NE591 MOOSE Project

Dr. Benjamin Beeler

Alex Chrystler

May 7th, 2021

Spring 2021

Introduction

MOOSE (Massively Object-Oriented Simulation Environment) is a parallel finite-element multiphysics framework that allows for modeling of complex geometries and physical properties with applications in many fields of study. In the case of this project, MOOSE will be utilized to perform fuel performance calculations, limiting the scope to temperature distributions of 2D fuel pins. Both steady-state temperature distributions and temperature distributions during transients will be analyzed.

The first of two geometries being modeled in this project is provided below in Figure 1, taken from [1]. In the "1D" case, the analysis being performed is done in the 2D scale, but with no variation in the vertical direction, effectively reducing the problem to only one dimension. The geometry includes a fuel region (assumed to be UO_2), a cladding region (assumed to be Zircaloy-4), and a gap region between them (assumed to be Argon gas). From these materials, relevant properties were determined, and are included in the discussion of results.

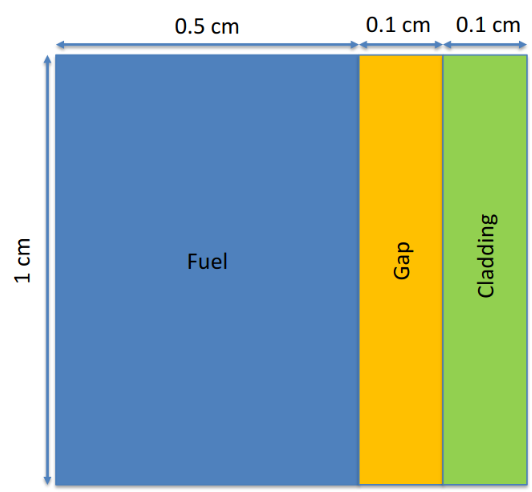

Figure 1: "1D" Fuel Pin Geometry

In this "1D" case, the outer cladding temperature is fixed at 500K in order to produce uniform results that have no z-dependence. In the steady-state case for this geometry, the fuel region was assigned an areal (volumetric) heating rate of 250 W/cm^2. In the transient case, the heating rate is modified to be a function of time, given below as Equation 1, where t represents time.

$$Q = 150 * (1 - exp(- 0.01 * t)) + 250 \quad (1)$$

The transient occurs over 200 seconds, utilizing a time step of 1 second. Both the steady-state and transient analysis is performed using a mesh of 100x100, producing results that will describe the temperature distribution with accuracy to the 100th of a centimeter. The quantities to be observed from these cases are the steady-state temperature profile, and the centerline temperature vs time for the transient case.

The second of the two geometries being modeled is the 2D geometry, shown below in Figure 2, taken from [1]. While being very similar to the original "1D" geometry, this case is noticeably different. In this case, the fuel, gap, and cladding thicknesses are held constant, but the fuel is extended to cover a 1 meter height rather than a 1 cm height. Again, a 200-second transient as well as a steady-state analysis is performed. For the steady-state analysis, the same areal (volumetric) heating rate of 250 W/cm^2 is utilized. In the transient analysis, the same heating rate is used as was used in the "1D" case, provided above in Equation 1. Where this case differs greatly is the boundary condition for the outer cladding. For this geometry, an axially varying cladding outer temperature profile is utilized to produce axial variation in the cladding temperature, which will propagate through the gap into the fuel.

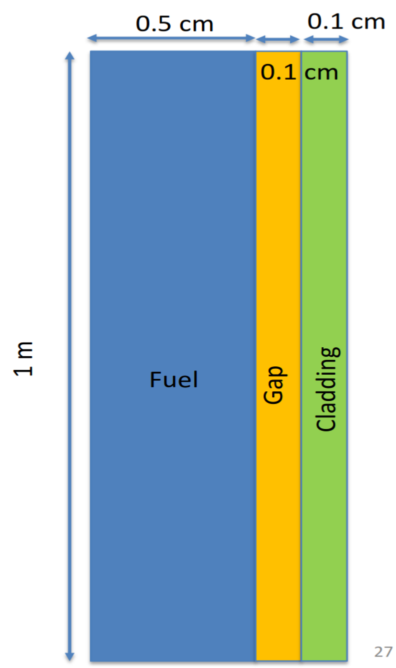

Figure 2: 2D Fuel Pin Geometry

The equation used for the axial temperature distribution comes from known thermohydraulics solutions where cladding temperature tends to peak ~75%-80% of the way axially up the fuel pin. Given an axial heat flux profile, the cladding outer temperature is calculated following Equations 2 and 3 below, from [2].

$$T_{\infty}(z) = \frac{1}{GA_x C_p} \int_0^z \pi D q''(z)\, dz + T_0 \tag{2}$$

$$T_{co}(z) = T_{\infty}(z) + \frac{q''(z)}{h_c} \tag{3}$$

In these equations, $T_{co}(z)$ is the outer cladding temperature, h_c is a convective heat transfer coefficient between the coolant and cladding, G is the mass flux through the coolant channel, C_p is the specific heat capacity of the coolant, D is the coolant channel diameter, and A_x is the coolant channel flow area. Given that heat flux profiles are generally sinusoidal, these functions tend to be cosine functions subtracted from sine functions.

The equation used to describe the cladding temperature was multiplied by a large constant in order to amplify the effect of the axial cladding temperature distribution on the fuel and gap regions, as we only solve for the location of the peak centerline temperature in this case, and the magnitude is irrelevant. This equation, set to start at 250K and increase dramatically, is provided below as Equation 4.

$$T_{co}(z) = 250(\pi z * sin(0.77\pi z) - cos(\frac{1}{0.77}\pi z)) + 500 \quad (4)$$

This is not a realistic temperature distribution in terms of magnitudes produced, but the shape is very realistic. This can be seen below in Figure 3.

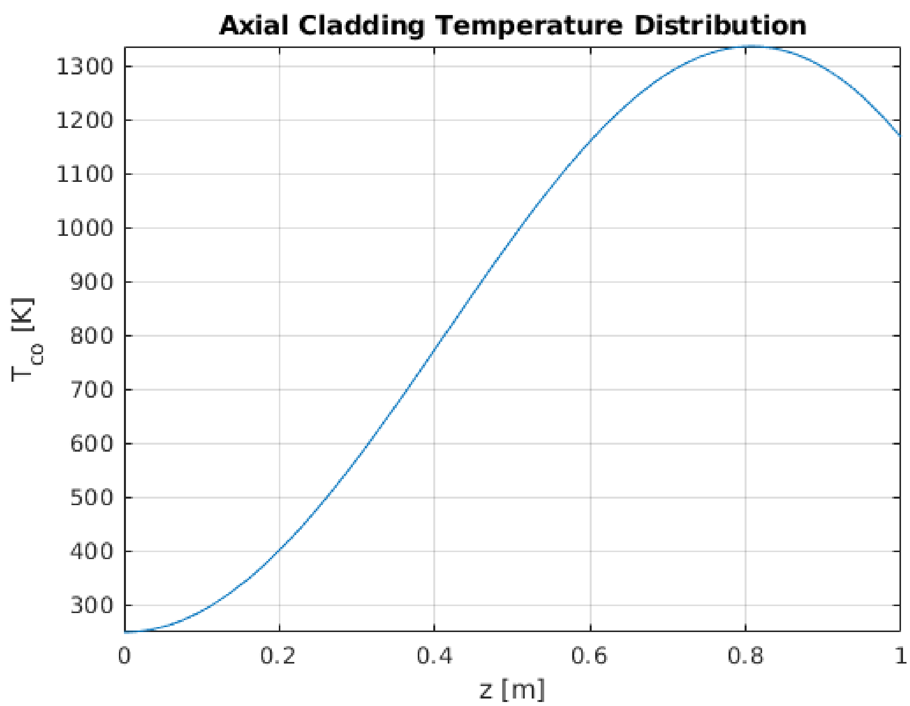

Figure 3: 2D Fuel Pin Axial Outer Cladding Temperature Distribution

In order to complete the description of information in the MOOSE input files, the boundary condition employed on the left boundary is a Neumann boundary condition, setting the derivative of the temperature distribution equal to zero at the boundary. As a result, the hottest temperature occurs at the left boundary, representing the fuel centerline.

Results and Discussion

For each simulation, certain material properties were necessary as inputs in order for MOOSE to perform its calculations. These properties are provided below in Table 1.

Table 1: Material Properties for Fuel Simulations

Material	Thermal Conductivity [W/m-K]	Specific Heat [J/kg-K]	Density [g/cc]
Fuel (UO_2)	0.33	0.260	10.97
Gap (Ar)	0.016	0.520	1
Cladding (Zircaloy-4)	21.5	0.285	6.56

"1D" Steady-State

For the 1D steady-state simulation, the goal was to calculate a temperature profile provided the areal (volumetric) heating rate of 250 W/cm^2. The input file for this simulation is "steady1D.i". The resulting surface temperature distribution is provided below in Figure 4.

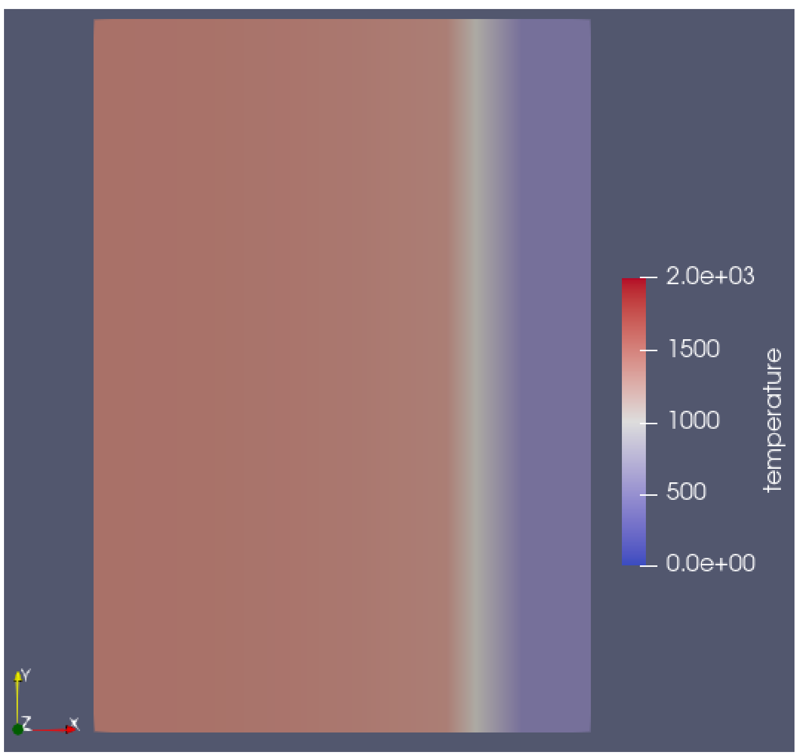

Figure 4: Steady-State "1D" Temperature Distribution Surface Plot

For this case, the cladding outer temperature remained constant at 500K. The centerline temperature of the fuel, measured at the left boundary of our fuel pin, was found to be 1409.52K. These can be seen further in Figure 5 below.

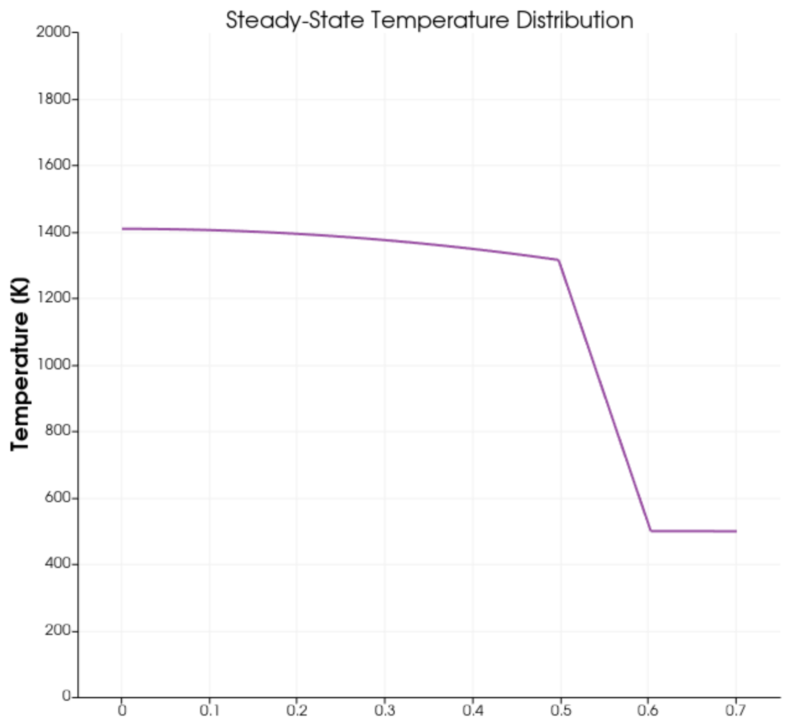

Figure 5: Steady-State "1D" Temperature Distribution Line Plot

"1D" Transient

For the "1D" transient simulation, the objective was to determine the fuel centerline temperature vs time, given the areal (volumetric) heating rate as shown in Equation 1. The input file for this simulation was "transient1D.i". The resulting temperature profile over time is provided below in Figure 6.

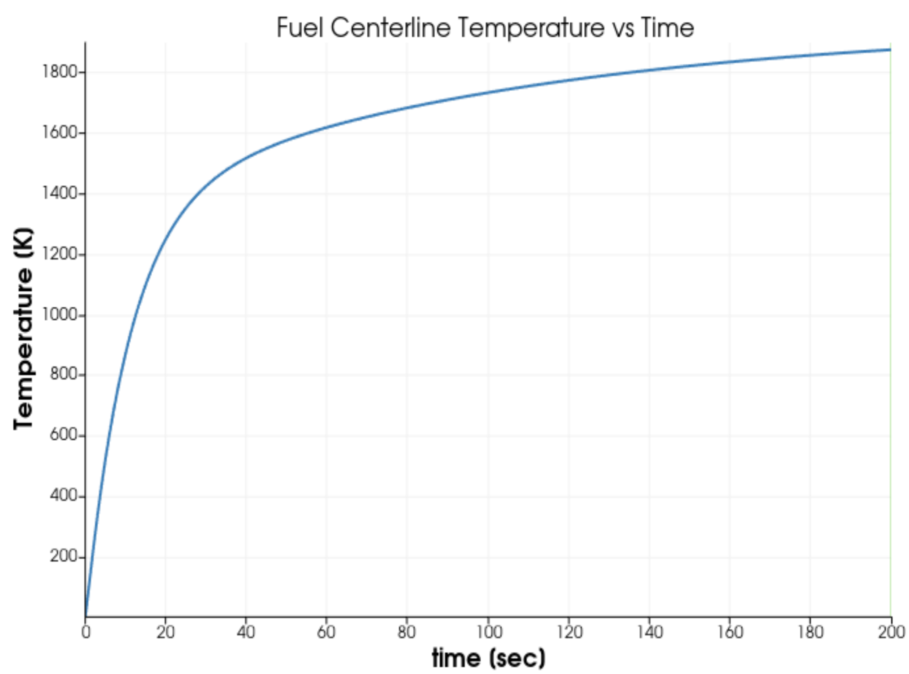

Figure 6: Transient "1D" Temperature Profile

Of additional interest is the temperature distribution over the fuel pin at the initial (time = 0, left) and final (t = 200 seconds, right) time in the transient, of which can be seen below in Figure 7.

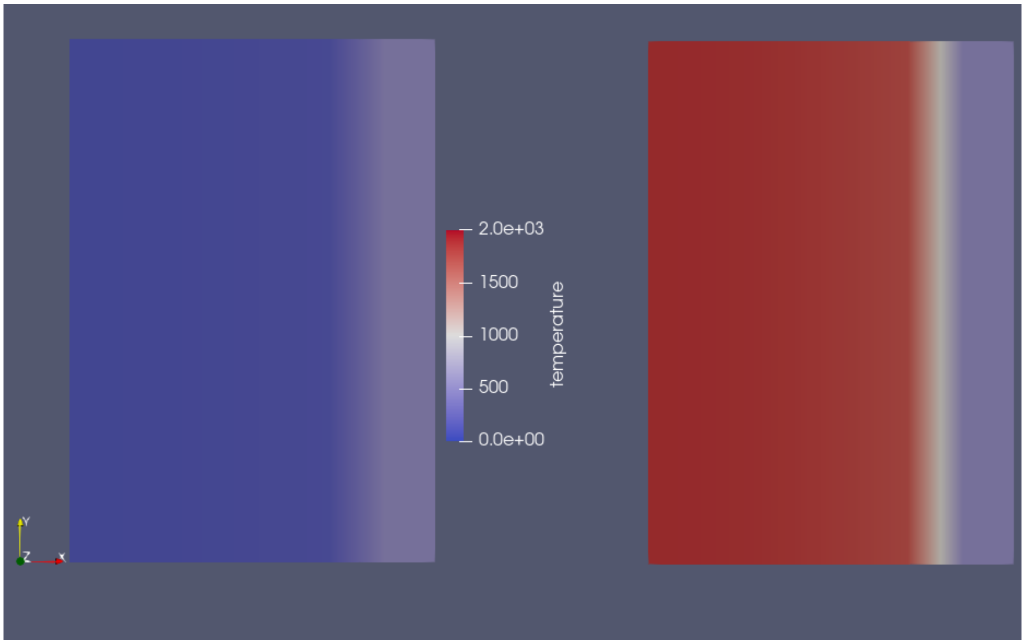

Figure 7: "1D" Transient Temperature Distributions at Start and End of Transient

2D Steady-State

For the 2D steady-state simulation, the objective was to calculate steady state temperatures at z = [0.25, 0.5, 1]. In this case, the outer cladding temperature is specified as shown above in Equation 4. The input file for this case is "steady2D.i". The resulting steady-state surface temperature profile is shown below in Figure 8.

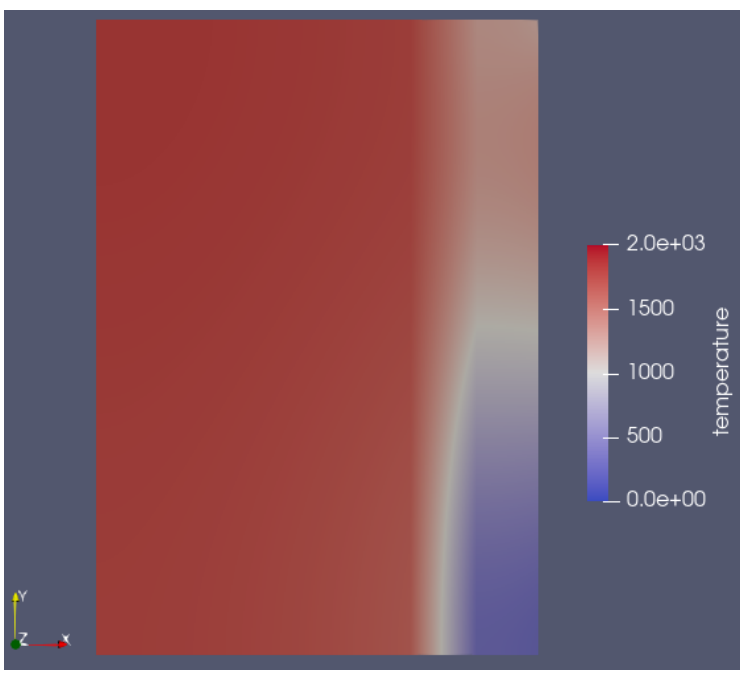

Figure 8: 2D Steady-State Surface Temperature Plot

To break this down further and investigate the temperature distribution at varying axial locations, Figures 9, 10, and 11 are provided below, for axial heights of 0.25m, 0.5m, and 1m. From this analysis, it was determined that the z-position of the peak centerline temperature was z = 1m.

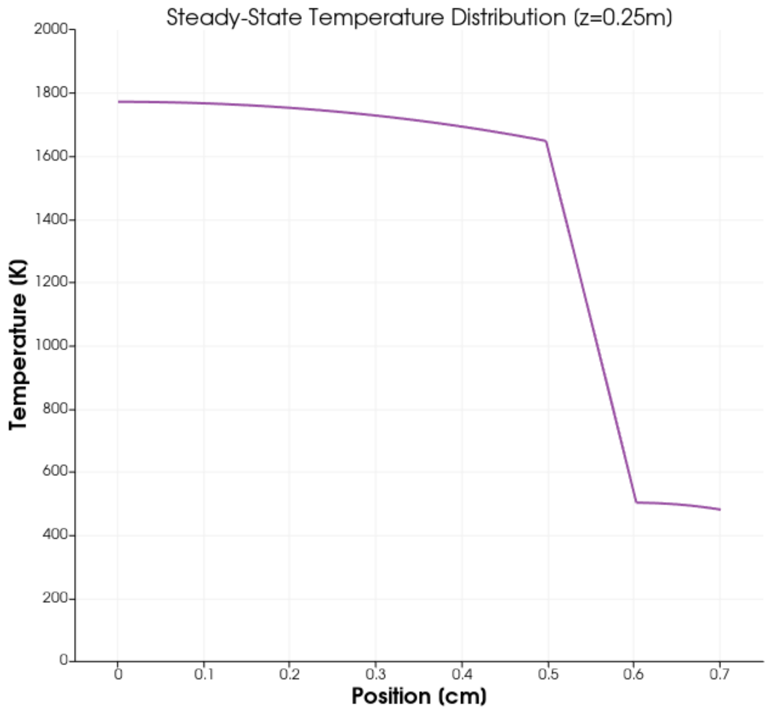

Figure 9: 2D Steady State Temperature Distribution Line Plot at z=0.25m

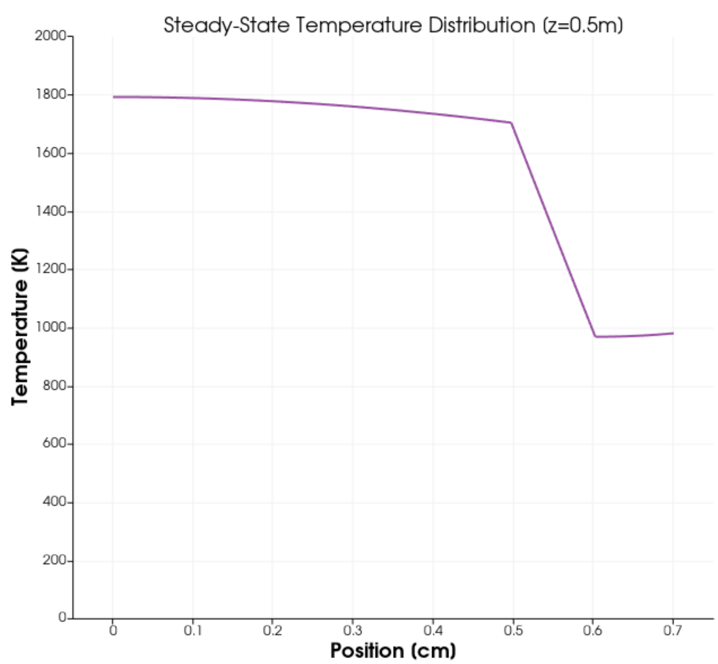

Figure 10: 2D Steady State Temperature Distribution Line Plot at z=0.5m

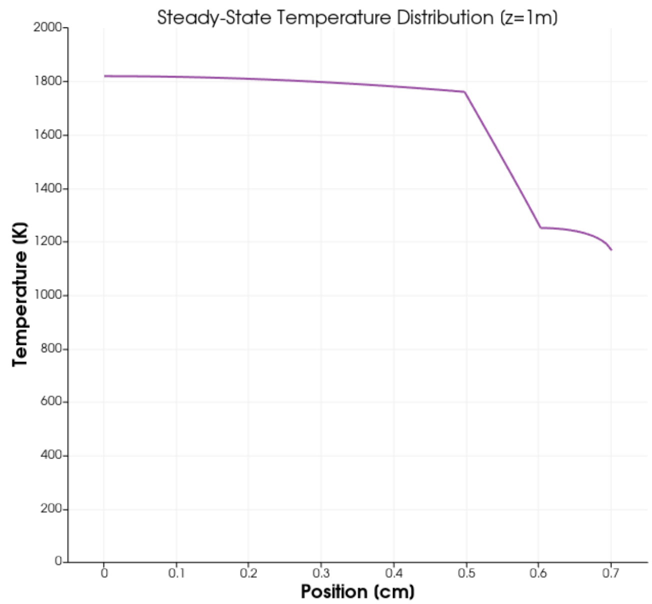

Figure 11: 2D Steady State Temperature Distribution Line Plot at z=1m

These profiles appear to be somewhat correct, but do not appear 100% as expected. In general, with axisymmetric, cylindrical fuel pins, given the cladding outer temperature profile as in Equation 4, the peak centerline temperature will not occur at the top of the fuel pin. This behavior is odd, and was unable to be corrected throughout the simulations.

2D Transient

For the 2D transient simulation, the same cladding outer temperature equation (Equation 4) was used as in the 2D steady-state case. The input file for this case is "transient2D.i". The objective was to calculate the fuel centerline temperature over time at the z = [0.25, 0.5, 1]. This is seen below in Figures 12, 13, and 14.

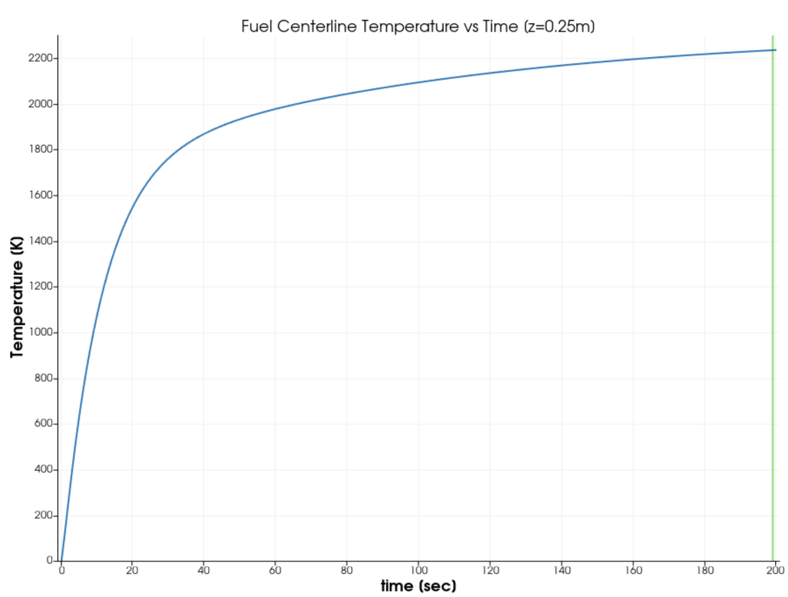

Figure 12: 2D Transient Centerline Temperature Profile at z=0.25m

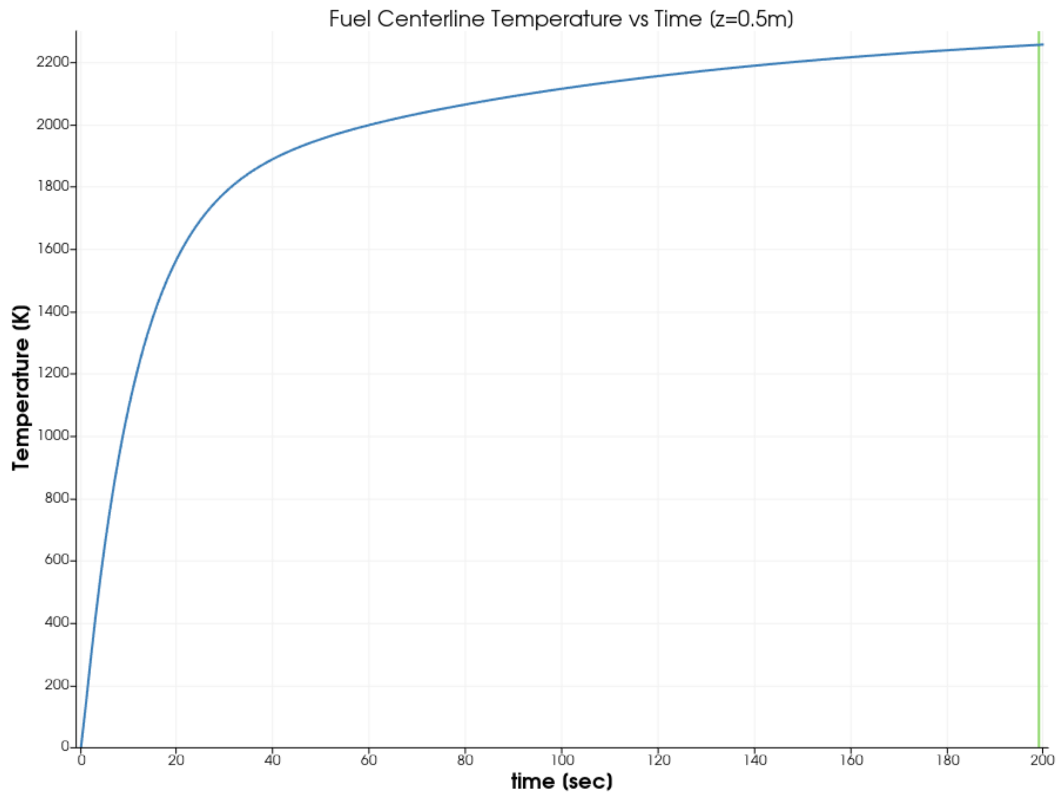

Figure 13: 2D Transient Centerline Temperature Profile at z=0.5m

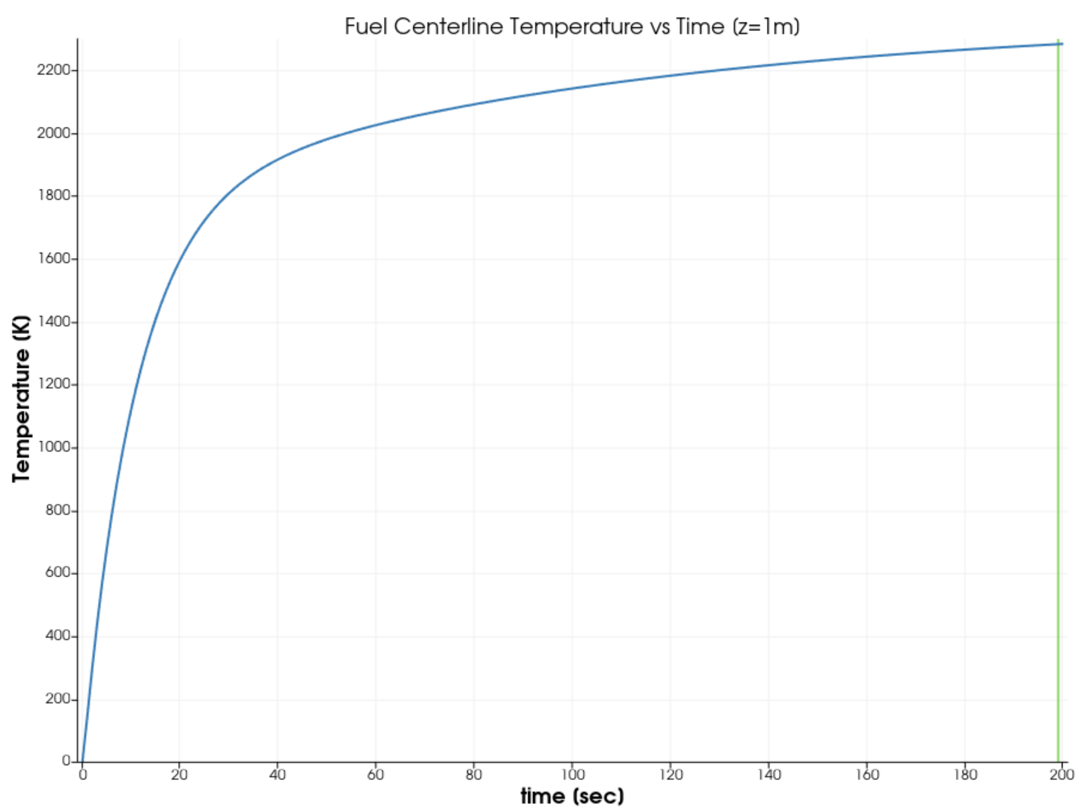

Figure 14: 2D Transient Centerline Temperature Profile at z=1.0m

Due to the massive similarity in these plots, it is necessary to further investigate the similarity of these plots. Shown below in Figure 15 is the range of the fuel centerline temperatures in the range z = [0.25, 1]. The upper end of the band plotted is the maximum value of the centerline temperature, which occurs at z = 1m in the transient case. The lower end of the band is the minimum value, occurring at z=0.25m.

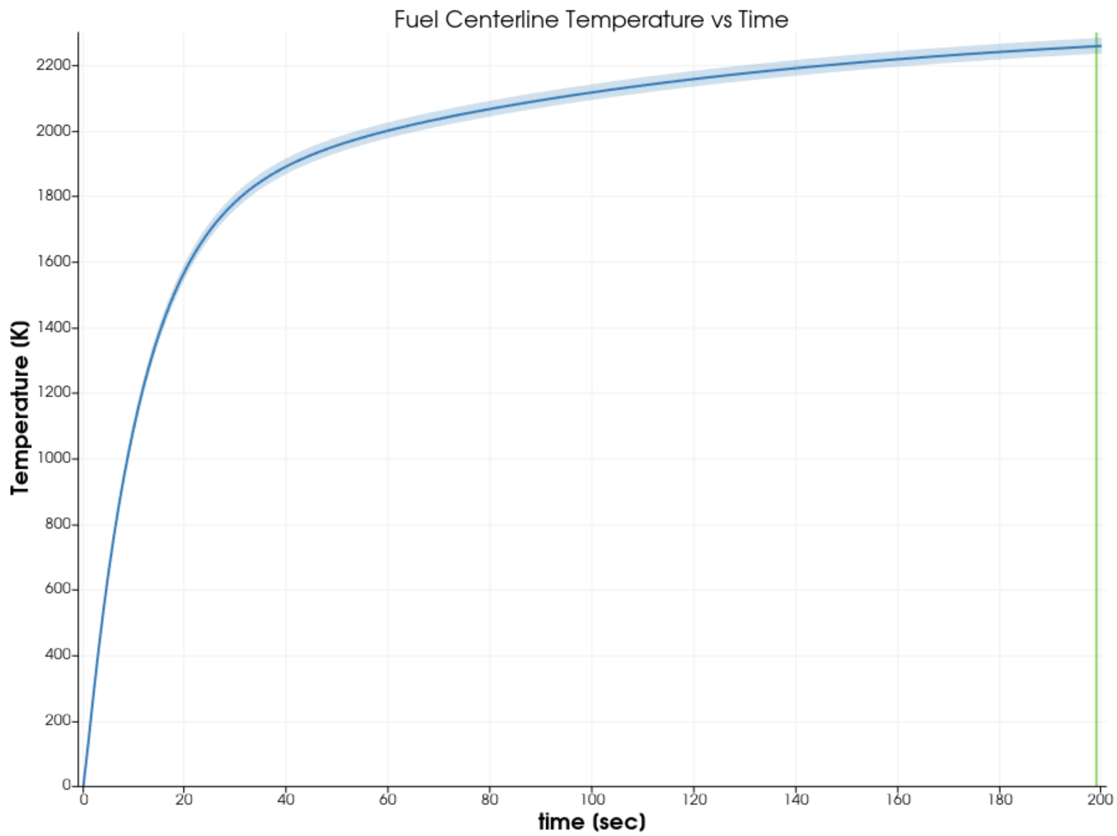

Figure 15: 2D Transient Centerline Temperatures

Again here, we observe the strange behavior of the profiles, which is the peak fuel centerline temperature occurring at the top of the fuel pin. A likely cause of this is having fluid properties be held constant throughout the simulations, resulting in the lack of enhancement of heat transfer from coolant to cladding due to local boiling in the coolant in the hot channels of power reactors. This would generally result in better heat transfer from fuel out into coolant with increased axial height, which does not occur in these models.

References

1. Beeler, B. 2021, *MOOSE Overview*. Course Notes, NE591, NC State University.
2. Doster, J. M. 2021, *Boiling Heat Transfer and Two Phase Flow*. Course Notes, NE402, NC State University.