Fuel Performance Project

Cole Takasugi

1. Specifications and problem statement

Meshing:

Because the suggested 100x100 mesh does not place nodes directly on x-direction material boundaries (i.e. 0.7/100 = 0.007 cm node size and neither 0.5 nor 0.6 are perfectly divisible by an integer number of nodes), the utilized mesh is instead 105x105. This mesh is able to split close to material boundaries and should achieve closer to expected results.

Volumetric/areal heating rate:

- Steady State (SS): $Q[W/(cm^2\ )] = 250$
- Transient (TR): $Q[W/(cm^2\ )] = 150 * (1 - \exp\left(-0.01 * t\right)\ ) + 250 \qquad 0 \leq t \leq 200$

The implementation in MOOSE corresponds to the volumetric heat rate in [W/cm^3], such that:

$$LHR = Q\pi R_f^2$$

This is done by directly utilizing Q as the volumetric heat rate and applying the RZ coordinate system in the problem type.

Material properties:

Fuel domain: $0.0 < x < 0.5$

Gap domain: $0.5 < x < 0.6$

Clad domain: $0.6 < x < 0.7$

The material domains in the problem specifications are not realistic for standard UO_2 fuel used for light water reactors. Specifically, the large gap size, when considering a helium-gap thermal conductivity, would be associated with a large temperature rise in the gap region and results would correspond to fuel-melting temperatures. To prevent this issue, thermal properties are selected loosely based on metallic U-Zr fuel with a sodium-filled gap and steel cladding, these may roughly correspond to design such as a sodium-cooled fast reactor (SFR). The large thermal conductivities in both fuel and gap regions significantly flatten the temperature profile and prevent unrealistic spikes in temperature present in UO_2 fuel with helium gap of the same dimensions.

Table 1. Selected thermal parameters

PARAMETER	VALUE	PARAMETER	VALUE
Fuel thermal conductivity	0.38 W/cm-K	Fuel density	15.5 g/cm^3
Gap conductivity	0.667 W/cm-K	Fuel specific heat	0.23 J/g-K
Clad thermal conductivity	0.2035 W/cm-K	Gap density	0.846 g/cm^3
Coolant specific heat	1272 J/kg-K	Gap specific heat	1.272 J/g-K
Heat transfer coefficient to coolant	6.0 W/cm^2-K	Clad density	7.8 g/cm^3
		Clad specific heat	0.5 J/g-K

Boundary conditions:

- In every case, a Neumann boundary condition is applied to the left (rod center) boundary, such that the x-derivative (r-derivative) of the temperature is zero at this boundary.
- For the 1-D cases, a Dirichlet boundary condition sets the right boundary (clad outer temperature) to a constant value of 500 K.
- For the 2-D cases, a semi-realistic water coolant boundary is created utilizing MOOSE's convective flux function boundary condition. The coolant inlet temperature for these cases is set to 623 K (~350 °C) and rises due to power production in the rod. 0.15 kg/s is selected as the corresponding mass flow utilized to calculate the coolant temperature profile.

Problem statement:

Required components:

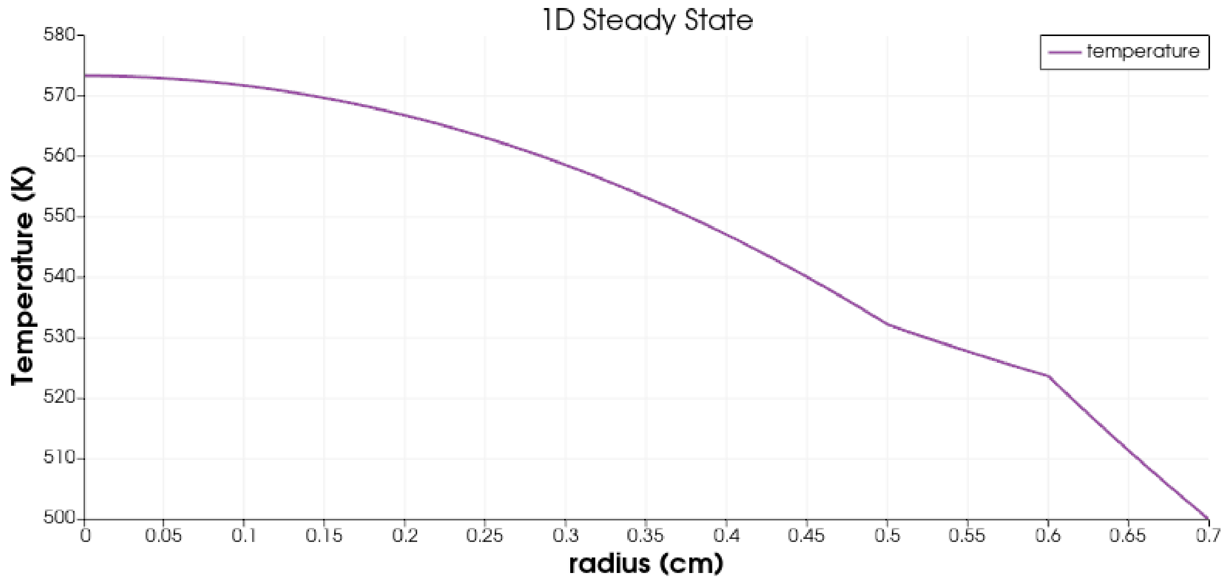
- 1-D steady state temperature profile
- 1-D transient fuel centerline temperature vs. time
- 2-D steady state temperature profile @ z=0.25 m, 0.5 m, 1 m
- 2-D transient fuel centerline temperature vs. time @ z=0.25 m, 0.5 m, 1 m
- Identification of peak centerline temperature location at steady state and t=200

Supplementary components:

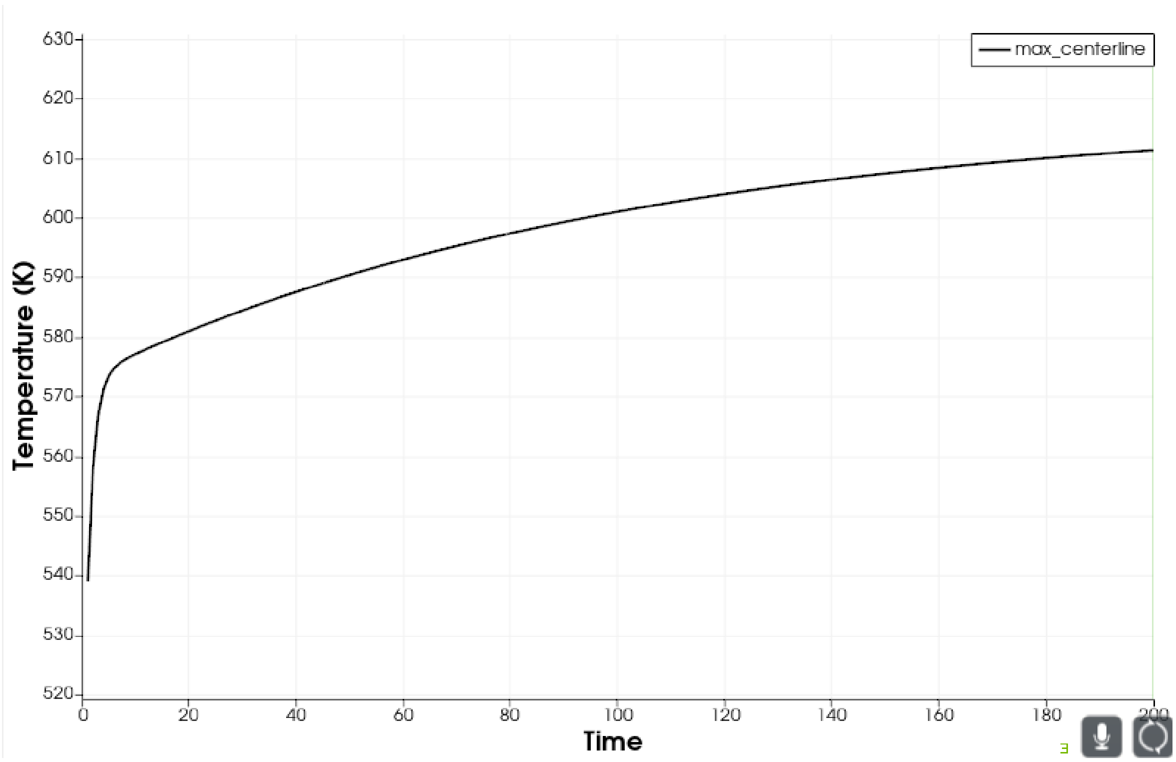
- Modified 2-D problem with non-uniform power profile
    - Steady state temperature profile @ z=0.25 m, 0.5 m, 1 m
    - Transient fuel centerline temperature vs. time @ z=0.25 m, 0.5 m, 1 m
    - Identification of peak centerline temperature location at steady state and t=200

2. 1-D Problem

a) ***Solve temperature profile for steady state:***



b) ***Solve for centerline temperature vs. time (transient):***



Results of the 1-D problem largely meet expectations. Due to the high conductivity of the sodium gap, only a small temperature rise is observed in this region. An initial quick rise in the transient centerline temperature is observed due to the heat conduction time derivative (incorporating delay in temperature diffusion, relating heat produced to specific heat and density of materials as a time-dependence on temperature propagation) and the low temperature of the initial condition. Because all thermal properties are kept constant, the transient centerline temperature then moves on to mimic the qualitative shape of the power production, that is the shape ($1-e^{-x}$). It should be noted however that the temperature profiles are lower than may typically be observed in a sodium-cooled fast reactor (which is the basis of the material properties selected), due to the 500 K boundary condition. The coolant temperature of an SFR, even at the inlet, is typically much higher in temperature than 500 K, so this boundary condition differentiates these results from what might be expected of a typical SFR fuel rod temperature profile.

Because of the simplicity of the steady state case, we can compare to an analytic solution to general heat conduction equations. The following evaluations can be compared with the steady state plot for each boundary point, and as a basic verification can be observed to closely match the MOOSE results.

$$T_{gap} = T_{clad} + \frac{Q_v R_f^2}{2k_{clad}} \ln\left(\frac{R_f + t_g + t_c}{R_f + t_g}\right) = 500\ \mathrm{K} + \frac{\left(250\,\frac{\mathrm{W}}{\mathrm{cm^3}}\right)(0.5\ \mathrm{cm})^2}{2\ \left(0.2035\,\frac{\mathrm{W}}{\mathrm{cm-K}}\right)} \ln\left(\frac{0.7}{0.6}\right) = 523.67\ \mathrm{K}$$

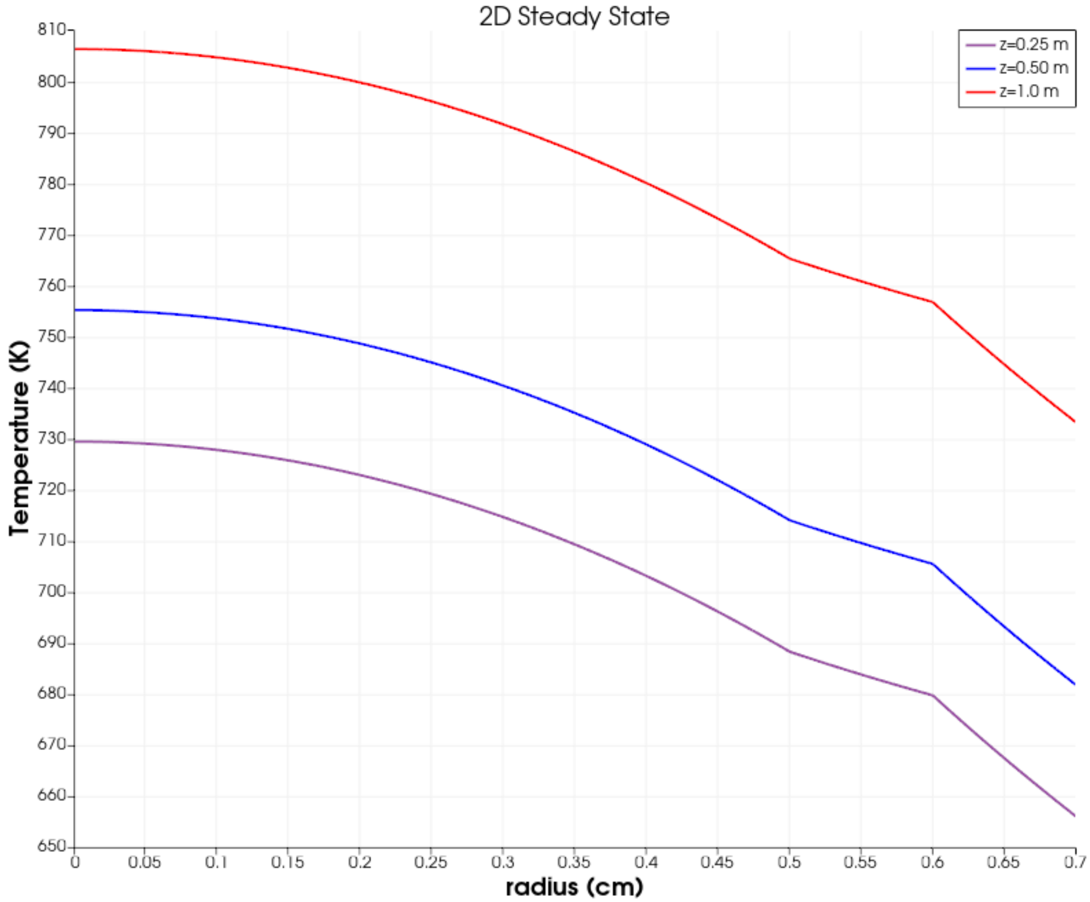
$$T_{fuel} = T_{gap} + \frac{Q_v R_f^2}{2k_{gap}} \ln\left(\frac{R_f + t_g}{R_f}\right) = 523.67\ \mathrm{K} + \frac{\left(250\,\frac{\mathrm{W}}{\mathrm{cm^3}}\right)(0.5\ \mathrm{cm})^2}{2\ \left(0.667\,\frac{\mathrm{W}}{\mathrm{cm-K}}\right)} \ln\left(\frac{0.6}{0.5}\right) = 532.21\ \mathrm{K}$$

$$T_{centerline} = T_{fuel} + \frac{Q_v R_{fuel}^2}{4k_{fuel}} = 532.21\ \mathrm{K} + \frac{\left(250\,\frac{\mathrm{W}}{\mathrm{cm^3}}\right)(0.5\ \mathrm{cm})^2}{4\left(0.38\,\frac{\mathrm{W}}{\mathrm{cm-K}}\right)} = 573.33\ \mathrm{K}$$

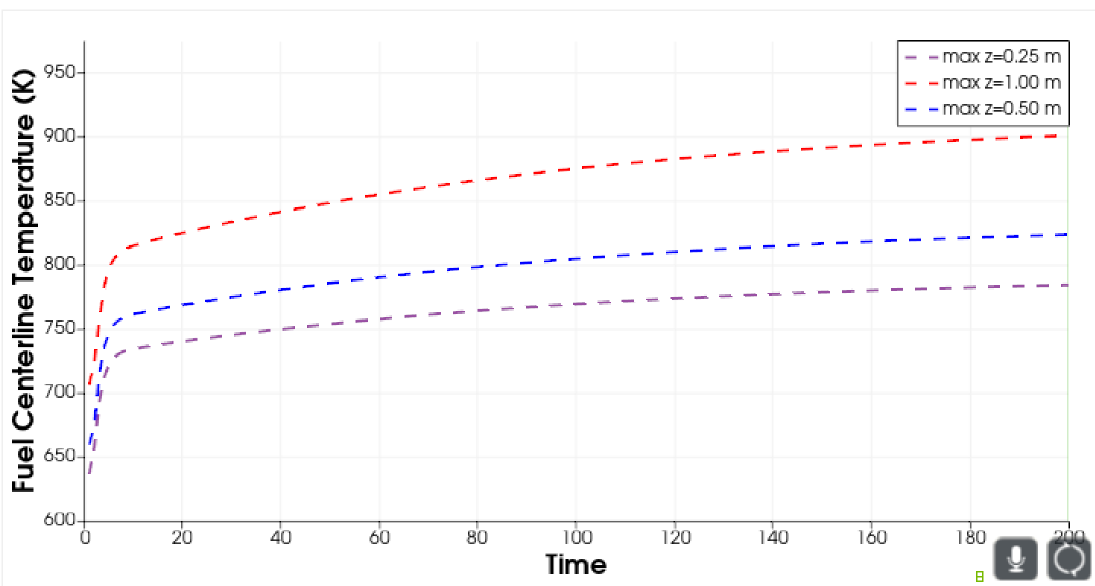
It should be additionally noted that these analytical equations differ from the versions used in class. The class equations assumed that the gap and clad thicknesses are small enough relative to the fuel pellet radius such that $\ln\left((R_f + t)/R_f\right) \cong t/R_f$. This is typically a reasonable approximation; however, the dimensions of the problems have gap and clad thicknesses significant enough to affect results by a few degrees when compared to the in-class equations.

3. 2-D Problem

a) ***Solve temperature profile for steady state locations @z-0.25, z=0.5, z=1:***

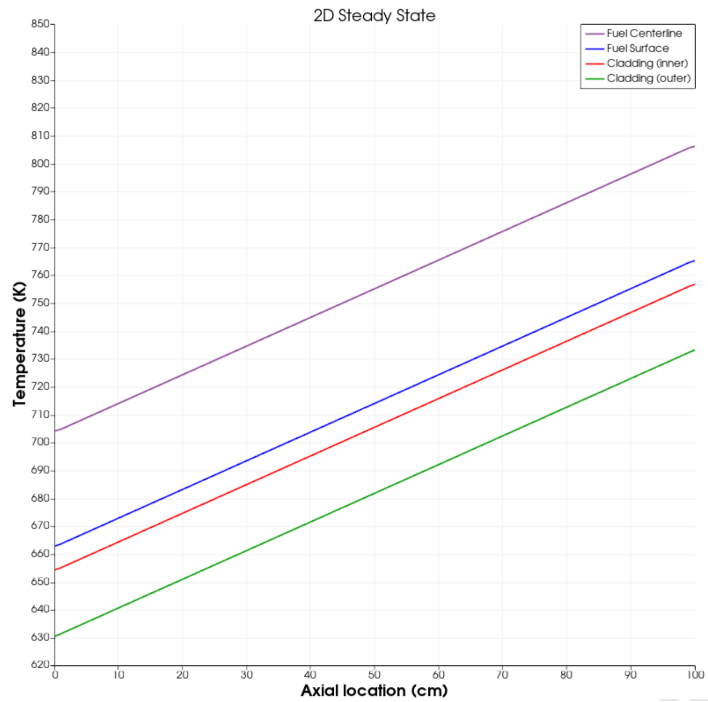


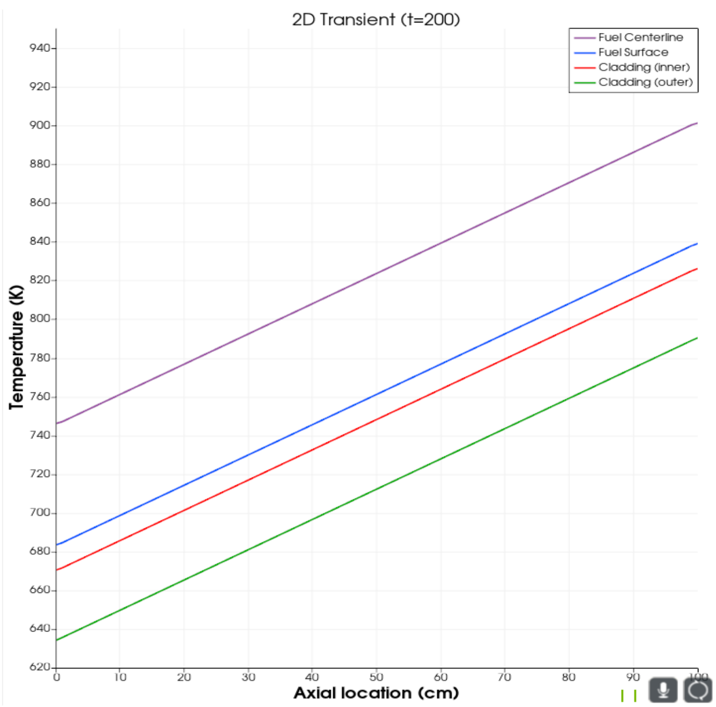
b) ***Solve for centerline temperature vs. time @z=0.25, z=0.5, z=1:***



c) *Find location of peak centerline temperature at steady state and t=200 in transient:*

Shown are the axial temperature profiles at centerline and each material boundary. It is apparent that the maximum centerline temperature is at the top of the model (i.e. z=1 m). This is expected due to the uniform volumetric heating rate applied.





Similar to the 1-D cases, the 2-D cases largely meet expectations. Qualitative radial behavior at any axial level is similar to the 1-D case in the radial temperature profile and fuel centerline over time plots. Temperatures are shifted upward at higher axial levels due to the convective boundary condition applied to the outside of the cladding (with temperature rise in the coolant accounted for). Similar behavior is observed in fuel centerline temperatures for the transient case. Based on the final question asked, we should be making some additional observations regarding the maximum fuel centerline position, which are not particularly interesting for the specified uniform volumetric heating rate, which results in consistent location at the top of the fuel model. To create a situation in which the question has a more interesting answer, an extension of the 2-D problem is created.

4. Extended 2-D Problem

One observation of the 2-D results is that the flat power profile (corresponding to the constant volumetric heating rate) leads to the maximum fuel centerline temperature always being at the top of the rod, where coolant temperature is highest. In a more realistic scenario, an axial profile could be applied (~cosine in shape) to the heating rate/power production. In this scenario, the maximum fuel centerline temperature is expected to be located slightly above the position of peak power. As a demonstration of this, an extension of the 2-D problem is given here. First, considering the following volumetric heating rate profile:

$$LHR = \gamma_p Q_v \pi R_f^2 \cos\left[\frac{\pi}{2\gamma}\left(\frac{z}{Z_o}-1\right)\right] \rightarrow LHR^o = \gamma_p Q_v \pi R_f^2$$

The extrapolation length and central position are set to $\gamma = 1.3, Z_o = 50$ cm. In addition to applying the shape, an additional normalization constant is incorporated to force the same total power production as the original 2-D problem:

$$\gamma_p = \frac{100}{\int_0^{100} \cos\left[\frac{\pi}{2\gamma}\left(\frac{z}{Z_o}-1\right)\right] dz} \cong 1.29228$$

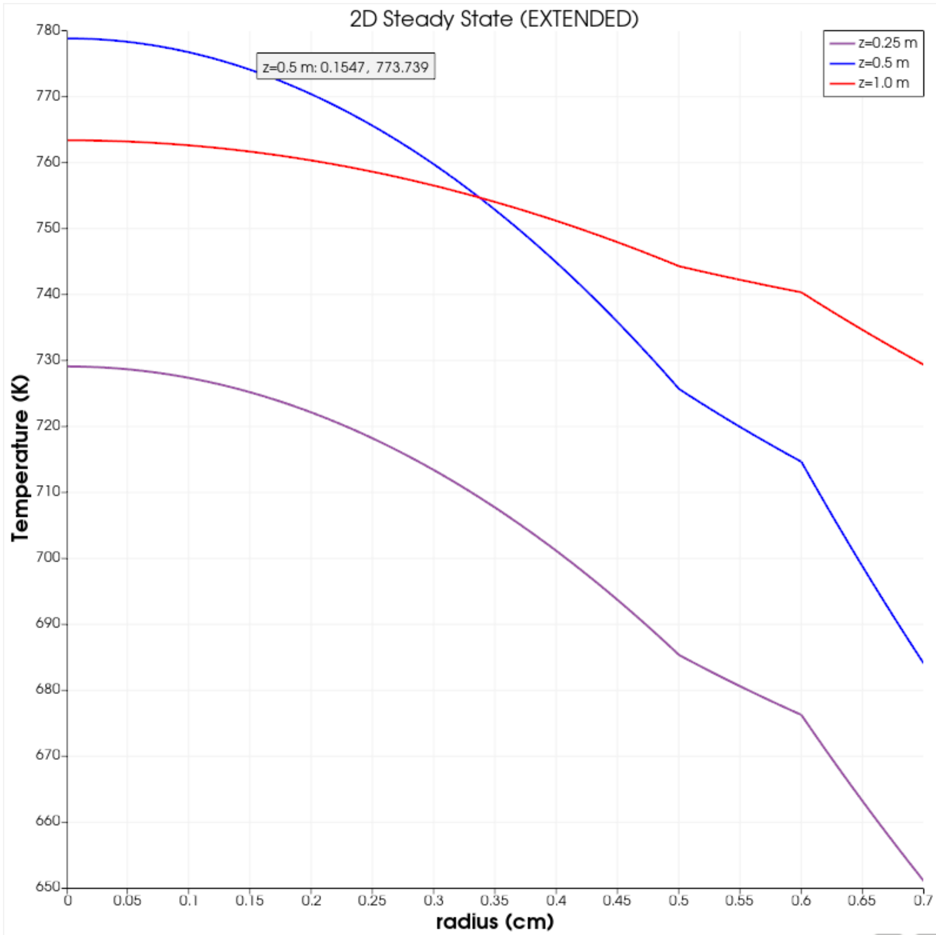
This also needs to be accounted for in the coolant temperature profile for boundary conditions:

$$T_{cool} = T_{in} + \frac{1}{\dot{m}C_p}\int_o^z LHR\, dz'$$

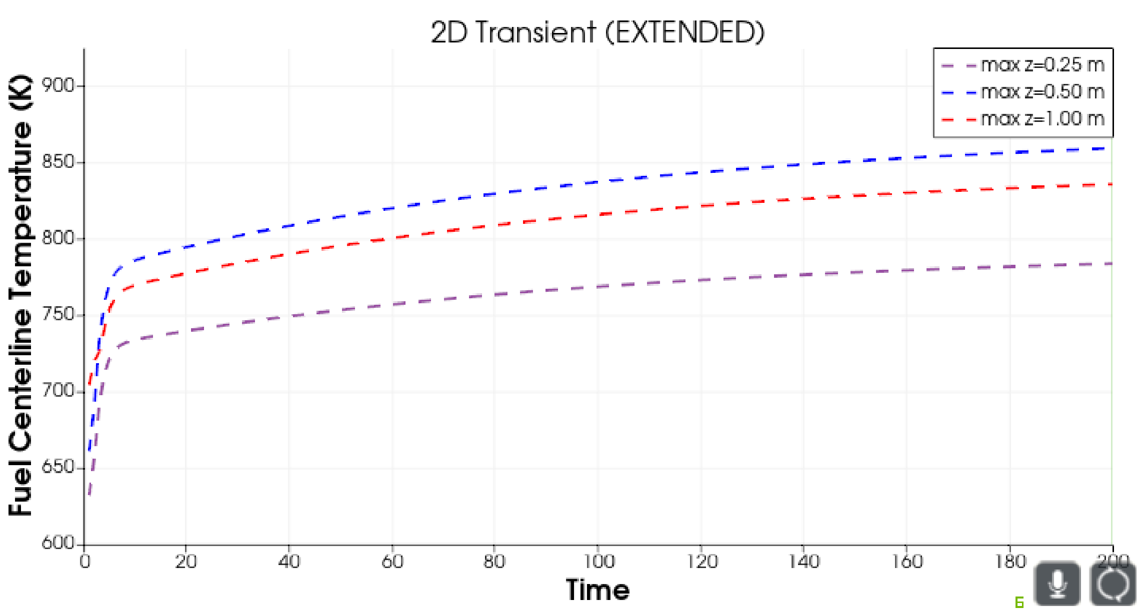
$$T_{cool} = T_{in} + \frac{2\gamma_p \gamma Z_o Q_v R_f^2}{\dot{m}C_p}\left(\sin\left(\frac{\pi\left(\frac{z}{Z_o}-1\right)}{2\gamma}\right) + \sin\left(\frac{\pi}{2\gamma}\right)\right)$$

The following plots are results in the same form as the original 2-D cases for comparison.

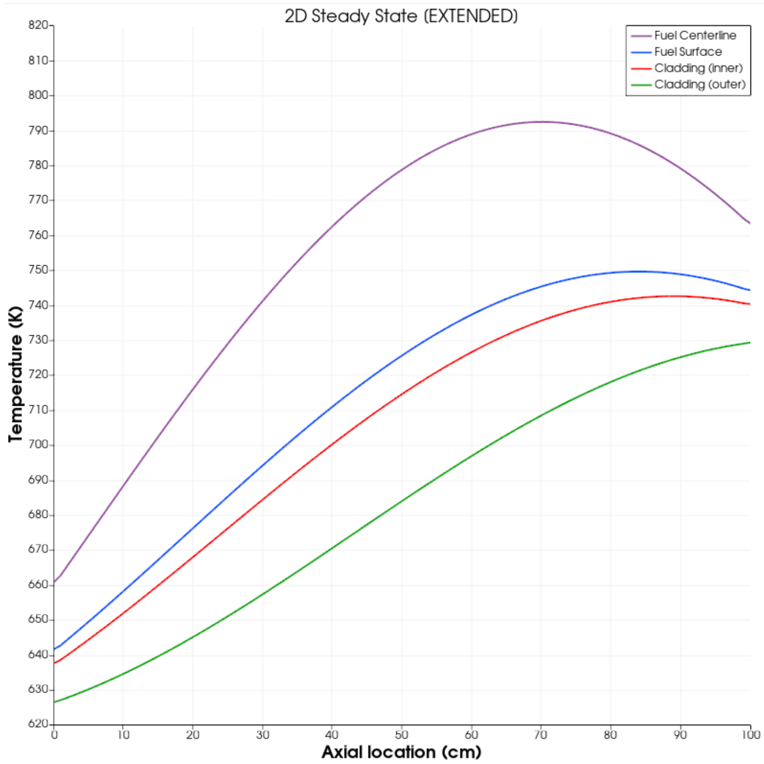
a) ***Solve temperature profile for steady state locations @z=0.25, z=0.5, z=1:***

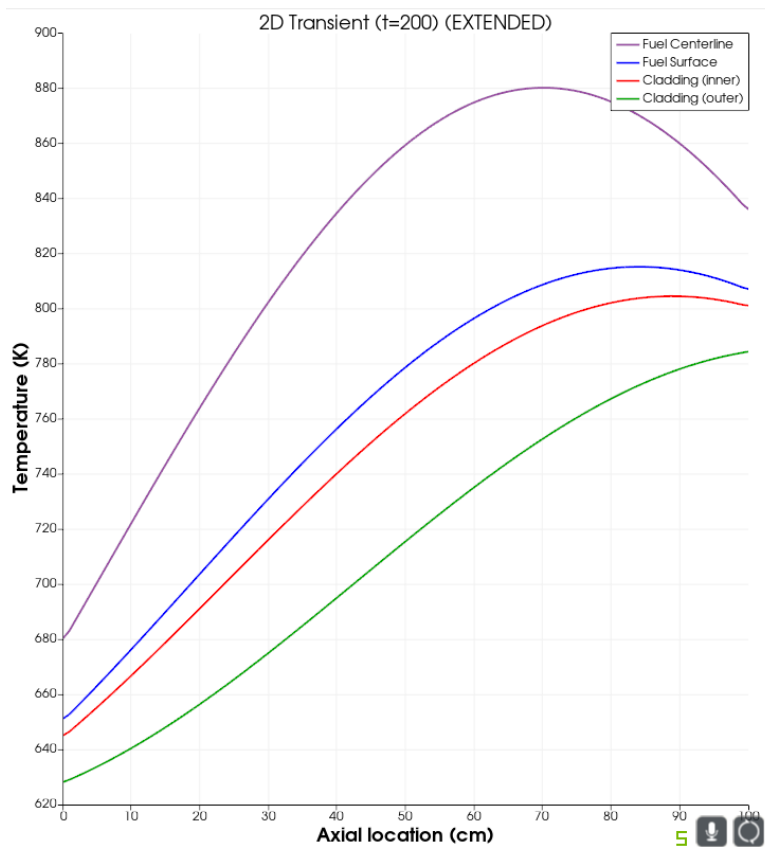


b) ***Solve centerline temperature vs. time @ z=0.25, z=0.5, z=1:***



c) ***Find location of peak centerline temperature at steady state and t=200 in transient:***





As expected, a significantly more complex temperature profile results when considering the non-uniform volumetric heat generation. The peak fuel centerline temperature is no longer located at the top of the model, but rather at 70 cm height in both cases. This height corresponds to competing effects between the power profile (centered at 50 cm) and the increased coolant temperature at higher axial positions. Peak fuel surface and peak inner clad temperatures are also similarly shifted downward from the top, though higher than 70 cm due to the closer relation to the coolant temperature. Another observation can be made regarding relative flattening of the radial temperature profile at axial levels with lower heat production rates.

All observations are consistent with the expectations of the defined problem. An even more detailed version could be created with a radial heat production profile, axial material variations, temperature dependent material properties, or various other considerations to more rigorously model the fuel rod.