# Advanced Finite Element Modeling of a Horizontal Nuclear Fuel Element using a Multiphysics Object-Oriented Simulation Environment

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## Introduction

- The ability to perform predictive thermomechanical modeling of nuclear fuel is of utmost importance from the perspective of industry and the regulators.
- As the geometry of the model increases from a pellet to a bundle the amount of coupled physics that can be included decreases due to computational constraints
- INL's Multiphysics Object-Oriented Simulation Environment (MOOSE) is a computational framework used for solving fully coupled partial differential equations using a Jacobian-Free Newton Krylov (JFNK) numerical method.
- A HORizontal nuclear fuel Simulation Environment (HORSE) is built upon MOOSE.
- RMC is the second institution in Canada to have a MOOSE license, AECL was the first.

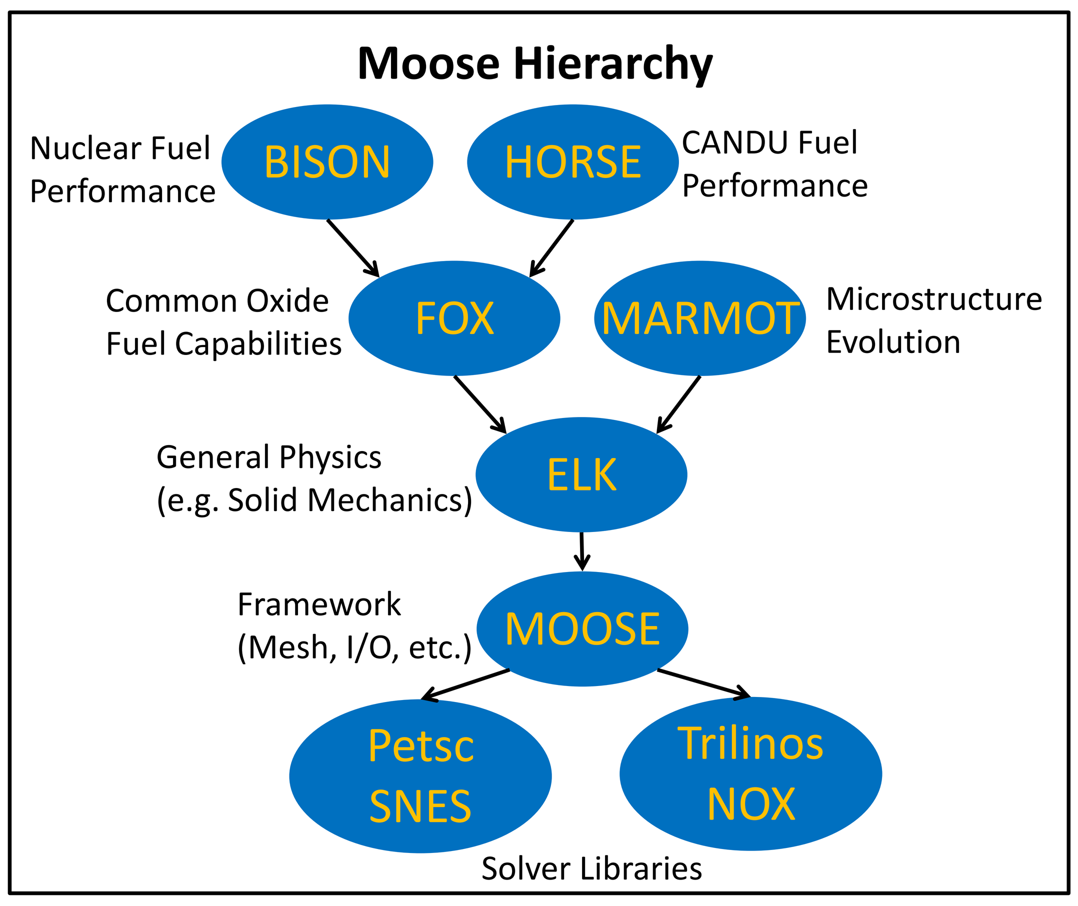


*Figure 1: Hierarchy of MOOSE and its associated applications. HORSE is added to show upon which animals it is to be built.*

## CANDU Fuel

- A CANDU reactor core contains 380 or 480 fuel channels that contain a pressure tube.
- The pressure tube contains 12-13 horizontal fuel bundles, depending on the reactor.
- A 37-element bundle contains 37 fuel elements with 30 or 31 individual natural uranium dioxide fuel pellets in a Zircaloy-4 sheath.
- Coolant and moderator is heavy water pressurized to 10 MPa.

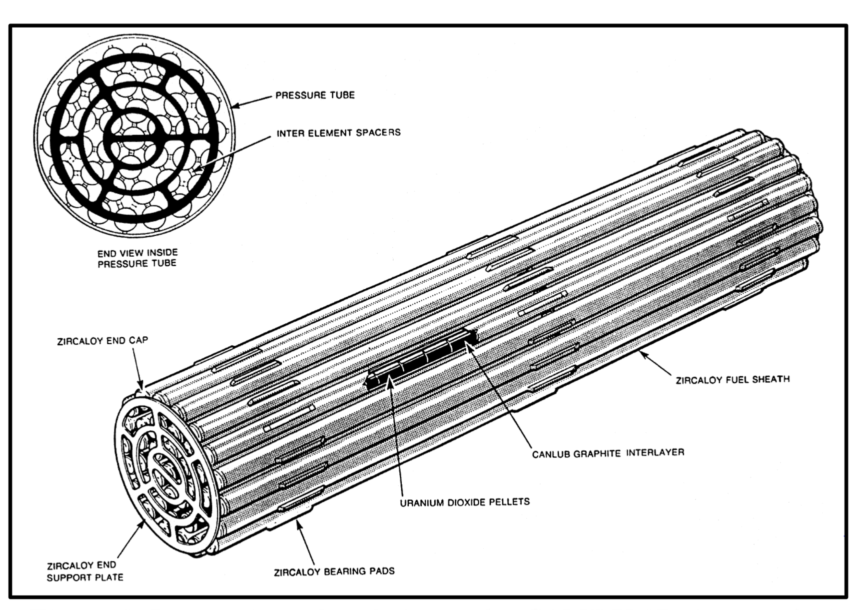

*Figure 2: Isometric and end views of a CANDU 37-element fuel bundle.*

## Objectives

- Develop a three-dimensional thermomechanical model of a CANDU fuel element using MOOSE.
- Examine the efficiency and robustness of the MOOSE framework for modeling CANDU fuel behaviour.
- Assess the feasibility of using MOOSE to model CANDU fuel.
- Develop a computational infrastructure that enables the analysis of different fuel types such as hyperstoichiometric $UO_2$ and thoria-based fuels.
- Build the preliminary framework that can be extended to the ultimate goal of a fully coupled 37-element bundle with computational fluid dynamics determining subchannel behaviour.

## Geometry and Material Properties

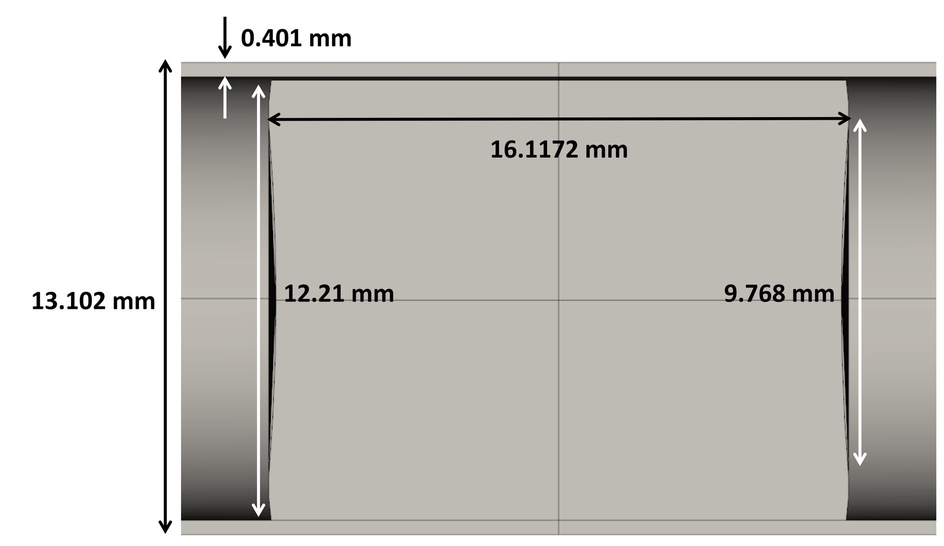


*Figure 3: Schematic view of a cross-section of a fuel pellet showing dimensions.*

| Parameter | Value (mm) |
|---|---|
| Axial Chamfer | 0.066 |
| Radial Chamfer | 0.63 |
| Dish Depth | 0.2 |
| Land Width | 0.591 |
| Initial Gap Width* | 0.045 |

**Due to pellet bottoming, the pellet initial rests on the bottom of the sheath and the gap is closed. Therefore, a 90μm exists at the top.*

| Uranium Dioxide Fuel | Zircaloy-4 Sheath | Fuel-to-Sheath Gap | Coolant Channel |
|---|---|---|---|
| • Constant heat generation<br>• Temperature dependent material properties<br>• Pellet-to-pellet contact | • Temperature dependent material properties | • Gas conductance<br>• Radiation<br>• Solid-solid contact<br>• Pellet-to-sheath contact<br>• Gas Pressure<br>• Gas Temperature | • Heat transfer coefficient<br>• Coolant pressure |

## Summary

- Using a state of the art computational framework, an application for horizontal nuclear fuel modeling is being developed.
- Seven pellet model produces convergent results, nine and fifteen pellet models are under development.

## Future Work

- Implementation of sheath creep, position dependent heat generation and additional pellets.
- Determine a way of constraining pellets to remove the fully glued approximation.
- Post-processing and benchmarking.

## Acknowledgements

- Funding for this project is provided by NSERC.
- The expertise of the MOOSE/BISON developers Derek Gaston, Cody Permann, Jason Hales, and Benjamin Spencer is greatly appreciated.

## Results

- The first step in the feasibility analysis was to determine the behaviour of the contact algorithm. Results of contact pressure and penetration as a function of penalty factor were obtained.
- Next step was to add temperature dependent material properties and begin to add multiple pellets to introduce pellet-to-pellet contact.

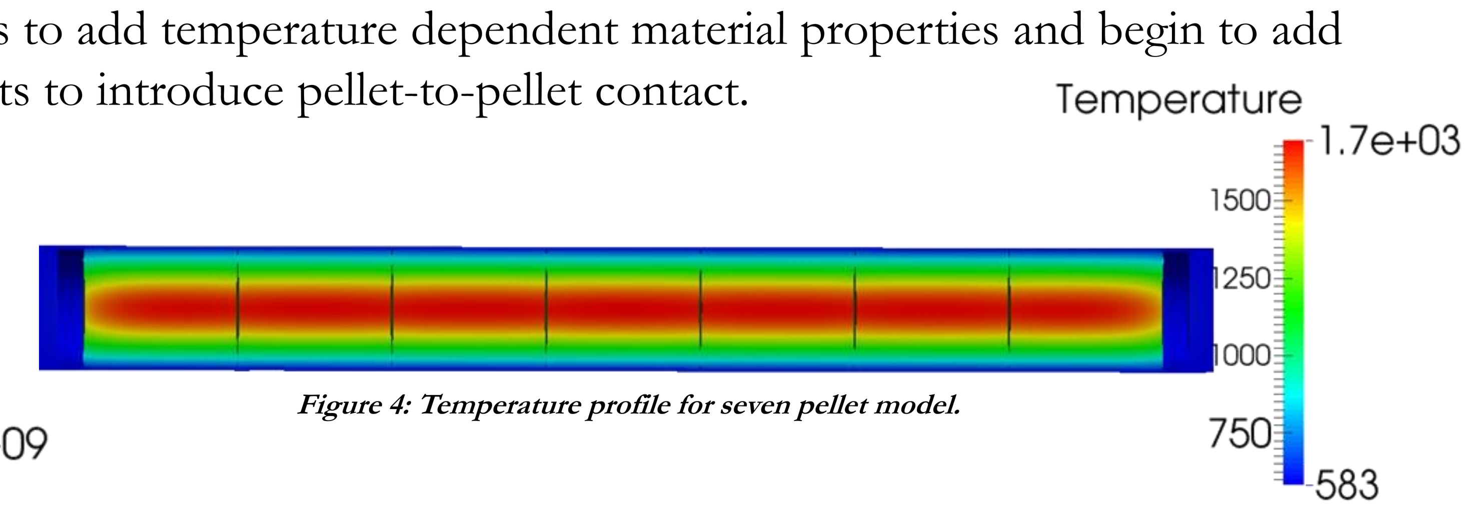


*Figure 4: Temperature profile for seven pellet model.*

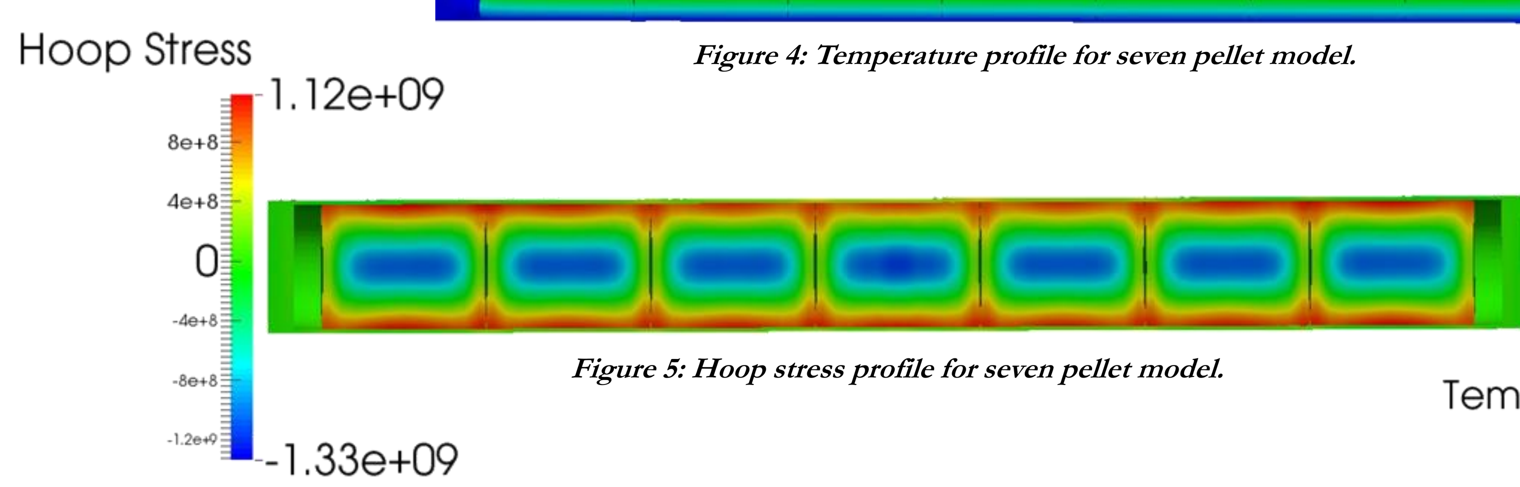


*Figure 5: Hoop stress profile for seven pellet model.*

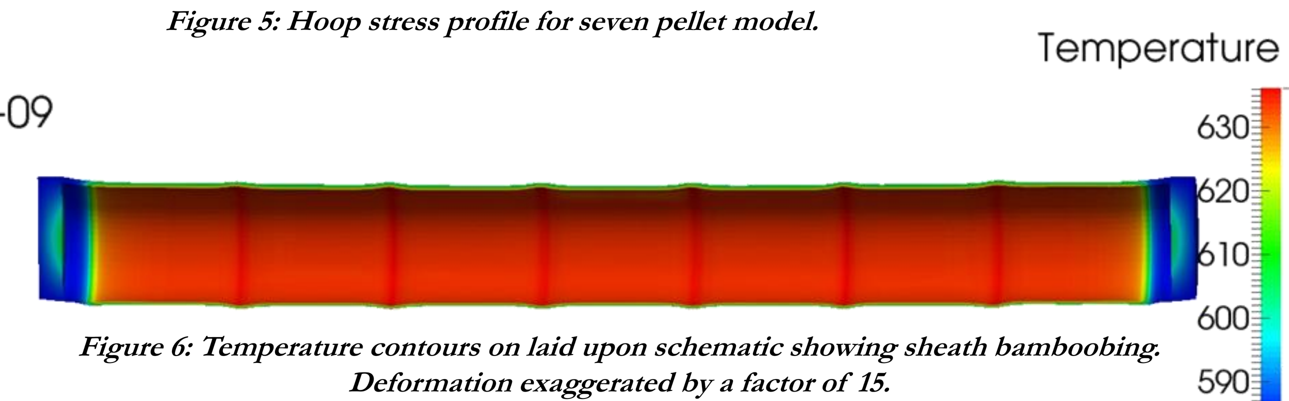


*Figure 6: Temperature contours on laid upon schematic showing sheath bamboobing. Deformation exaggerated by a factor of 15.*

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