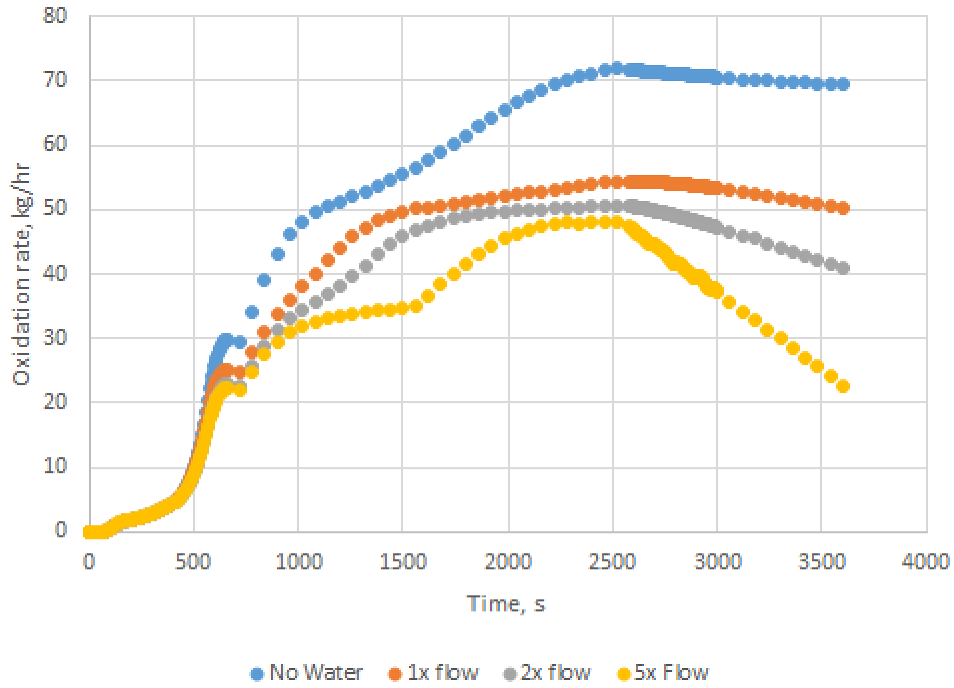
No Water Flow

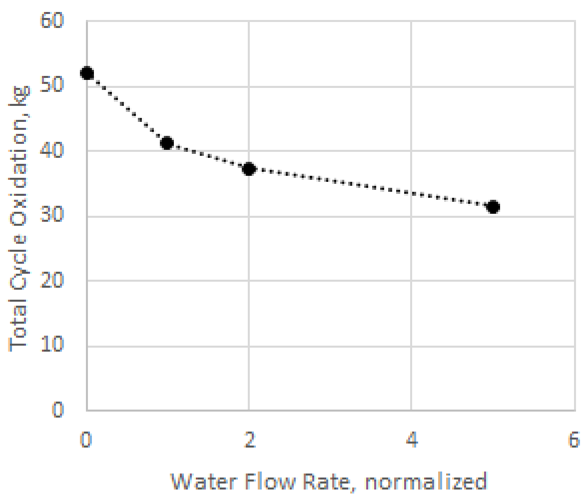
With Reference Water Flow

Oxidation

- Use in-house testing to develop temp vs oxidation rate curves
- Integrate vs temperature and time
- Simulate total oxidation

- Test different materials' oxidation rates, simulate consumption rate savings
- Predicted oxidation rates match reality quite well





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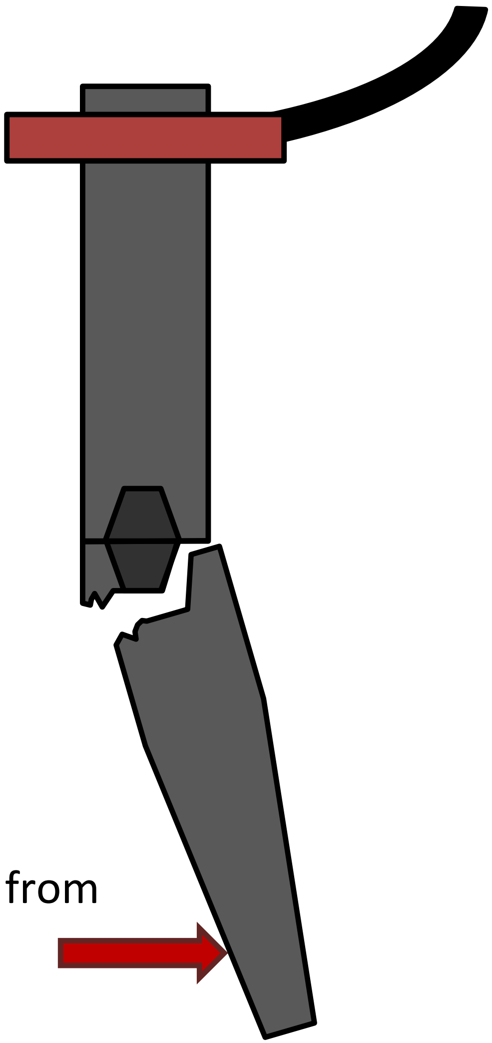
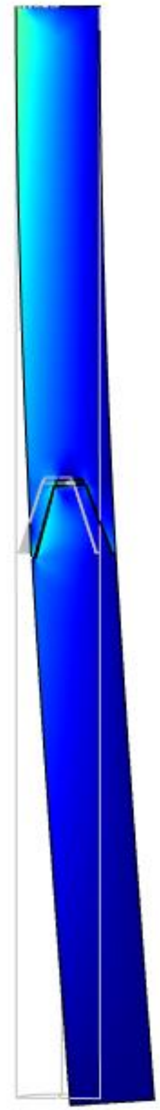
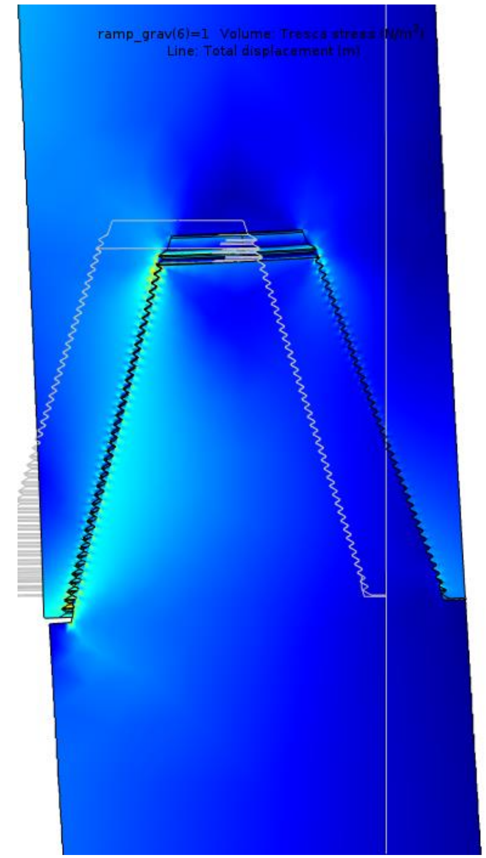
Electrode Bending



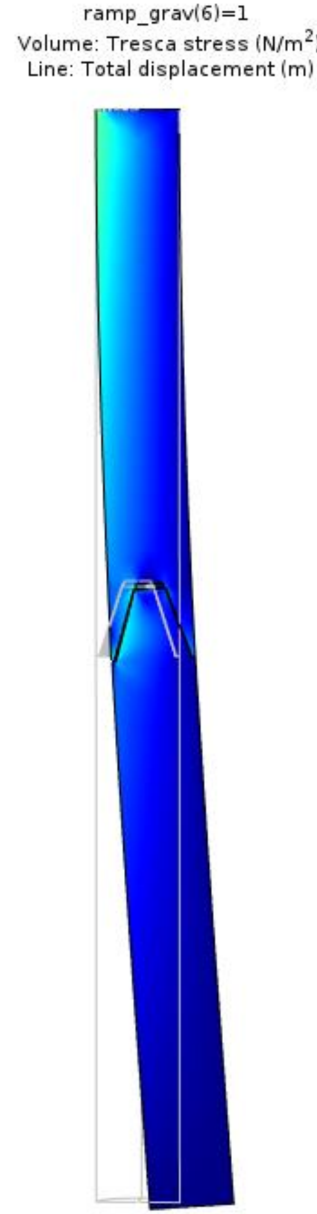
Bending force from
scrap pile

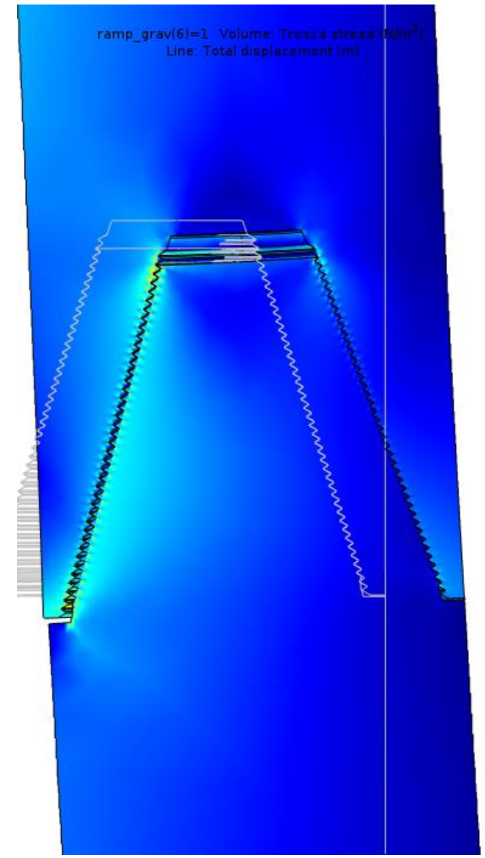




3D Cases

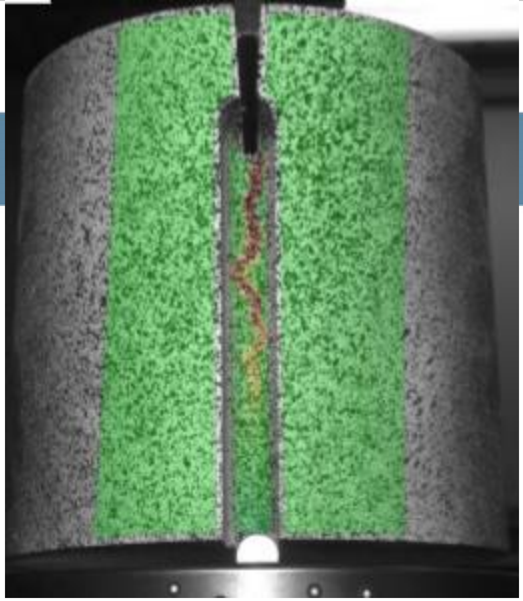
- 3D geometry is required for bending and other stress states
- Results make the model even more powerful, though require increasingly demanding hardware
- Model DoF/memory can exceed 2e7/350 Gb
- Results are very useful in understanding column breaks

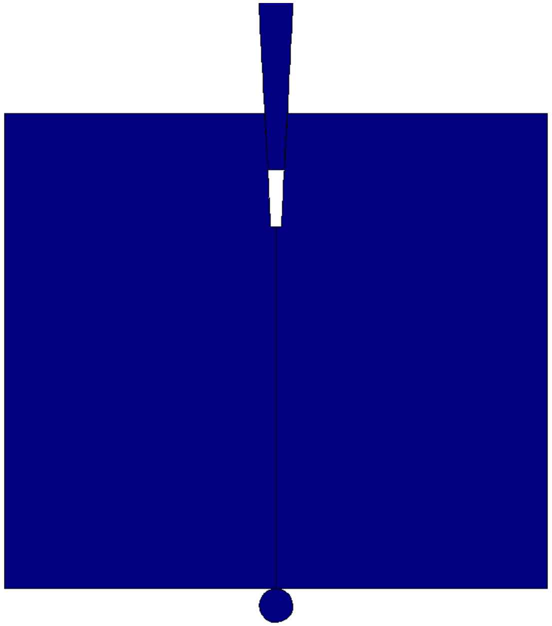




Future Work

- Already a useful design and engineering tool for GrafTech
- More 3D simulations!
- Deeper sensitivity analysis vs furnace conditions and materials
- Crack propagation and failure at high temperature
  - Cohesive zone debonding
  - Physical testing/comparison with DIC





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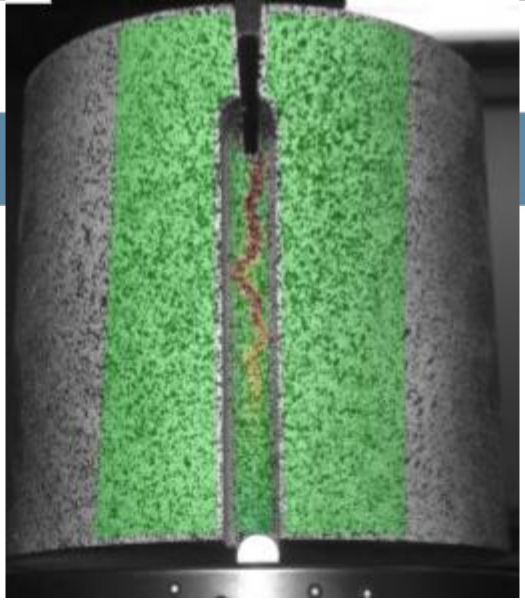
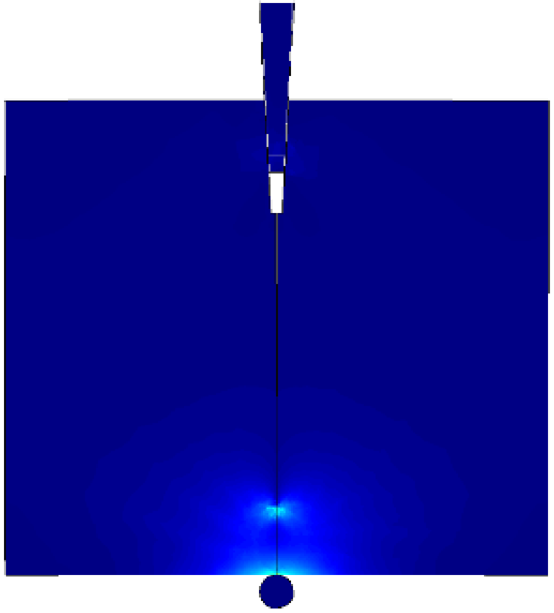


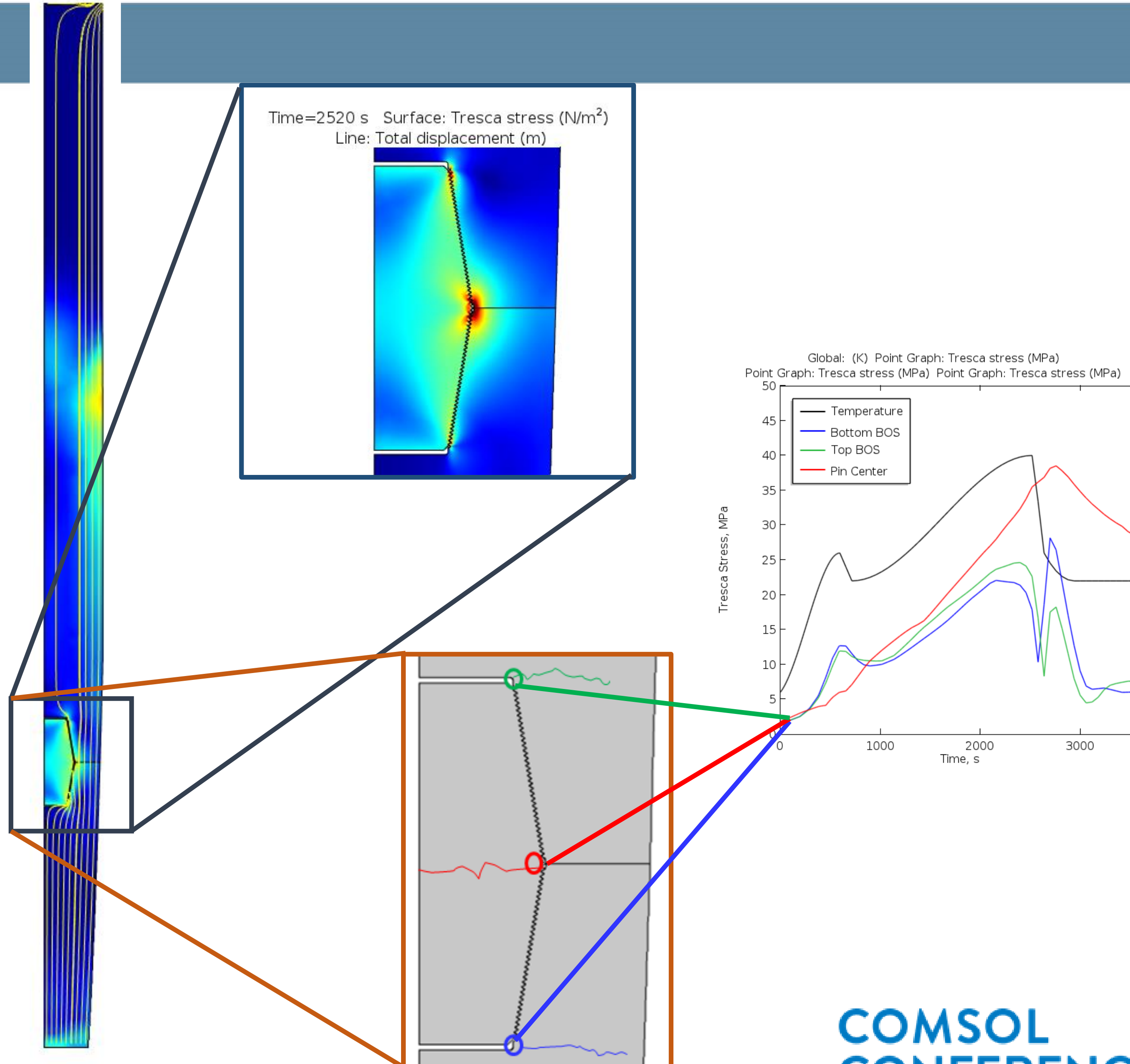


Thanks to Josh Thomas of AltaSim for help setting up early model version!

¿Questions?

Thank you for listening!

Model Validation



Oxidation

- Oxidation is the baseline driver of graphite electrode consumption rates
- Around **half** of electrode baseline consumption is wasted as oxidation
- Improved technology has steadily reduced oxidation rates, but more can be achieved!
- Water cooling is one key reducer of oxidation
- Modeling can help us understand key operating parameters to control and limit oxidation