COMSOL-Based Multiphysics Simulations to Support HFIR's Conversion to LEU Fuel

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INTRODUCTION

The primary mission of the Global Threat Reduction Initiative (GTRI)—a program of the U.S. Department of Energy's National Nuclear Security Administration—is "to reduce and protect vulnerable nuclear and radiological materials located at civilian sites worldwide" [1] to prevent their illegal acquisition by terrorist elements. Through one of GTRI's subprograms, the Reduced Enrichment for Research and Test Reactors, the Oak Ridge National Laboratory's High Flux Isotope Reactor (HFIR) is being converted from its present highly enriched uranium (HEU) fuel core to a low enriched uranium (LEU) fuel core. Because HFIR is the highest flux reactor-based neutron source for condensed matter research in the United States, its conversion to a high-density, U-Mo based, LEU fuel should not impact its current neutron flux performance. Furthermore, cost, budgetary, and availability issues have dictated minimal changes to the overall HFIR facility. Therefore, the goal is to only substitute the fuel type in the existing fuel plate design, retaining the same number of fuel plates, with the same physical dimensions, as in the current HFIR core.

HFIR was designed and constructed in the mid-1960s. At that time, its thermal safety analyses were based on an in-house code named the Steady State Heat Transfer Code (SSHTC). This code used results from several experiments and validation exercises performed during HFIR's original design stages. SSHTC is still in use at HFIR and has changed very little since its original development. However, several of its empirical correlations may not be applicable to the LEU fuel core, and in the absence of an extensive experimental effort (to revalidate SSHTC for the LEU fuel design), the focus now is on adopting the best available multiphysics simulation technology to answer the needs of the conversion process. A commercial, finite-element method based, modeling and simulation software, COMSOL MULTIPHYSICS [2], has been identified to support these needs [3–5] and eventually replace SSHTC.

In this paper, development of at least one form of the COMSOL-based modeling framework for HFIR is presented, key simulation steps are identified, and several of the milestones achieved toward a coupled multiphysics capability are highlighted.

HFIR CORE

In its present design, HFIR is a beryllium-reflected, light water cooled, HEU-fueled research reactor operating at 85 MW power. The original design for HFIR was at a power level of 100 MW. Its dimensional core design is shown in Fig. 1. To remove the core heat, a highly turbulent water flow passes through involute-shaped coolant channels from the top to the bottom of the core. Several physical phenomena, including turbulent flow, conjugate heat transfer, thermal-structure interaction, and fluid-structure interaction, are of significant interest for the thermal safety analyses of HFIR's new LEU fuel core.

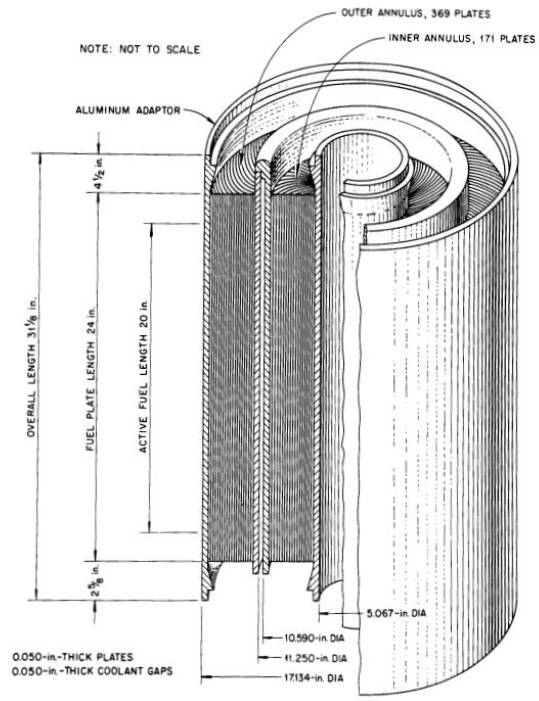

Fig. 1: HFIR fuel assembly. There are 171 involute-shaped fuel plates in the inner annulus (*inner plates*) and 369 in the outer annulus (*outer plates*). All the plates are of the same thickness (0.05 inch) and are uniformly distributed in the azimuthal direction to create uniform coolant channels.

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KEY CAPABILITIES

Several infrastructural simulation capabilities were developed during this project before the acquisition of any real predictive capability, including the following.

***Material library*:** COMSOL has its own material library containing property data for more than 2,500 materials. In addition, it also has the ability to import externally developed material libraries and to develop new material libraries within its own interactive graphical user interface (GUI). A GUI-based material library for thermophysical properties of the LEU fuel (U10-Mo alloy) has been developed in COMSOL from the available data [6–7].

***Involute geometry*:** For creation of the three-dimensional (3D) geometry, COMSOL has its own computer-aided design (CAD) interface and it also supports other popular commercial CAD packages (Pro-E, SolidWorks, etc.). HFIR's fuel plate (both the inner as well as the outer) has a very specific shape—a mathematical involute—which must be correctly represented to capture the geometry and, consequently, the physics correctly. Using the equations of an involute for the convex and concave edges of the fuel plate, a representative 3D geometry has been created in COMSOL. Based on the single plate geometry, a strategy has been identified to automatically create any number of plates and their respective channels in a minimal number of user steps. This capability will be essential for multiplate and multichannel simulations.

***Mapped meshing*:** HFIR's fuel plate geometry has a very large aspect ratio (height of the plate divided by its thickness) equal to 480. Because of this large aspect ratio and the plate's unique involute shape, the default tetrahedral meshing of COMSOL fills the computational domain with an unreasonably large number of elements. A mapped-mesh approach, or a mixture of free-mesh with mapped-mesh, with full user control over the number of elements, has been identified to reduce the total number of elements. The top surface of the plate is meshed with quadrilateral elements and then this surface mesh is swept through the entire height of the fuel plate. In this approach, the user also obtains control over the grid spacing and grid distribution at the interfaces and boundaries of the computational domain, which is sometimes needed to capture various gradients.

***Tabular heat source distribution*:** A capability has been developed within the COMSOL GUI to use the plate's 3D heat source distribution, which comes from external reactor physics codes, in either a tabular form, or in an equation form (through curve fits to the distribution).

The above components in relation to their COMSOL implementation will be highlighted in the presentation.

PATH TO MULTIPHYSICS

Several scenarios, with increasing physical complexity, have been simulated using the developed 3D models in COMSOL and are listed below:

- laminar flow in a single involute channel;
- laminar flow with conjugate heat transfer in a single-plate, single-channel domain;
- turbulent flow in a single involute channel;
- turbulent flow with conjugate heat transfer in a single-plate, single-channel domain;
- thermal deformation study for a single involute fuel plate with different heat source distributions; and
- coupled turbulent flow, conjugate heat transfer, and thermal-structural interaction for a single-plate, single-channel domain.

All the above scenarios will also be simulated for multiplate, multichannel domains, leading toward simulating the full HFIR core with the LEU fuel. Simulation results for the aforementioned single-plate, single-channel scenarios will be discussed during the presentation. Additional multiphysics simulations, including detailed 3D simulations (hot spots, entrance and exit effects) and fluid-structure interactions, are also being investigated by other researchers on the project using COMSOL.

Figure 2 describes the boundary and initial conditions for simulation of turbulent flow in a coolant channel adjacent to an involute fuel plate. Figure 3 shows the resulting rise in the cladding temperature in the direction of the coolant flow for a uniform heat source in the fuel region of the plate.

In addition, to validate the COMSOL results for the thermal deformation of the fuel plate, a representative case with the aluminum *outer plate* was also simulated. For this problem, there exist experimentally obtained thermal deformation results [8] for heating of the plate in an oven from 80°F to 400°F while being constrained at its longitudinal sides. Figure 4 shows the resulting deformation from the COMSOL simulation.

CONCLUSIONS

COMSOL-based multiphysics simulations are able to answer the need for predictive 3D simulations of HFIR's involute plate and channels. Step-by-step development and analyses of COMSOL models for the single and multiple channels will lead to the desired full-core simulation capability for HFIR. Along with the planned experiments to support the conversion process, these 3D simulations will become the basis for the nuclear safety analysis of HFIR's LEU fuel core.

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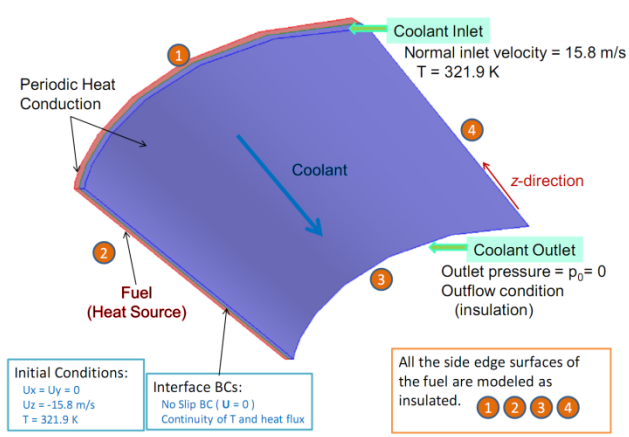

Fig. 2: Boundary and initial conditions for the turbulent flow and conjugate heat transfer problem in a single *inner plate* and a single coolant channel computational domain. In the above panel, the domain in the blue color (in front) represents the coolant channel while the domain in the orange color (in back) represents the *inner* fuel plate.

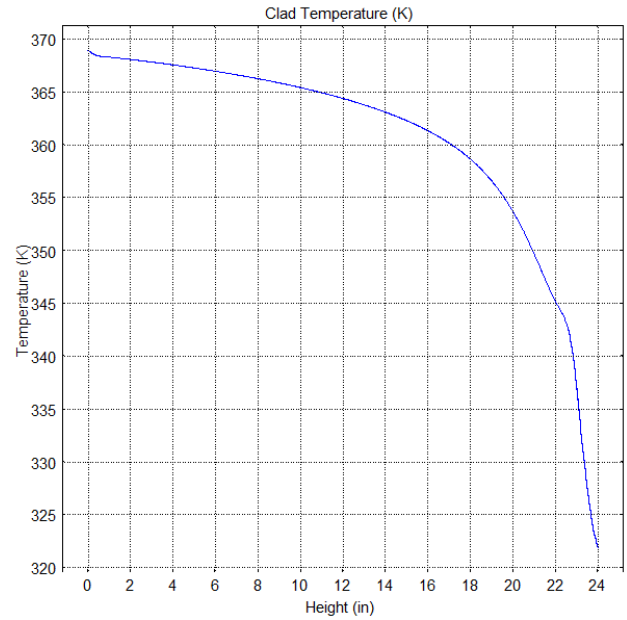

Fig. 3: Longitudinal variation in the fuel plate cladding temperature (in graph, going from *right* to *left* in the direction of decreasing height) for a uniform heat source (10^9 W/m^3) in the fuel region. Boundary and initial conditions for the problem are the same as in Fig. 2.

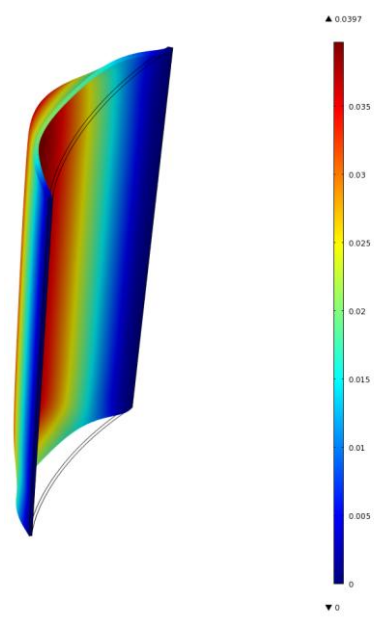

Fig. 4: Deformation (in inches) in HFIR's *outer plate* (made of aluminum) due to thermal expansion caused by its convective heating from 80°F to 400°F. The plate is fully constrained on both of its longitudinal sides. (The relative deformation of the plate is significantly scaled up in the above panel for the purpose of visual clarity.)