TRIGA mk. II Loss of Coolant Accident (LOCA):

An open source approach to modelling and analysis

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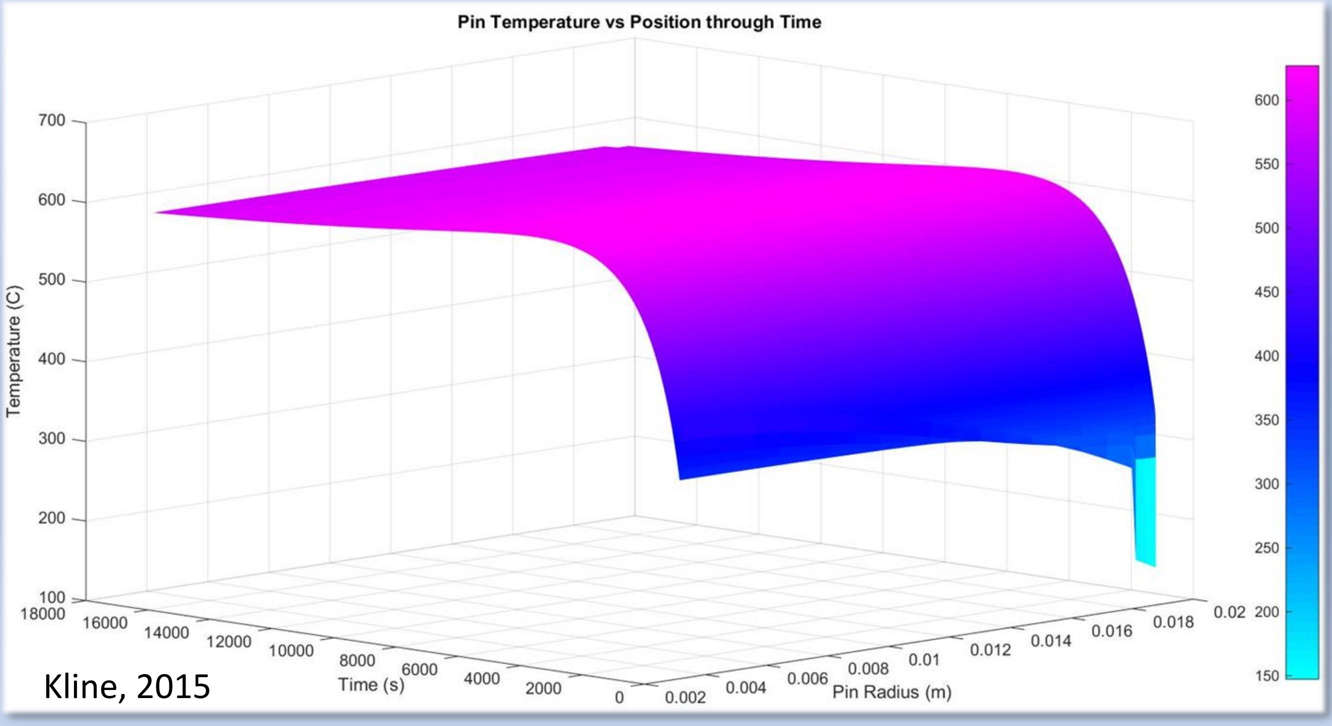
Design Criteria

- Meet the NRC RAI criteria of the UT 2016 relicensing
- Accurate 1D, transient CFD model, with reasonable solution time
- Expandability to other TRIGA reactor configurations
- Open source approach
- Repeatability and versatility
- Meets validation criteria



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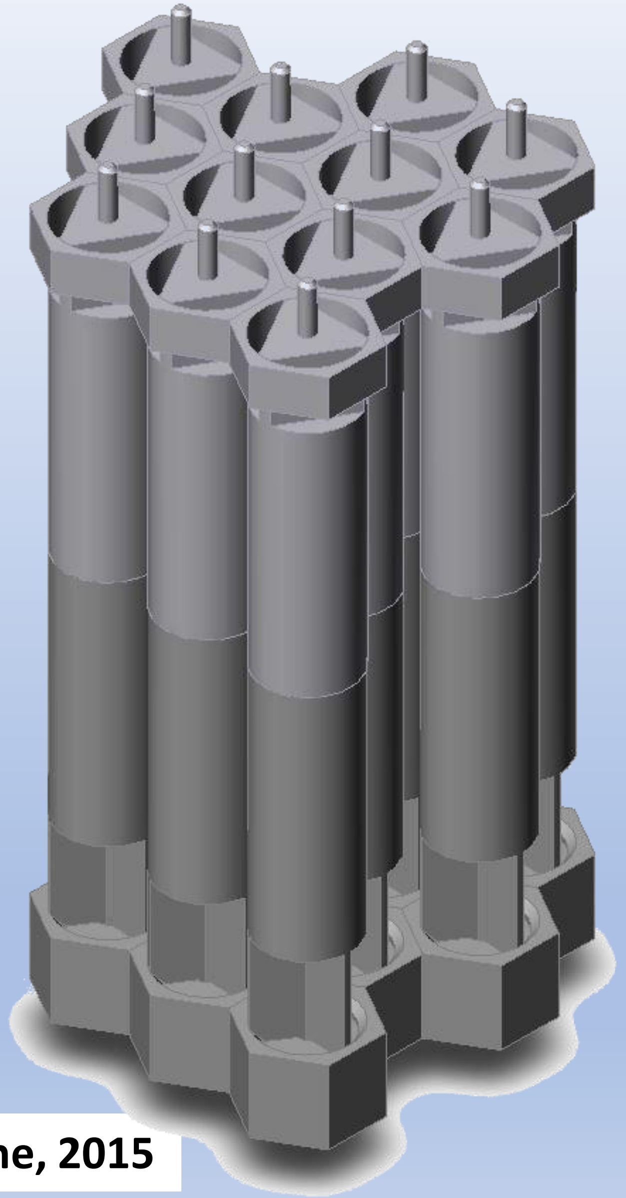
General Parameters

- Limiting core configuration based on critical heat flux ratio of 2.0
- Instantaneous scram and loss of coolant
- Radial one-dimensional model
- Area of maximum axial heat flux
- Decay heat IAW Kansas State decay curve[2]
- Initial power and channel air temperatures varied IAW VnV



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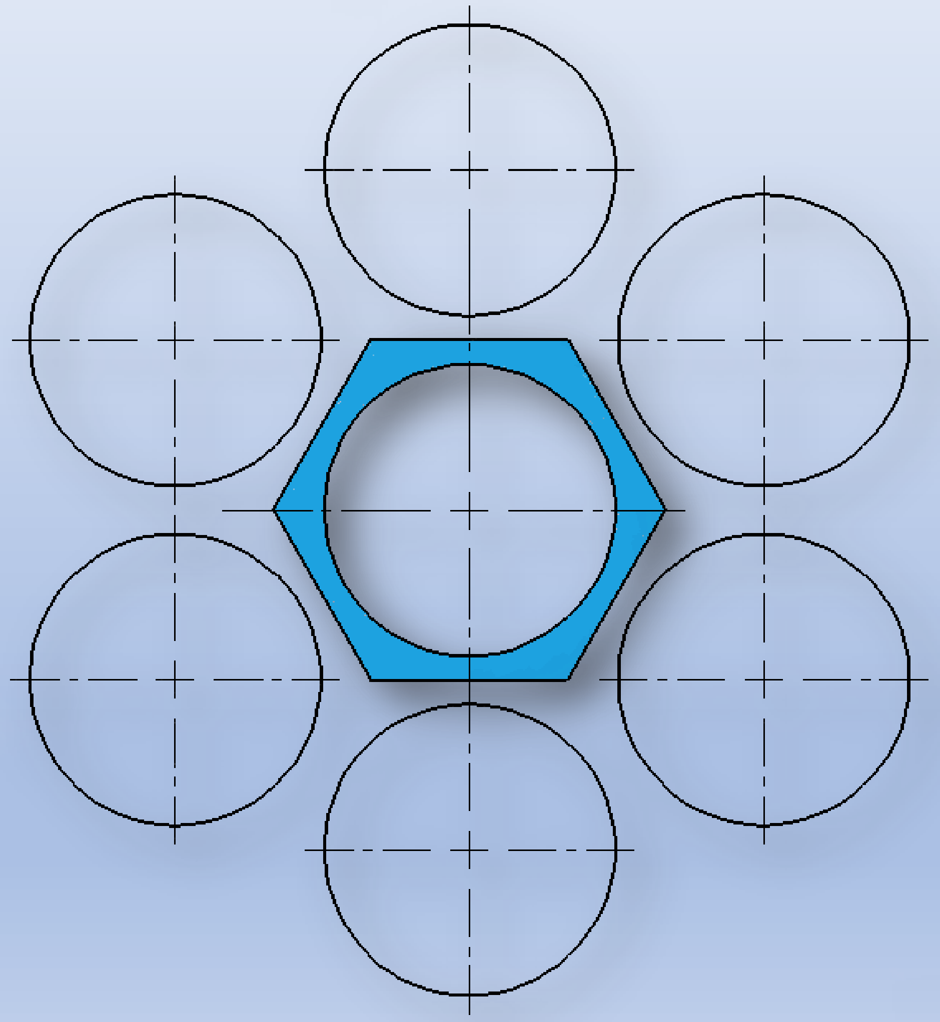
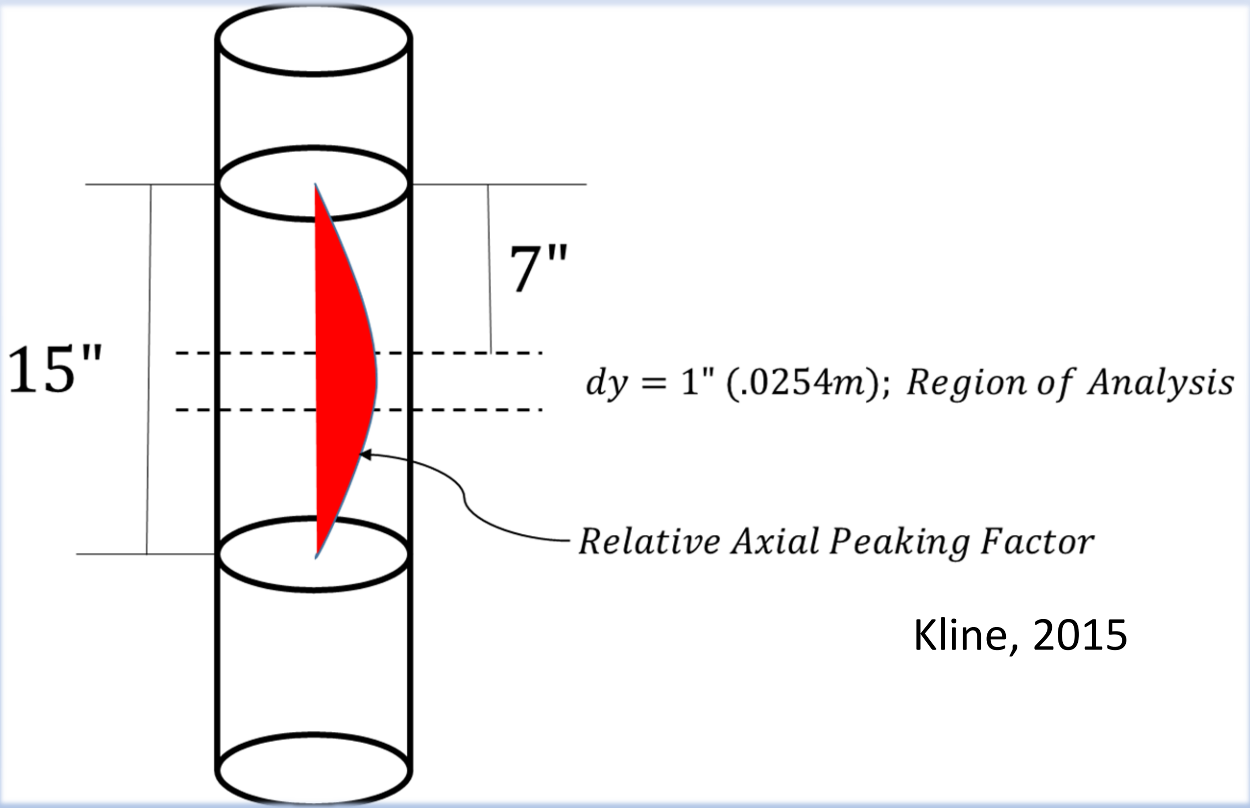
UT LOCA Model: Geometry

- Fuel dimensions IAW UT Technical Specifications[1]:
  - 8.5% wt. 19.7% enriched U
  - Zr:H of 1.6
  - 0.020” ($5.08e^{-4}$m) cladding thickness
  - ~0.005” ($1.97e^{-5}$m) gas gap
  - 1” active fission region, representing maximum segment
- Air channel width based on hexagonal geometry and symmetry
  - Symmetrical channel flow
  - Constant radial velocity
  - Constant axial velocity



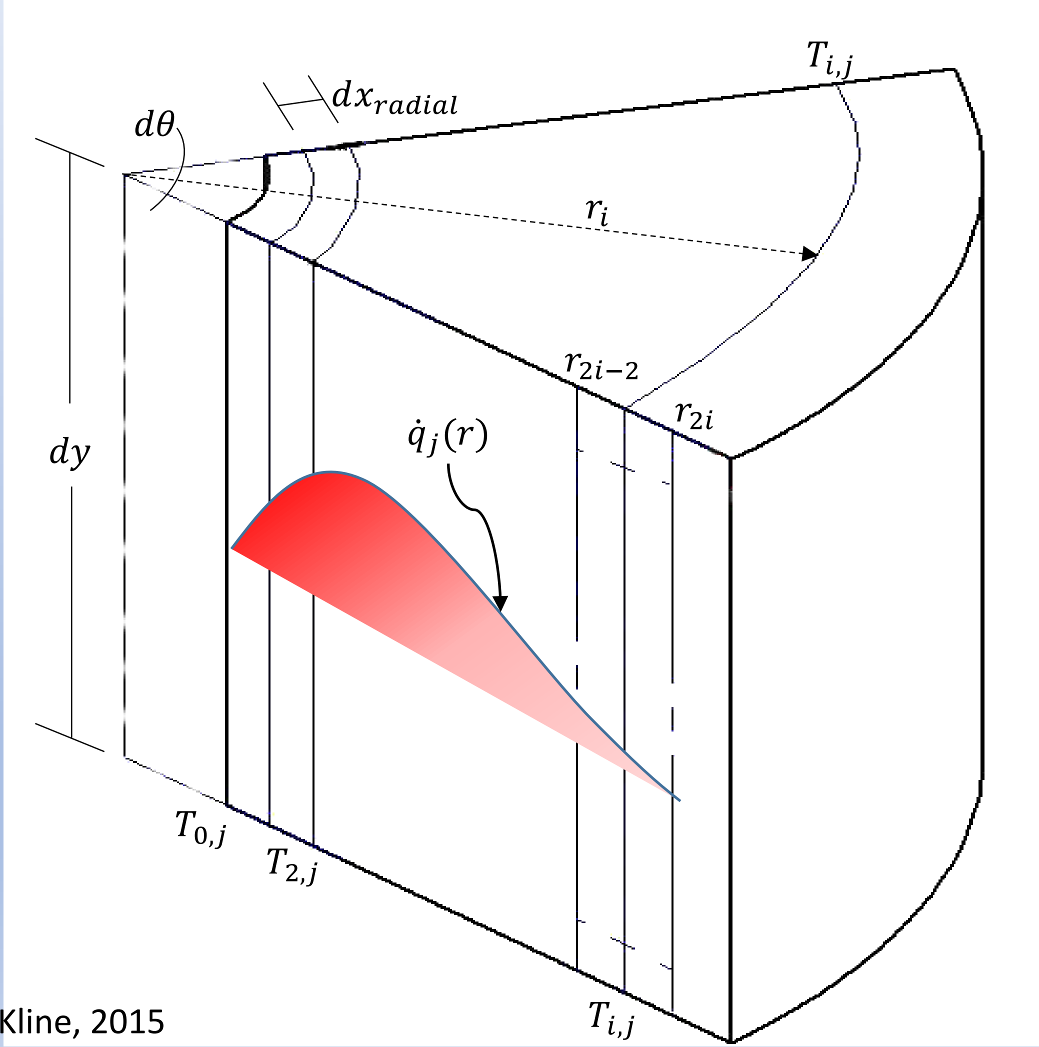
UT LOCA Model: Geometry, Axial

- Axial modelling slice is taken at the region of maximum relative axial peaking factor of 1.2
- This was considered for the pin with the highest radial peaking factor
- The segment height is relative to the axial peaking factor curve subdivisions (15)



UT LOCA Model: Geometry, Radial

- The model is a 1D radial layout[10]
  - $d\boldsymbol{\theta}$ is 2π Radians around
  - $\boldsymbol{dy}$ is based on peaking factor slice
  - $\boldsymbol{dx_{radial}}$ is set to accommodate Biot number
  - $\boldsymbol{dr}$ is set to allow volume calculations for transient analysis portion and is (2n-1) times the length of $\boldsymbol{dx_{radial}}$
  - Axial peaking factor is **1.2**
  - Radial peaking factor IAW polynomial curve fit from TRACE data and volumetric correction
    - $\boldsymbol{q_{gen,SS,r} = q_{max} \cdot q(r) \cdot \pi \cdot dy \cdot \left({r_{2i}}^2 - {r_{2i-2}}^2\right)}$
    - $\boldsymbol{q(r) = C_{axial,peak} q_{max}(247192r^3 - 5377r^2 + 45.882r + .7335)}$



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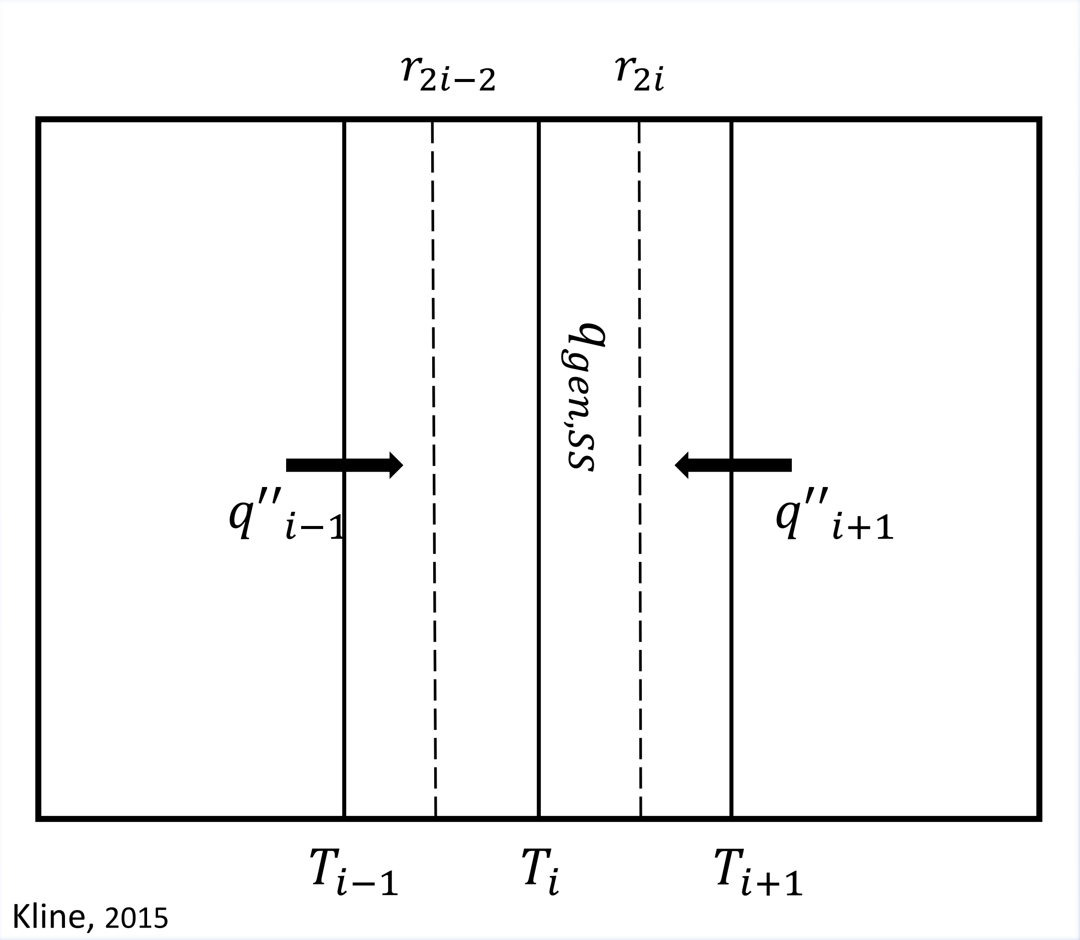
UT LOCA Model: Steady State Finite Element Analysis (FEA)

- Establish a SS initial temperature profile at t^{0-} just prior to LOCA
  - Water cooled constant element power
- Basis for FEA is elemental energy balance[4]:
  - $\dot{\boldsymbol{E}}_{st} = \dot{\boldsymbol{E}}_{gen} + \dot{\boldsymbol{E}}_{in} - \dot{\boldsymbol{E}}_{out} \rightarrow$
  - $\boldsymbol{\rho} \cdot \boldsymbol{V} \cdot \boldsymbol{c}_p \cdot \frac{\boldsymbol{dT}}{\boldsymbol{dt}} = \boldsymbol{q}_{gen} + \boldsymbol{q}_{cond} + \boldsymbol{q}_{conv}$
- For the steady state analysis $\dot{\boldsymbol{E}}_{st} = \mathbf{0}$; and in FEA energy is always considered coming into each element $\Rightarrow \dot{\boldsymbol{E}}_{out} = \mathbf{0}$;
- Thus the energy balance becomes:
  - $\dot{\boldsymbol{E}}_{in} + \dot{\boldsymbol{E}}_{gen} = \mathbf{0}$

UT LOCA Model: Steady State Finite Element Analysis (FEA)

- Energy is transferred via conduction with all but the outer radial element
  - It contains a convection term as well
  - Gas layer is considered conductive
- Radially corrected conduction term[3,4]:
  - $\boldsymbol{q_{cond,SS} = \frac{2 \cdot \pi \cdot dy \cdot k_{fuel} \cdot (T_{i\pm1} - T_i)}{ln\left(\frac{r_{larger}}{r_{smaller}}\right)}}$
- Final element exposed to fluid contains convection[3,4]::
  - $\boldsymbol{q_{conv,SS} = h_{water} \cdot \pi \cdot r_{max} \cdot dy \cdot (T_s - T_{inf})}$



UT LOCA Model: Steady State Finite Element Analysis (FEA)

- Set up a matrix format for solution[10]
  - $\boldsymbol{A}$ invertible matrix represents temperature dependent items
  - $\vec{\boldsymbol{x}}$ vector represents the radial temperature array
  - $\vec{\boldsymbol{b}}$ vector represents temperature independent items
  - $\boldsymbol{A\vec{x} = \vec{b} \Longrightarrow \vec{x} = A^{-1}\overrightarrow{b};}$
- Example of a row of ***A:***
  - $\boldsymbol{a_i = \left[\ldots, \frac{2\cdot\pi\cdot dy\cdot k_{fuel(gas,clad)}\cdot(T_{i-1}-T_i)}{ln\left(\frac{r_{2i-1}}{r_{2i-3}}\right)}, -\left(\frac{2\cdot\pi\cdot dy\cdot k_{fuel(gas,clad)}\cdot(T_{i-1}-T_i)}{ln\left(\frac{r_{2i-1}}{r_{2i-3}}\right)} + \frac{2\cdot\pi\cdot dy\cdot k_{fuel(gas,clad)}\cdot(T_i}{ln\left(\frac{r_{2i+1}}{r_{2i-1}}\right)}\right.\right.}$

UT LOCA Model: Transient FEA

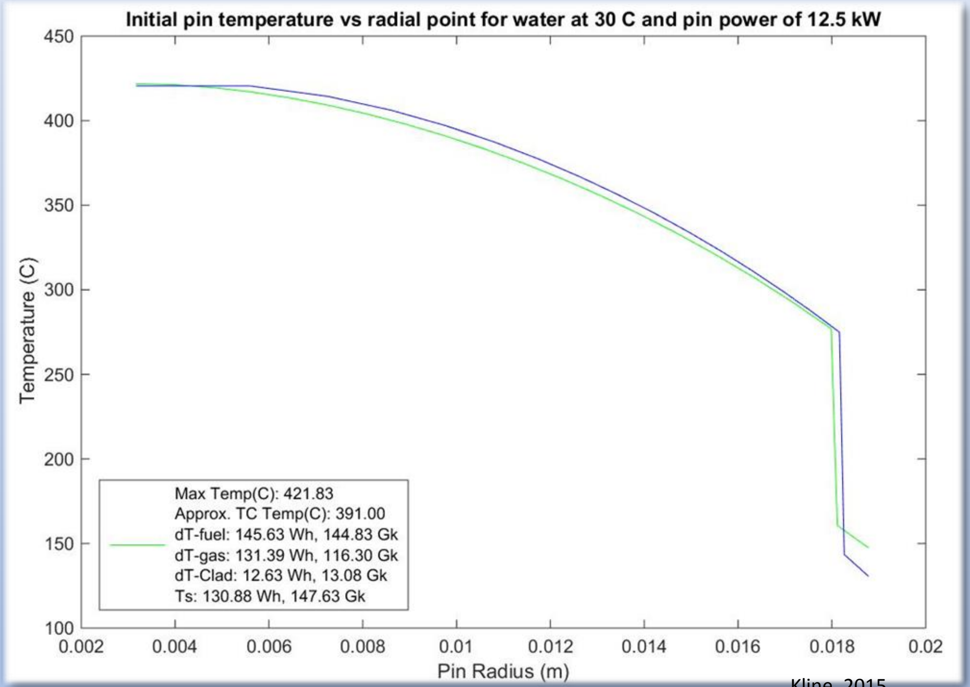
- The effects of mass, specific heat, and energy absorption can no longer be ignored[3,4]
- Time must be iterated and is done so explicitly; thus the equation becomes:
  - $\rho \forall c_p \frac{(T_i^{p+1} - T_i^p)}{\Delta t} = q_{cond} + q_{conv} + q_{gen}$
- The time dependent temperature equation becomes:
  - $T_i^{p+1} = \frac{\Delta t}{\rho \forall c_p}[a_i] + T_i^p$

UT LOCA Model: VnV

- The steady state model needed geometric validation based on the Biot number[3,4]:
  - $\boldsymbol{Bi = \frac{h \cdot L_c}{k}}$
- The transient model needed geometric and time dependence validation found through the Fourier number:
  - $\boldsymbol{Fo = \frac{\alpha \cdot t}{L_c}}$

UT LOCA Model: VnV

Steady State, IC VnV with LOCA, TRACE



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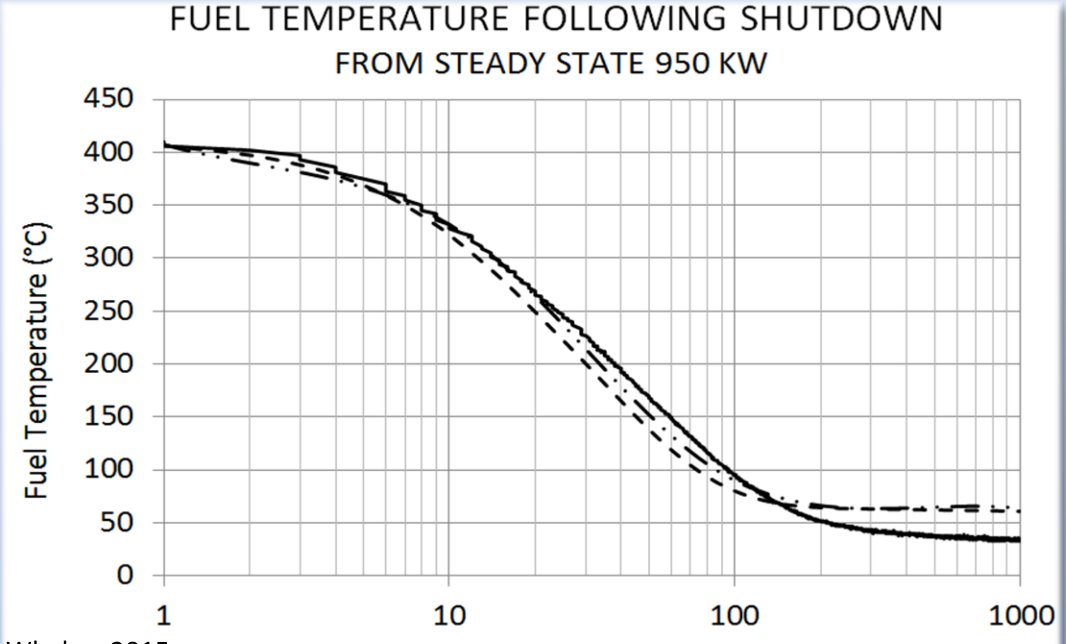
Transient VnV with LOCA, TRACE, and Real RX Ops



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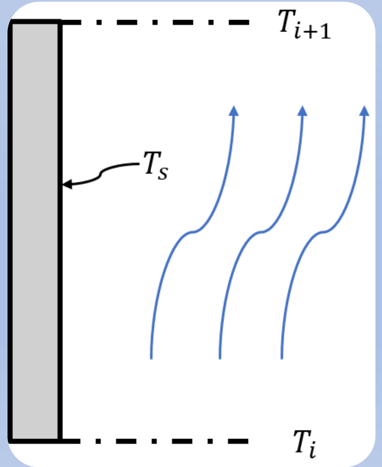
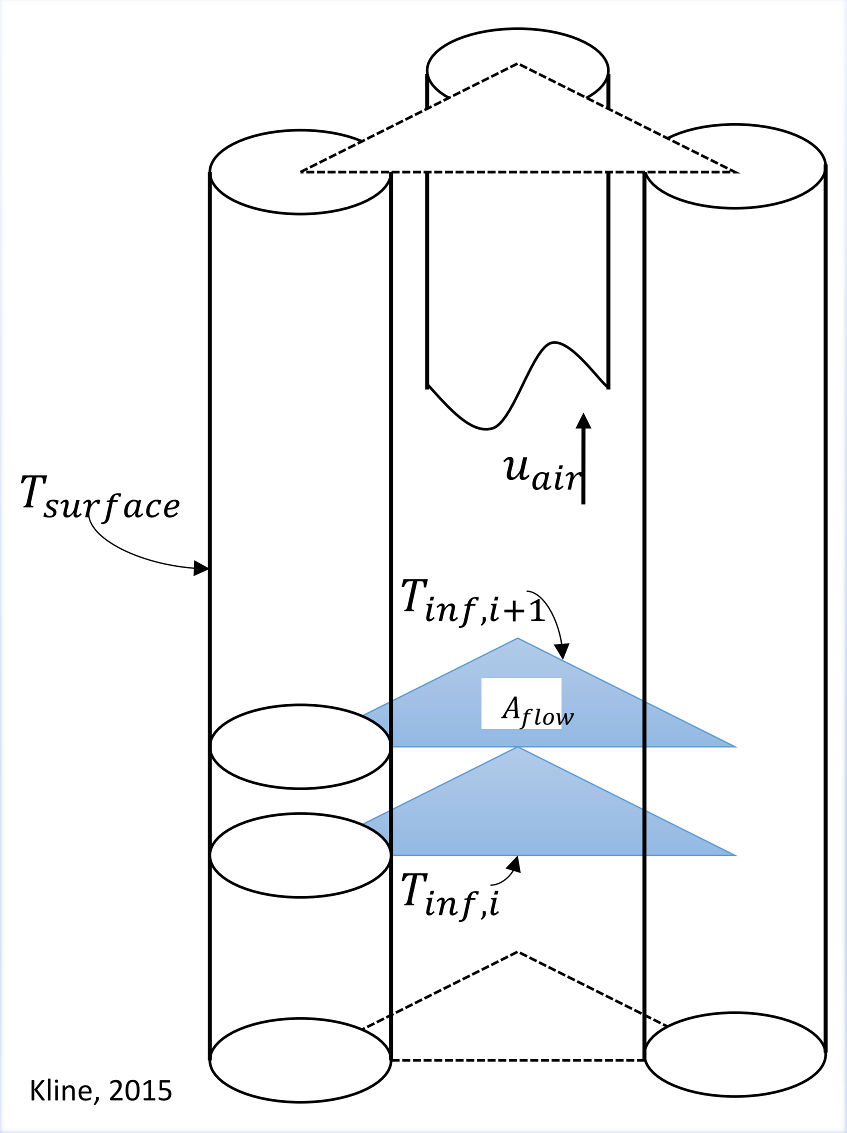
UT LOCA Model: Air Channel

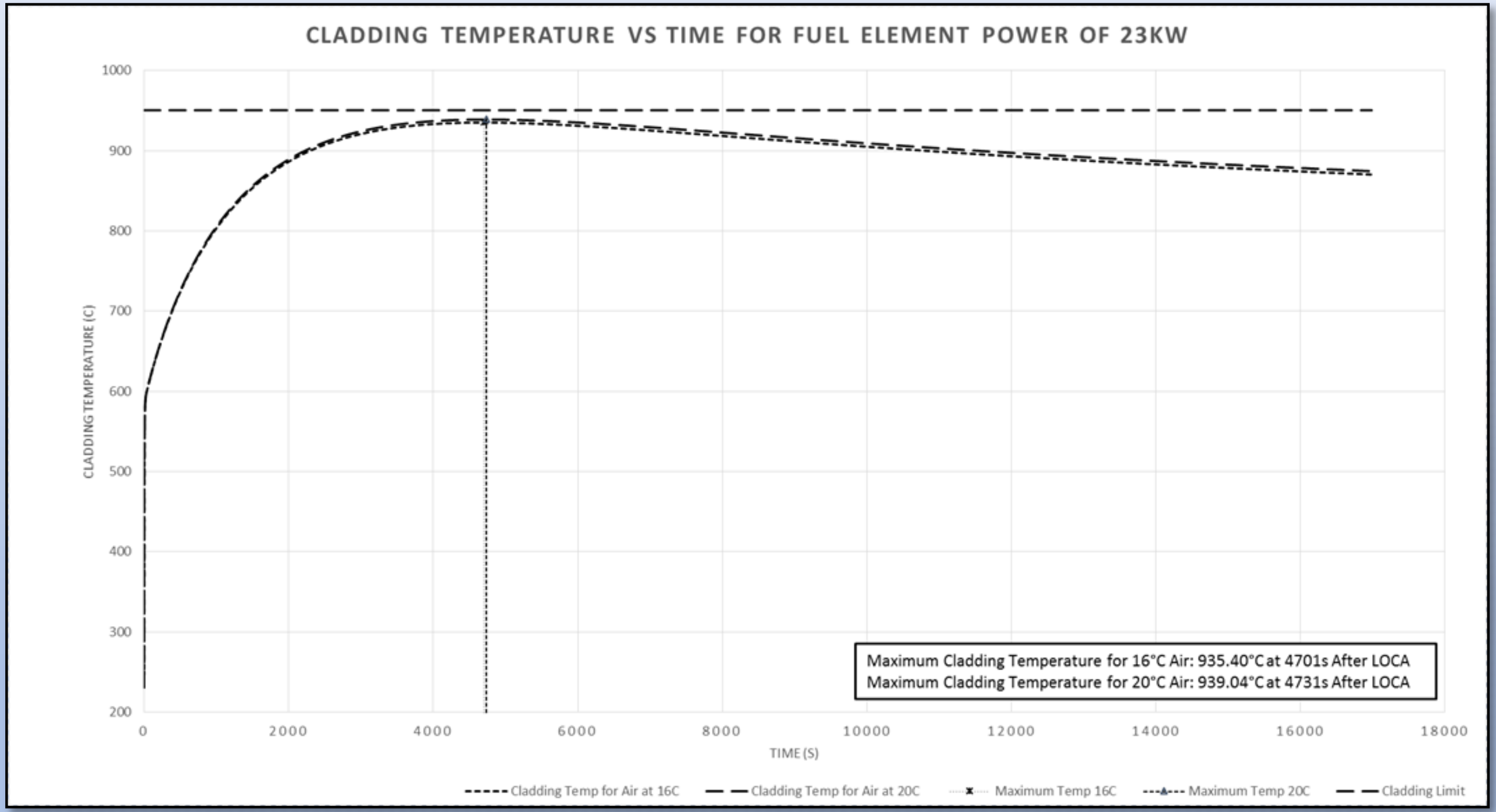
- Prior to parametric variation, an order of magnitude estimate of maximum air temperature in the channel was asked for[10]
- 1D vertical model incorporating iterated energy addition from a constant surface temperature to air





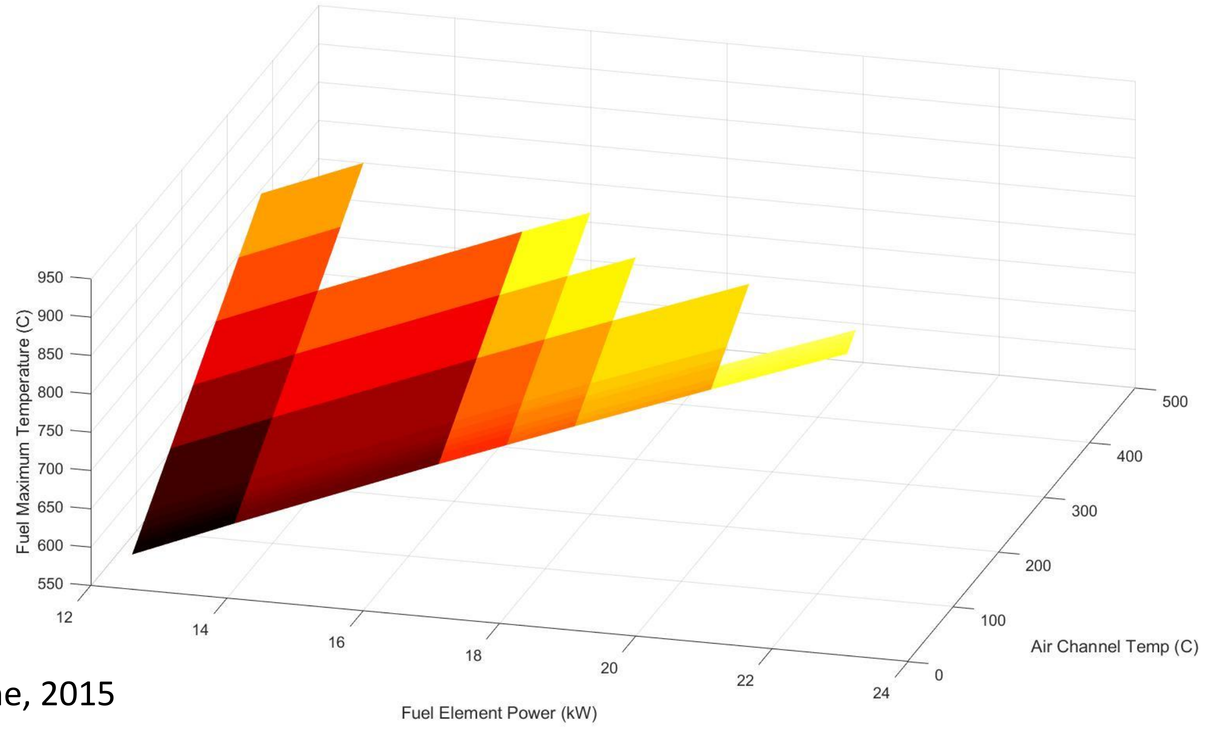
UT LOCA Model: Results

- The model outputs the cladding temperature vs. time for the entire transient.
- The model was run long enough to find the maximum temperature and ensure a proper trend.



UT LOCA Model: Parametric Variation

- The model was varied, using an in-house script, across a range of temperatures and fuel element powers
  - 16°C → 600°C
  - 12.5kW → 27kW



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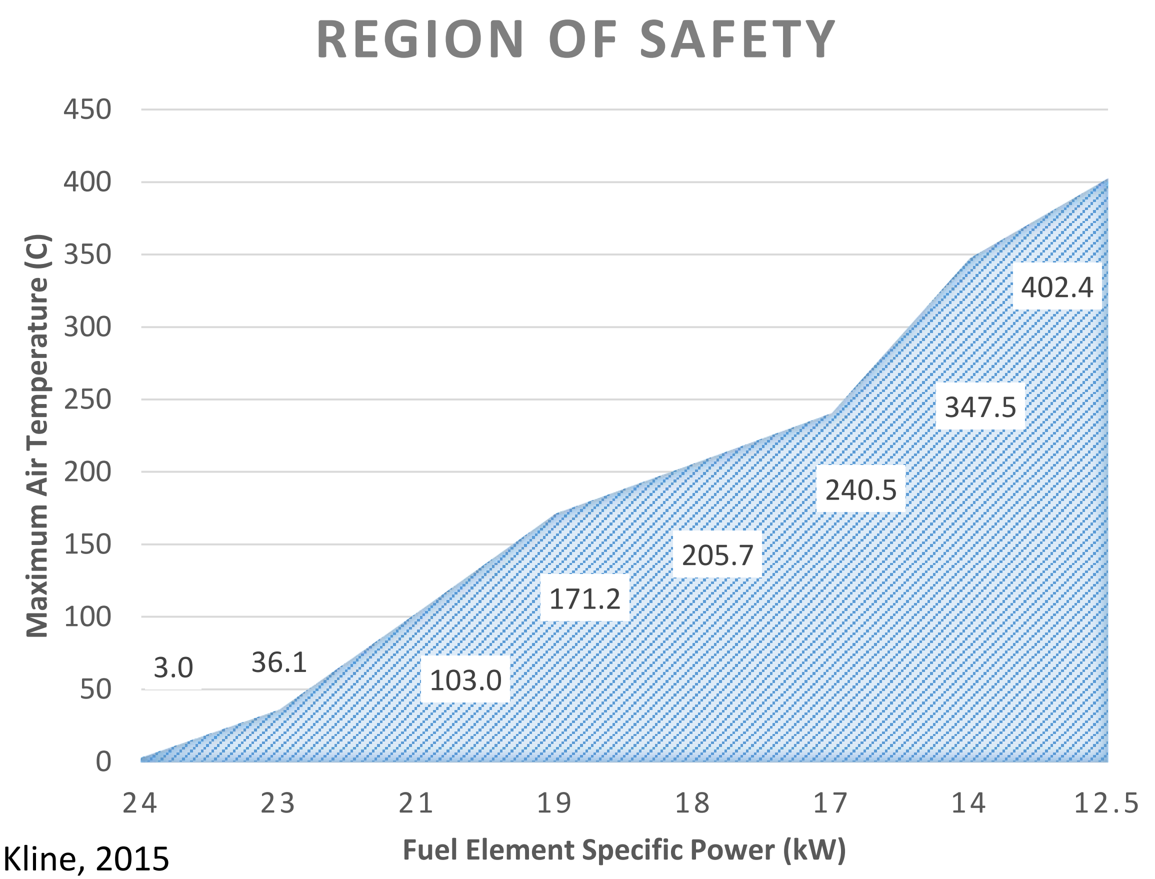
UT LOCA Model: Parametric Variation

- By using 950°C cladding maximum temperature as a criteria, a region of safety is developed [10]
- This shows the maximum allowable inlet air temperature for a given specific element power in order to not exceed the safety limit
  - The maximum fuel element power for nominal bay temperature of 16°C is 23.6kW
  - The maximum allowable air temperature for a nominal fuel element power of 12.5kW is 402°C



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Questions?

Thank You

References

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- [3] T. L. Bergman, A. S. Lavine, F. P. Incropera, and D. P. DeWitt, *Fundamentals of Heat and Mass Transfer*. 2011.
- [4] F. P. Incropera, D. P. DeWitt, T. L. Bergman, and A. S. Lavine, *Fundamentals of Heat and Mass Transfer*, vol. 6th. 2007.
- [5] Henri Fenech, *Heat Transfer and Fluid Flow in Nuclear Systems*. Pergamon Press, 1981.
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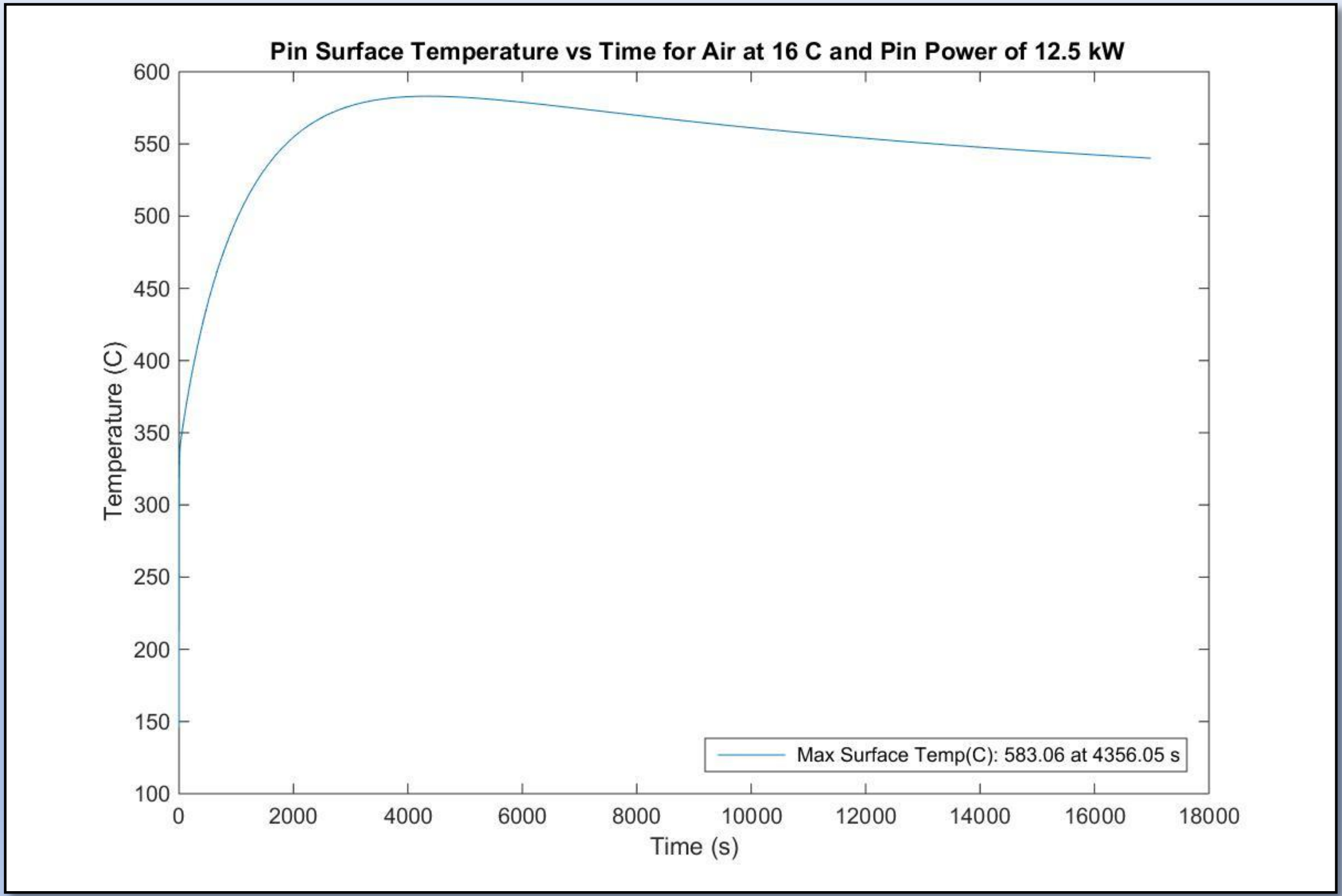
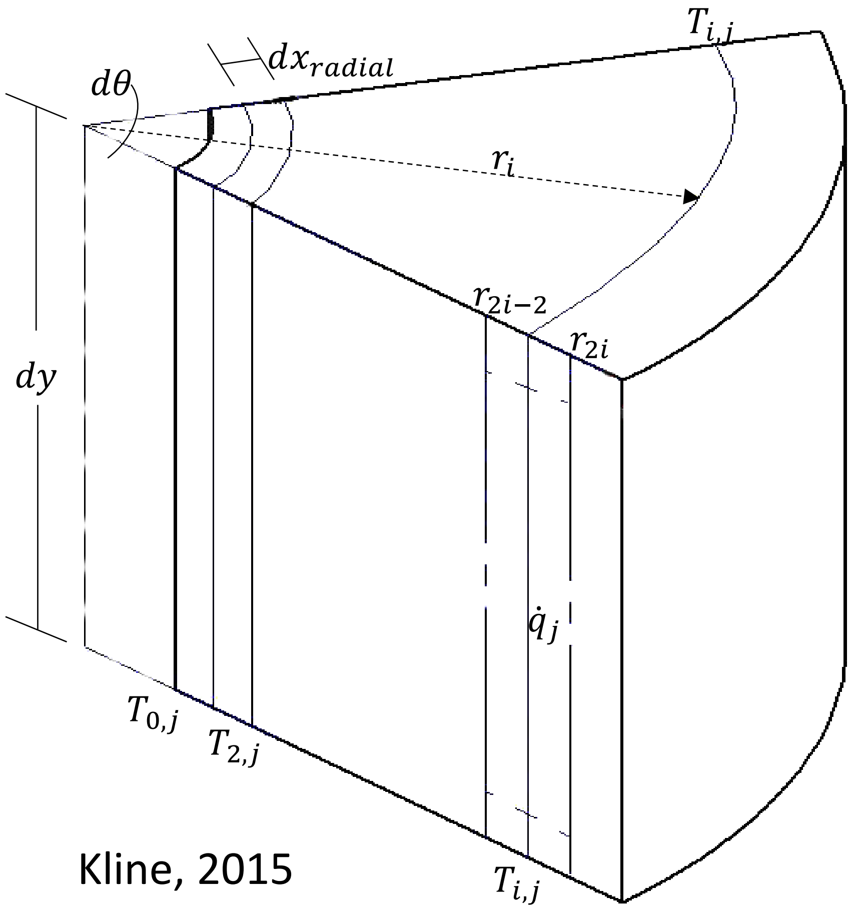
- [7] C. O. Popiel and J. Wojtkowiak, “Simple formulas for thermophysical properties of liquid water for heat transfer calculations (from 0 to 150 degrees C) (vol 19, pg 87, 1998),” *Heat Transf. Eng.*, vol. 19, no. 3, pp. 87–101, 1998.
- [8] G. Kline, “channel_air_temp_3_0.” Greg Kline, Austin, p. 5, 2015.
- [9] K. Vafai, C. P. Desai, S. V. Iyer, and M. P. Dyko, “Buoyancy Induced Convection in a Narrow Open-Ended Annulus,” *J. Heat Transfer*, vol. 119, p. 483, 1997.
- [10] G. Kline, “LOCA_8_5_3_FEM.” Greg Kline, Austin, p. 20, 2015.
- [11] G. Kline, “PXIe_ICS_Power_Cal_Etc_2015.” Greg Kline, Austin, p. 100, 2015.

Appendix

UT LOCA Model: Output





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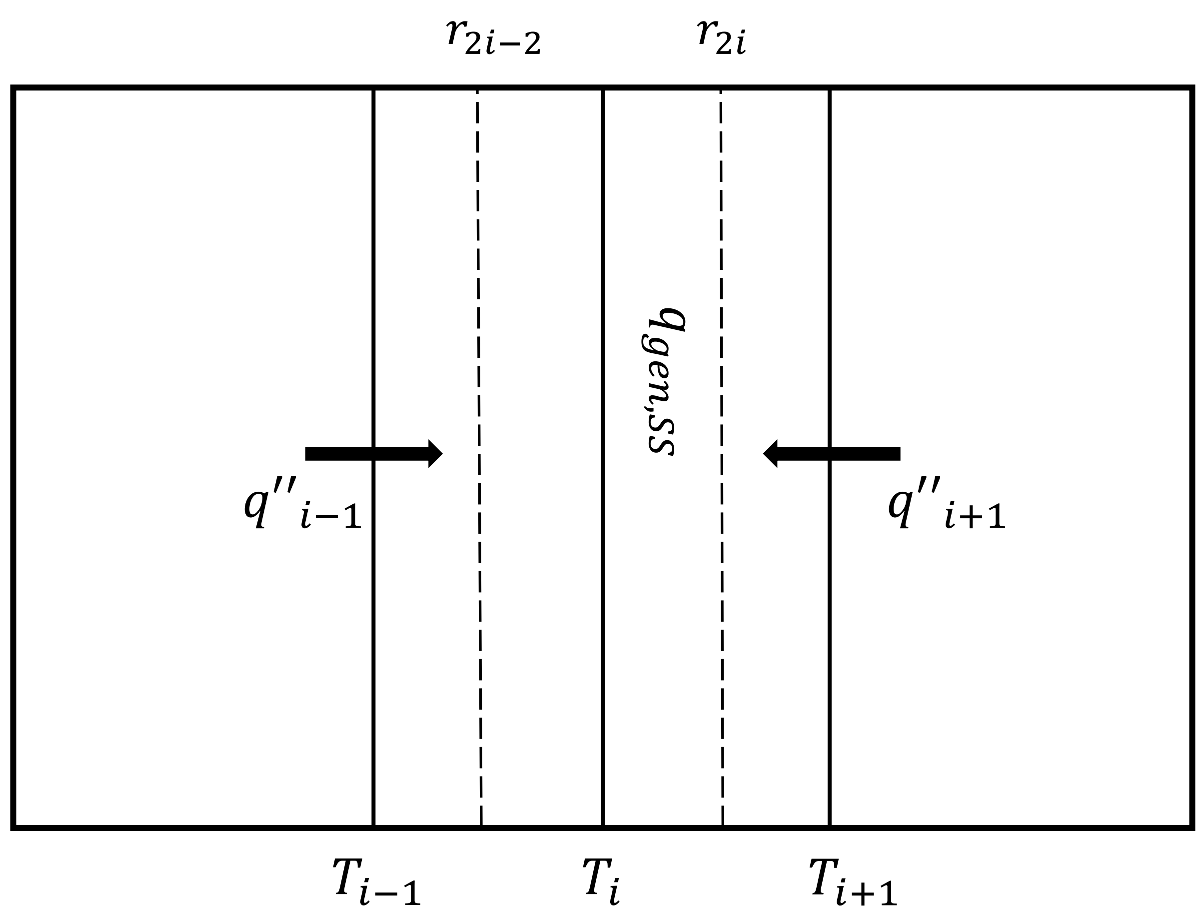
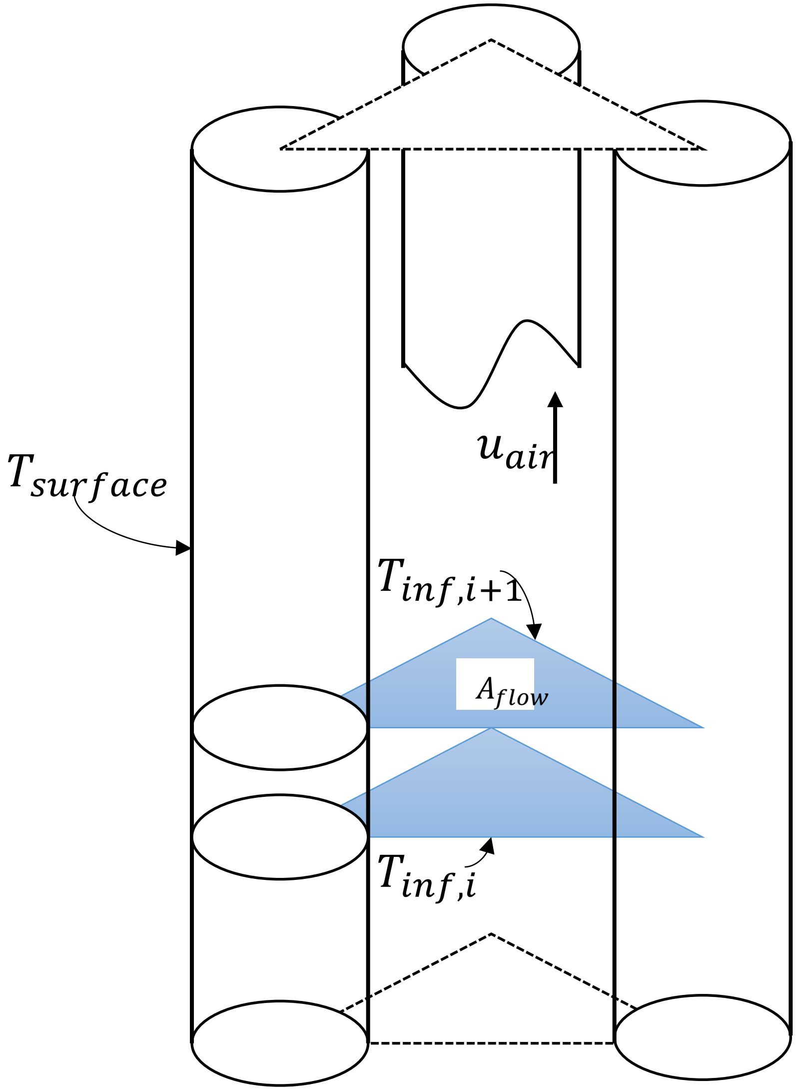
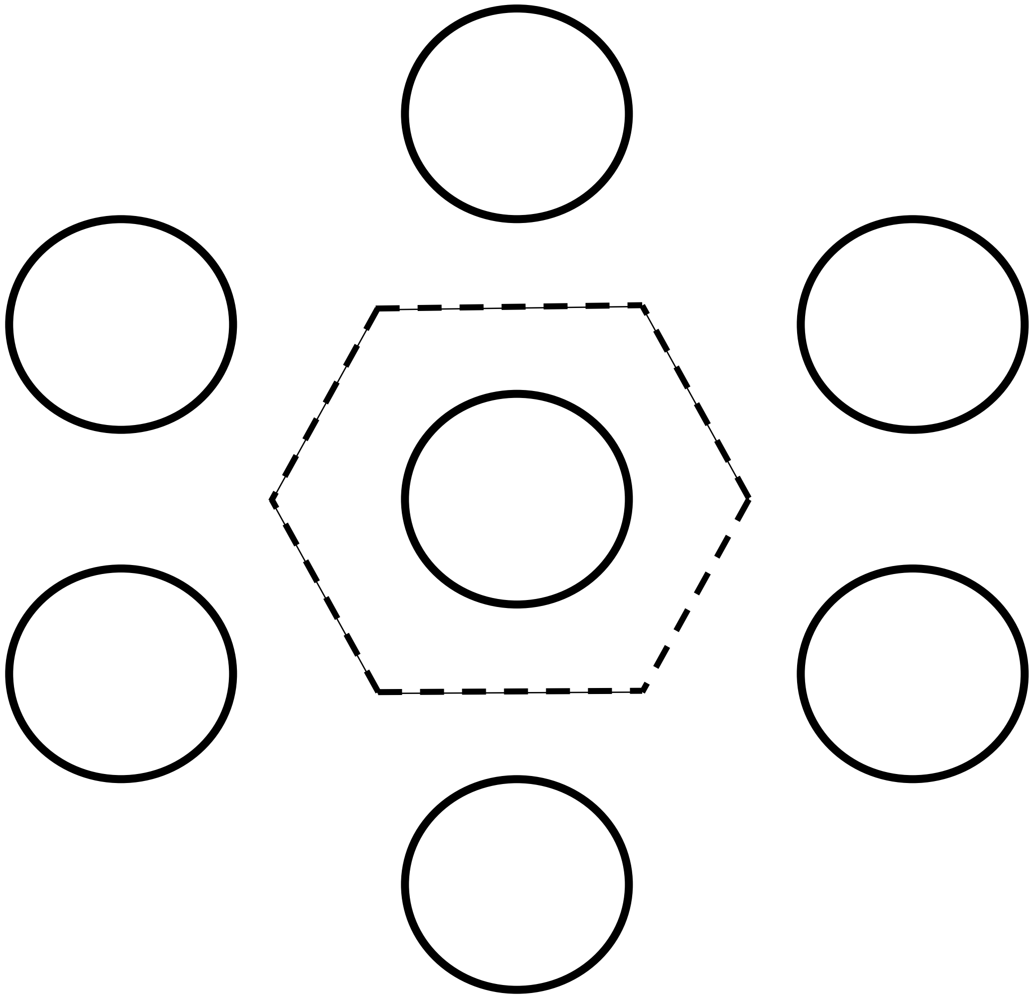
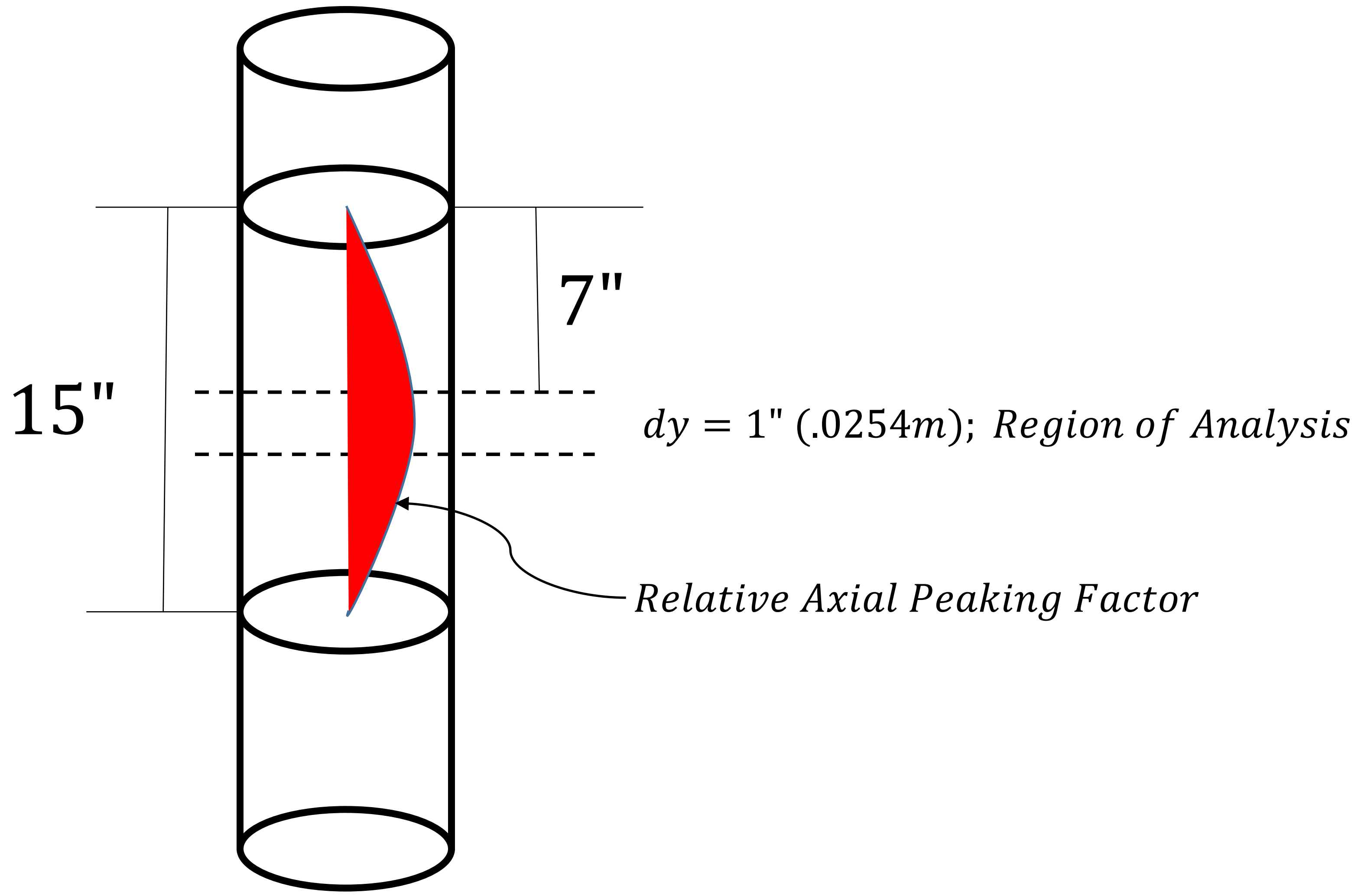


r_{2i-2}
r_{2i}
$q_{gen,SS}$
q''_{i-1}
q''_{i+1}
T_{i-1}
T_i
T_{i+1}

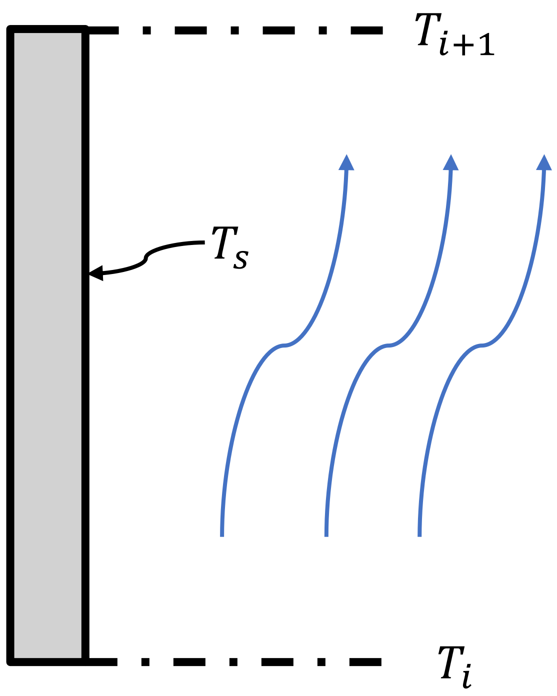


$T_{surface}$
u_{air}
$T_{inf,i+1}$
A_{flow}
$T_{inf,i}$





15"
7"
$dy = 1"\ (.0254m);\ Region\ of\ Analysis$
$Relative\ Axial\ Peaking\ Factor$



T_{i+1}
T_s
T_i