2008 International ANSYS Conference

Applying CFD to Characterize Gear Response During Intensive Quenching Process

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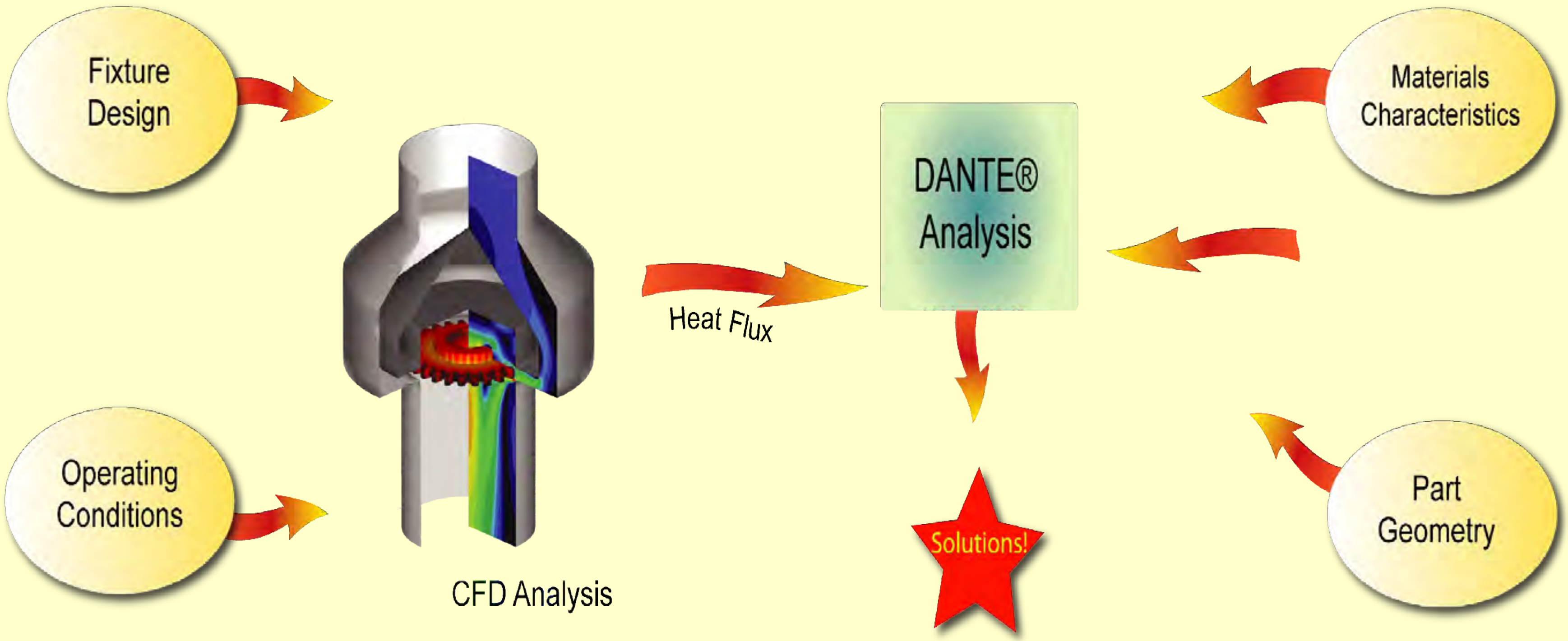
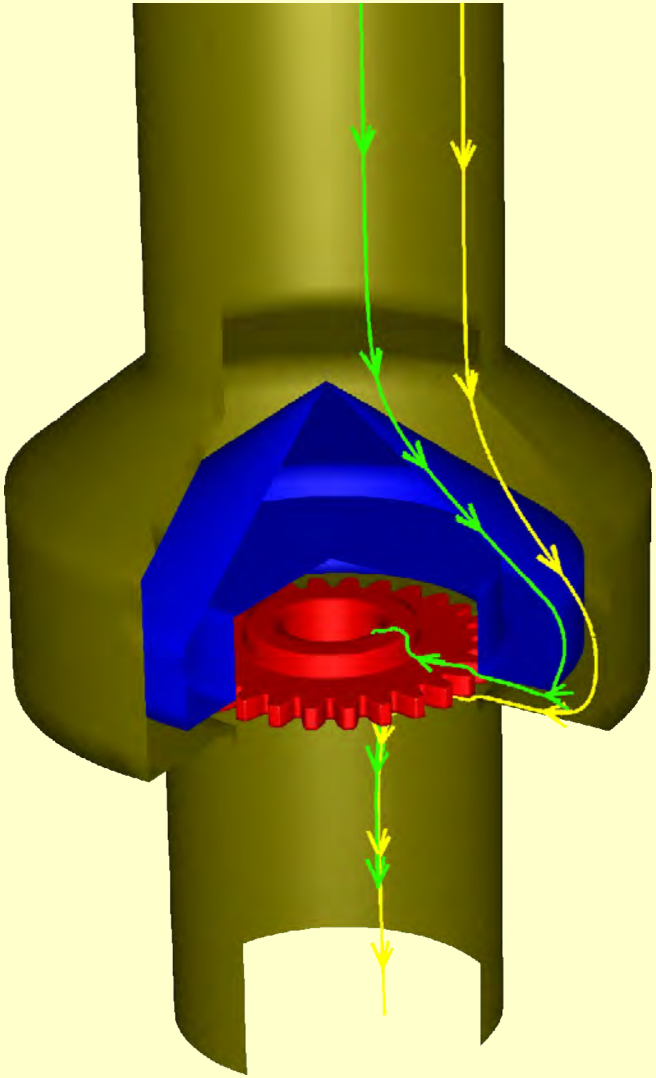
Overview

- The fluid flow field that exists in any quenching operation can lead to variations in surface heat flux that lead to distortion, as well as variations of residual stress, phase and hardness distributions, etc.
- Flow field and heat flux predicted by CFD (Fluent).
- Applying CFD results as thermal boundary condition, DANTE transient thermal/stress analysis is used to predict distortion, residual stress, hardness and phase distributions.

Analysis Workflow



Fixture Design



Quench flow is radially inward toward the gear teeth to provide the best quenching to the wear surfaces.

Water flow rate: 500 GPM

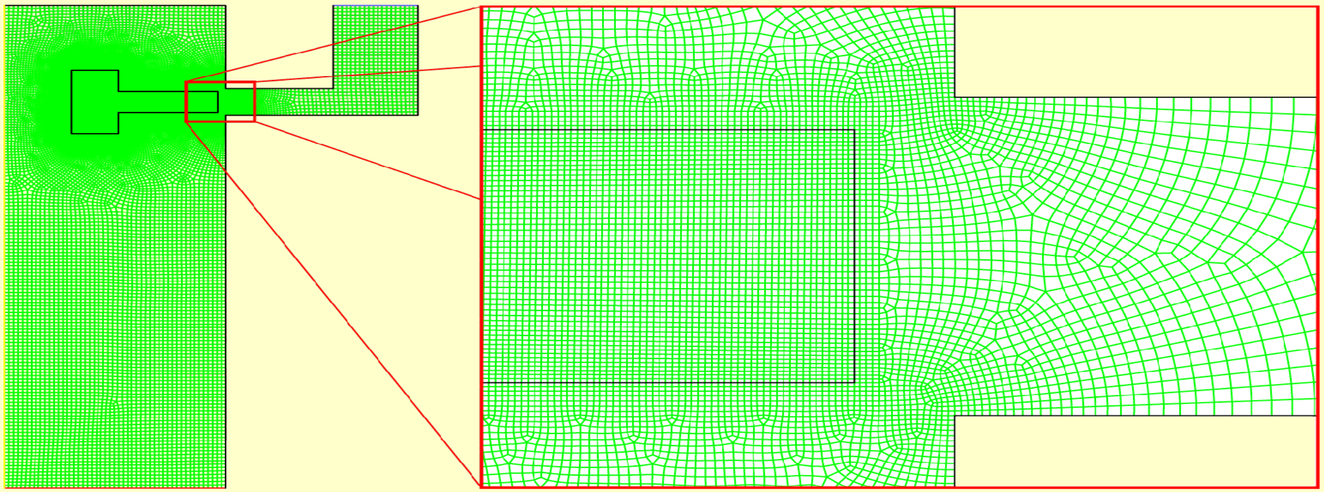
CFD Goal

Provide accurate surface heat flux rates for use in FEA (DANTE) modeling

Challenges

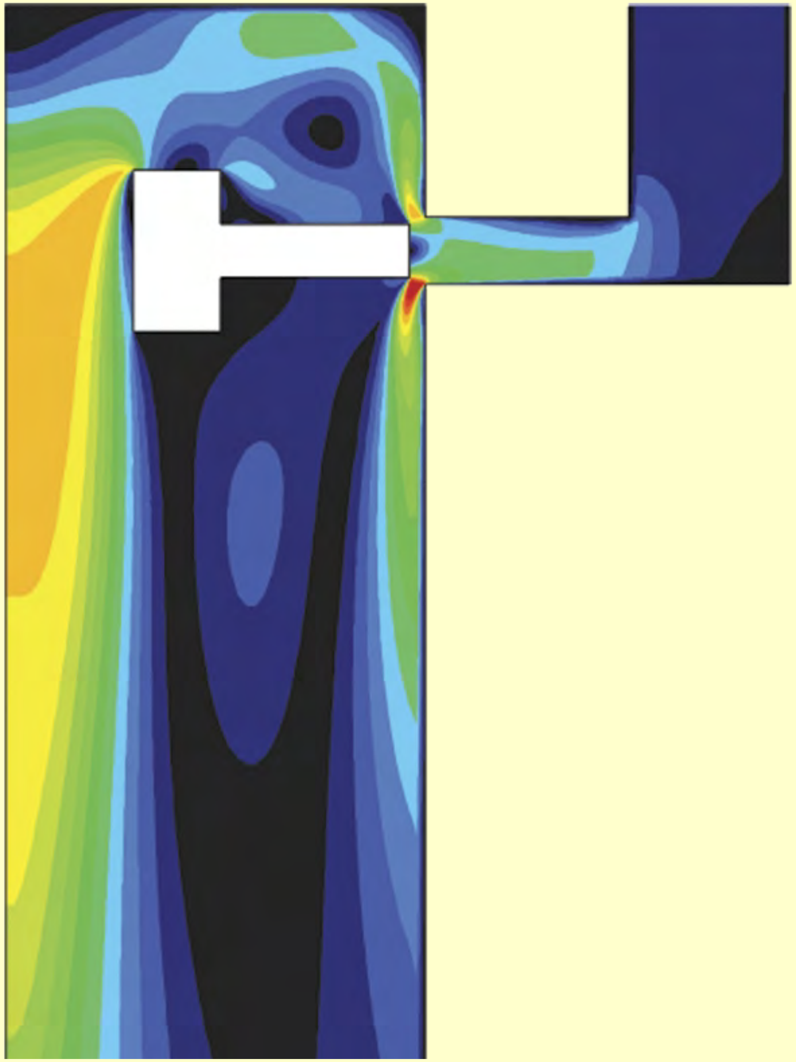
- Full transient 3D simulation of geometrics would take too long to be a practical engineering tool
- How do heat fluxes vary in space in time?
- Investigate with 2D model

2D Analyses
Computational Grid



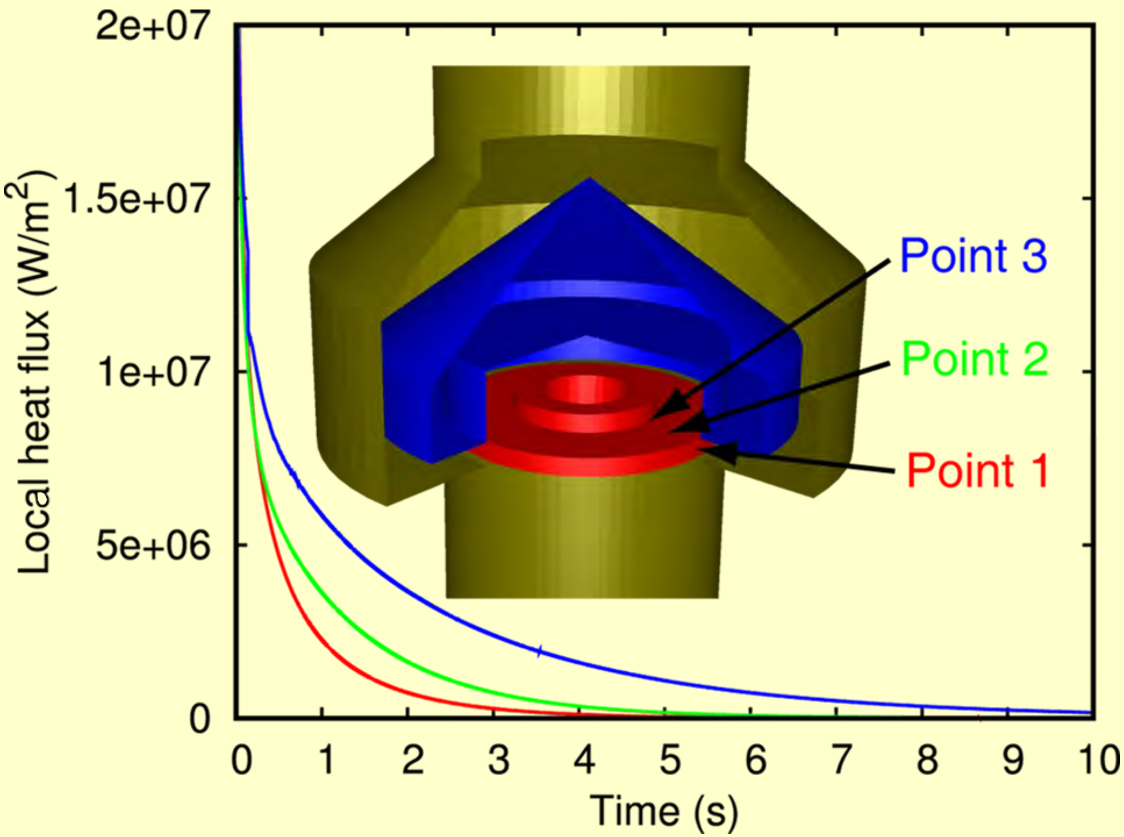
- 2D representation of gear (no teeth)
- Solid included in simulation
- 50,391 cells, with 22,121 in the solid
- Transient simulation with time step of 0.001 seconds
- 10 seconds of time simulated

2D Analyses
Flow Field



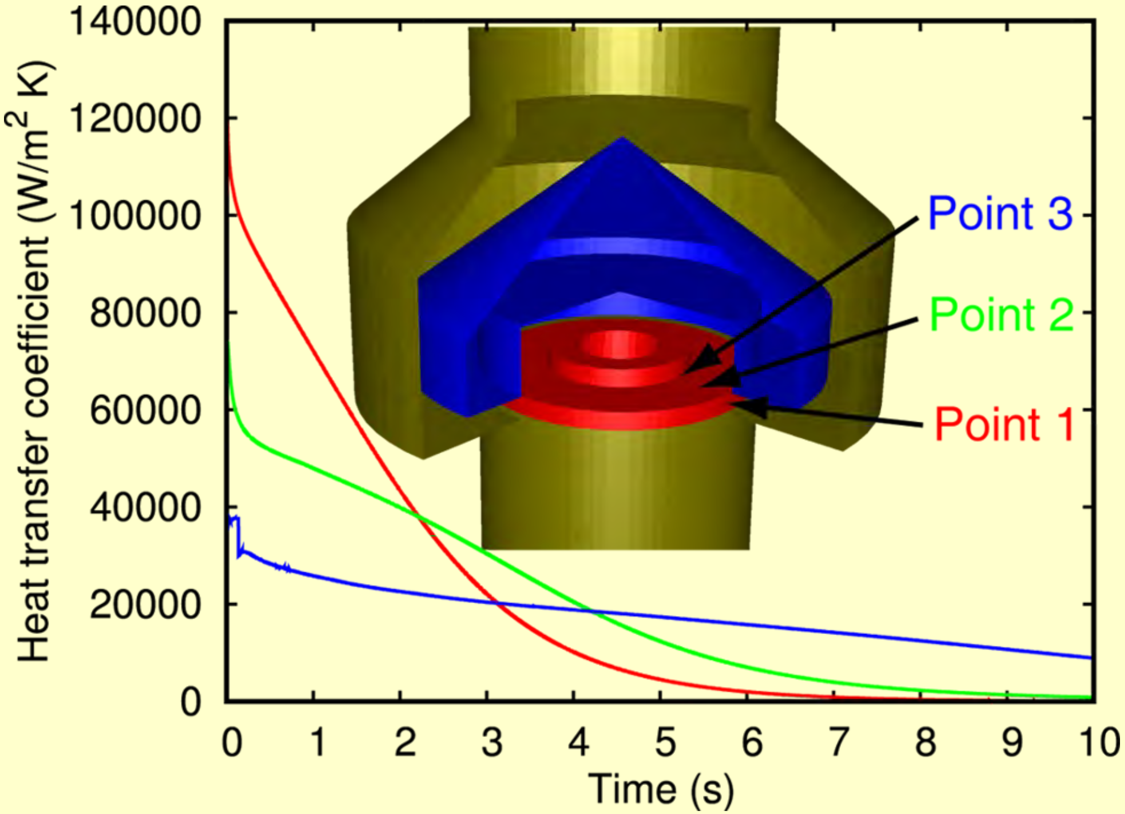
- Impingement on gear tooth face provides good heat transfer
- High velocity around “corners” of gear disk also provide high heat transfer
- Asymmetry on top and bottom corners
- Velocities on faces of gear disk are lower

2D Analyses
Transient Heat Flux



- For three representative points on the gear blank, heat flux rate varies considerably
- An assumption of equal heat flux everywhere would not be appropriate

2D Analyses
Transient Heat Flux



- Heat transfer coefficient for same three points varies both with location and with time
- Assumption of constant and equal heat transfer coefficient is not appropriate

2D Analyses
Correlation Method

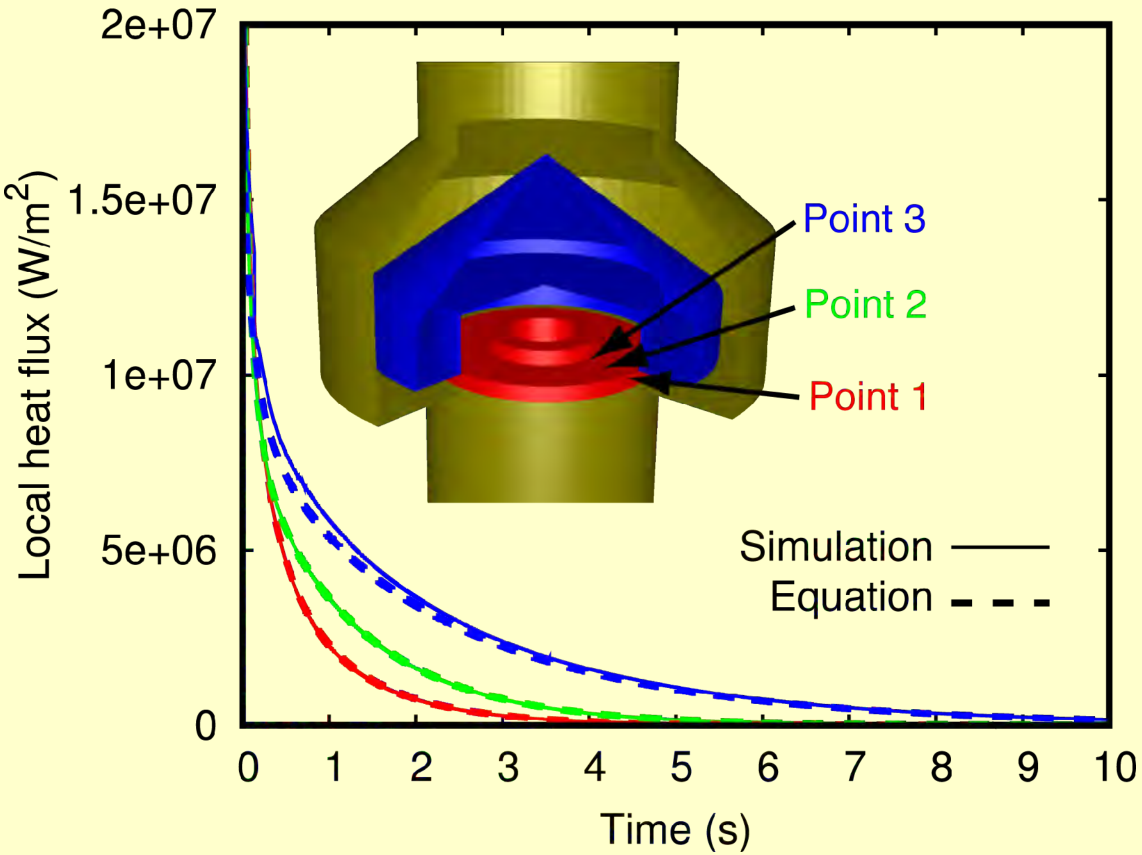
Is it possible to approximate the transient heat flux from steady state simulations?

$$q=\left\{h^{o}\frac{T_{w}-T_{r}}{T_{w}^{o}-T_{r}}+h^{f}\frac{T_{w}^{o}-T_{w}}{T_{w}^{o}-T_{r}}\right\}\left[T_{w}-\left\{T_{o}\frac{T_{w}-T_{r}}{T_{w}^{o}-T_{r}}+T_{r}\frac{T_{w}^{o}-T_{w}}{T_{w}^{o}-T_{r}}\right\}\right]$$

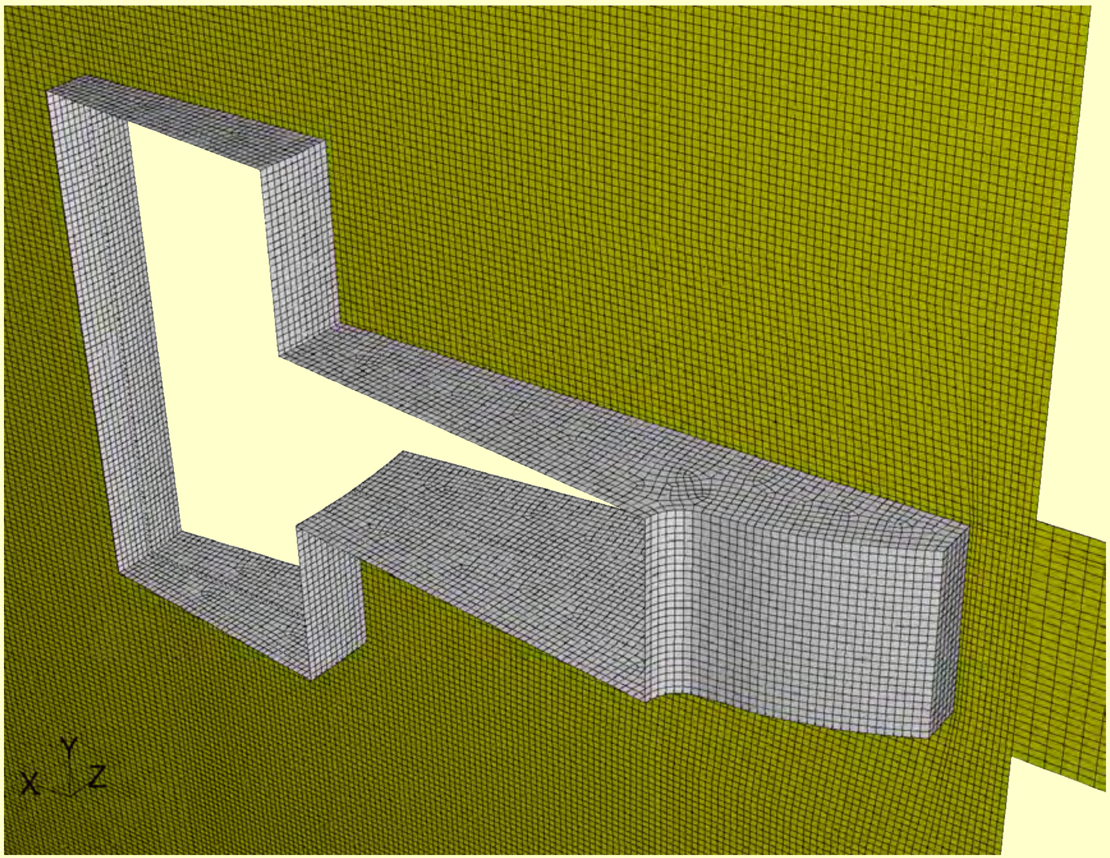
ho is the initial local heat transfer coefficient;
hf is the final local heat transfer coefficient (when the part is fully cooled);
Tw is the initial temperature of the part;
Tr is the reference fluid temperature (inlet fluid temperature);
To is the initial near surface characterization temperature and
Tw is the current wall temperature.

2D Analyses
Correlation Method

Is it possible to approximate the transient heat flux from steady state simulations?

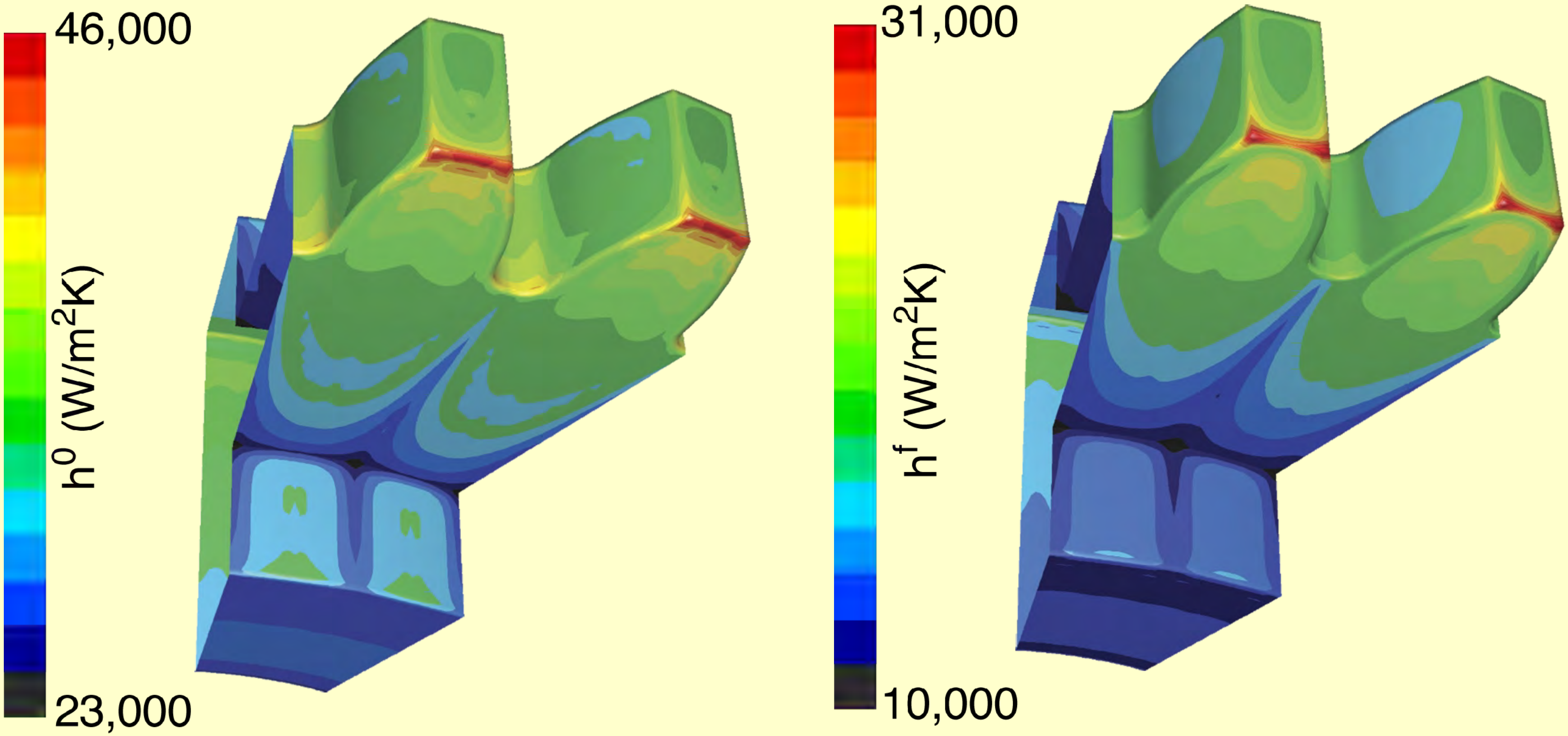


3D Analyses
Computational Grid



- 1,721,070 computational cells (fluid only)
- Gear surface temperature held constant
- Hot surface and ambient surface simulations made

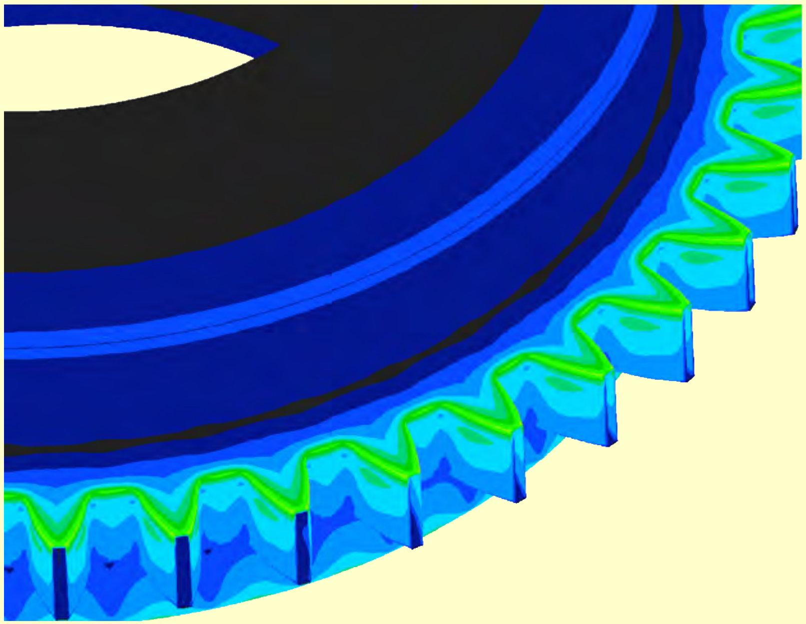
3D Analyses Results



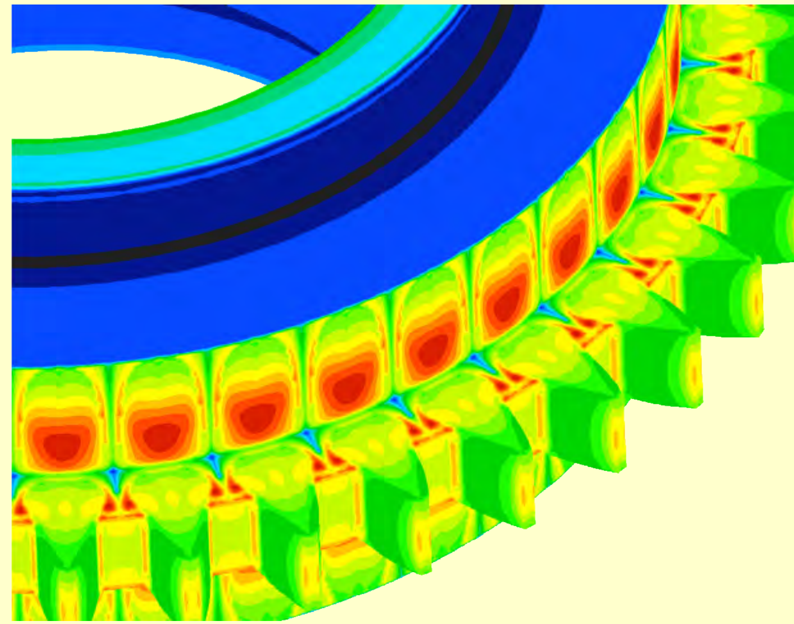
Local heat transfer coefficients displayed

(related to film temperature, not inlet fluid temperature)

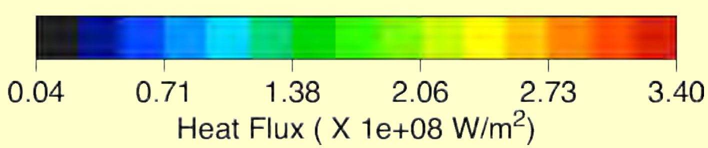
CFD As Design Tool



Axial Flow Fixture



Radial Flow Fixture



Interface with DANTE

- Computational grids for CFD and DANTE do not necessarily match
- Data exported for each gear surface node in the CFD model, including position, and three governing parameters
- Data are interpolated by DANTE boundary condition routine
- At each time step, the current local wall temperature is used to compute the wall heat flux

$$q=\left\{h^{o}\frac{T_{w}-T_{r}}{T_{w}^{o}-T_{r}}+h^{f}\frac{T_{w}^{o}-T_{w}}{T_{w}^{o}-T_{r}}\right\}\left[T_{w}-\left\{T_{o}\frac{T_{w}-T_{r}}{T_{w}^{o}-T_{r}}+T_{r}\frac{T_{w}^{o}-T_{w}}{T_{w}^{o}-T_{r}}\right\}\right]$$

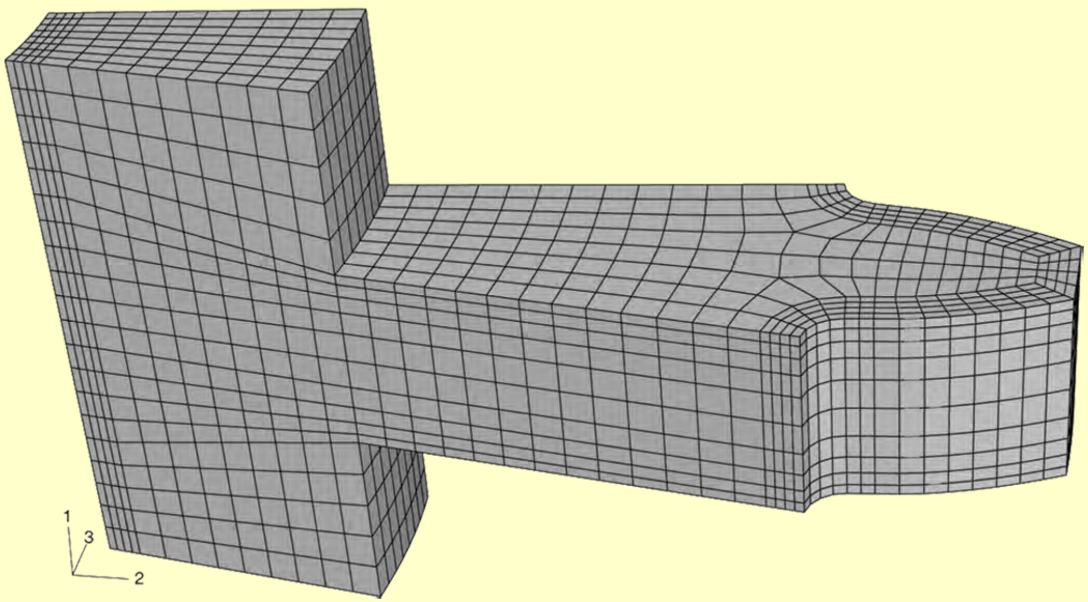
DANTE
Finite Element Meshing

3D single gear tooth model

- Material: Pyrowear53
- Fine surface elements are used to more accurately catch the thermal and carbon gradients in the surface
- Cyclic boundary condition is applied

5959 nodes

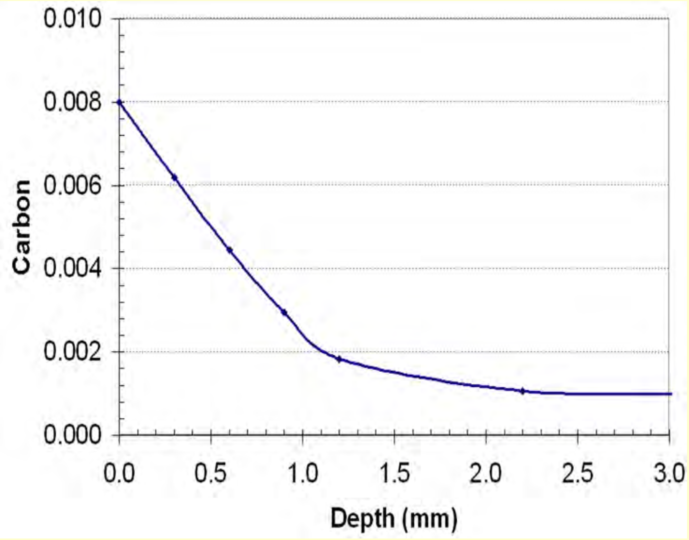
4820 elements

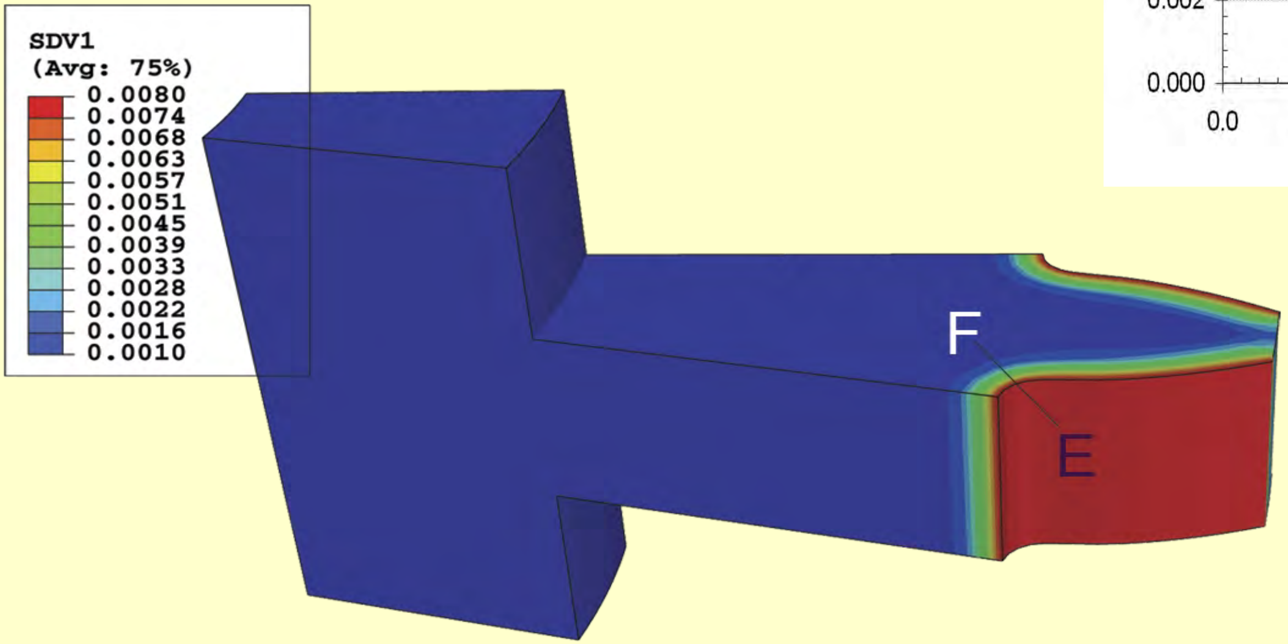


Carbon Distribution

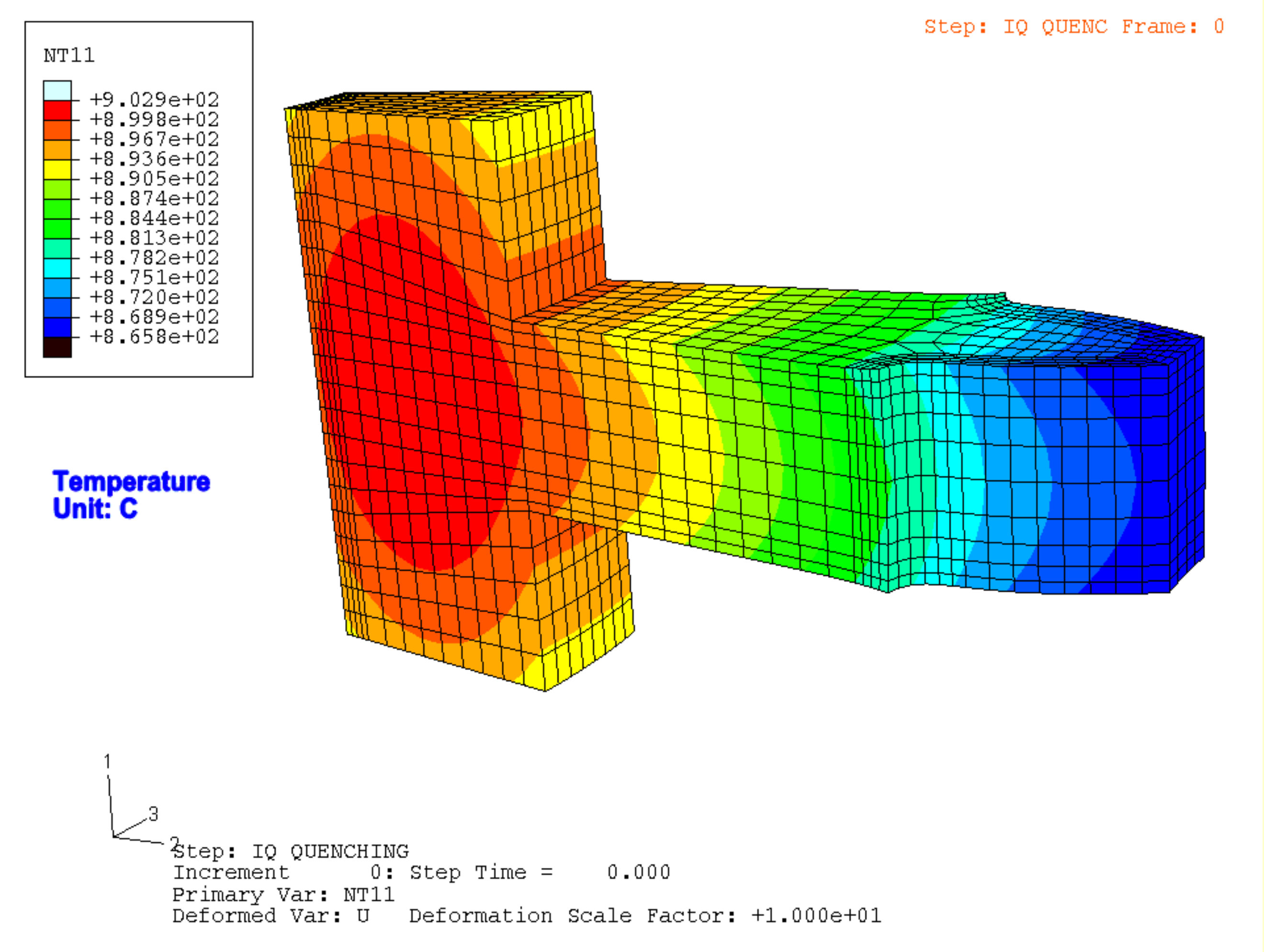
Carburization Schedule:

- Carburization temperature is 926.7º C,
- Carbon potential is 0.8%,
- Carburization time period is 8 hours.
- Only the gear tooth surface is carburized.



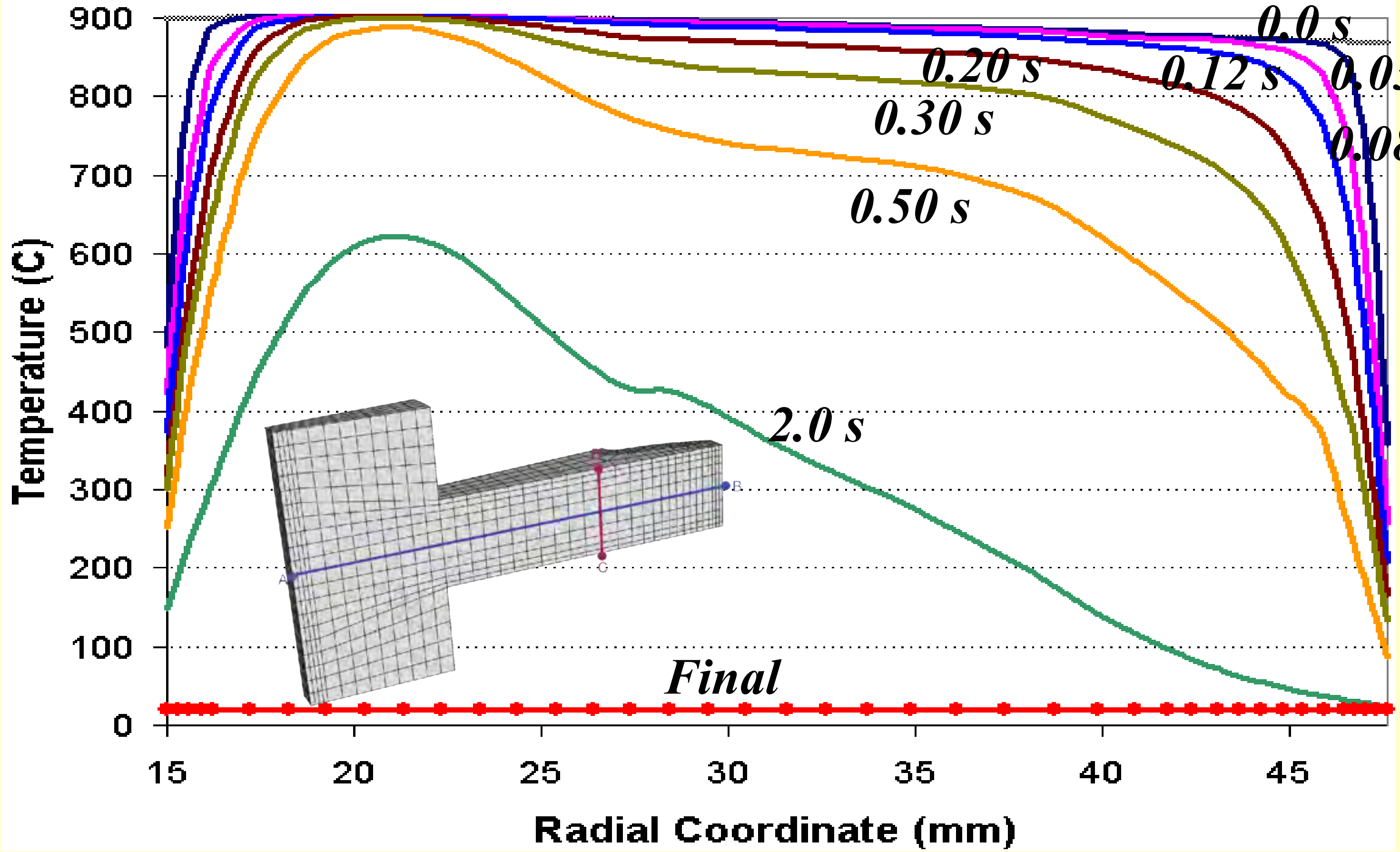


Temperature History During Quenching



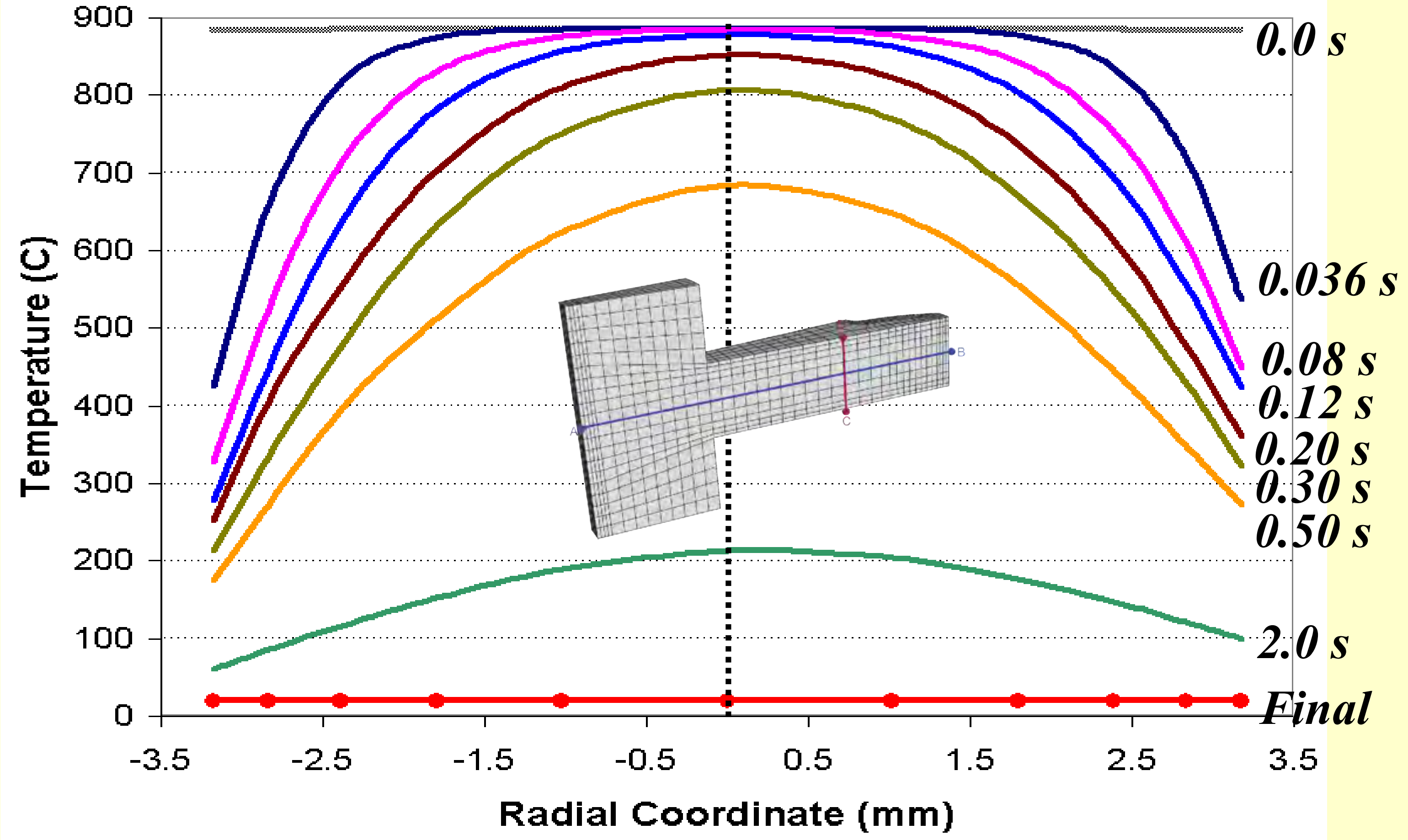
Temperature History During Quenching

Along the Radial Line

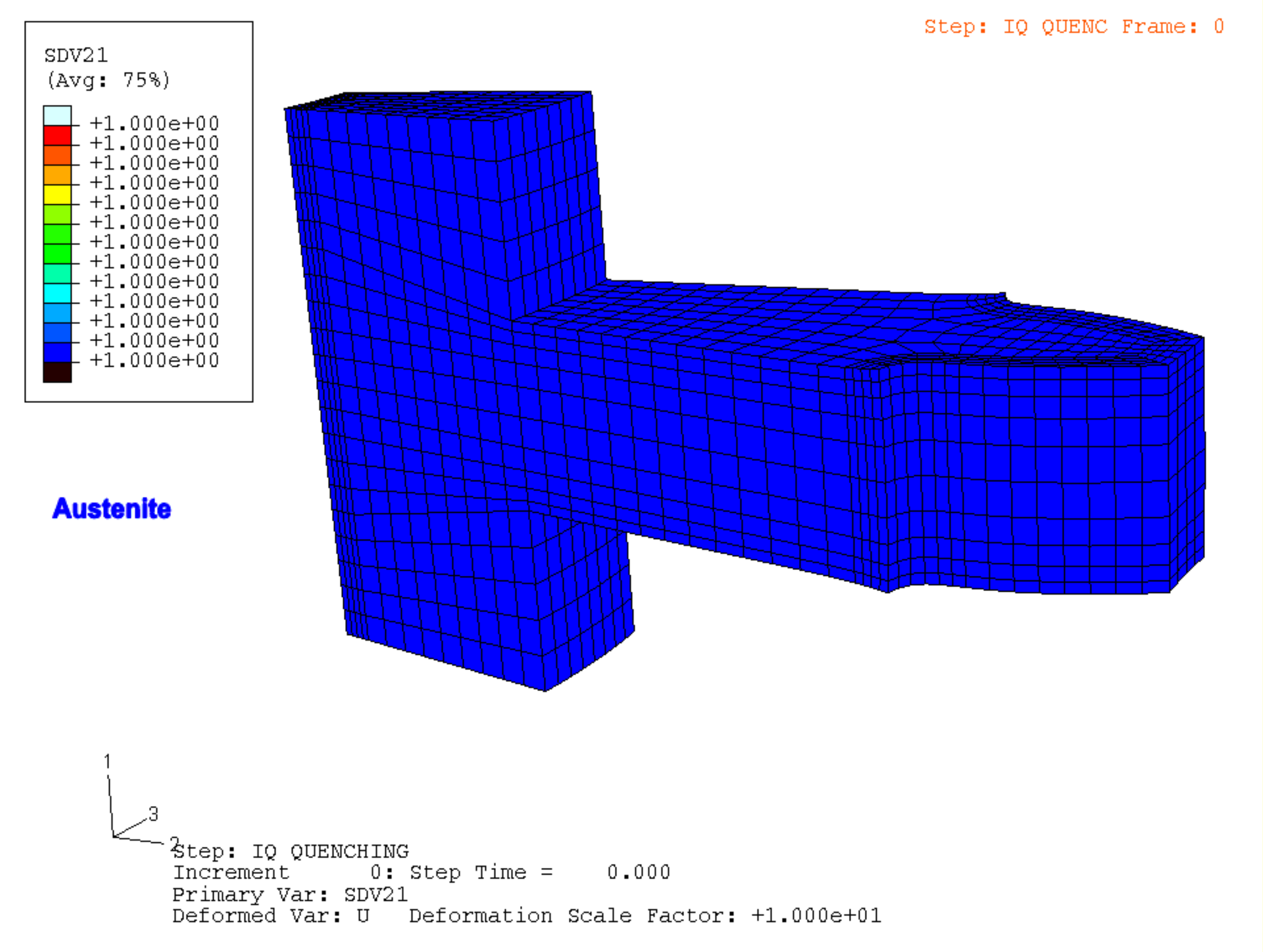


Temperature History During Quenching

Along the Vertical Line

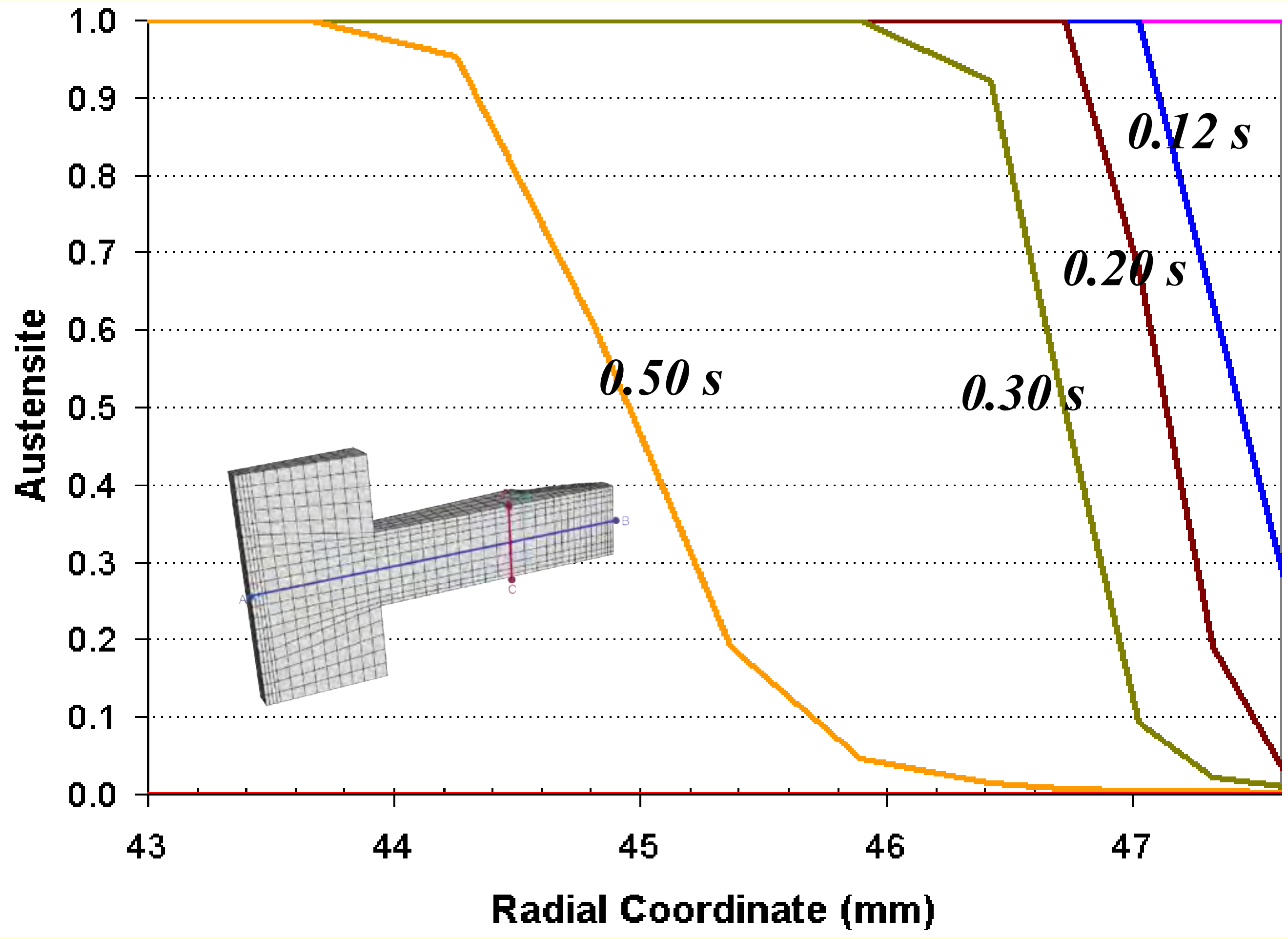


Phase History During Quenching



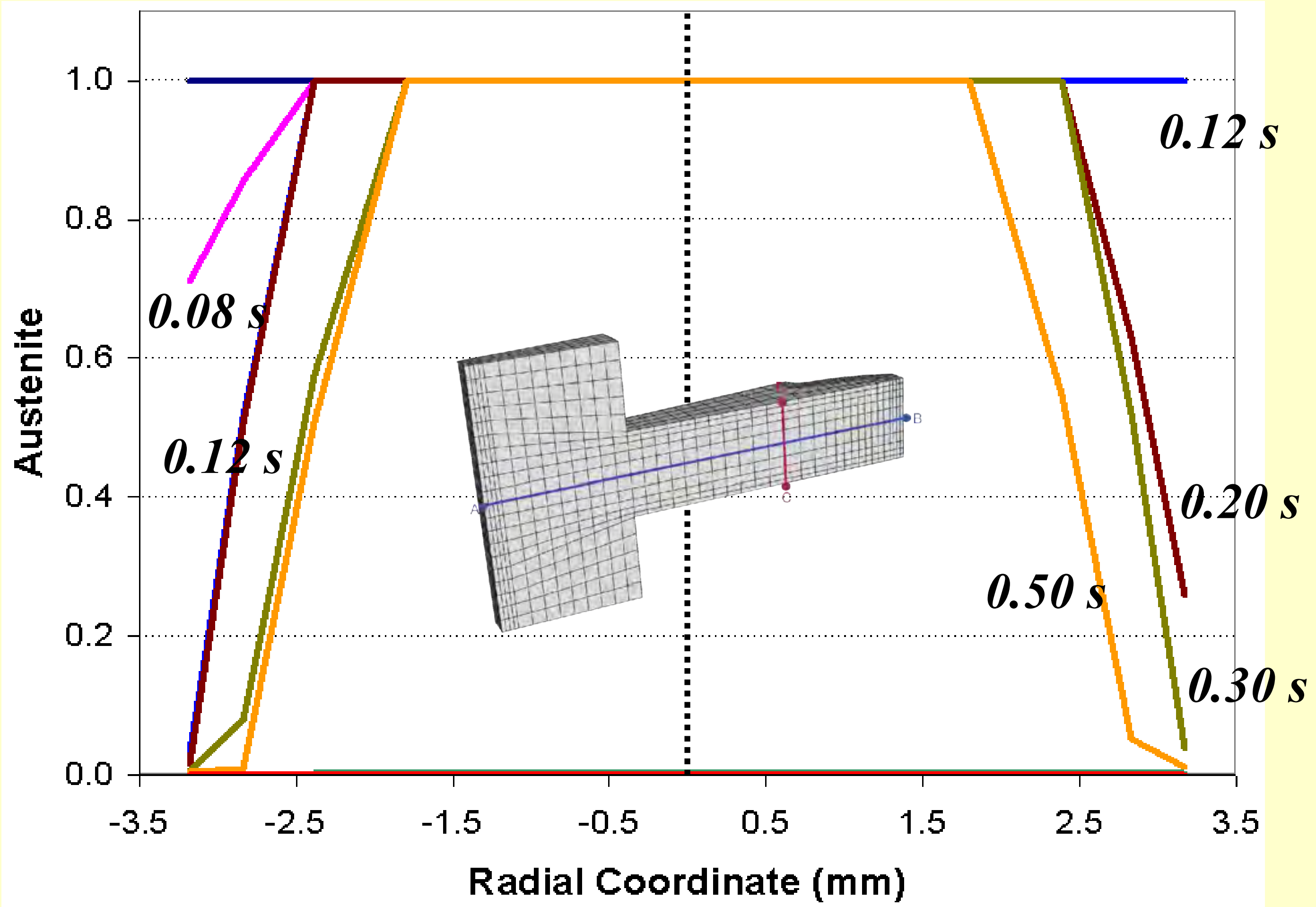
Phase History During Quenching

Along the Radial Line

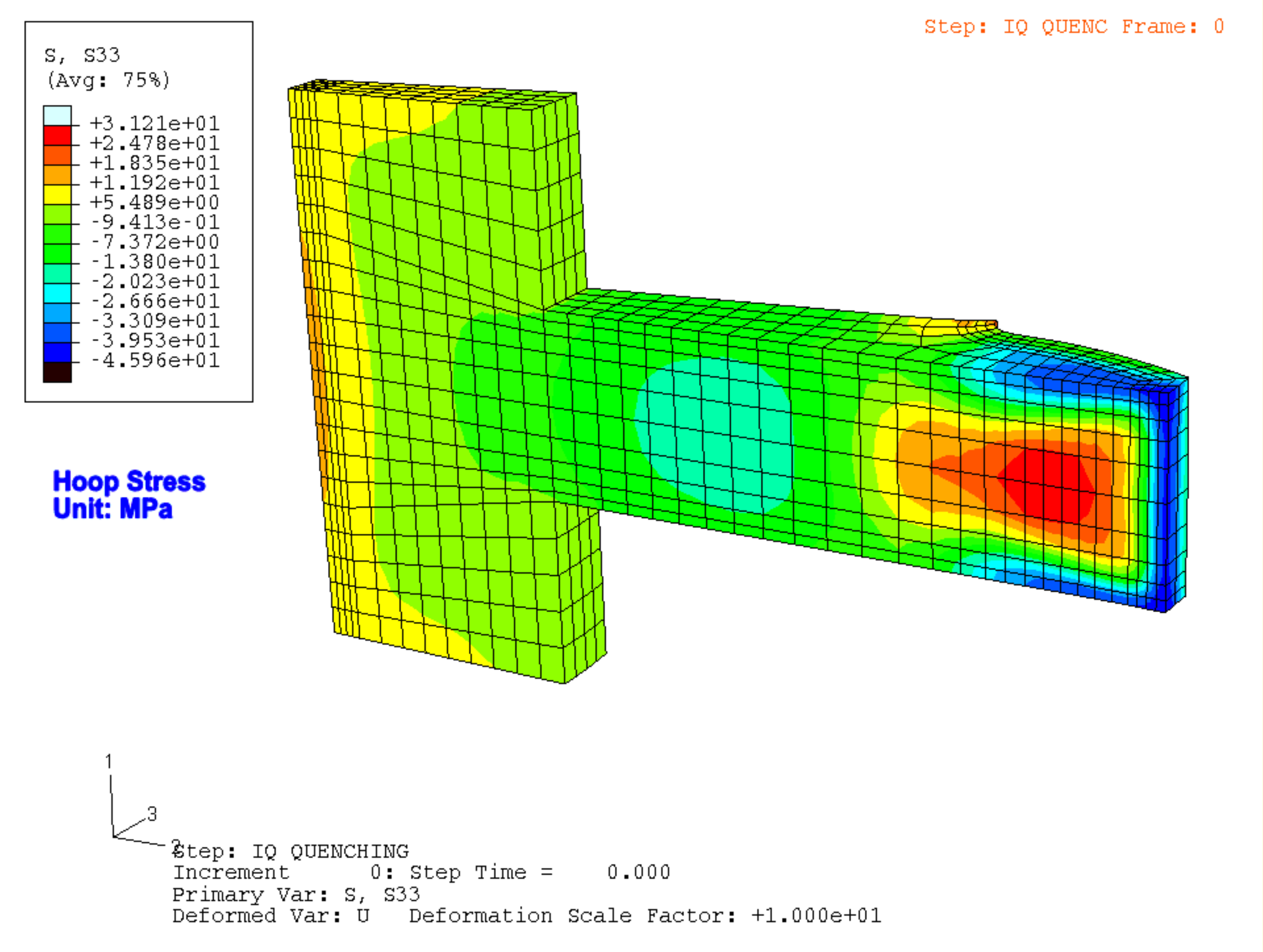


Phase History During Quenching

Along the Vertical Line

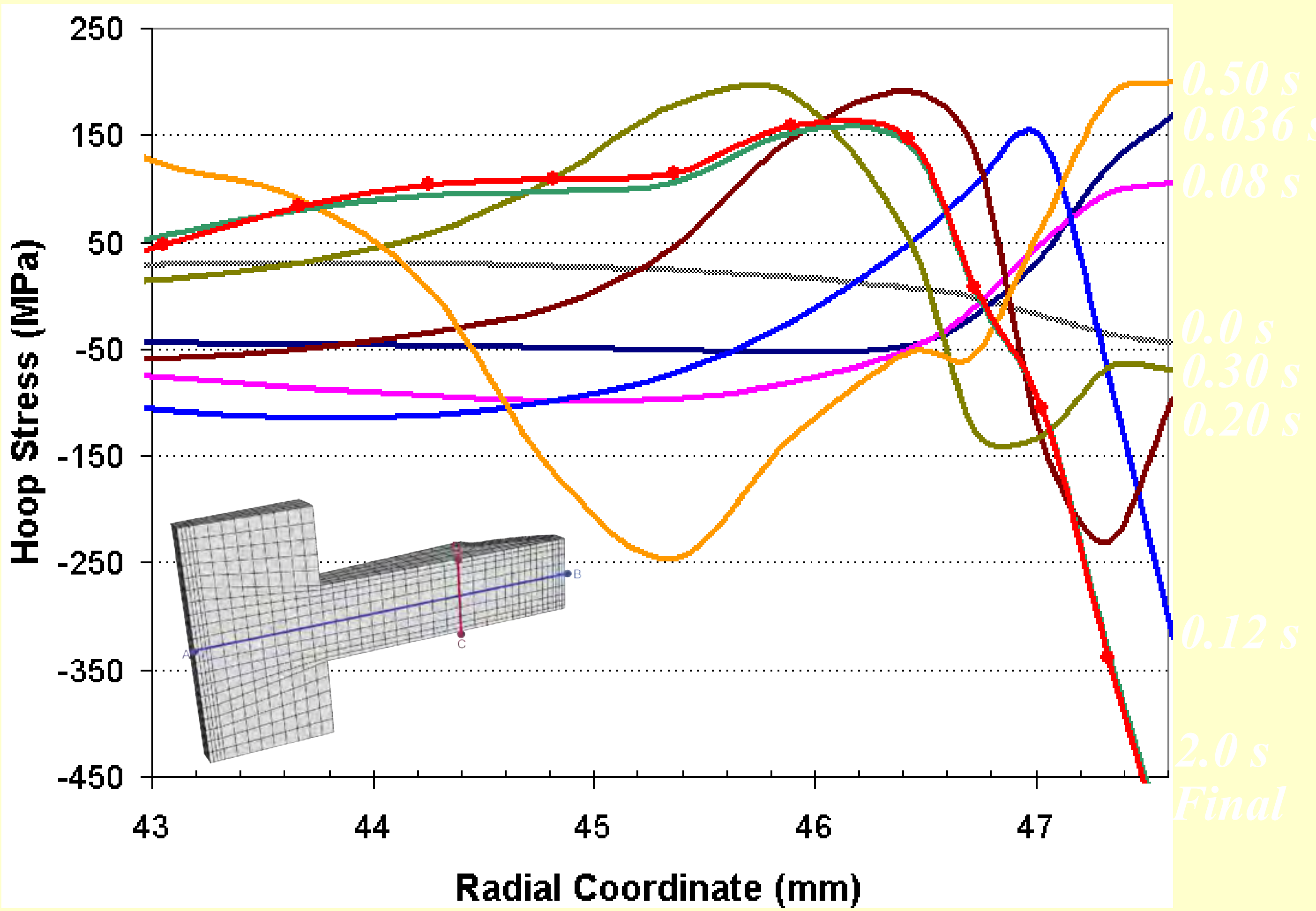


Hoop Stress Evolution During Quenching

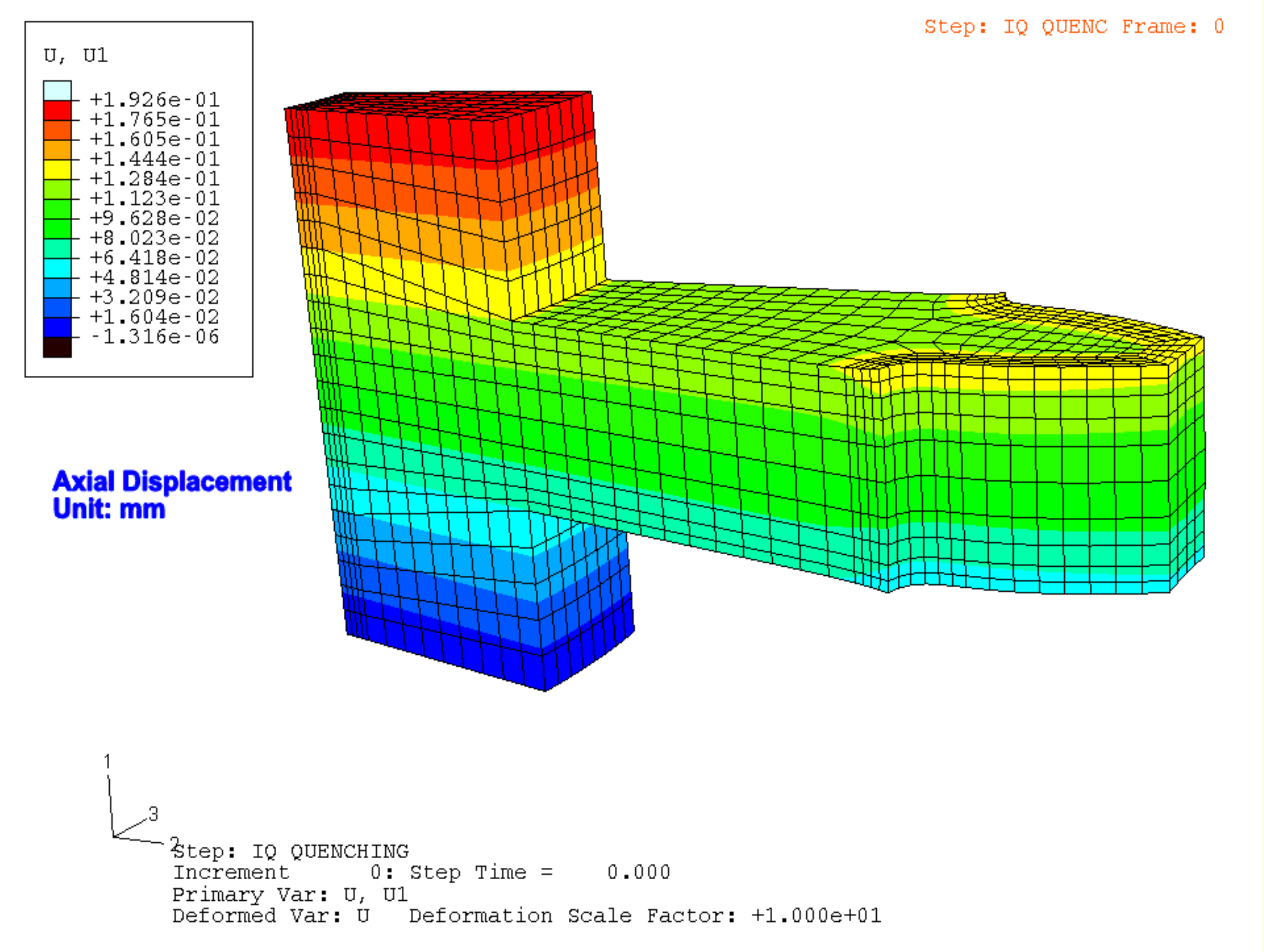


Hoop Stress Evolution During Quenching

Along the Radial Line

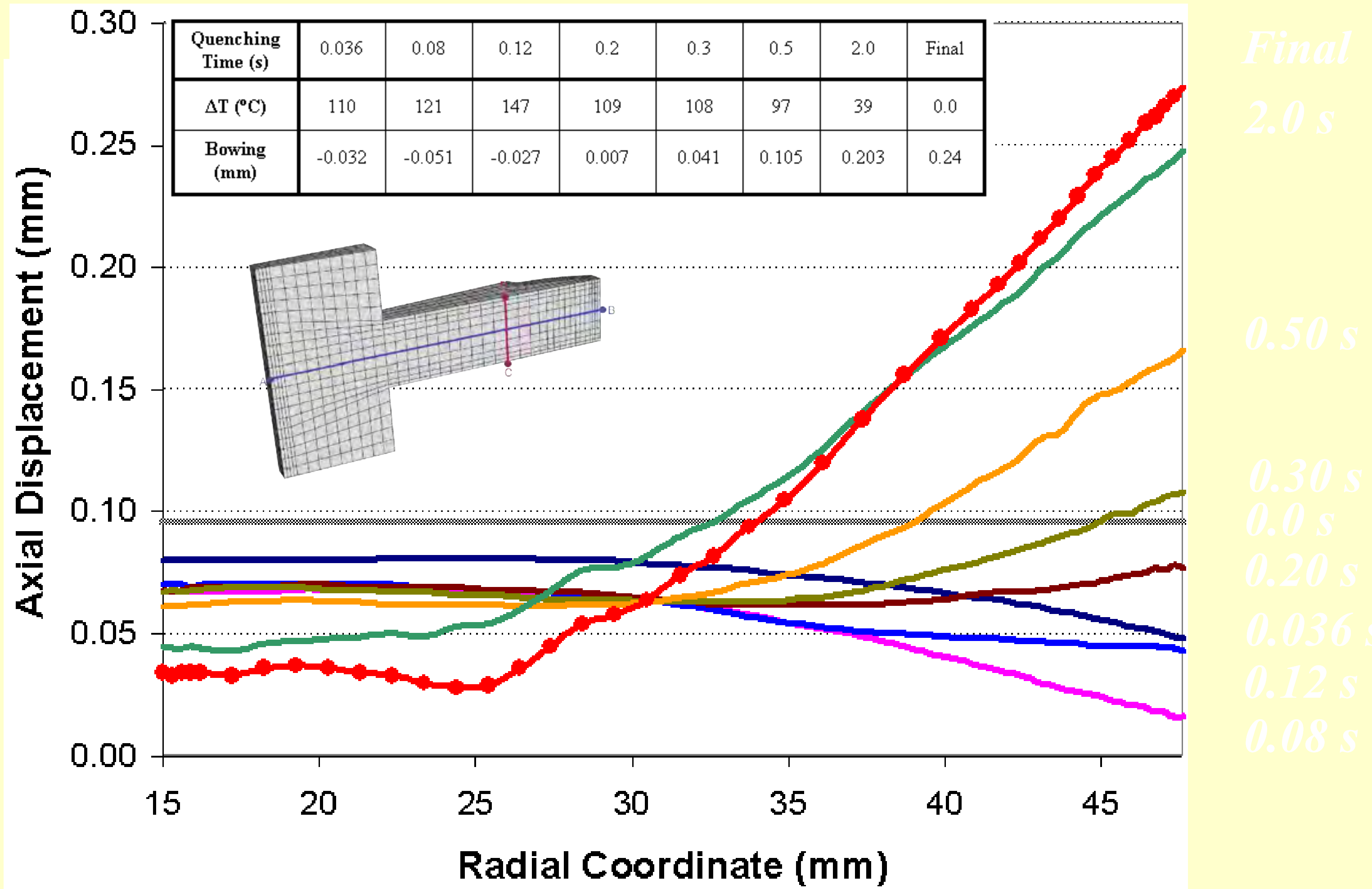


Axial Displacement During Quenching



Axial Displacement During Quenching

Along the Radial Line



Quenching Time (s)	0.036	0.08	0.12	0.2	0.3	0.5	2.0	Final
ΔT (°C)	110	121	147	109	108	97	39	0.0
Bowing (mm)	-0.032	-0.051	-0.027	0.007	0.041	0.105	0.203	0.24

Summary & Conclusions

- A method was developed to closely predict the transient 3D surface heat fluxes from a pair of steady-state CFD analyses.
- Those heat fluxes were supplied to a DANTE model for a more complete analysis of the quenching process.
- The DANTE results show that inclusion of the CFD predicted heat flux rates has a significant effect on distortion, compared to the assumption of constant heat transfer coefficient.
- A combination of CFD and DANTE provides more accuracy of the simulations.

Acknowledgments

This work was conducted under the Cooperative Agreement No. W15QKN-06-2-0105 between the Edison Materials Technology Center and the US Army Benet Laboratories. DCT and ASC would also like to acknowledge the contributions of IQ Technologies Inc. and NexTec Corp. to this project.