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# Preliminary Model of Ideal Soft Reduction

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## Phenomena governing macrosegregation / ideal soft reduction

- turbulent, transient **fluid flow** in a complex geometry (inlet nozzle and strand liquid pool), affected by argon gas bubbles, thermal and solutal buoyancies
- transport of **superheat** through the turbulent molten steel
- transport of **solute** on microscopic (between dendrites), mesoscopic (between grains, columnar-equiaxed regions, etc.) & macroscopic scales (center to surface)
- coupled **segregation** (including micro, meso, and macro scales)
- **solidification** of the steel shell, including the growth of dendrites, grains and microstructures, phase transformations, and microsegregation
- **microstructure** evolution, including columnar-equiaxed transition, nucleation of solid crystals, both in the melt and against mold walls
- **shrinkage** of the solidifying steel shell, due to thermal contraction, phase transformations, and internal stresses
- thermal-mechanical deformation of the **mushy-zone**, and its effective **permeability**, which control transport of solute-rich fluid
- **stress** in the solidifying shell, due to loading from external forces, (mold friction, **bulging** between support rolls, withdrawal, gravity pressure) thermal strains, creep, and plasticity (which varies with temperature, steel composition, and cooling rate)
- **thermal-distortion**, warping, misalignment, and wear of the support and drive **rolls**

# Simple ideal soft-reduction model

1) 1-D Heat transfer model of entire strand (CON1D, validated with 1D and 2D ABAQUS)
2) 1-D Thermal stress model of free-shrinkage of solidifying shell, including the liquid phase
   - assume shell deforms exactly to match liquid shrinkage, so generates no fluid flow, thus avoids segregation
3) 3-D thermal-mechanical model of shell in mushy zone (ignoring liquid), to calculate:
   **soft-reduction efficiency** = liquid-core reduction / surface reduction

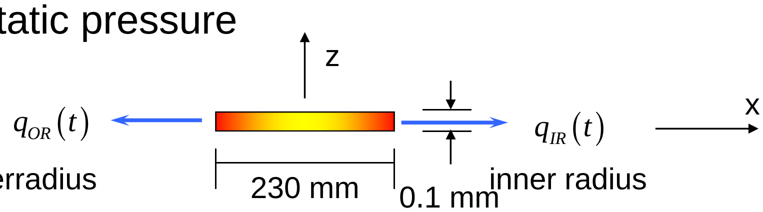
   accounts for:

   bulging of narrow faces, plastic strain,
   bulging of wide faces between rolls, etc.

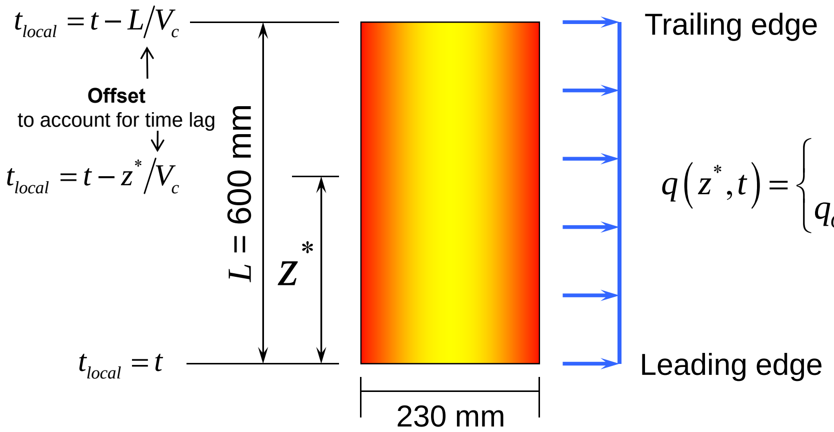


# Lagrangian Slice Model of thermal stress through thickness

- Calibrate CON1D to match typical thick-slab caster
- Heat flux time-history from CON1D as heat loads to Abaqus
  - Independent inner and outer radius
  - Top and bottom edges insulated
- x-displacement fixed at centerline
- Generalized plane strain finite elements (quad)
- Generalized plane strain imposed in z-direction
  - Fix top edge z-displacement
  - Constraint equations on bottom edge z-displacements
- No ferrostatic pressure



# 2D Lagrangian Slice Model



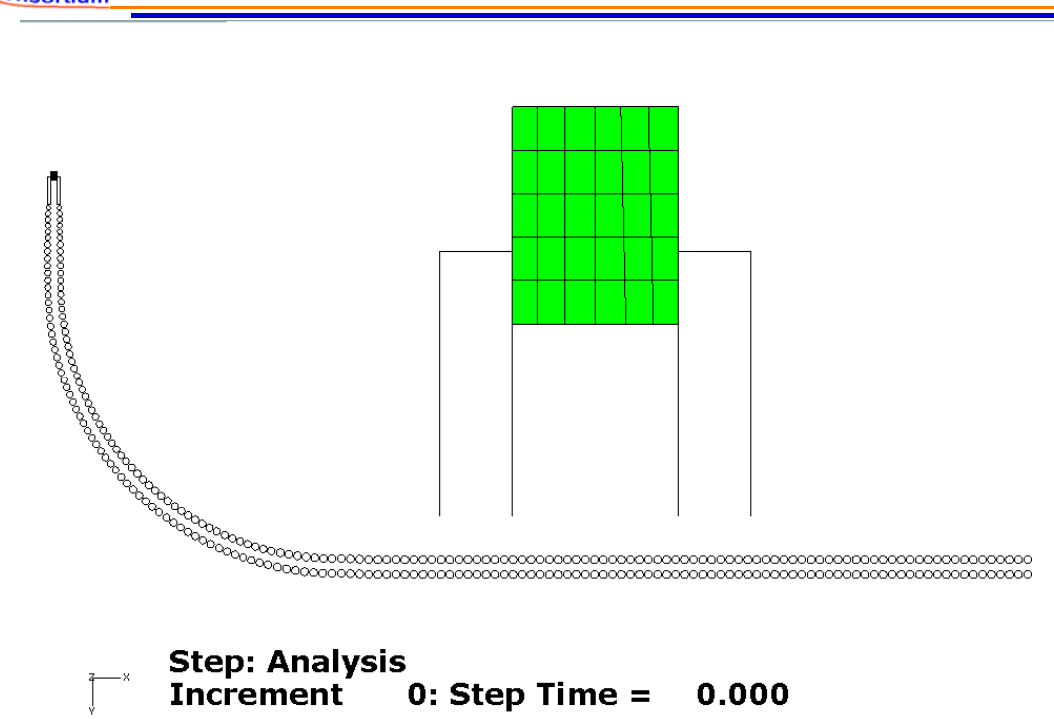

$$q(z^*, t) = \begin{cases} 0 & t_{local} < 0 \\ q_{CON1D}(t_{local}) & \text{otherwise} \end{cases}$$

The heat flux time-history from CON1D is shifted to account for the finite domain thickness in the casting direction

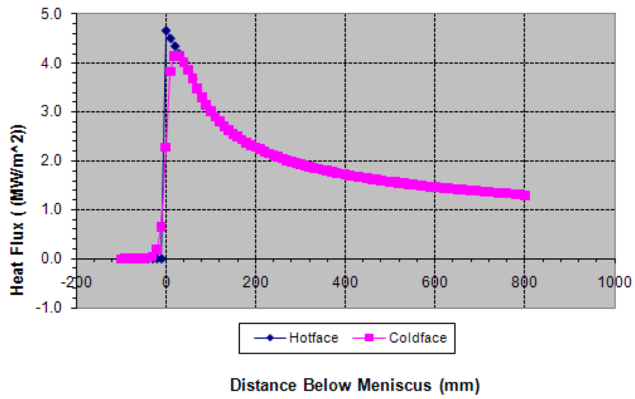
- Independent inner and outer radius heat loads
- Assumes constant casting speed



# Baosteel Caster Simulation



# Thermal model (mold): Heat Flux boundary condition

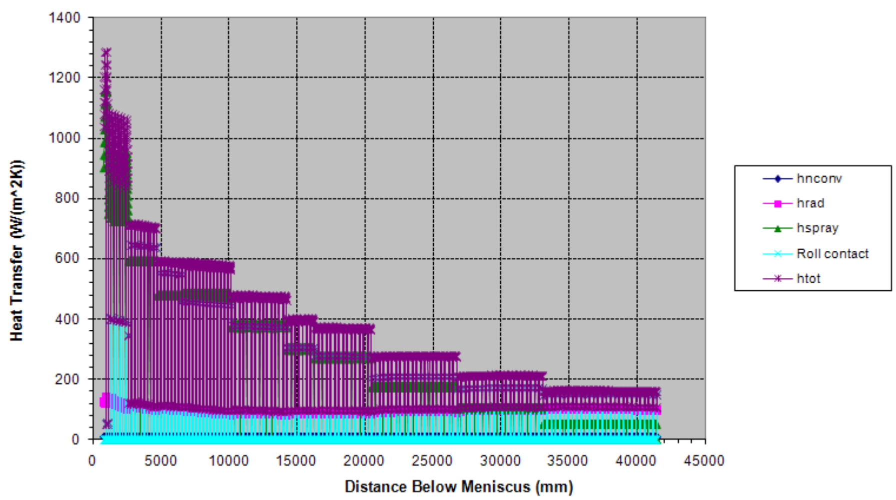



**Heat Flux in the mold**

In this case, heat flux based on the mold water temperature increase.

Y. Wang, 2010

# Thermal model (spray zones): Convection boundary condition

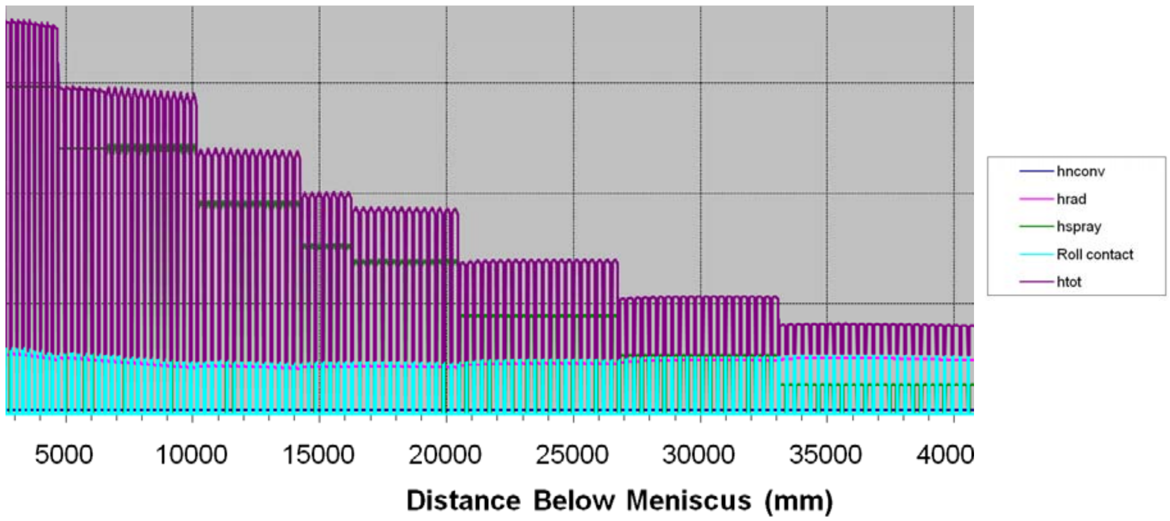



**Heat transfer Coefficient in  Secondary cooling zones**

Secondary cooling zone includes four heat transfer methods: Radiation, spray, roll contact and convection.

Y. Wang, 2010

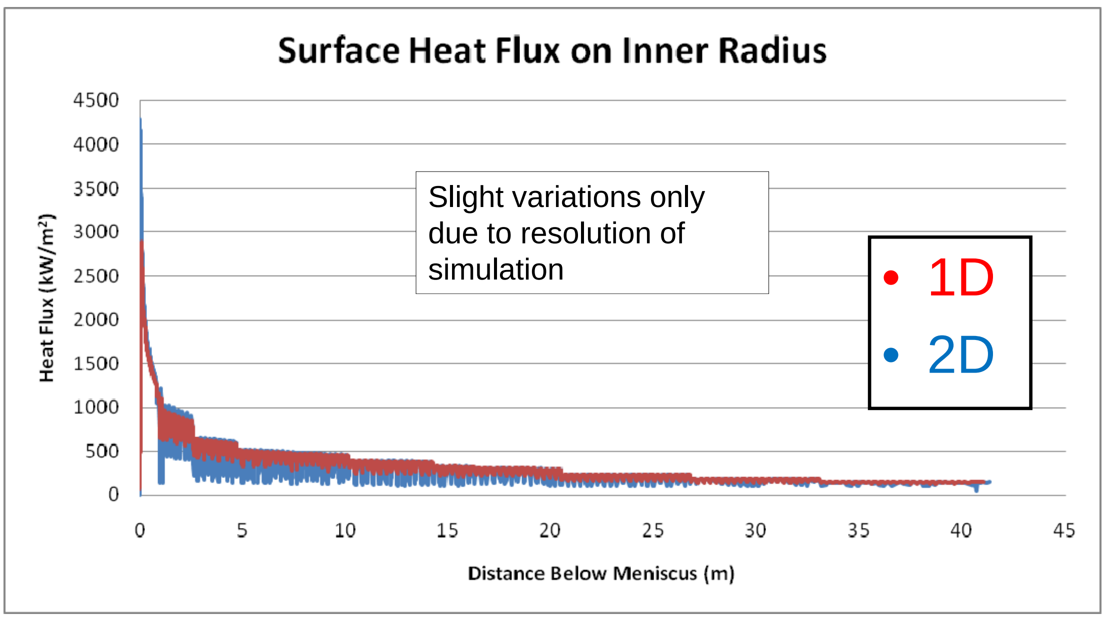
## Temperature BC: heat transfer coefficient



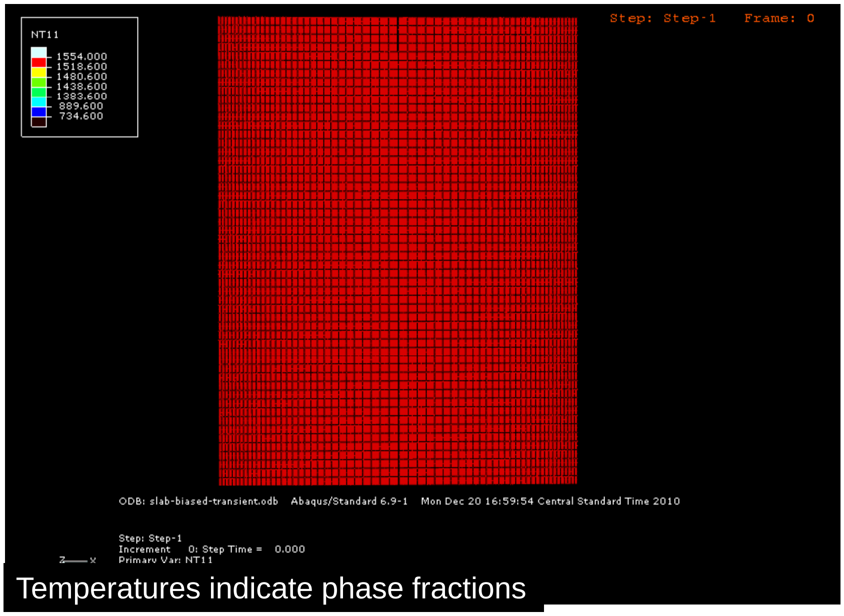

Part ZOOM IN

Y. Wang, 2010

# Surface Heat Flux



# Temperature Profile Development



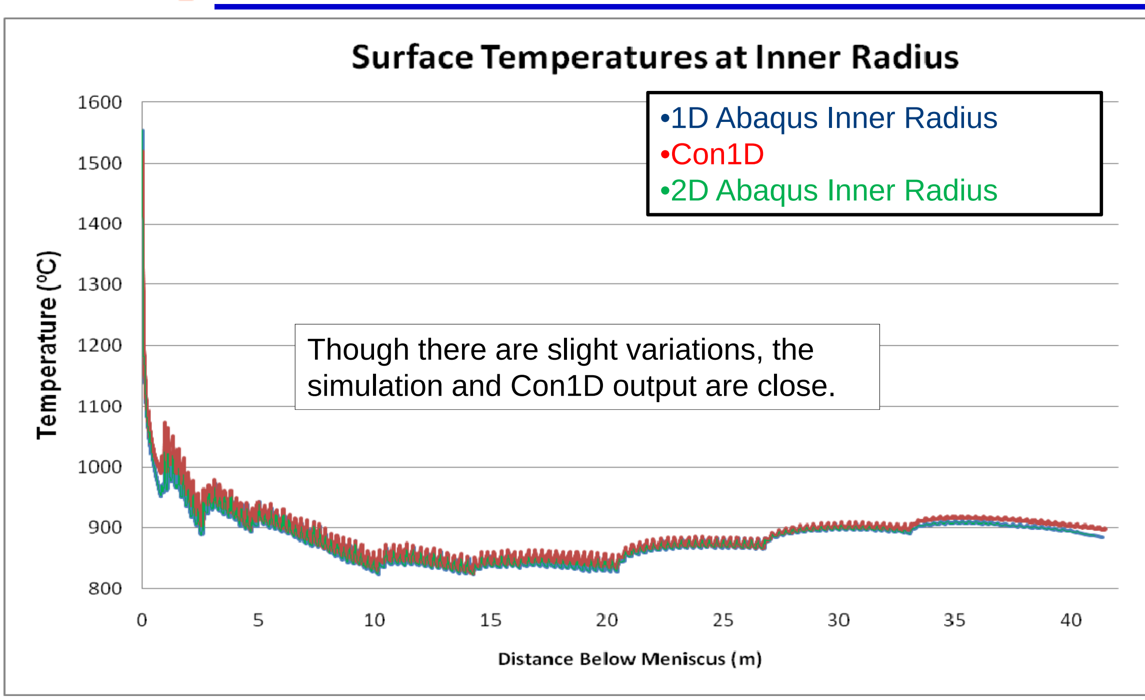

Temperatures indicate phase fractions

liquid | mush | δ | δ & γ | γ | γ & α | α + $Fe_3C$

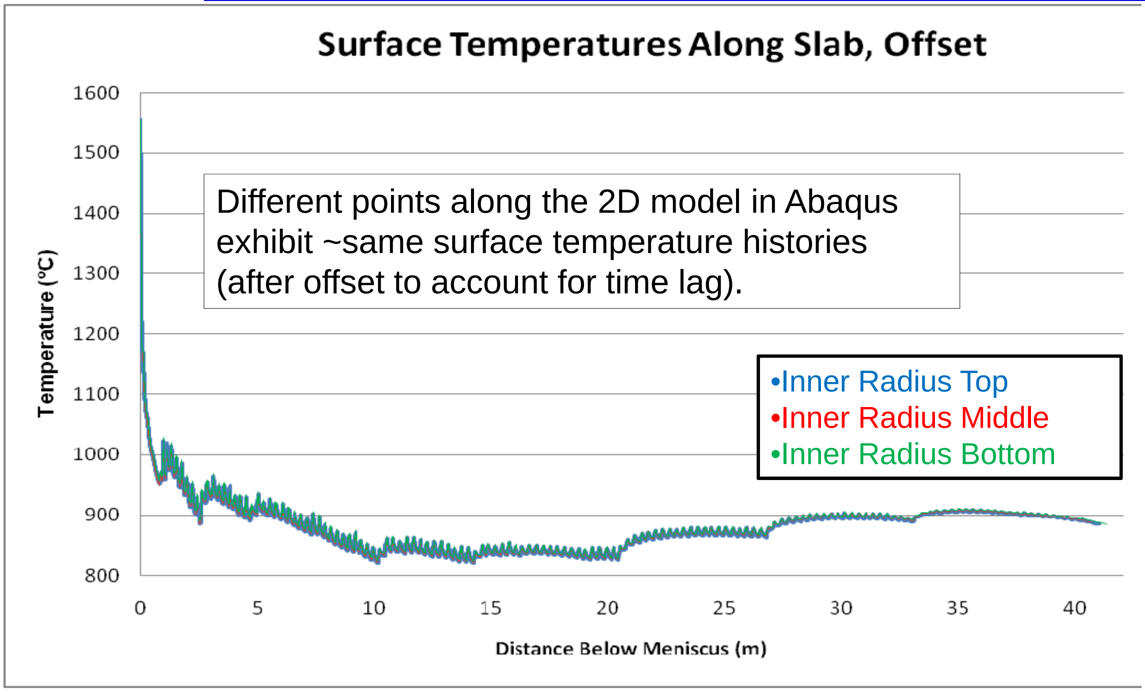
1518.6°C 1480.6°C 1438.6°C 1383.6°C 889.6°C 734.6°C



# Surface Temperatures

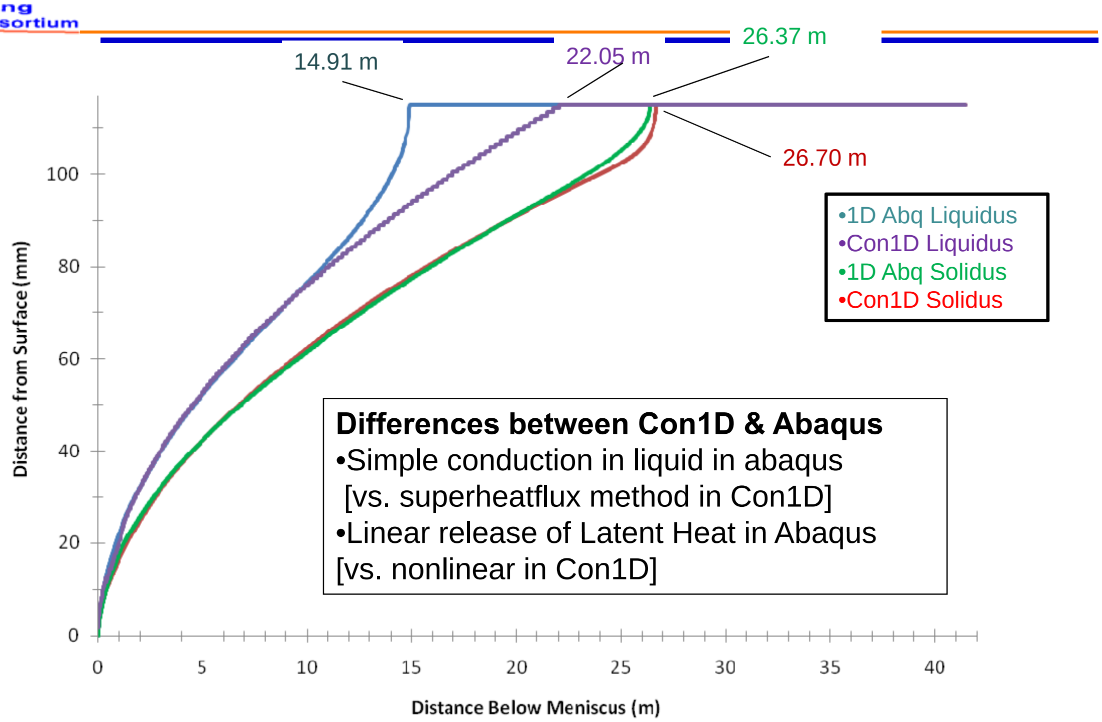


# 2D Surface Temperatures

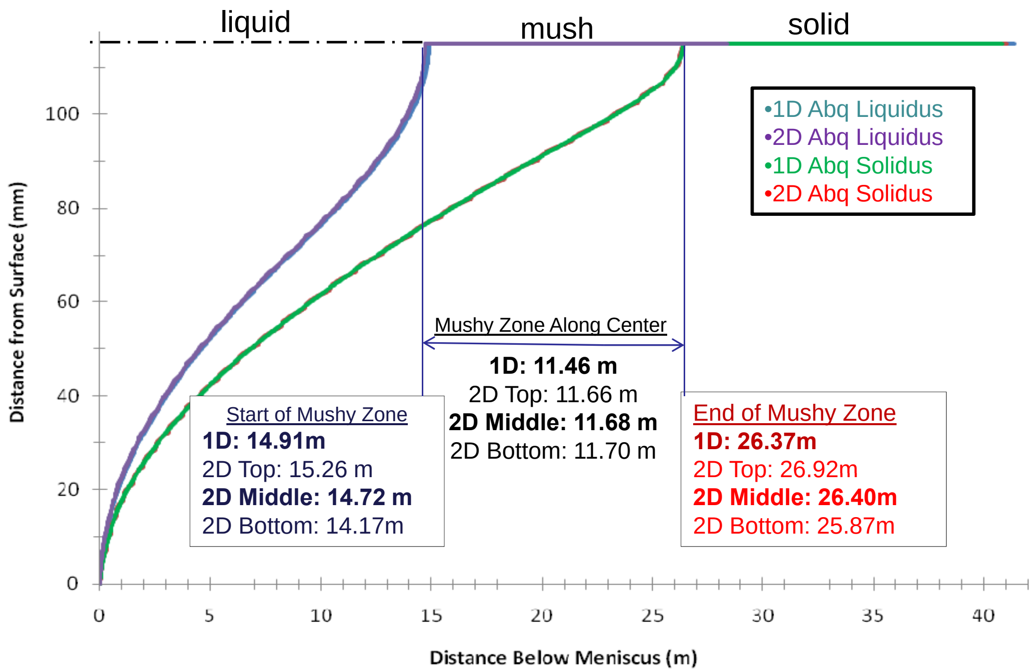





# Shell Thickness Comparison

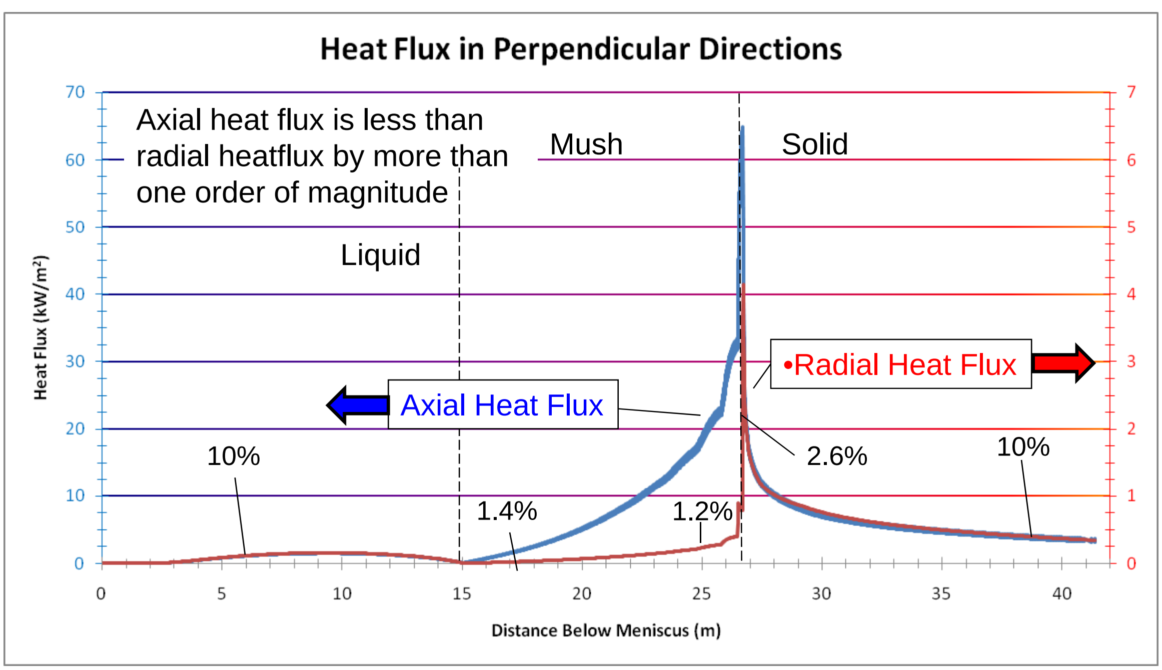


# 1D & 2D Shell Comparison in Abaqus



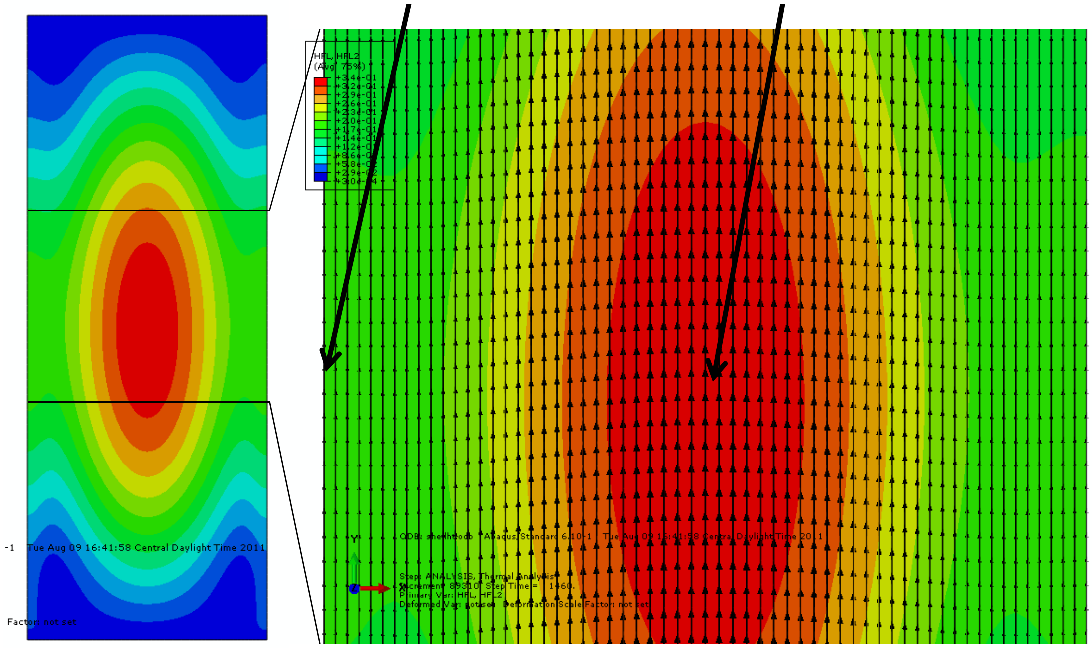



# Heat Flux at Center of 2D Slab



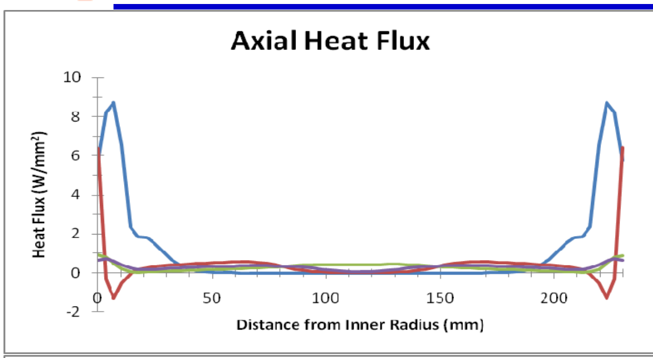
# Axial Heat Flux

$HF_{axial}$=0.195 kW/m$^2$ $HF_{axial}$=0.345 kW/m$^2$



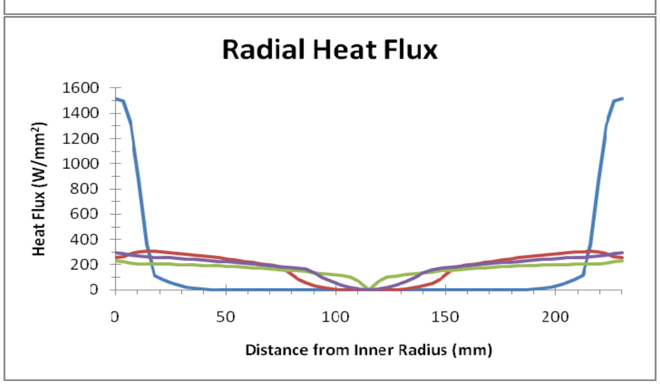


# Heat Flux Through Width




(Middle of 2D Domain)

<u>Distance Below Meniscus</u>
- 0.766974 m (Mold Exit)
- 14.92866 m (Liquid/Mush)
- 19.83 m (Mushy Zone)
- 26.37802 m (Mush/Solid)

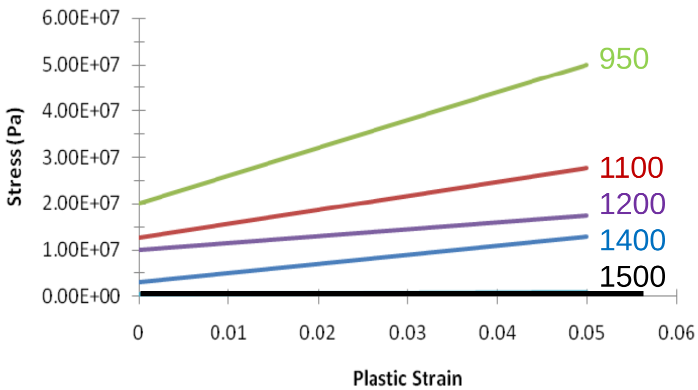



In solid shell,
Axial Heat Flux is always less than 1% of the Radial heat flux

# Thermal-Elastic-Plastic Stress Analysis

## (Temperature-Dependent Property Data in Abaqus)

Yield Stress versus Plastic Strain data
For Elastic-Thermal-Plastic Analysis in Abaqus

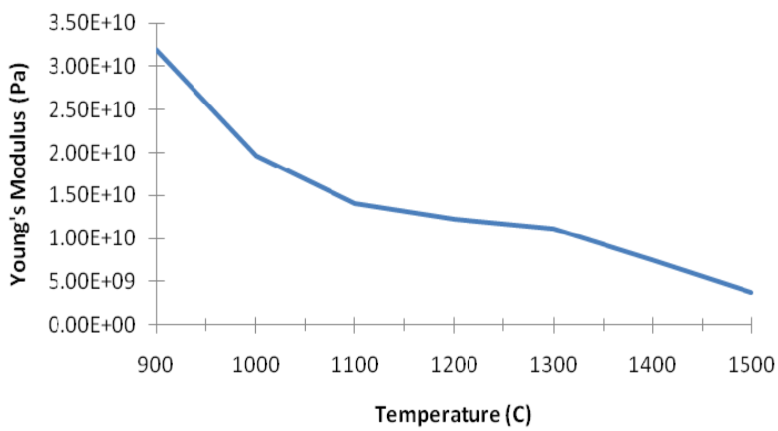



| Plastic Stress (Pa) | Plastic Strain | Temperature (C) |
|---|---|---|
| 2.00E+07 | 0 | 950 |
| 5.00E+07 | 0.05 | 950 |
| 1.27E+07 | 0 | 1100 |
| 2.77E+07 | 0.05 | 1100 |
| 1.00E+07 | 0 | 1200 |
| 1.75E+07 | 0.05 | 1200 |
| 3.00E+06 | 0 | 1400 |
| 1.30E+07 | 0.05 | 1400 |
| 5.00E+05 | 0 | 1500 |
| 1.00E+06 | 0.05 | 1500 |



# Elastic Modulus

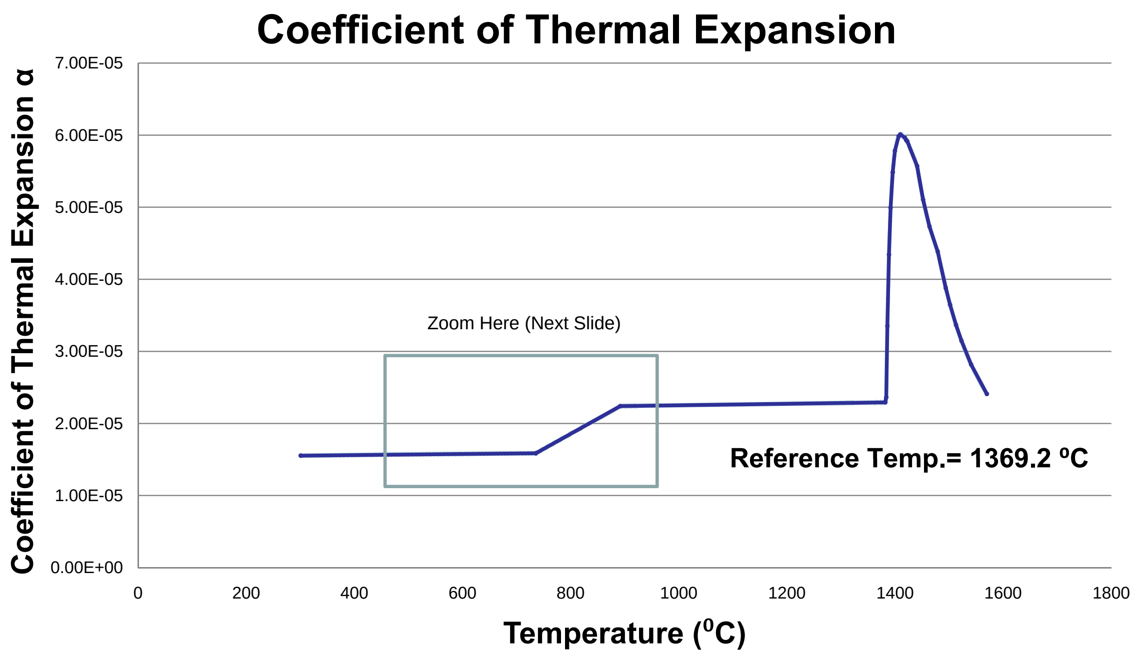
## (Temperature-Dependent Property Data in Abaqus)




| Young's Modulus (Pa) | Temperature (C) |
|---|---|
| 3.20E+10 | 900 |
| 1.96E+10 | 1000 |
| 1.40E+10 | 1100 |
| 1.22E+10 | 1200 |
| 1.11E+10 | 1300 |
| 7.51E+09 | 1400 |
| 3.75E+09 | 1500 |

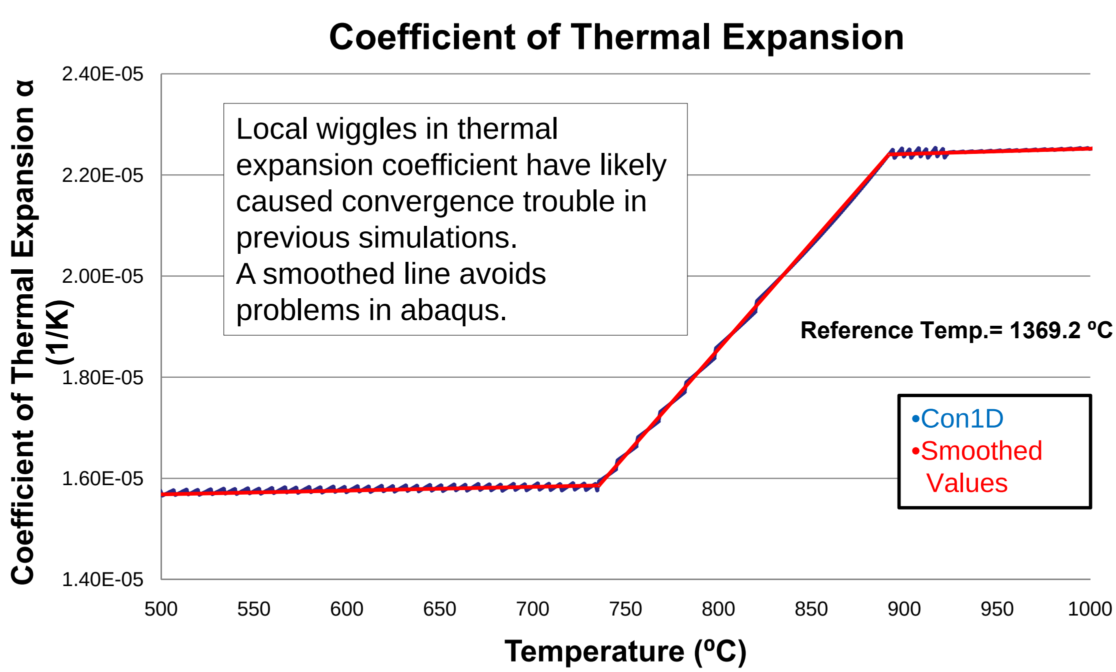
Poisson Ratio = 0.3

# Thermal Expansion Coefficient

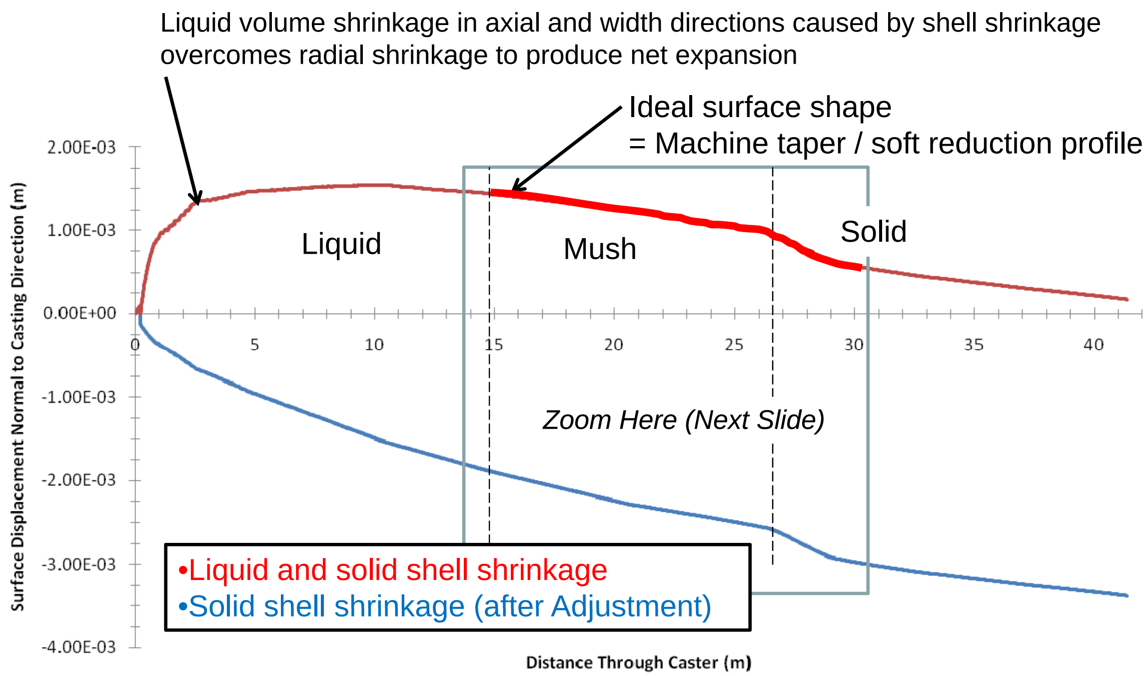





# Variations in α



# Displacement of Surface






# Adjustment to account for constraint of the liquid

- The two generalized plane strain conditions constrain the liquid and causes shell to bulge out
- Alternatively, this strain in the liquid can be subtracted to find just the solid shell shrinkage

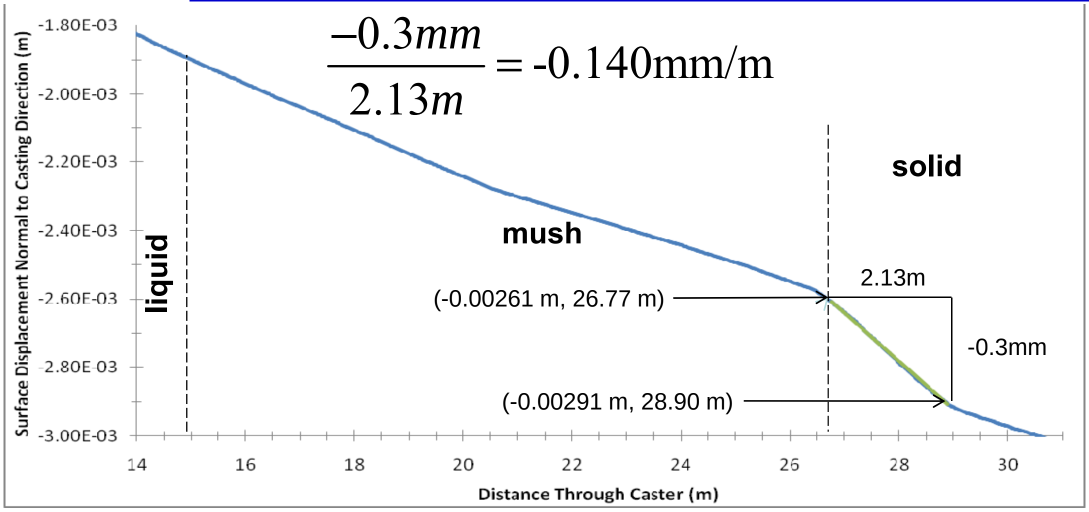
If $t < t_{finalsolidification}$ :

$$u_x(x,t) - \int_{\text{centerline}}^{x} \varepsilon_{xx}(\text{centerline}, t)\,dx$$

Otherwise:

$$u_x(x,t) - \int_{\text{centerline}}^{x} \varepsilon_{xx}(\text{centerline}, t_{finalsolidification})\,dx$$

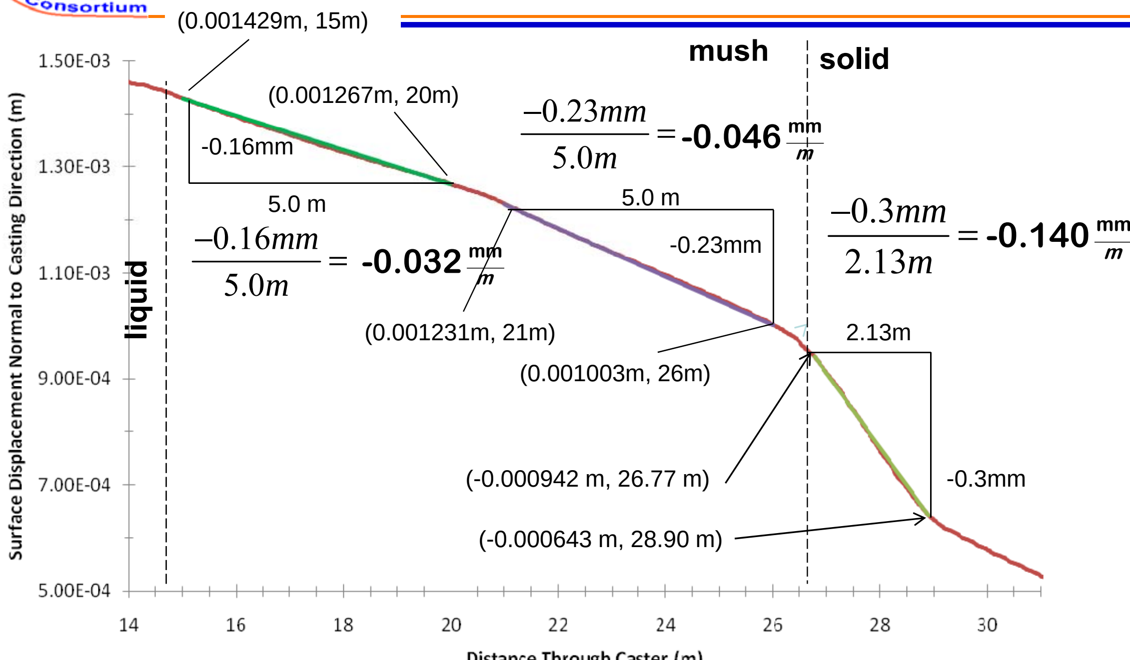
# Shell Shrinkage




- Accounting for both sides, the maximum rate of shrinkage is **0.280 mm/m** found just **after final solidification**
- This accelerated shrinkage should be accounted for by extending soft reduction slightly beyond final solidification



# Liquid and Solid (total) Shrinkage




Ideal surface shape
= Machine taper / soft reduction profile (after accounting for “soft reduction efficiency”)

# Conclusion

- Rapid fluctuations in material properties may cause convergence problems in simulations
- One-dimensional simulation matches two-dimensional for this high-Pe number problem
- Axial heat transfer is 100X smaller than radial heat flux near surface, but only 10X smaller in the liquid and solid center where temperature gradients are very small.
- Accelerated shrinkage occurs immediately after final solidification.



# Future Work

- Two Dimensional Mechanical Model
  - Rollers modeled
  - Proper bending and rotation already applied
  - Working on incorporating heat flux
  - Thorough stress analysis

- Three Dimensional thermal-mechanical model of shell in mushy zone (ignoring liquid)

  Calculating Soft Reduction Efficiency to account for NF Bulging, WF Bulging, and plasticity effects

# Acknowledgements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- Brian Thomas, UIUC