PennState
College of Engineering

NucE 497: Reactor Fuel Performance

Lecture 6: Intro to Heat Conduction

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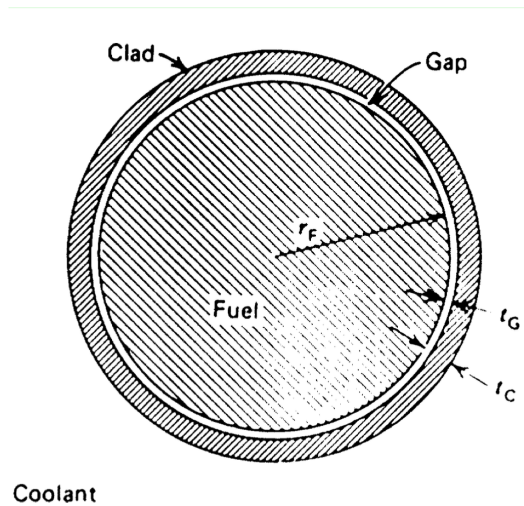
Some content taken from Olander's previous book and slides from ANT international

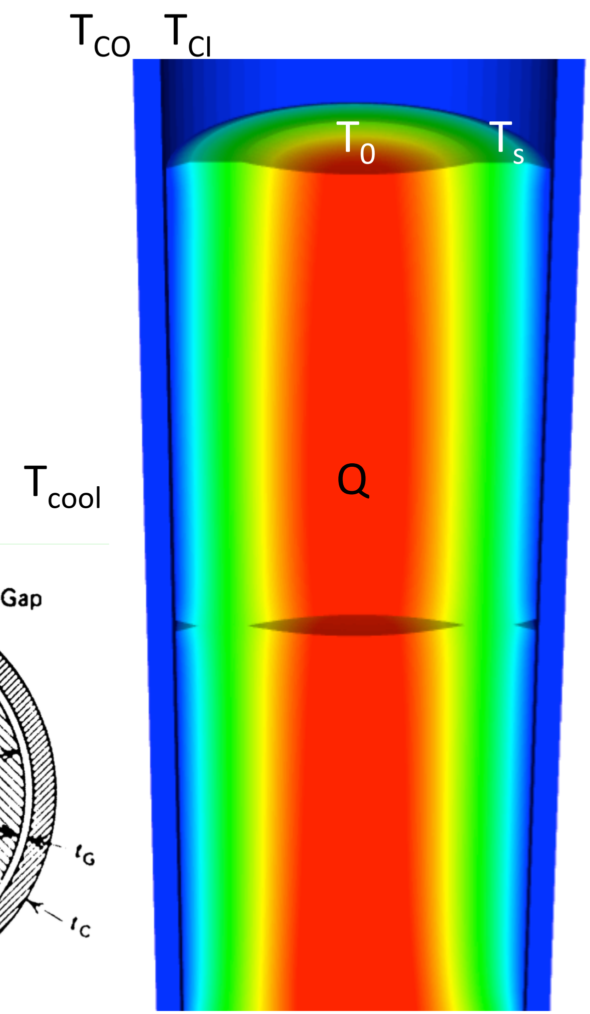
Today we will begin our discussion of heat transport in the fuel

- Module 1: Fuel basics
- Module 2: Heat transport
  - **Intro to heat transport and the heat equation**
  - Analytical solution of the heat equation
  - Numerical solution of the heat equation
  - 1D solution of the heat equation using Matlab
  - 2D solution of the heat equation using Matlab
  - Coolant temperature change, power generation, and melting
- Module 3: Mechanical behavior
- Module 4: Materials issues in the fuel
- Module 5: Materials issues in the cladding
- Module 6: Accidents, used fuel, and fuel cycle

Heat is produced in the fuel, transports through the cladding and gap, and into the coolant

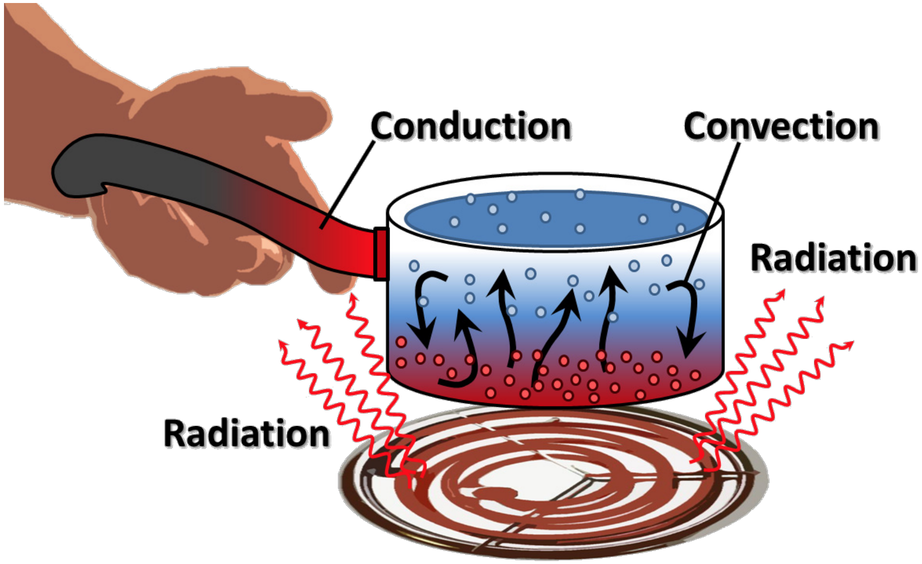
- Important quantities include
  - Volumetric heat generation rate Q (W/cm^3)
  - Fuel Centerline temperature T_0
  - Surface temperature of the fuel T_S
  - Inner cladding temperature T_{CI}
  - Outer cladding temperature T_{CO}
  - Coolant temperature T_{cool}
  - Pellet radius R_F
  - Gap thickness t_G
  - Cladding thickness t_c





Heat can be transported in three ways

- Convection
  - Heat transfer through mass movement of liquid or gas
- Radiation
  - Heat transfer by means of photons in electromagnetic waves
- Conduction
  - Heat transfer by molecular or atomic motion



How is heat transported through the various parts of the fuel and reactor?

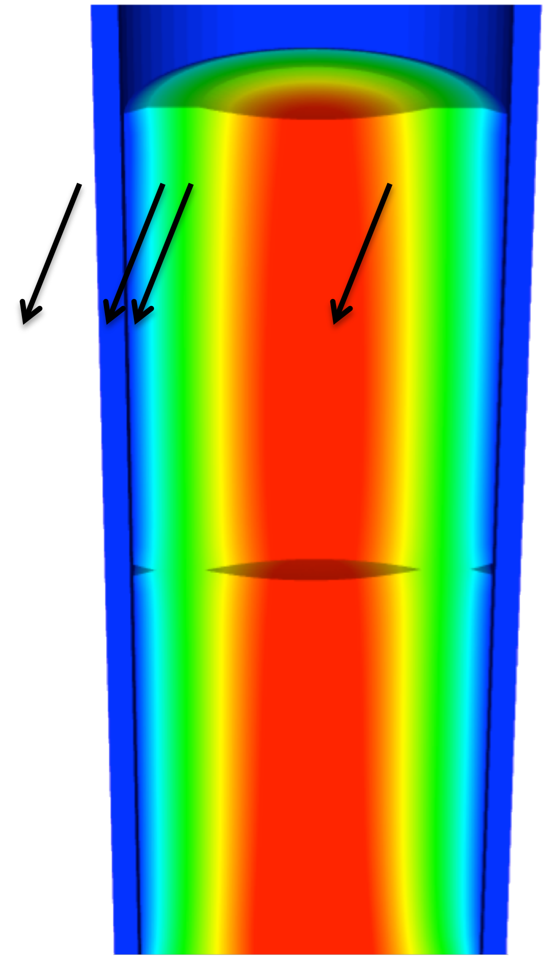
- How is heat transported through the fuel?

  Conduction
- How is the heat transported through the gap?

  Mostly conduction, some convection
- How is heat transported through the cladding?

  Conduction
- How is heat transported through the coolant?

  Convection



Quiz question: Label the parameters in the heat conduction equation

$$\rho c_p \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T)$$

Attempts: 23 out of 23

-0.00

Discrimination Index

Label the parameters in the heat conduction equation:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T)$$

is the density, cp is the specific heat, t is the temperature, T is the time, and k is the thermal diffusivity		0 %
is the probability, cp is the concentration of protons, T is the temperature, t is the time, and k is the thermal conductivity		0 %
is the density, cp is the specific heat, T is the temperature, t is the time, and k is the thermal diffusivity		0 %
is the density, cp is the specific heat, T is the temperature, t is the time, and k is the thermal conductivity	23 respondents	100 %

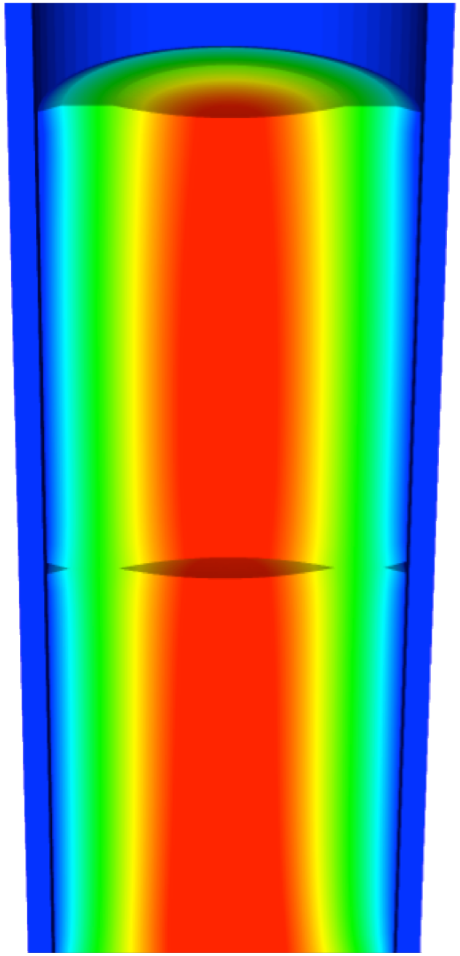
100% answered correctly

To solve for the temperature profile throughout the fuel and cladding, we solve the heat equation

- It is a partial differential equation in time and space

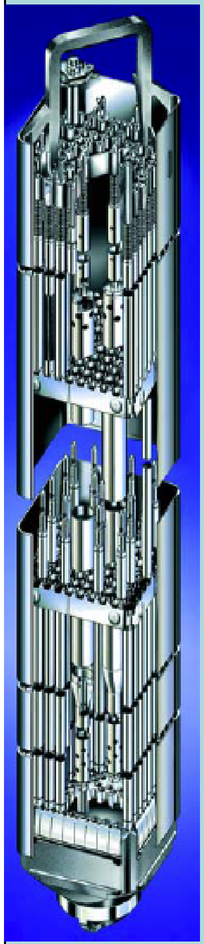
$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q$$

- We are solving for the T as a function of space and time
  - T(**x**, t), where **x** is a vector defining the position in space
- What do we need to know to solve this equation?

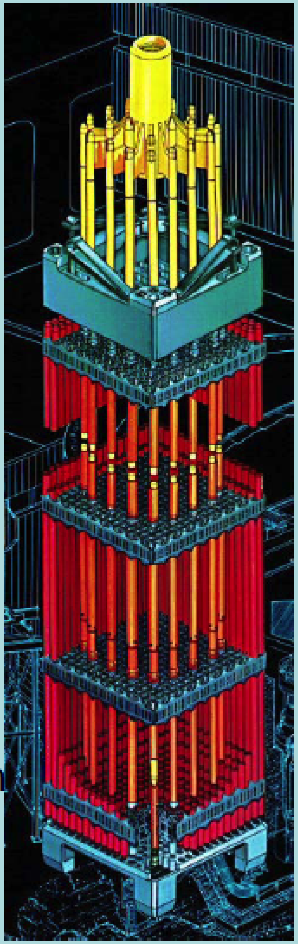


- The geometry of our problem
- The initial condition of T
- The boundary conditions of T
- If each parameter is a function of T
- If they aren't a function of T, do they vary in space and time for some other reason?

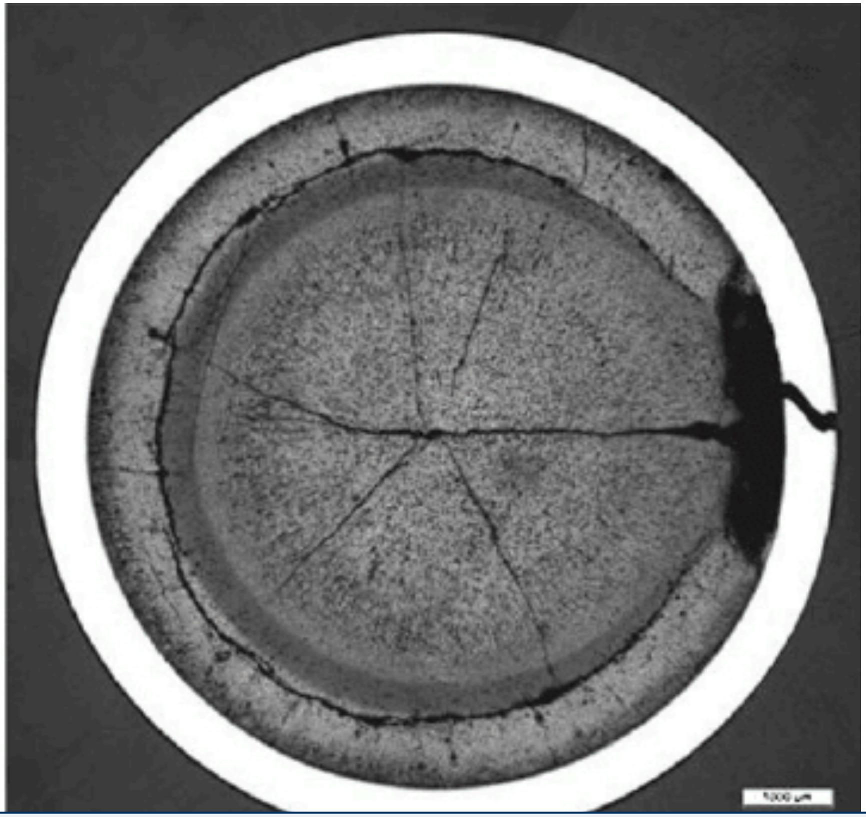
The geometry of the fuel assemblies vary between BWRs and PWRs

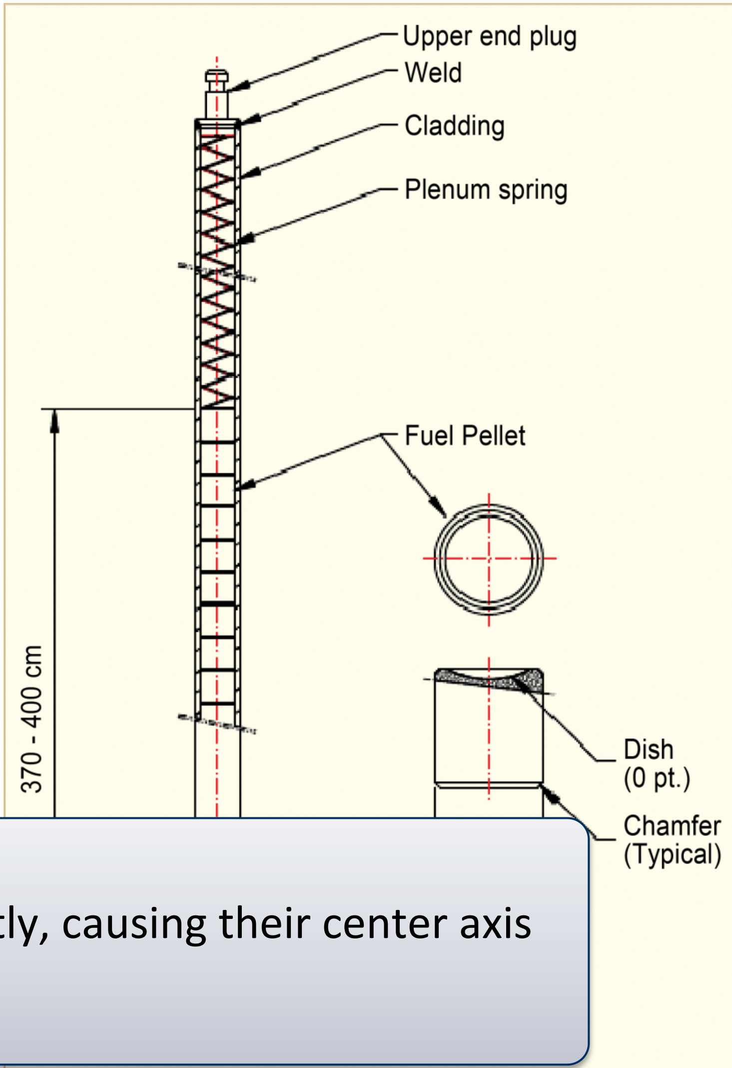


	BWR	PWR
Lattice	10x10	14x14 – 18x18
Lattice size	~5.3”	~9”
Height	120”-150”	144”-168”
Fuel	UO_2/MOx	UO_2/MOx
Fuel rods	~92	176-300
Part length rods	~14	0
Non-fueled rods	~2	20-25
Control	Ext. control rod	Int. control cluster
Cladding	Zr2 for PCI, nodular corrosion	Zr4/Zirlo/M5 for uniform corrosion & hydrogen
Channels	Yes	No
Fuel mass	~180 kgU	~600 kgU



The ideal geometry of each fuel rod is axisymmetric, but in reality it is 3D

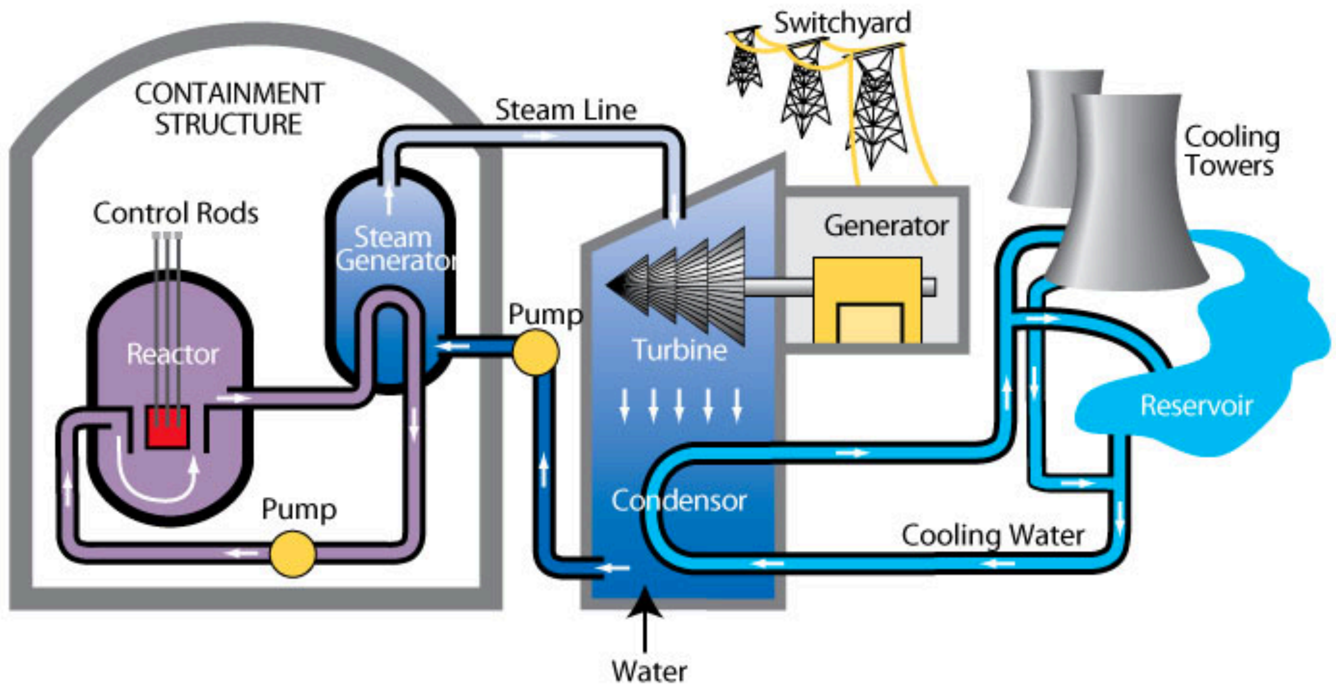




- Fuel pellet defects cause 3D geometry
- The stacked pellets may not be stacked perfectly, causing their center axis to not be aligned, also causing 3D geometry

The initial condition of T is set by the state of the reactor directly before startup

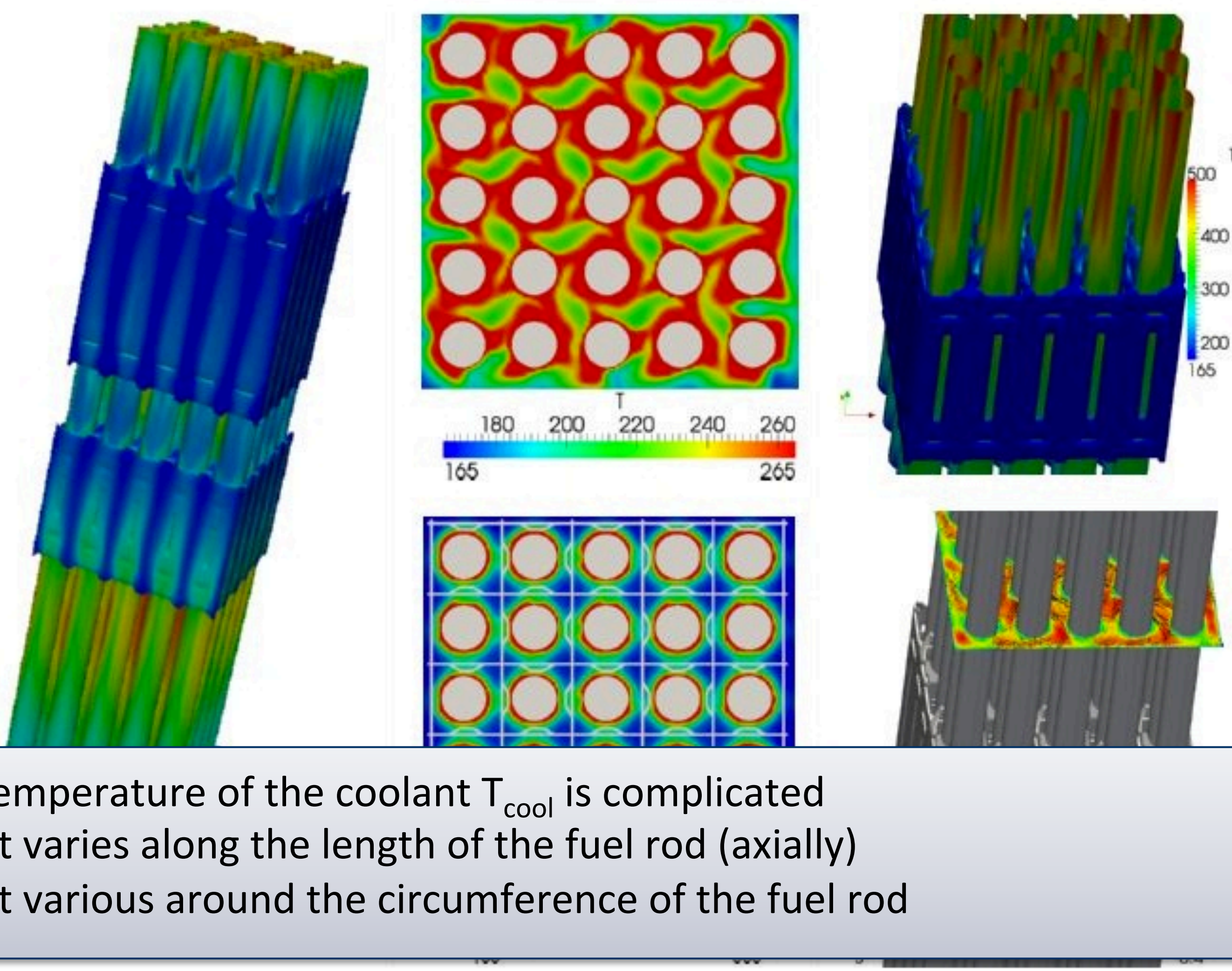
- What is the initial temperature profile of the fuel?



- The initial temperature is uniform throughout the fuel
- It is equal to the initial coolant temperature
- $T(\mathbf{x}, 0) = T_{cool}(0)$

The boundary conditions on T is set by the coolant flow

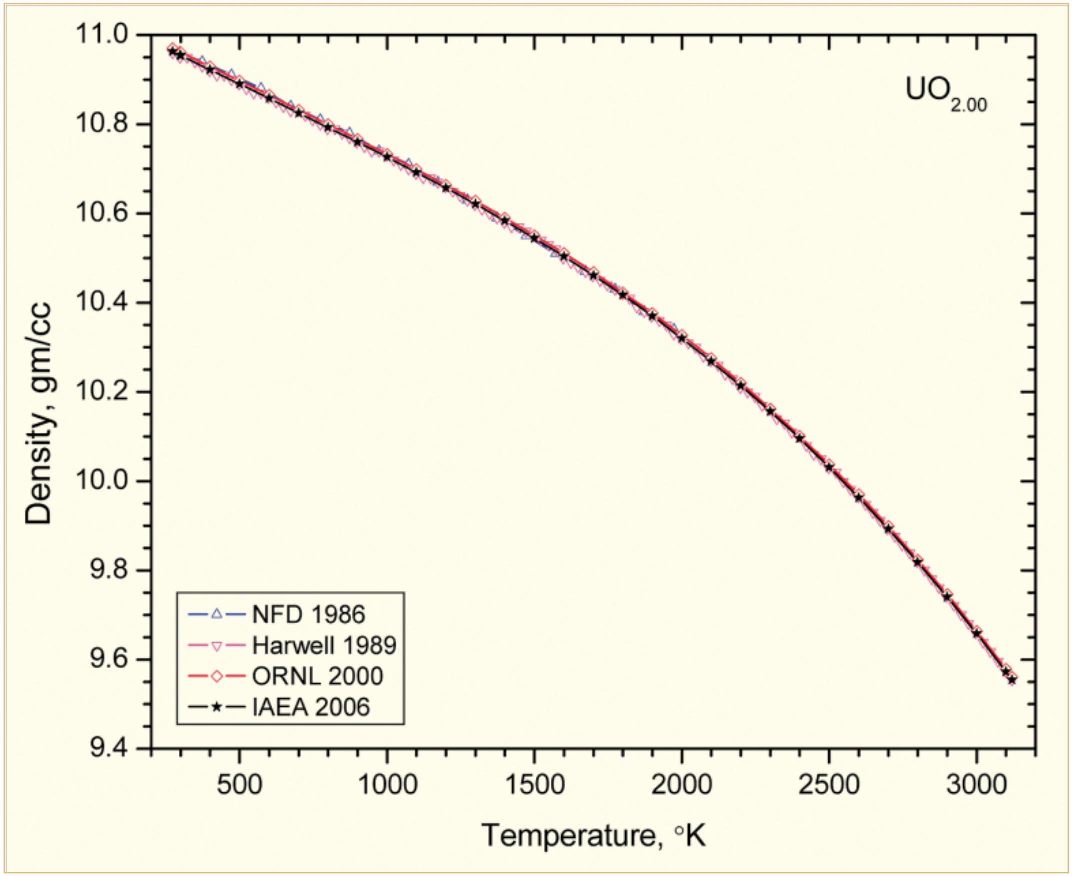
From the Consortium for Advanced Simulation of LWRs



- The temperature of the coolant T_{cool} is complicated
  - It varies along the length of the fuel rod (axially)
  - It various around the circumference of the fuel rod

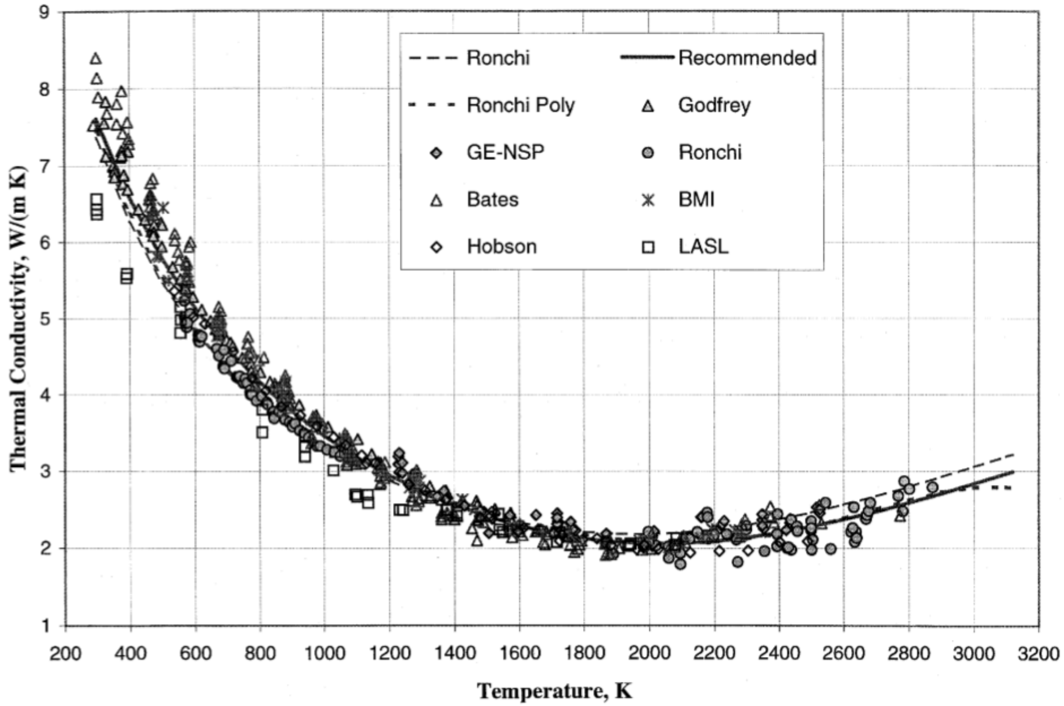
The density of the fuel is a function of temperature, but is fairly homogeneous

- Theoretical density (ρ_{TD}) varies with composition and temperature
- At 273 K, density in gm/cc is 10.960 - 10.970



from equations of [Une 1986], [Harding et al, 1989], [Popov et al, 2000] and [IAEA, 2006]

The thermal conductivity also varies with temperature

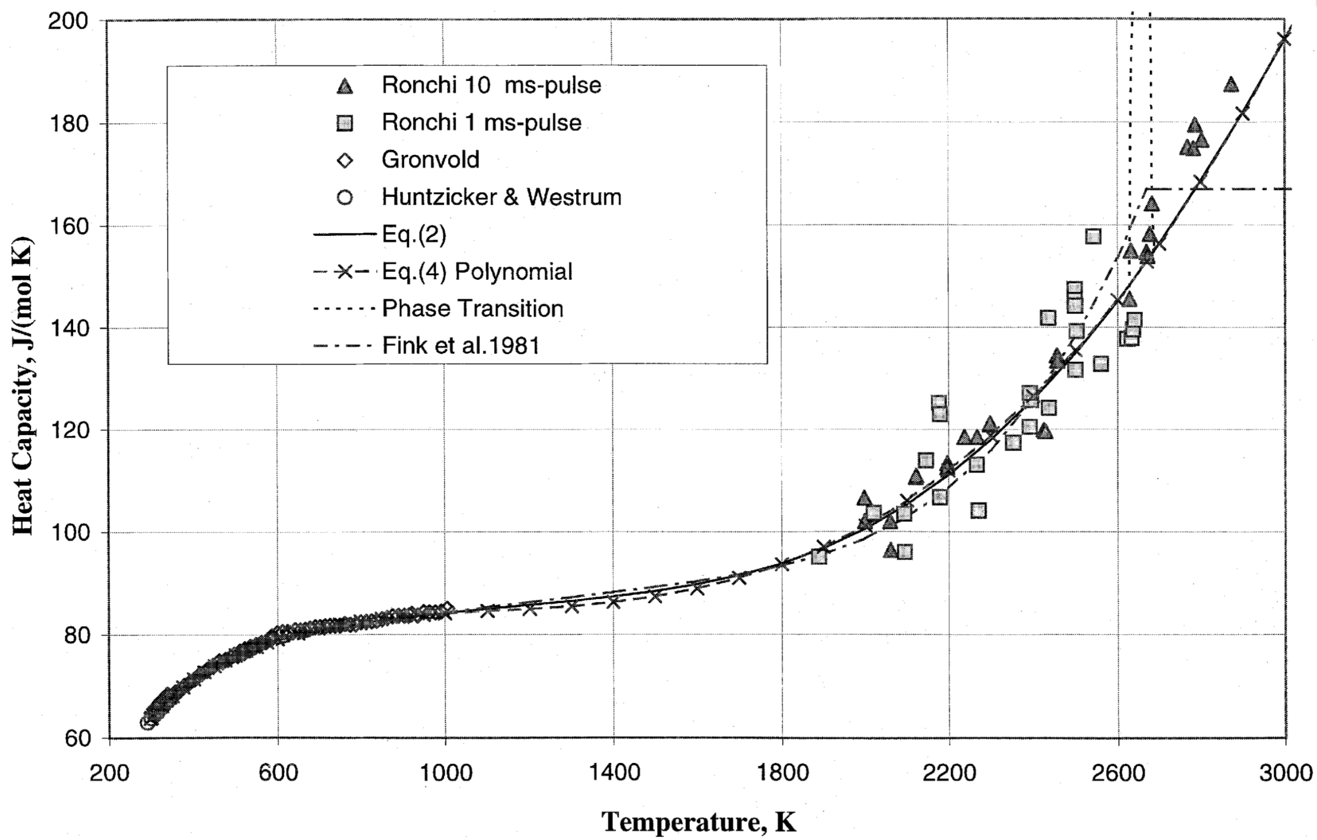


$$k_0 = \frac{100}{7.5408 + 17.629t + 3.6142t^2} + \frac{6400}{t^{5/2}} \exp\left(\frac{-16.35}{t}\right)$$

- Where t = T/1000
- The first part of the equation describes the phonon interactions
- The second part describes electronic transport which becomes significant at high temperature

J.K. Fink, J. Nucl. Mater. 279 (2000) 1-18

The heat capacity is a function of temperature as well



$$C_P = \frac{C_1\theta^2 e^{\theta/T}}{T^2(e^{\theta/T}-1)^2} + 2C_2T + \frac{C_3E_a e^{-E_a/T}}{T^2}$$

θ = 548.68,
$C_2 = 2.285 \times 10^{-3}$
$C_3 = 2.360 \times 10^{7}$
$E_a = 18531.7$

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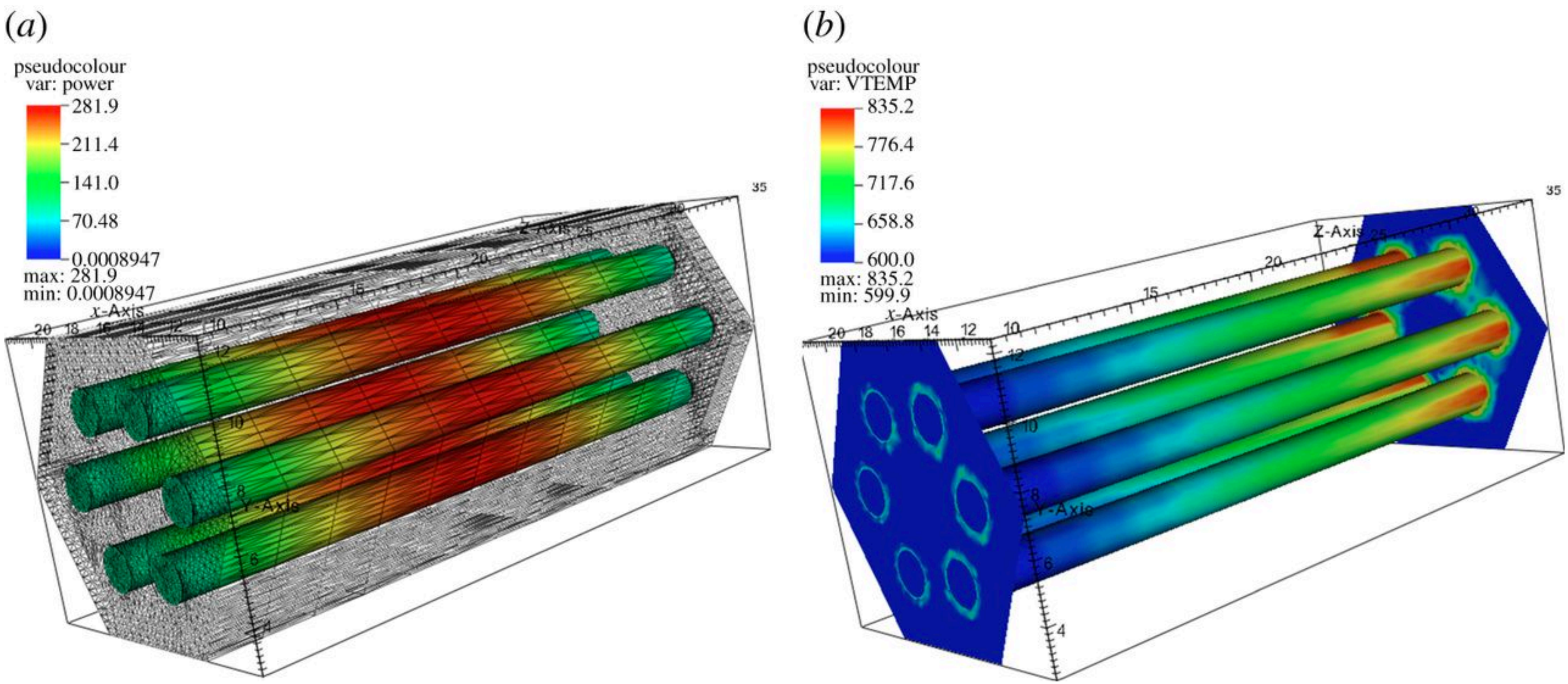
The heat generation rate is a function of the thermal neutron flux, which varies in time and space

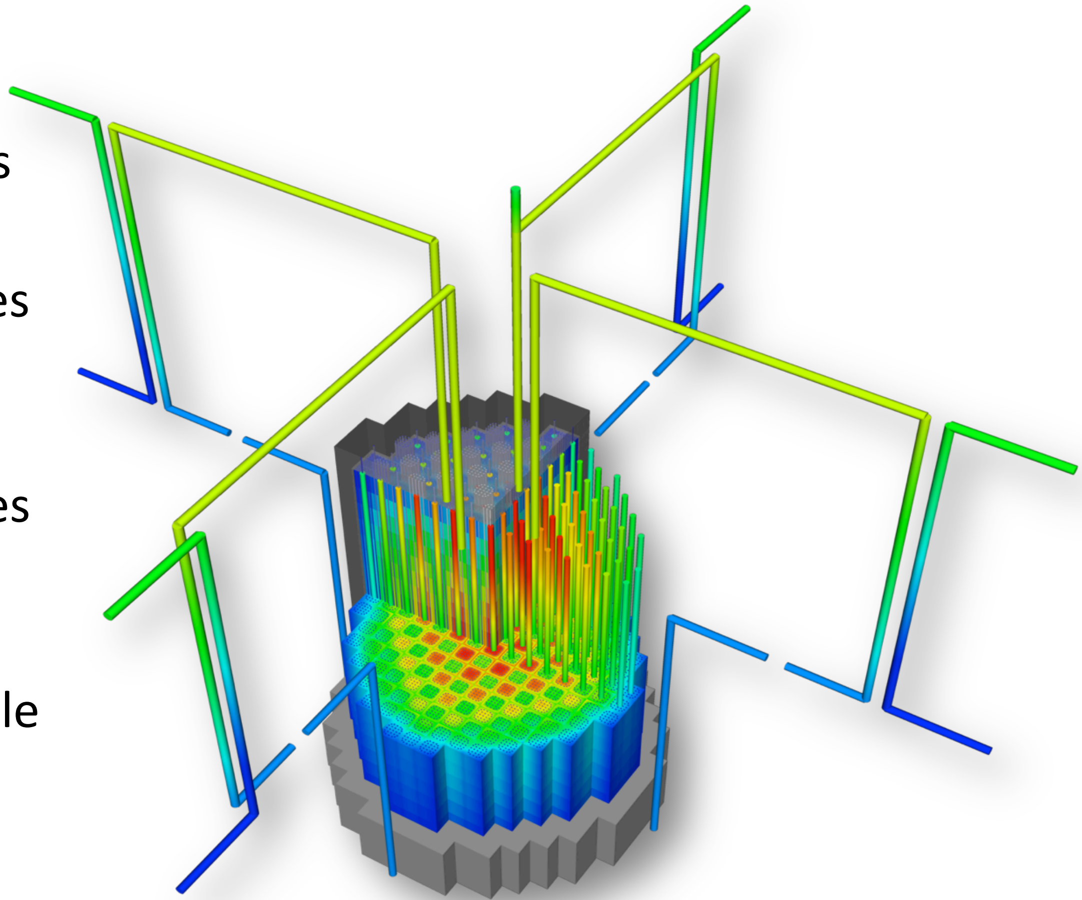
$$Q = E_f \, N_f \, \sigma_f \, \varphi_{th}$$



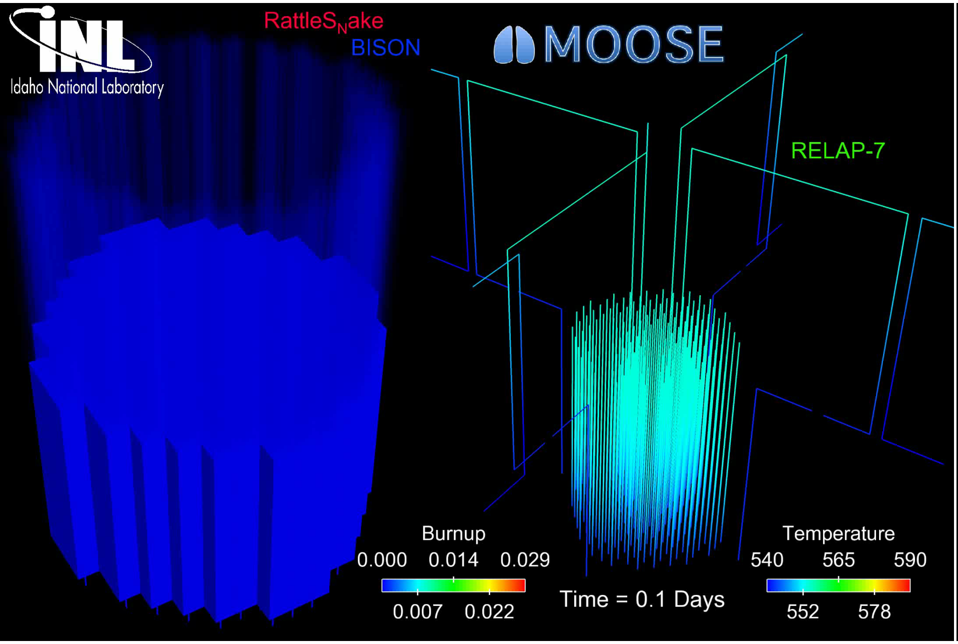
The most accurate solution of our problem must be numeric

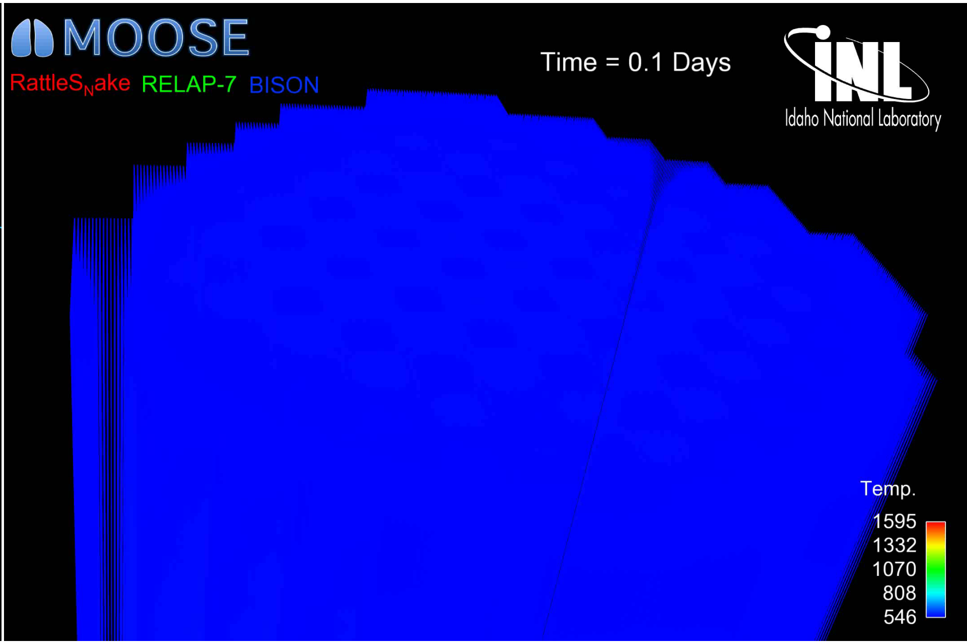
$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q$$

- Solution is 3D and changes in time
- All the properties are functions of temperature
- The boundary conditions comes from information about the coolant flow
- The heat generation rate comes from information about the neutronics in the reactor
- No analytical solution is possible



The most accurate solution is 3D, requires modeling the entire core, and is multiphysics

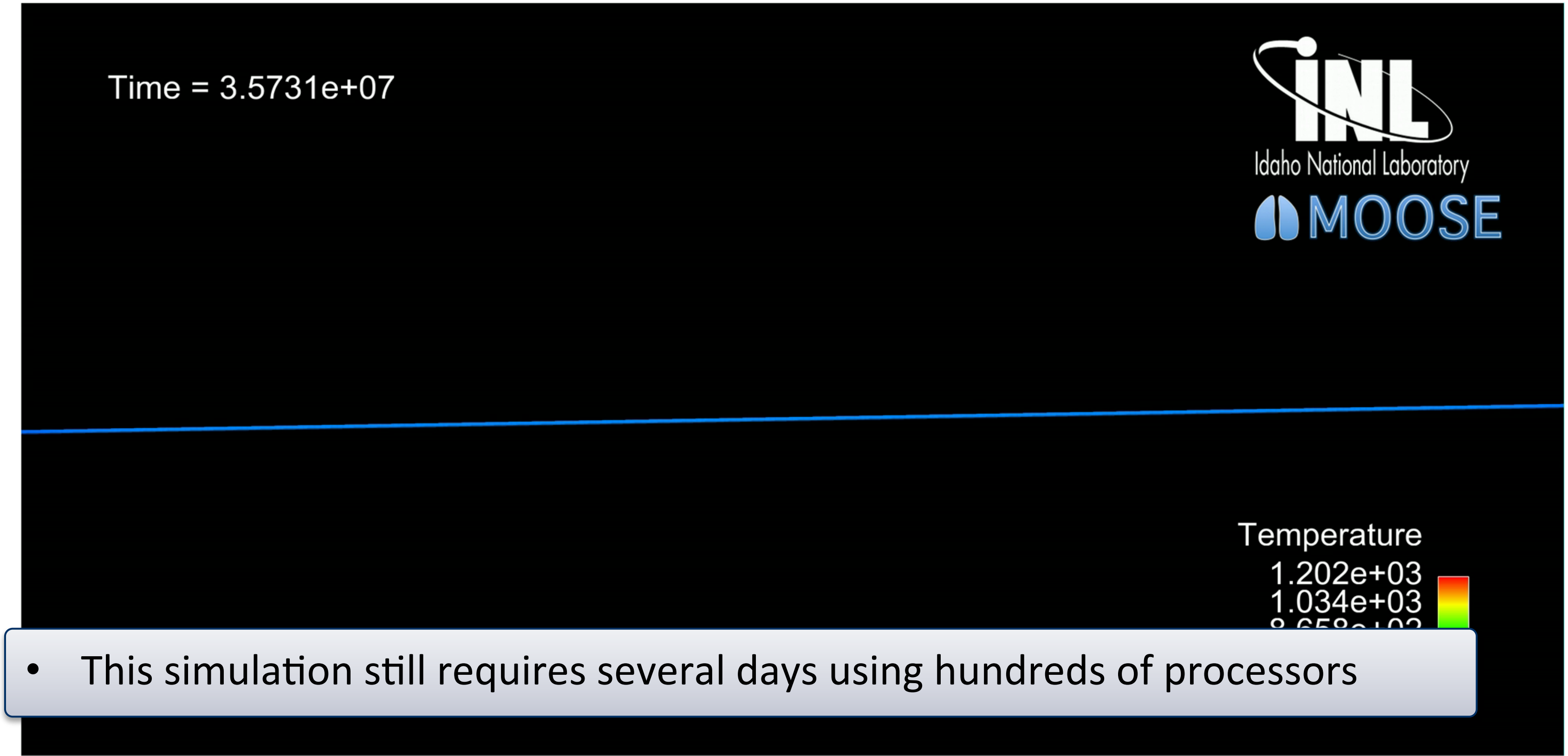




- This simulation required 48 hours of computation using hundreds of processors

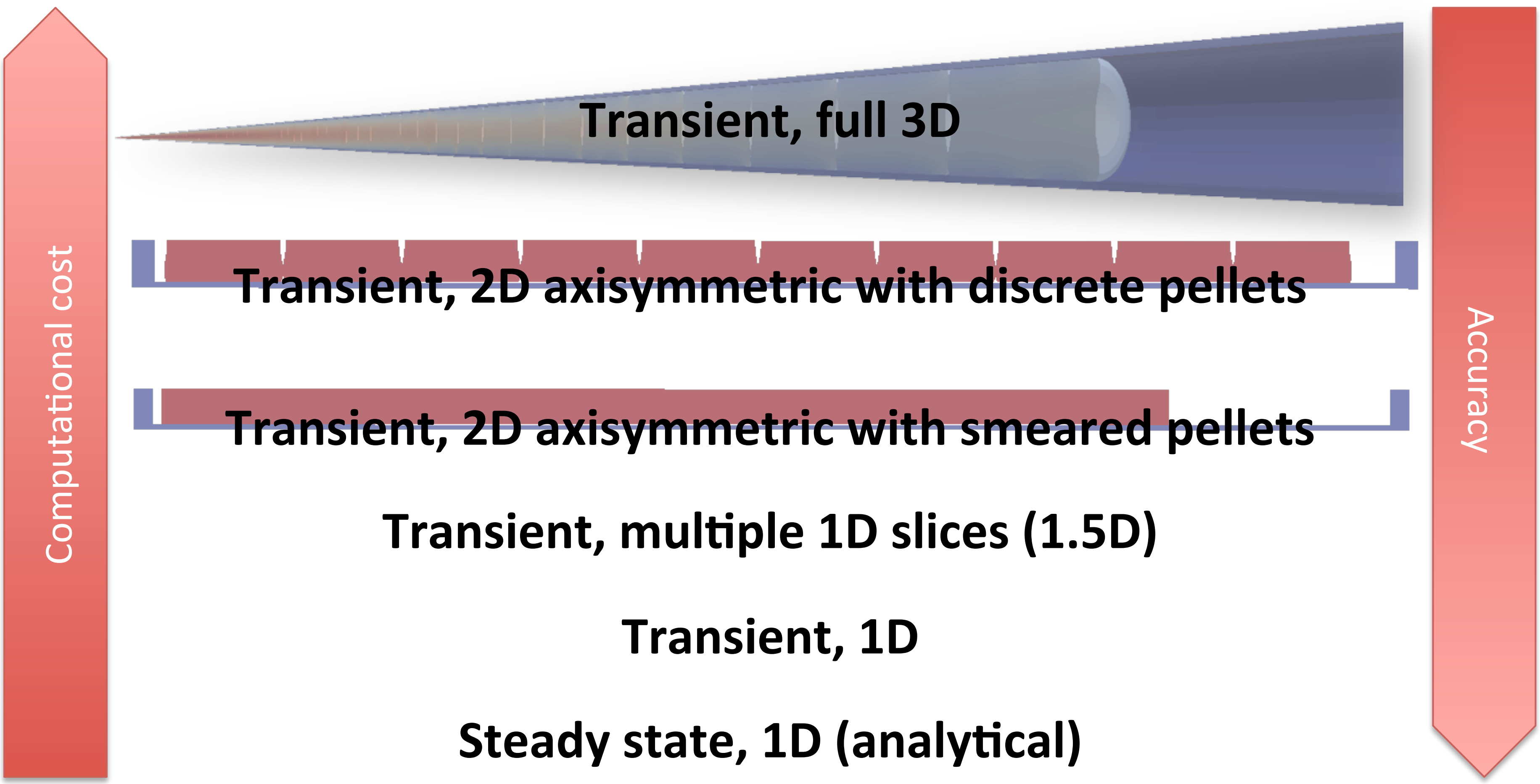
We can simplify the solution by making assumptions

- Things would be much easier if we could model only one fuel rod
  - Assume a neutron flux that is a function of axial position and radius to decouple from the neutronics
  - Use a simple coolant channel model to decouple from the thermal hydraulics



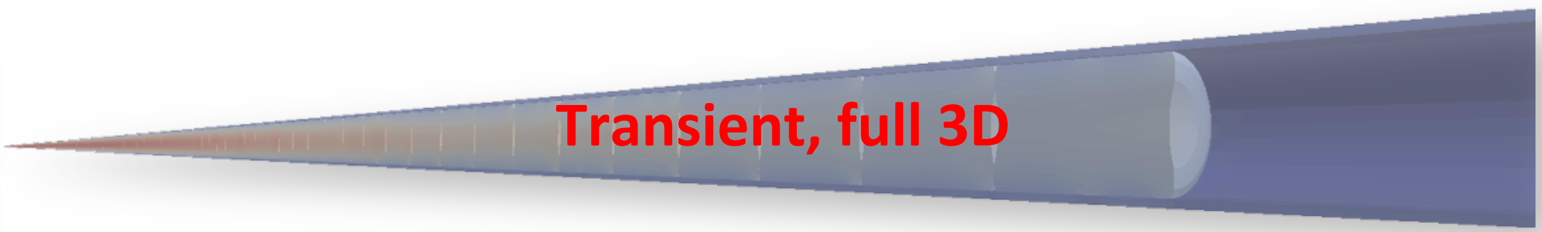
- This simulation still requires several days using hundreds of processors

The more assumptions we make, the faster the calculation, but the less accurate the results are



In this course, we will focus on the less complex solutions

Computational cost



Transient, full 3D

Transient, 2D axisymmetric with discrete pellets

Transient, 2D axisymmetric with smeared pellets

Transient, multiple 1D slices (1.5D)

Transient, 1D

Steady state, 1D (analytical)

Accuracy

We will do in the homework

You could do in the project

Summary

- The temperature profile throughout the fuel and cladding is predicted by solving the heat equation
- An accurate solution of the temperature profile in a fuel pellet requires a 3D numerical approach coupled to other physics codes
- Typically we focus on a single fuel rod
- We make simplifying assumptions to lower the computational cost, but it also decreases the accuracy
  - Transient, full 3D
  - Transient, 2D axisymmetric with discretized pellets
  - Transient, 2D axisymmetric with smeared pellets
  - Transient, 1.5D
  - Transient, 1D
  - Steady state, 1D (analytical)