NE 533 **Final Moose Project** **Spring 2022**

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1. Introduction

The aim of this project is to simulate simple nuclear fuel systems using MOOSE. In this software, the partial differential equations are solved using the finite element method. In this project, only two modules will be used. These are the heat conduction module to solve for temperature profiles and the tensor mechanics module to simulate thermal expansion in part 3. The results of the simulation for the 3 parts of the project are summarized in the following section below.

2. Results

2.1. Heat Conduction in 1-D Fuel System

First, the fuel-gap-clad system was simulated in the steady-state. Constant thermal conductivities of 0.03, 0.003, and 0.17 W/cm-K were assumed for the fuel, gap, and clad, respectively. Although the problem is one-dimensional, the geometry was set in a 2D-RZ coordinate system. A mesh of 602×10 was chosen. The 602 was necessary to match the dimensions provided and to cover the gap region which has a thickness of 0.002 cm. While a small number of elements in the Z direction was chosen because of the symmetry of the problem. The input parameters for the steady-state were a linear heating rate (LHR) of 150 W/cm^2 and an outer cladding temperature of 500 K. The output file in exodus format was visualized in Peacock and Paraview. The resulting temperature profile is plotted in Figure 1. The centerline temperature was around 614 K and fuel surface temperature is nearly 515 K.

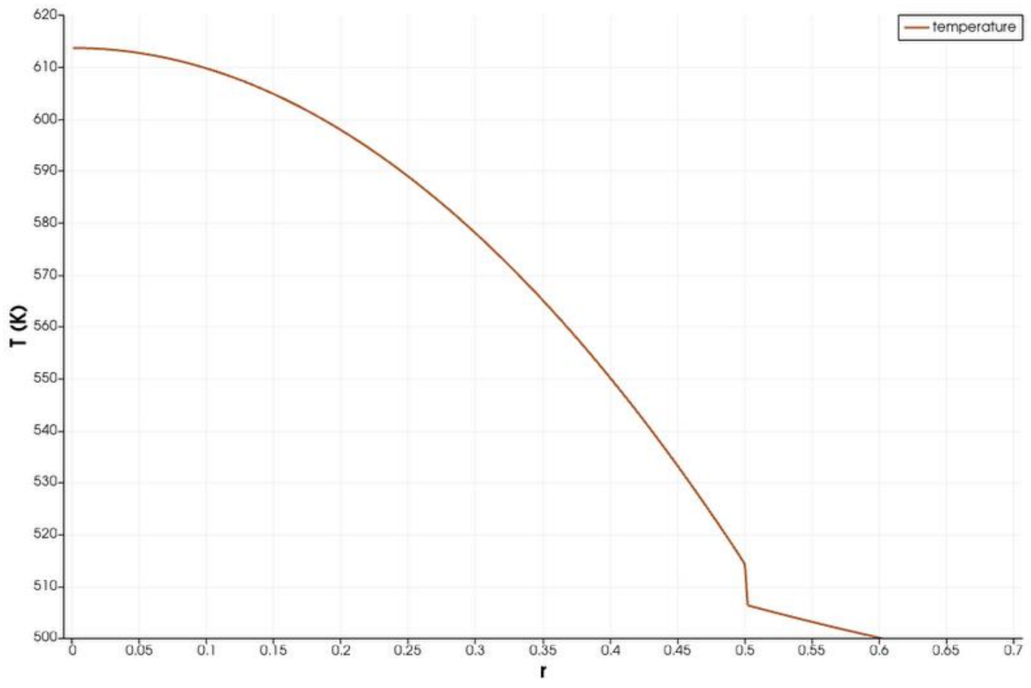

Figure 1 Steady-state temperature profile at temperature profile in 1D problem. R is in centimeters and temperatures are in Kelvin.

Second, an attempt was made to simulate a transient system where the LHR increases from 150 W/cm to 300 W/cm according to the following relation: $LHR(t) = 150(1 - e^{-0.05t}) + 150$. An initial condition of T = 614 K was implemented based on the steady-state solution. This simulation did not converge when using the same parameters as in steady-state. It always stops after t = 30 – 40 seconds. Changing the mesh size or decreasing the time step did not solve this problem. The two options to make it converge for 100 seconds were (a) either to change the boundary condition of the outer cladding temperature or (b) to decrease the thermal conductivity of the fuel. The second option was followed assuming that fuel thermal conductivity decreases with temperature. The radial temperature profile at the end of the simulation is shown in Figure 2. While the time evolution of temperature is shown in Figure 3.

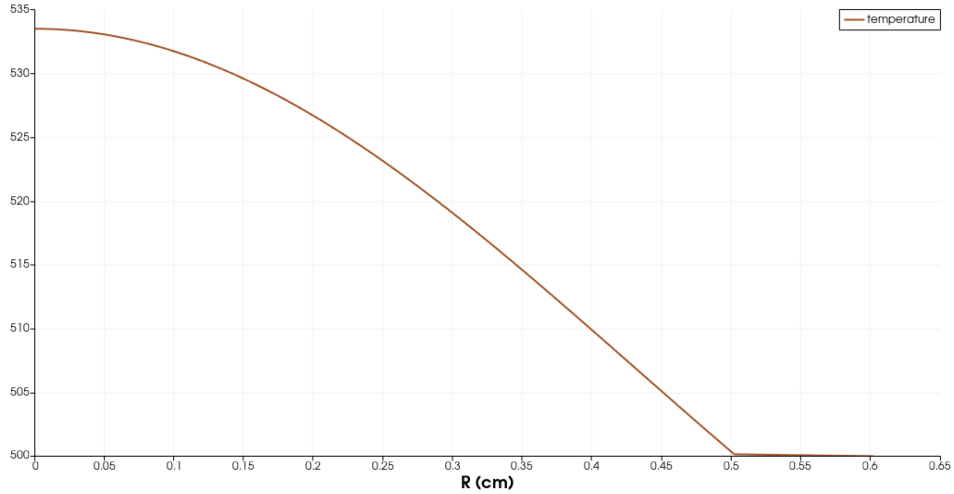

Figure 2 Temperature profile at t = 100 seconds in 1D transient problem

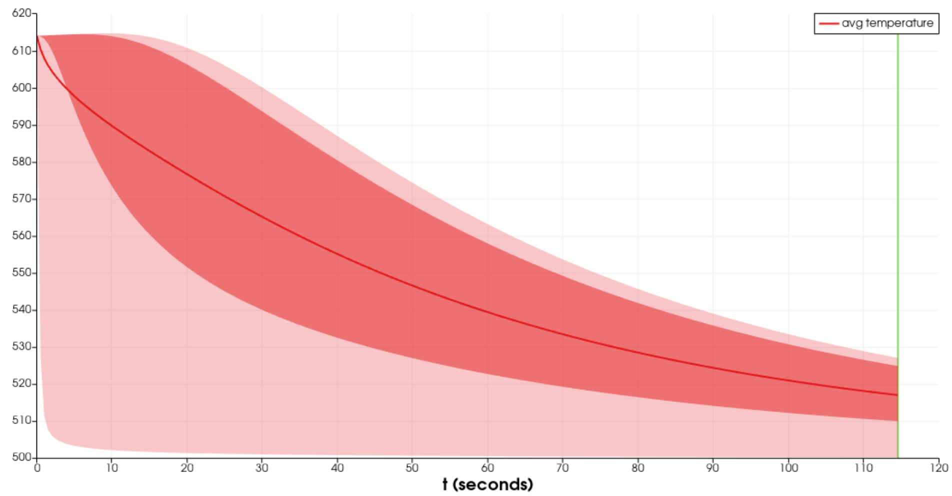

Figure 3 Average fuel temperature versus time in 1D transient problem

2.2. Heat Conduction in 2-D Fuel System

Now, we add more complexity to the problem by including axial dependence of LHR along a fuel rod of 100 cm length and also z-dependent coolant temperature (convective surface). The given equations were applied first to simulate the steady-state. Constant thermal conductivities were used with the same values used in part 1. The coolant heat transfer coefficient was assigned a value of h = 3 W/K. The radial temperature profiles at z = 25, 50, and 100 cm are in Figure 4, Figure 5, and Figure 6, respectively. While the axial temperature profile is plotted in Figure 7. The maximum temperature across the length of the fuel rod was found to be 521 K and is at z = 55 cm.

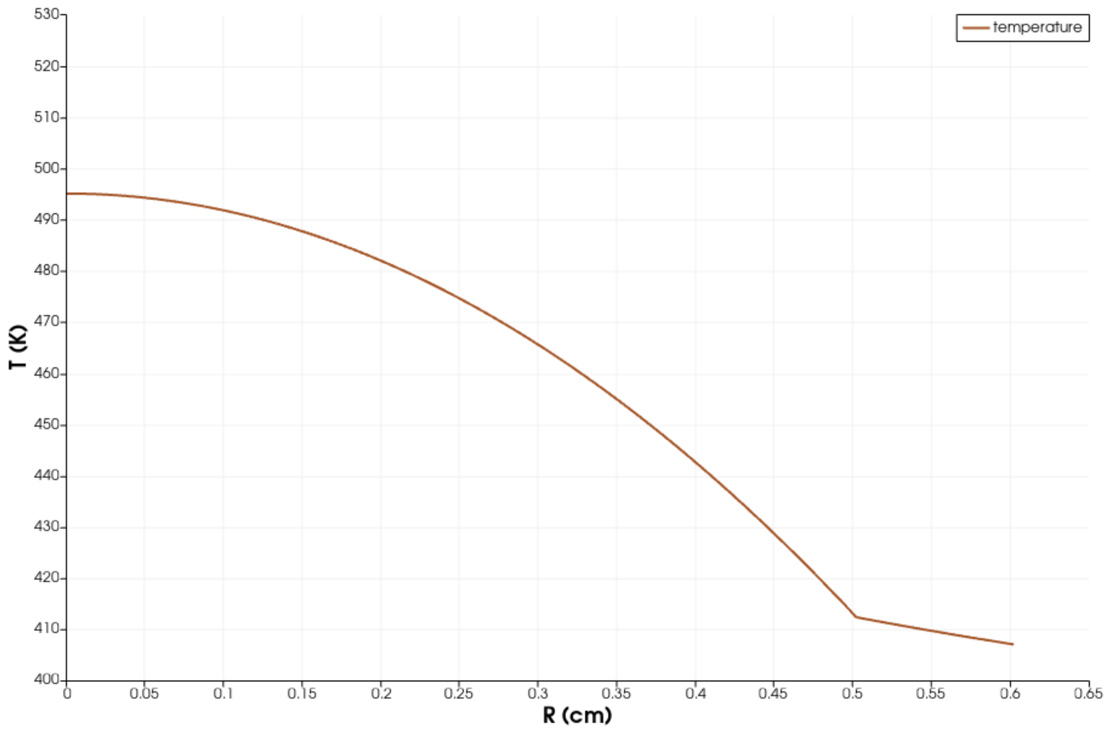

Figure 4 Steady-state temperature profile in a 2D problem at z = 25 cm

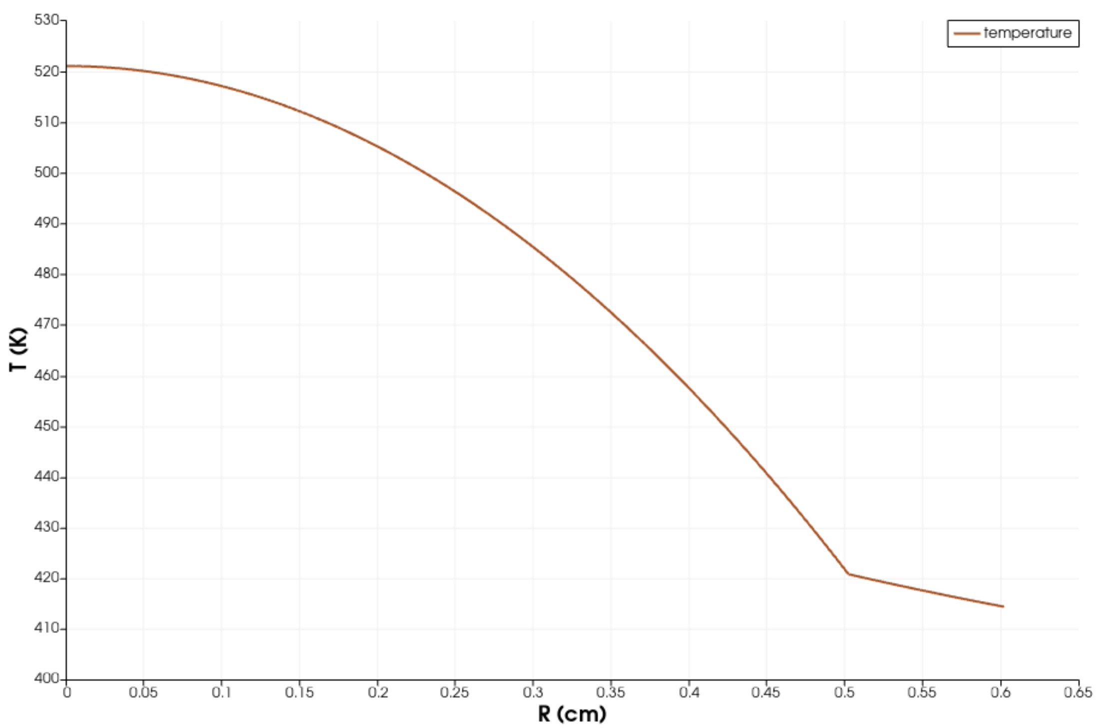

Figure 5 Steady-state temperature profile in a 2D problem at z = 50cm

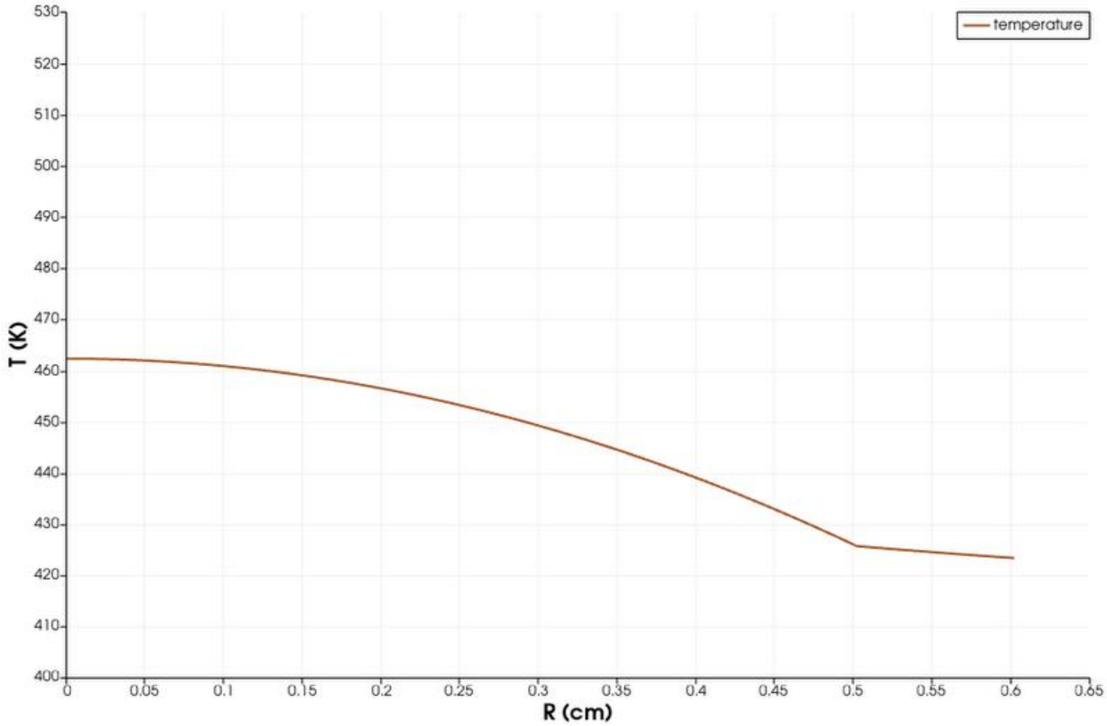

Figure 6 Steady-state temperature profile in a 2D problem at z = 100 cm

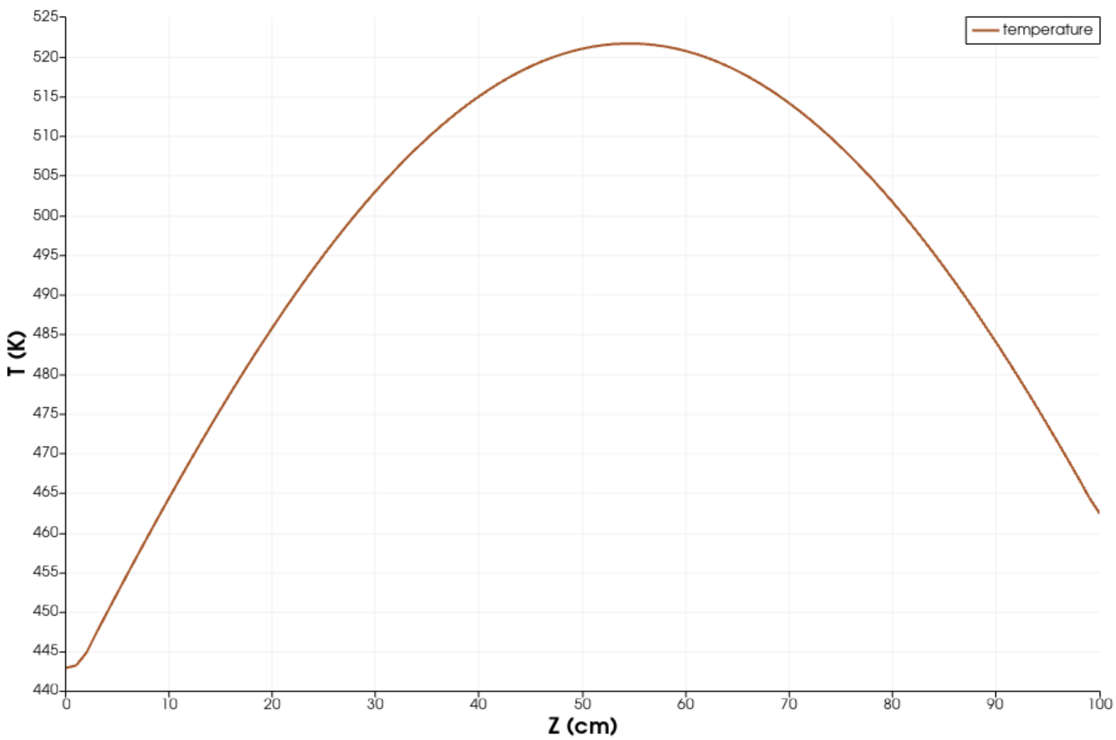

Figure 7 Maximum centerline temperature at z = 55 cm is 521 K

After that, transient state of the 2D system was considered using the same parameters but with a ramping LHR from 50 W/cm to 200 W/cm. The system approached steady state at around t = 26 seconds. The radial temperature profile in the midpoint of the fuel rod is given in Figure 8. And, the axial temperature profile at the centerline is given at Figure 9. Finally the average temperature versus time is shown in Figure 10.

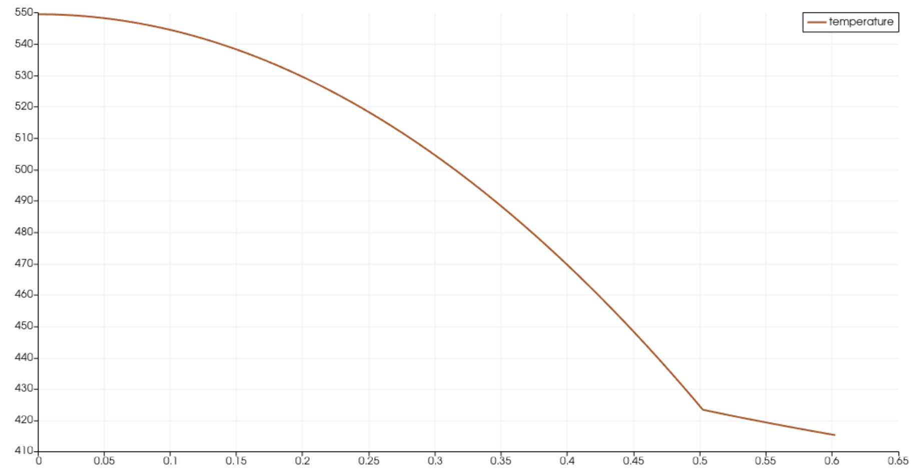

Figure 8 Radial temperature profile for 2D transient system. Horizontal axis is (r) in centimeters and vertical axis is T in K

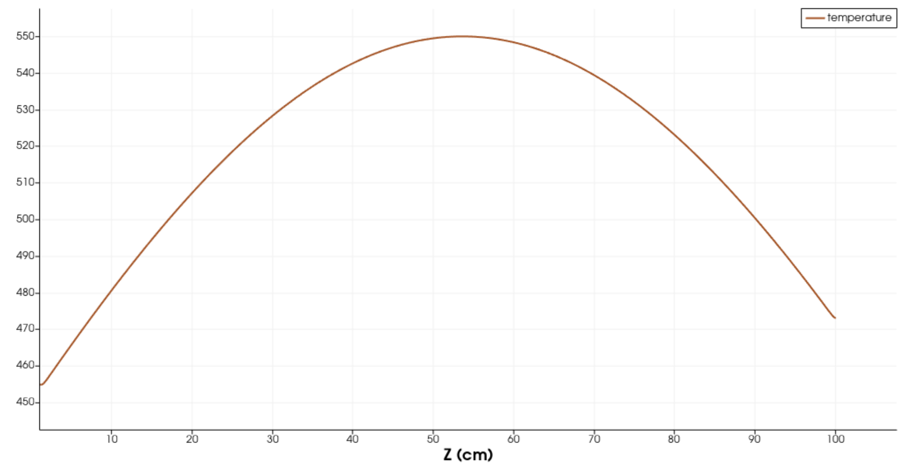

Figure 9 Final fuel centerline temperature for 2D transient system

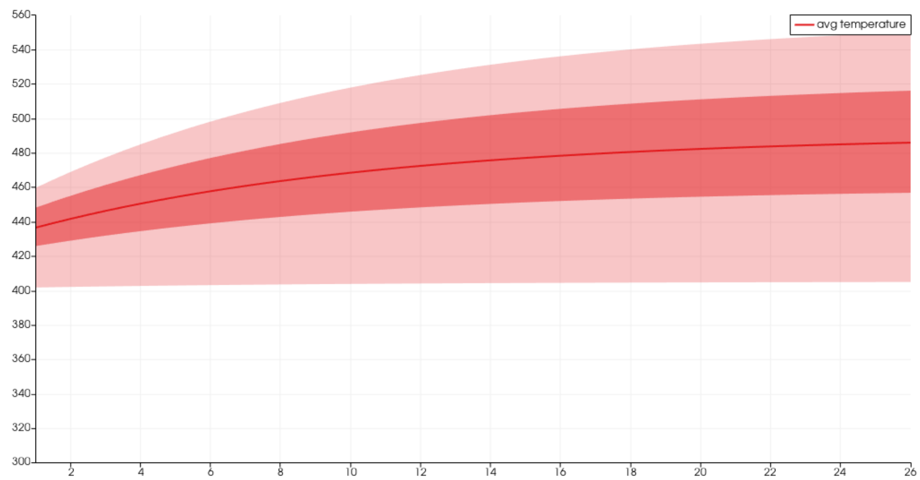

Figure 10 Time evolution of average temperature in the 2D system

2.3. Thermal Expansion

The third and last task was to model thermal expansion in a fuel pellet. The tensor mechanics module was enabled to calculate stresses and strains due to thermal expansion. The thermal expansion coefficient was set to $11 \times 10^{6} 1/K$. And, a constant elastic constant independent of temperature of 200 GPa was assumed for simplicity. This simulation was executed as a transient state. Output values converged to steady-state after about 30 seconds. The final strain components in rr and zz directions are plotted in Figure 11 and the Von Mises stress is plotted in Figure 12.

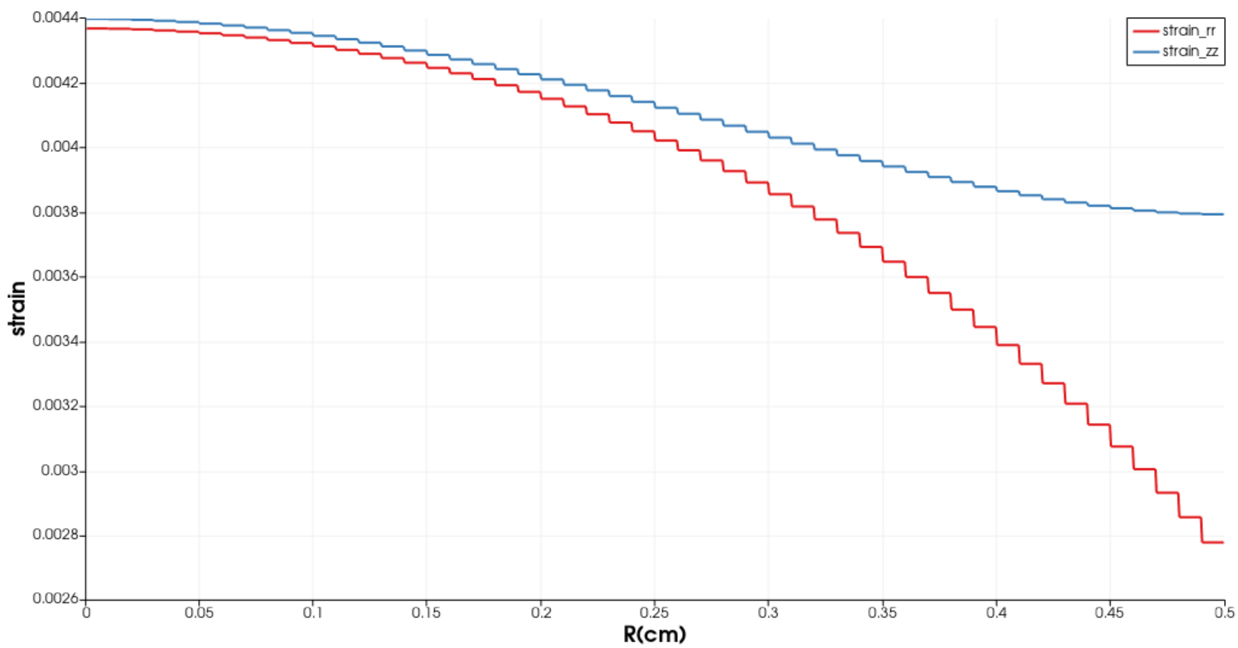

Figure 11 The rr strain (red) and zz strain (blue) as functions of radial distance (R) at the end of the simulation

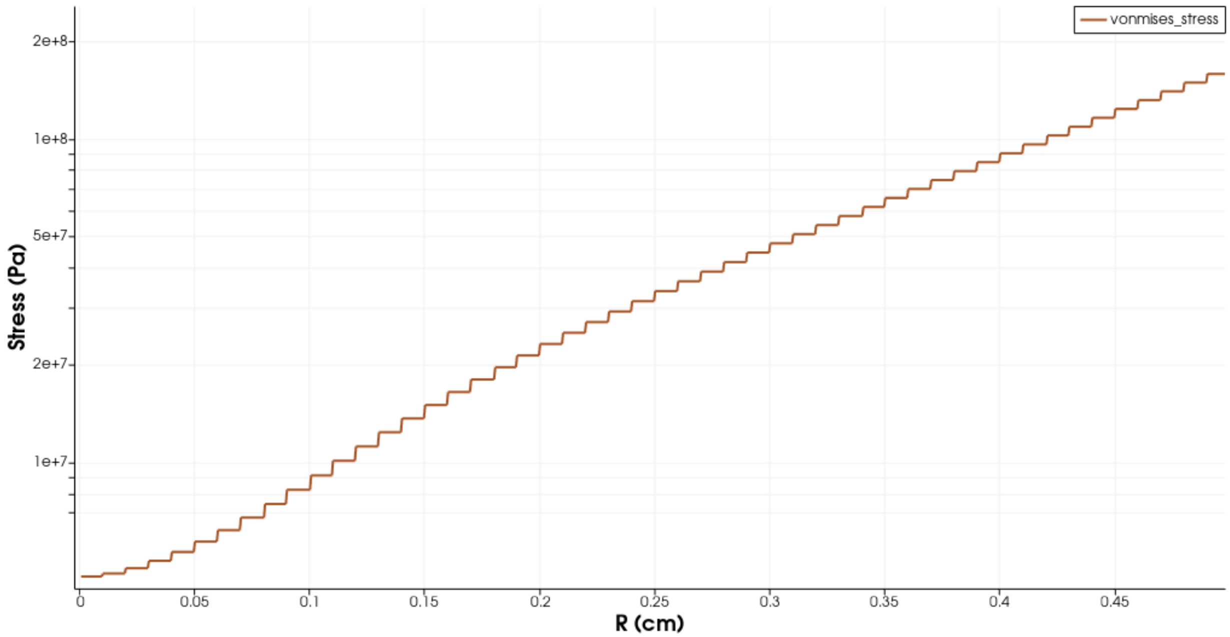

Figure 12 Von mises stress at the end of the simulation.