A Multiphysics Framework to Characterize Fuel Bowing Effects in PWRs

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U.S. Operating Nuclear Plants

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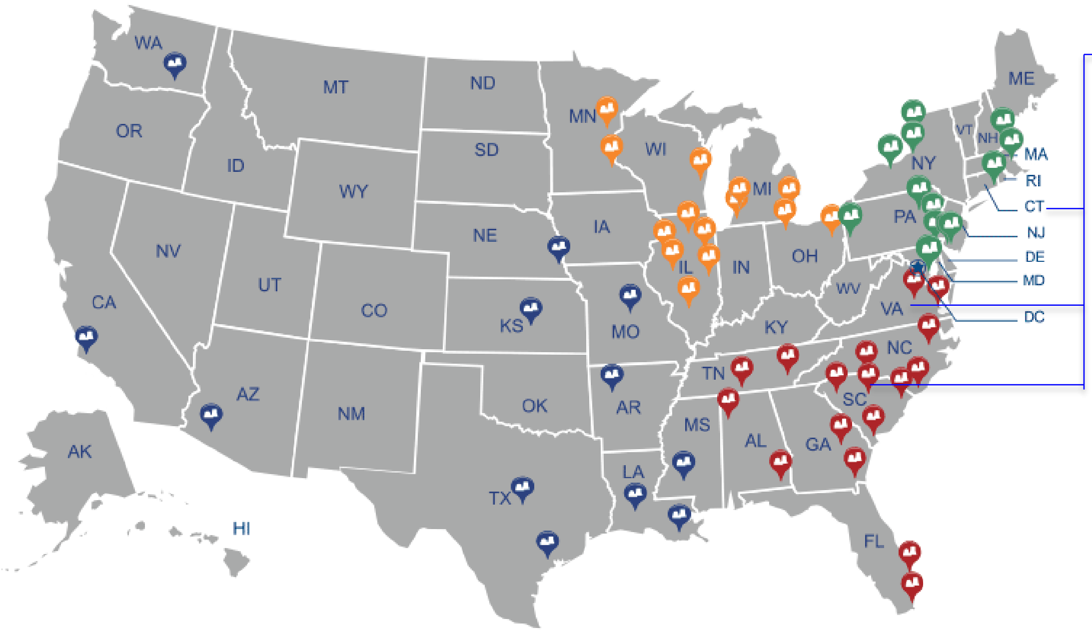
October 2021

U.S. Operating Commercial Nuclear Power Reactors



Dominion Energy

- Millstone (CT)
- North Anna (VA)
- Surry (VA)
- V.C. Summer (SC)

Reference link: https://www.nrc.gov/reactors/operating/map-power-reactors.html

Fuel Bowing in PWRs - Overview

- ❑ One of the major nuclear fuel performance issues
- ❑ Widely observed in PWR operations
- ❑ Few modeling work in the literature, especially with fuel rod bow
- ❑ A multiphysics phenomenon encompassing neutronics, mechanics, and thermal hydraulics
  - How do these parameter affect one another?
  - Are there any feedback effects?
  - What can we do to benefit operations?

A phenomenon known as lateral deflections from the normal positions of the nuclear fuel structures during normal operating conditions, as a result of reactor core thermal gradient, flow conditions, and irradiation creep.

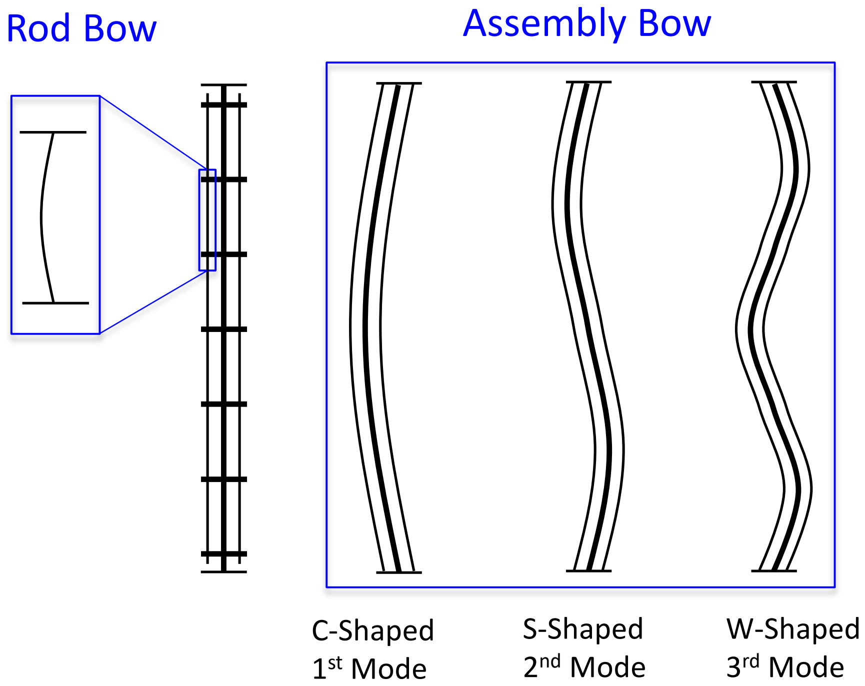
Roberts (1981), Structural Material in Nuclear Power Systems

Photo showing a bowed fuel assembly

Franzen (2017), Evaluation of Fuel Assembly Bow Penalty Peaking Factors for **Ringhals 3**

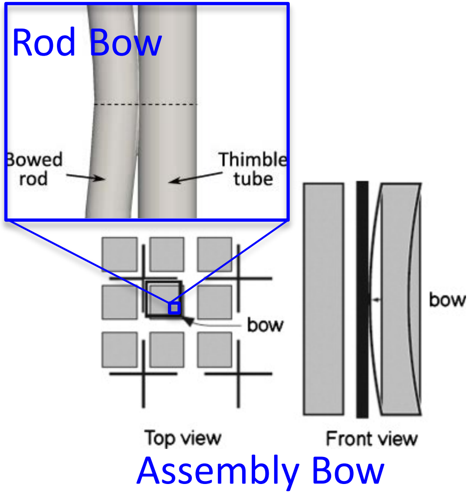
Fuel Rod vs. Assembly Bow - Differences

- Fuel rod vs. Assembly (GT+Grid+FR)
- Axial loading: friction forces vs. hold-down forces
- Constrained between grids vs. top and bottom tie-plates
- Bowing at each span between grids with Max deflection at mid-span elevations vs. bowing between tie-plates with max deflections at grid elevations



A Schematic Illustration of Fuel Rod and Fuel Assembly Bowing Configuration

Fuel Rod vs. Assembly Bow - Similarities



Schematic illustration of fuel rod and assembly bowing.

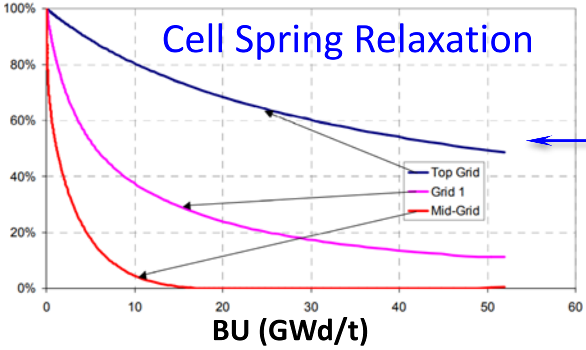
- Lateral deflections under compressive axial loading
- Time-dependent behavior involving irradiation growth, creep, relaxation etc.
- Multiphysics phenomenon concerning structural, thermal hydraulic, and neutronic aspects

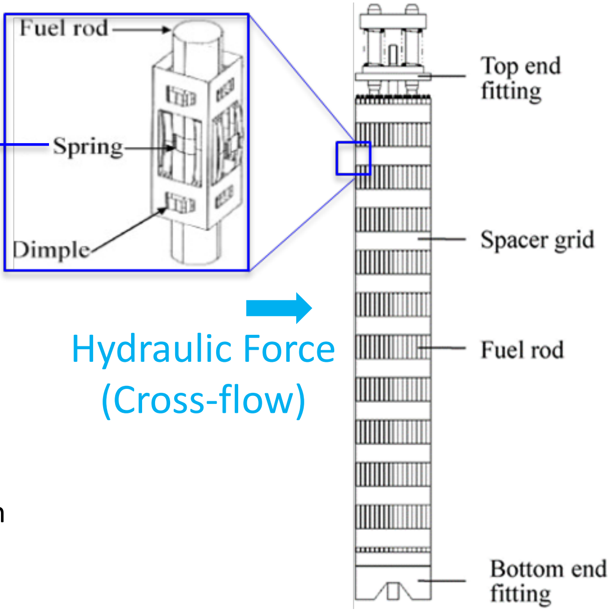
Fuel Structural Behavior

A non-linear time-dependent behavior

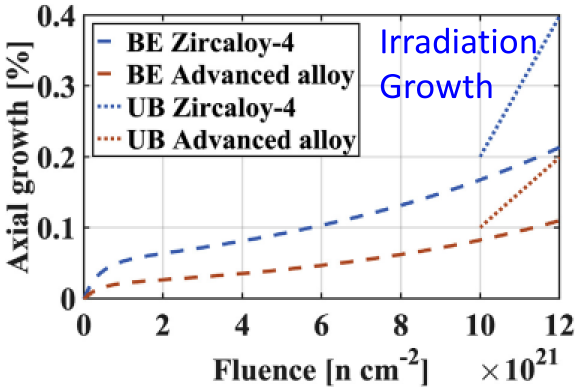
Cell Clamping Mechanism (Friction)

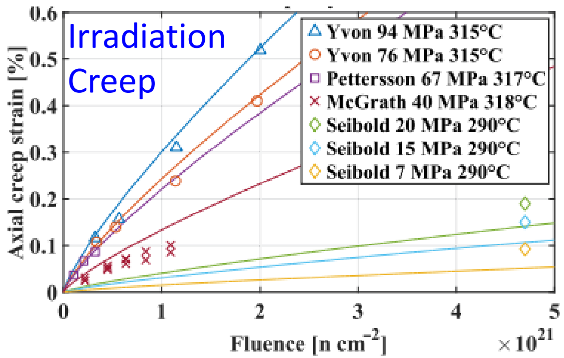
Hold-down Force





Hydraulic Force (Cross-flow)





Billerey (2004), "Evolution Of Fuel Rod Support Under Irradiation – Impact on The Mechanical Behavior of Fuel Assemblies," Proceedings of a Technical Meeting Held in Cadarache, France

Wanninger et al (2018), "Mechanical Analysis of A Row of Fuel Assemblies in A PWR Core ", *Nuclear Engineering and Technology*, 50: 297 - 305

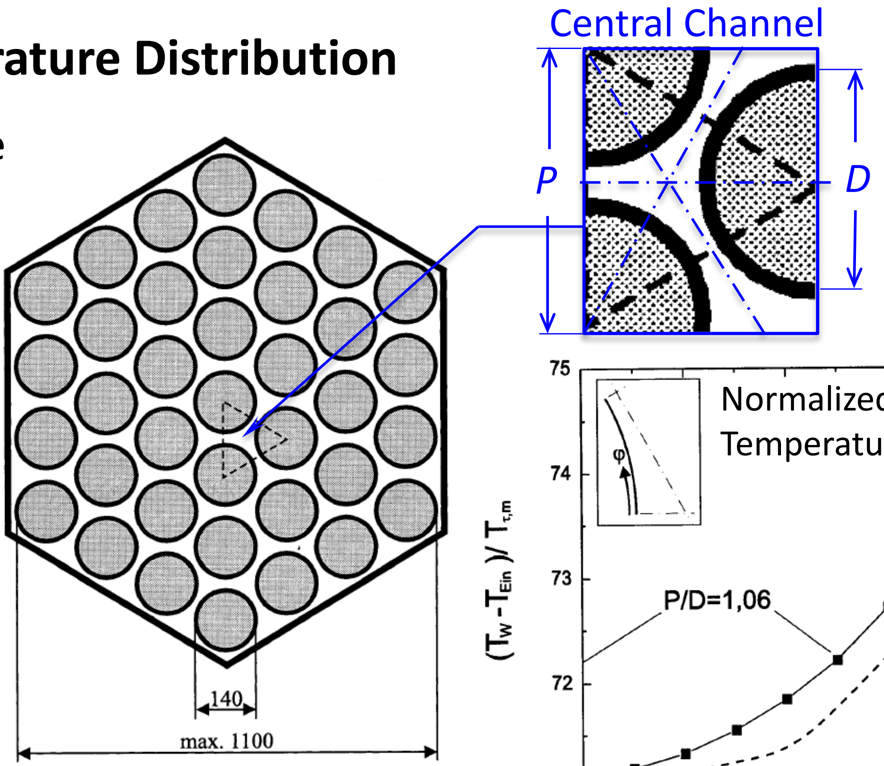
Thermal Hydraulics Behavior

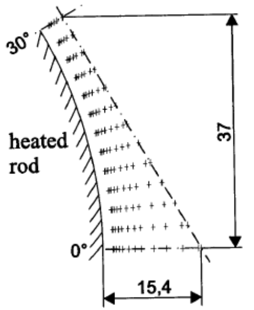
Circumferential Temperature Distribution

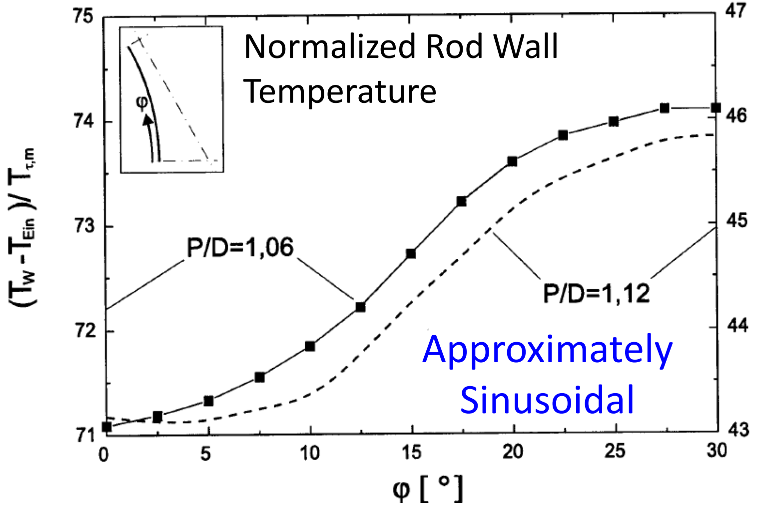
37-Rod Bundle Hex Lattice
- Monel sheathed epoxy rod
- Infrared pyrometer

Periodical temperature distribution around the circumference
- Lattice type
- Pitch-to-diameter (*P*/*D*)

More pronounced in tight lattice







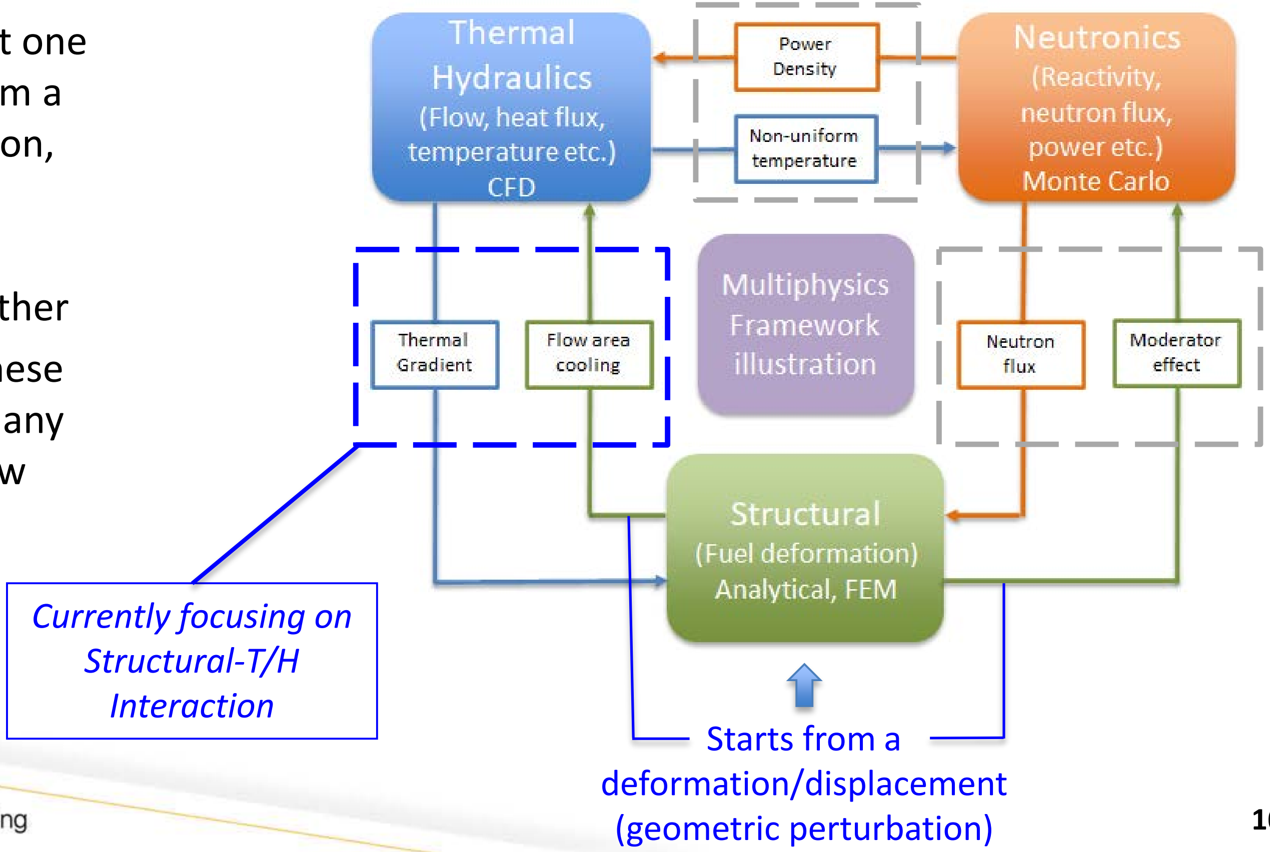
Krauss & Meyer (1998), "Experimental Investigation of Turbulent Transport in a Heated Rod Bundle", *Nuclear Engineering and Design*, 180: 185 - 206

Motivation and Objectives

- Difficulties in predicting the bowing behavior:
  - Variations in core and fuel designs
  - Lack of measurements
  - Complicated operating conditions with various **contributors/uncertainties**
- Literature work:
  - Focused primarily on thermal-hydraulics effects (e.g., CHF)
- Goals and benefits of this work:
  - Capture more precise local effects
  - Develop a framework that is applicable to similar issues
  - Fundamental understanding on **sensitivities/uncertainties** of different factors

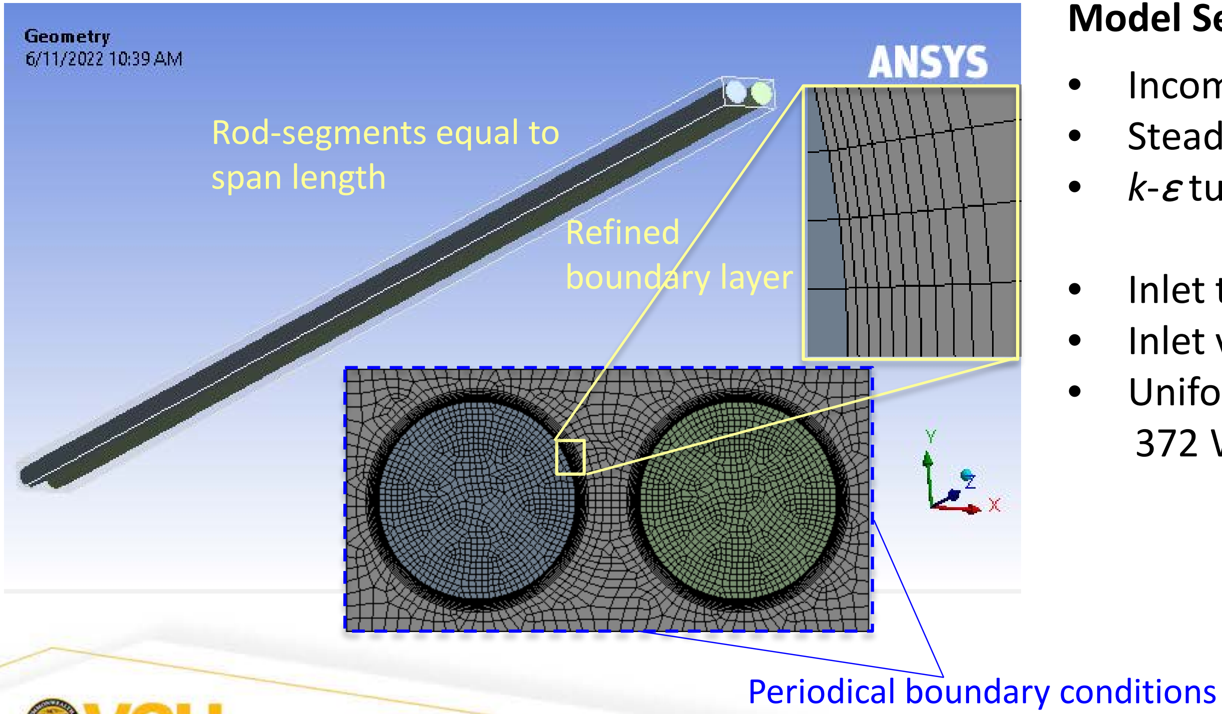
Multiphysics Framework

- Three subjects affect one another, starting from a structural deformation, forming a loop
- Every two subjects interact with each other
- How sensitive are these effects, and is there any feedback effect? How significant?



Thermal Hydraulics Modeling – CFD

Two-Rod CFD Model (ANSYS Fluent)

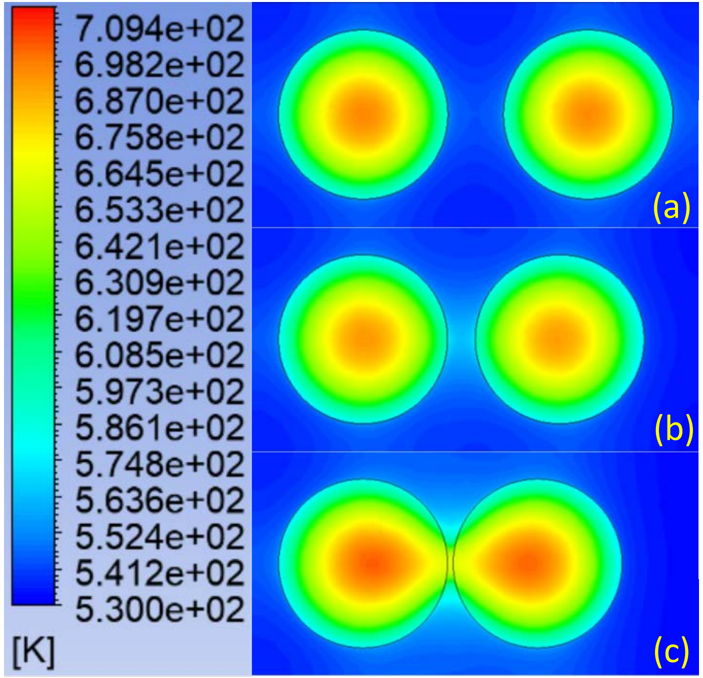


Model Setup

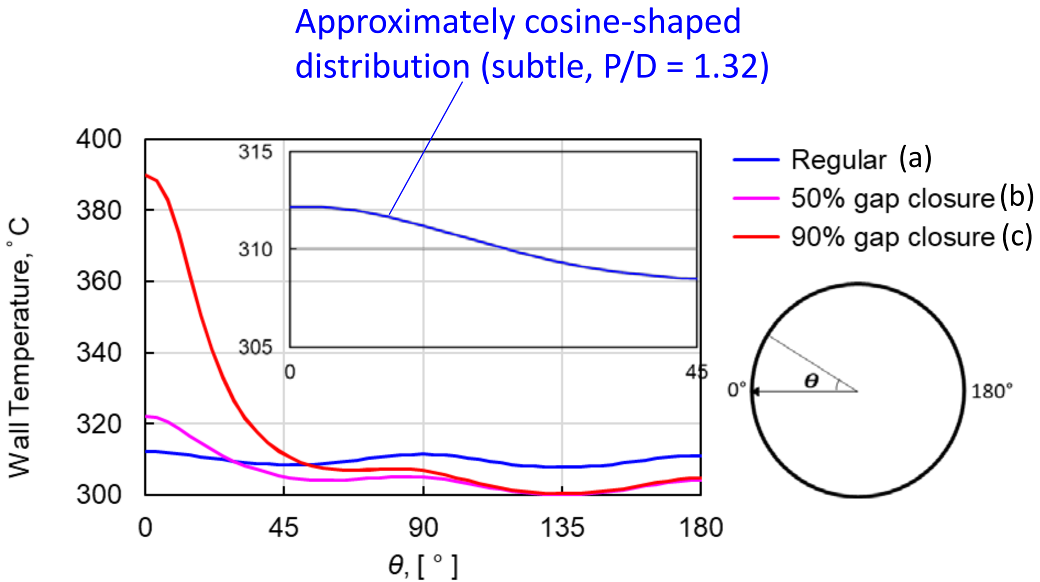
- Incompressible Newtonian flow
- Steady-state, conjugate heat transfer
- *k*-*ε* turbulence model

- Inlet temperature: 530 K
- Inlet velocity: 2.35 m/s
- Uniform volumetric heating rate: 372 W/cm^3

Fuel Rod Temperature Distribution



Fuel Rod Temperature Contour
at Mid-span Elevation

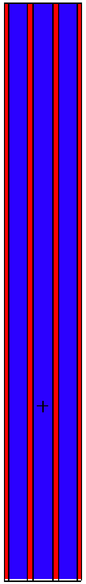


Circumferential Temperature Distribution

As the rod displaces towards its neighboring rod, temperature increases at the gap closure side, while decreases at the opposite side, forming a thermal gradient in the transverse direction that leads to further deformation.

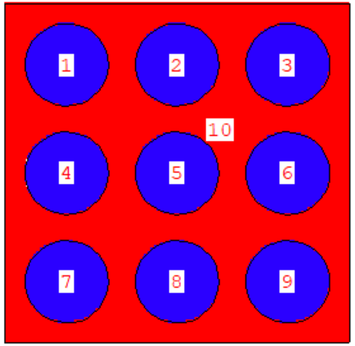
Neutronics Modeling – Monte Carlo

3X3 Rod Bundle Model (MCNP 6.2)



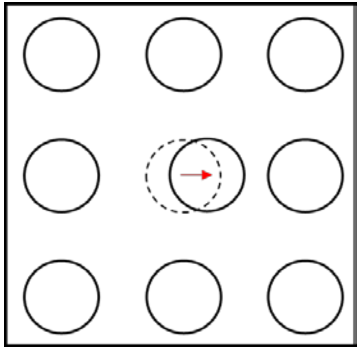
Side View

Reflective boundary conditions



Top View

Consider the center rod displaced towards neighboring rod



Model Setup

- Reflective boundary conditions
- Water coolant
- Fresh Uranium ^{235} fuel
- Neglecting cladding and gap

A slight increase of k_{eff} value is noticed at 90% gap closure, δk_{eff} = 0.00040 with a standard deviation of 0.00017 . Local effect in power distribution to be investigated.

Summary

- A Multi-physics framework is proposed to the structural-T/H-neutronics problem, particularly for the PWRs and may be extended to other applications;
- A geometric perturbation by displacing a fuel rod in a square lattice is considered, using CFD and Monte Carlo simulations;
- Fuel rod wall temperature increases as the flow area reduces, forming a thermal gradient in the transverse direction. This can lead to further deformation;
- Monte Carlo simulation suggests insignificant neutronics effect.

Future Work

Structural – Thermal Hydraulics:

- ❑ Understand the impact of single rod spacing to flow and temperature distribution
- ❑ Understand the sensitivity of such impact and incorporate the deflections from the structural model to check the feedback effect

Structural – Neutronics:

- ❑ Understand the impact of single rod spacing to power distribution, both in-plane and axially

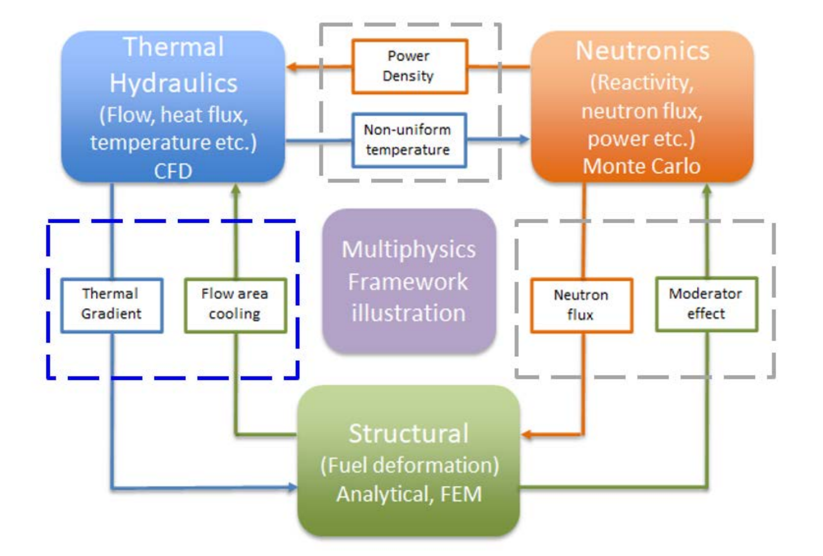
Thermal Hydraulics – Neutronics:

- ❑ Understand the impact of the temperature distribution on power re-distribution (and vice versa)

Validation of modeling results:

- ❑ Experimental measurements that are available
- ❑ Alternative modeling results available in literature

Thank You & Questions?



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