Multiphysics Simulations of the Complex 3D Geometry of the High Flux Isotope Reactor (HFIR) Fuel Elements Using COMSOL

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HFIR is a Multi-Purpose High-Performance Research Reactor

- Operated since 1966 with one of the world’s highest thermal neutron fluxes
- Original primary mission was production of transuranium isotopes in its central flux trap
- Pressurized light water cooled and moderated
- Central flux trap with vertical experimental targets
The HFIR Core

~ 0.6 m

~ 0.4 m
Physics of Interest for HFIR Safety Analyses

- **Unique features for HFIR modeling**
  - Multi-physics problem
  - Non-uniform spatial heat source distribution inside the fuel plates (fuel, mixture, clad, radial and axial variation)
  - Nonlinear material property variation \( \sim f(T) \)
  - Very narrow flow channels
    - High aspect ratio = \( H/t = 24 \text{ inch}/0.05 \text{ inch} = 480 \)
  - Desired high level of accuracy and fidelity because of impacts on nuclear safety
**HFIR Single Fuel Plate 3D Model uses an Assembly of Parts to Create the Geometry**

Equation of the involute of a circle:

\[
x(s) = R_b \left[ \sin(s) - s \cdot \cos(s) \right],
\]

\[
y(s) = R_b \left[ \cos(s) + s \cdot \sin(s) \right], \quad \text{where}
\]

\[
\theta_{\min} \leq s \leq \theta_{\max},
\]

\[R_b \] = base radius of the involute, and

\[
\theta_{\min} = \text{angle for the starting point of the involute, and}
\]

\[
\theta_{\max} = \text{angle for the end point of the involute.}
\]

Side plate removed to expose coolant adjacent to the fuel plate.

Top portion of the model.
3D Meshing starts with a 2D Working Plane of the Involute Plate to be Extruded in the Axial Direction.

- side plate
- filler
- fuel meat
- coolant (coupled to the opposite side through periodic boundary condition)
- clad (typical)
- entrance region
Coarse-Mesh SS Temperature Distributions for Proposed Designs of LEU Fuel for HFIR

Axially Contoured

Radial grading

Axial grading (bottom of the fuel)

433.507 K max

433.51 K

432.342 K max

432.43 K

314.68 K

314.85 K

No Axial Contour
Thermal Expansion Simulation Results Agree Well with the Past Experiments

Test plate is heated from 80 °F to 400 °F in an oven to measure its thermally induced deflections.

Simulated profile and maximum mid-plane deformation (= 38.4 mils) agree well with the experimental data (= 37 mils).
Thermally-induced Plate Deformations

Deformation: Total Displacement (mils)

△ 39.518

20x scaled

Un-scaled

Top-edge

Mid-edge

Bottom-edge
Efforts have just started for full-core model developments

Steady state heat conduction in a 1-in cross-section of the HFIR’s inner core geometry.

Hypothetical constant temperature boundary conditions of 50 °C and 500 °C are assumed at the inner and outer side plates respectively for model verifications.

Steady state temperature distribution for the chosen heat conduction problem

Steady state deformations due to thermal Expansion of the plates (in inches)
COMSOL’s increasing visibility at ORNL

What would have happened if Fukushima’s Spent Fuel Pool # 4 was entombed with Sand?

@ 4 days

@ 16 days

@ 50 days

Irradiation Engineering @ORNL

Capsule

Spacer
Conclusions and Current Status

- The HFIR LEU fuel conversion study is an ongoing project with advances being made in developing 3D modeling & simulation capabilities by adapting COMSOL as a baseline software.

- COMSOL is providing a modern simulation environment for the design of proposed LEU fuel, and analysis of present HEU fuel.

- COMSOL’s unique capabilities to customize the models based on user-defined equations and in coupling multiple physics is very useful in detailed analyses, and in estimating nuclear safety margins.

- Parallel COMSOL computations are being performed on a 128-core cluster, and capabilities will soon be tested and utilized on some of the larger ORNL clusters.
Thank you for your attention.

Questions?

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