## NE 533-001 project 2 Report

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## Project 1

This report summarizes the findings of Projects 1,2, and 3 for NE 533- Fuel Performance. A description of input file creation is provided, and sources are given for quantities not sourced from Lecture notes. The modeling results are organized by case, summarized, and analyzed, and compared to one another. There are 4 cases, found in Table 1 below. The results follow what we expect based on the input file changes, namely that a temperature dependent fuel and gap thermal conductivity increases maximum fuel temperature in both transient and steady state cases. The transient cases show the effect of linear heat rate changes on temperature profiles in the fuel pin.

Table 1: Project 1 Modeled MOOSE cases

|  |  |
| --- | --- |
| Case Number | Description |
| Case 1 | Steady State with constant fuel thermal conductivity |
| Case 2 | Steady State with temperature dependent thermal conductivity in Equations 1 and 2 |
| Case 3 | Transient with linear heat rate in Equation 3 and constant fuel thermal conductivity |
| Case 4 | Transient with linear heat rate in Equation 3 and temperature dependent fuel thermal conductivity in in Equations 1 and 2 |

The geometry of the model is shown in Figure 1 below. It is a 2-dimensional axisymmetric system about the Y axis. This effectively models a cylinder. The material properties are sourced from the lecture notes for the cladding and fuel thermal conductivities. The fuel was taken to be UO2 and the cladding to be Zirconium, as these are prototypical materials in LWR fuel. The gap was taken to be Helium, with properties for specific heat and density taken from Reference 2. The constant material quantities provided were taken from the lecture notes (Reference 1) or online sources (Reference 2). These are shown below in Table 2.

Table 2: Material Constants in Fuel model

|  |  |  |  |
| --- | --- | --- | --- |
| Material | Thermal Conductivity | Density | Specific Heat |
| Fuel | 0.03 | 10.98 | 0.33 |
| Gap | 0.002556 | 0.00178 | 5.188 |
| Cladding | 0.17 | 6.5 | 0.35 |

The constant helium thermal conductivity was calculated from Equation 2 using T = 615 K. This was determined to be a cladding interior temperature for the model, as calculated by Equation 4.

A diagram of a fuel gap and cladding

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Figure 1: Fuel model geometry

The mesh was generated according to the dimensions in Figure 1, and materials were assigned from Table 2. The gap was treated as a separate material, instead of the built-in gap treatment for simplicity’s sake. For future projects, this may change. The temperature was initialized as a first order LaGrange. Both the thermal conductivity functions were linearized to a piecewise function, with conductivity values between 600k and 1800 K. This operation was performed in MATLAB. Some instability in the transient model initialization is likely due to initial conditions being slightly out of that range (550 K at the cladding boundary), but the effect is likely negligeable. The linear heat rate was not linearized, as this capability is built into MOOSE. A Dirichlet boundary condition was established at the cladding surface, and while a Neumann boundary condition is not necessary in the built in MOOSE RZ coordinate system, one was still initialized for my completeness.

For the steady state models, only a heat conduction and heat source kernel were necessary. For the transient models, a heat conduction time derivative kernel is required. This necessitates the changing of the fuel and gap material types to include additional quantities that are not required without the time derivative kernel. Initial conditions were selected for the cladding and fuel average temperatures. A more precise way of including initial conditions would be to assign boundary conditions as well, but the simulations appeared to perform well enough. For the steady state models, the preconditioned Jacobian Free Newton Krylov (PJFNK) solver was selected. For the transient models, this was also selected with the time integrator method selected as the Implicit Euler for numerical stability. Three post-processors are included: a maximum temperature (assumed to correspond to centerline temperature), a global minimum temperature (assumed to correspond to cladding temperature) and the temperature at the left boundary, or the centerline temperature.

The steady state results are shown as a temperature color map. The maximum (i.e. centerline in our simplified case) temperature is also presented. The case for a constant fuel and gap thermal conductivity is shown in Figure 2. The temperature dependent fuel and gap thermal conductivity is shown in Figure 3 below.

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Figure 2: Steady State for k = 0.03 W/cm-K

The centerline temperature calculated is 1,291.66 K. The cladding outer temperature does not change. Both Figure 2 and Figure 3 are shown on the same scale. The gap is hardly visible in the figures, but the location is visible by the large change in temperature relative to radial distance. This is due to the significantly lower thermal conductivity of He compared to both the fuel and cladding.

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Figure 3: Steady State for variable k(T)

The centerline temperature calculated is 1,534.57 K. The cladding outer temperature also does not change. We note that the centerline temperature for a variable thermal conductivity is higher than the constant case. We expect this, as the relationships between temperature and thermal conductivity are inversely proportional for UO2 and this has the largest effect on net conductivity. The relationship is proportional for he, but the effect is significantly smaller.

The results for the transient cases are shown below. Block 2 represents the fuel, block 4 the gap, and block 6 the cladding. The average(solid) and maximum(dashed) temperatures in each block are shown. Instability in temperatures from until 5 seconds is due to the initial conditions being a scalar

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Figure 4: Transient for k = 0.03 W/cm-K

The maximum centerline temperature calculated is 1110.54 K, the maximum gap temperature is 711.28 K, and the maximum cladding temperature is 586.6 K.

A graph with lines and numbers

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Figure 5: Transient for variable k(T)

The maximum cladding temperature is 601.06 K, the maximum gap temperature is 772.28 K, and the maximum centerline temperature is 2427.17 K. This is not realistic and there is certainly something incorrect about the model, as the temperature profile behavior seems much too sudden in both its rise and return to steady state. I was not able to figure out why that is the case but was able to reach a solution convergence with some help from Dr. Jiang. The converged solution is assumed to be incorrect.

## Project 2

Project 2 consists of a steady state simulation of a uranium dioxide fuel rod similar characteristics as Project 1. The material properties used, and the geometry are the same as in Project 1 with the exception that the rod height is 100 cm and the thermal conductivity is constant. The gap conductance is calculated by dividing the thermal conductivity of the fill gas by the gap thickness. The radial temperature distributions at z = 25 cm, z = 50 cm, and z = 100 cm are provided visually in Figures 6, 7, and 8 below with some analysis. The equations for the cladding outer surface boundary condition and the linear heat rate are provided below, where cm, , , and .

The gap material block was replaced with the built in GapHeatTransfer capability. The gap conductance provided was 0.002556, as in Table 11.

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Figure 6: Radial Temperature distribution at z = 25 cm

The most important realization is that the gap temperature difference does not appear to be correct. Using the analytical solution as z = 50 cm, we expect the change in temperature across the gap to be around 214 ℃ for our materials. This is not the case, potentially due to a mesh creation problem that was unable to be resolved. This is the case for all calculations.

A graph with a curved line

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Figure 7: Radial Temperature distribution at z = 50 cm

The same comments for Figure 6 are valid for Figure 7 and 8.

A graph with a line going up

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Figure 7: Radial Temperature distribution at z = 100 cm

In addition, a colormap is provided for the whole fuel rod in Figure 9 below.

A red and blue gradient

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Figure 9: Project 2 Fuel Rod colormap

The rod view has been scaled across the x axis to view the temperature distribution across the fuel. We notice the higher temperature in the axial center of the fuel compared to the top and bottom, proving the axially dependent temperature and linear heat rates were implemented correctly. As a note, the bottom of the fuel rod is on the right and the top is on the left, following the direction of the positive y-axis.

The maximum fuel rod temperature is 1314.71℃, found at y = 50.5 cm. This number is too low, as we would expect it to be around 60 cm in height.

## Project 3

Project 3 takes the same input as the Project 2 input file with several small differences. The thermal conductivity is a function of temperature, taking the values provided in Equations 1 and 2 above. The axially varying linear heat rate and the boundary conditions are the same as in project 2. Boundary condition reduction was offered as an option, but since the inlet temperature appeared to function correctly, it was kept as the boundary condition in Project 3.

The input file for Project 3 did not reach convergence. Most likely it is due to errors in the mesh and tensor mechanics modules added to the input. A copy of the input file is attached to this report.

As part of Project 3, the inputs for Project 1 and 2 were updated to fix mistakes in the previous sections. In Projects 1 and 2, specific heat material properties were added to the cladding and fuel blocks. In Project 2, the fuel surface was the primary surface for thermal contact and the cladding surface was the secondary surface.

## References

1. Beeler, B. (2024, Spring). *Lecture 3.* [PowerPoint presentation]. North Carolina State University.
2. The Engineering Toolbox. (n.d.). *Helium - thermophysical properties*. Engineering ToolBox. https://www.engineeringtoolbox.com/helium-d\_1418.html#google\_vignette
3. Github. (n.d.). *Home*. MOOSE. https://mooseframework.inl.gov/