Researching a New Fuel for the HFIR: Advancements at ORNL Require Multiphysics Simulation to Support Safety and Reliability

Research into the conversion of the High Flux Isotope Reactor to low-enriched uranium fuel to meet requirements established by the Global Threat Reduction Initiative is ongoing at Oak Ridge National Laboratory. Researchers have turned to multiphysics simulations to evaluate the safety and performance of the new fuel and reactor core design.

BY ALEXANDRA FOLEY

In simple terms, when a beam of neutrons is aimed at a sample, some neutrons pass through the material, while others scatter away at an angle, similar to balls colliding in a game of pool. The final deflection patterns and energies of the neutrons can then be interpreted, allowing scientists to gain information about the fundamental properties of studied matter. This enables neutron-scattering scientists to determine the atomic and magnetic structures of materials and ultimately to achieve a deeper understanding of the world around us.

The High Flux Isotope Reactor or HFIR (pronounced High-FIR) at the Oak Ridge National Laboratory (ORNL) includes a neutron scattering facility that is used by over 500 researchers from around the world each year. The HFIR is a multi-purpose research reactor that also provides stable and radio isotopes to customers in academia, industry, and the medical field. In addition, the HFIR offers unique irradiation experiment facilities and neutron-activation analysis capabilities. The high power production of the HFIR (85 MW) likewise produces a high flux of neutrons to the targets, thereby providing one of the highest steady-state neutron fluxes of any research reactor in the world (see Figure 1).

The HFIR was designed to use highly enriched uranium (93 percent U-235 or HEU), which is similar to a weapons-grade uranium. However, in response to the increasing awareness of the risks caused by the proliferation of nuclear materials, the Global Threat Reduction Initiative has called for the conversion of research reactors using HEU fuel to low-enriched uranium (LEU) fuel.

While many of the world's nuclear reactors have already been converted, a few high-performance HEU reactors still remain. Among these is the HFIR, which, due to its unique fuel and core design (see Figure 2) as well as the high power density of the reactor, presents a complex and challenging task for fuel conversion. Researchers at ORNL are using COMSOL Multiphysics® simulation software to explore the impact that the fuel change will have on the HFIR's performance and on neutron scattering initiatives, isotope production, irradiation experiments, and neutron activation analyses.

"Successful conversion of the HFIR will preserve reactor performance, minimize negative effects on operation efficiency, and help to ensure safety," says Franklin Curtis, PhD graduate student at ORNL. "We have found that COMSOL is a superior tool for achieving these goals because of its multiphysics capabilities, its use of the finite-element method, and the ability to input user-defined equations."

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A PROPOSED LEU FUEL FOR THE HFIR

ORNL researchers involved in the project have developed alternative fuel designs that use a uranium-235 enrichment of 19.75 percent instead of the current 93 percent. In order to accommodate the changes in nuclear characteristics, density, and thermal properties of the LEU fuel, the HFIR core fuel meat — the fissile material located in the fuel plates — must be redesigned (see Figures 2 and 3). The new design will retain the existing overall geometrical characteristics of the current HFIR core external to the fuel meat.

Additionally, preliminary studies have found that in order to maintain the same neutron flux, the HFIR will have to operate at 100 MW instead of 85 MW, presenting greater demands on the thermal margin of the reactor. "Because we are working with a nuclear reactor, safety is of the utmost importance to us, and we need to know that our models are accurate and reliable," says James D. Freels, a senior research staff engineer at ORNL. "Our models must undergo a rigorous validation process and ultimately must be reviewed and accepted by our Department of Energy regulator in order to continue with the conversion."

Researchers at ORNL are conducting validation studies of the COMSOL code to prove its accuracy. As Curtis describes, "My project at ORNL has been to establish a fluid-structure interaction (FSI) simulation technique that is validated against current safety basis calculations for the HEU fuel and that will allow for the evaluation and safety analysis of the designs using the LEU fuel, while still allowing the reactor to retain the required coolant flow rate."

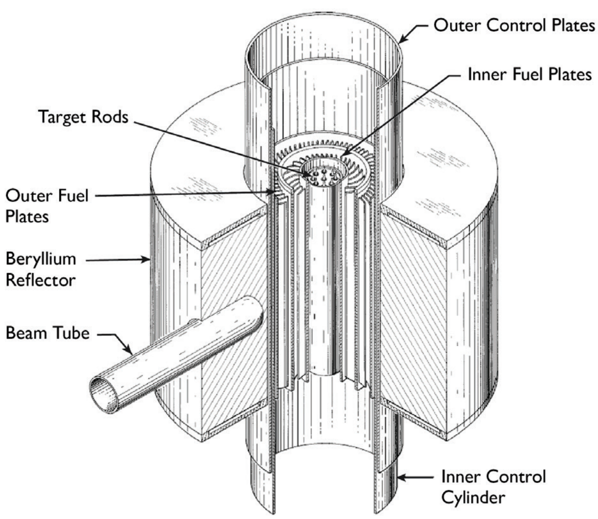
FIGURE 1. Technicians replace a fuel element of the HFIR at ORNL. The HFIR has operated since 1966 (over 452 fuel cycles) and is currently the only operating nuclear reactor at ORNL. *Image courtesy of the Oak Ridge National Laboratory, U.S. Dept. of Energy.*

FSI MODELING OF FUEL PLATE DEFLECTIONS

One of the main components of the HFIR is the fuel plates, which control the distribution of velocity and temperature at which coolant enters and flows through the reactor core. These fuel plates can slightly oscillate and deform in response to changes in velocity and temperature due to reactor operation. One of the most important studies conducted on plate-type research nuclear reactors is to determine the maximum flow rate possible before the deflections interfere with the reactor's performance and safety. "If the deflections are large enough," says Curtis, "It can cause the fuel plates to reduce flow area or even touch one another, altering flow within the channels and disrupting the rate at which coolant flow enters the core."

Representative tests using flow geometries similar to the HFIR can offer insight into fuel plate deflections and be used for code validation. The Advanced Neutron Source Reactor (ANSR), a proposed reactor at ORNL that has since been canceled, had a similar design to that of the HFIR and underwent extensive experimental testing, providing valuable results to validate the COMSOL code[1].

The ANSR was designed to have fuel plates with a similar involute shape to the HFIR and with cooling flow velocities of about 25 m/s. One test of the ANSR involved experiments to determine the deflection characteristics of the fuel plates. "The involute fuel plates of the HFIR and ANSR have different fuel meat designs than those of other, simpler curved-plate research reactors in the U.S.," says Curtis. "The overall shape maintains a constant coolant channel



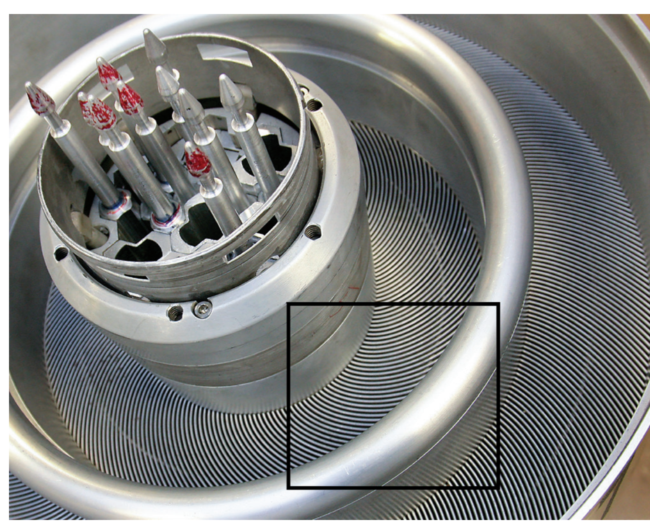


FIGURE 2. Left: A simplified schematic of the current HFIR core. The core of the reactor consists of a series of concentric annular regions divided into inner fuel plates and outer fuel plates. Right: The black box represents the leading edge of the fuel plate that was analyzed in fluid-structure analysis at ORNL. *Images courtesy of the Oak Ridge National Laboratory, U.S. Dept. of Energy.*

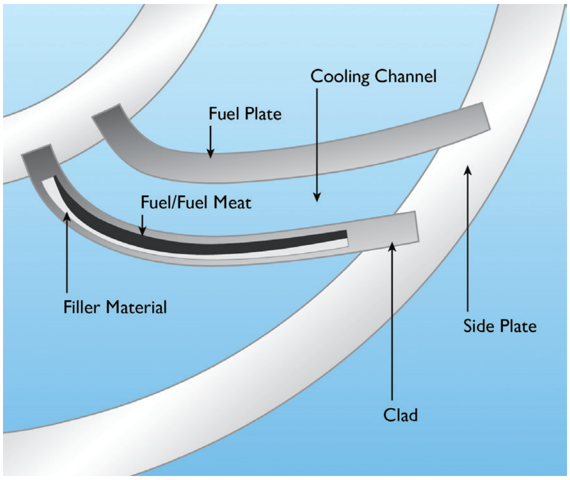


FIGURE 3. The three regions that make up the current HFIR HEU fuel plate — the fuel (or fuel meat), filler material, and clad. The coolant channel surrounds the fuel plate. The LEU conversion process will change the internal fuel meat. *This image is not to scale and is not an official ORNL figure. It is a reproduction of the design concept of the HFIR core created by COMSOL.*

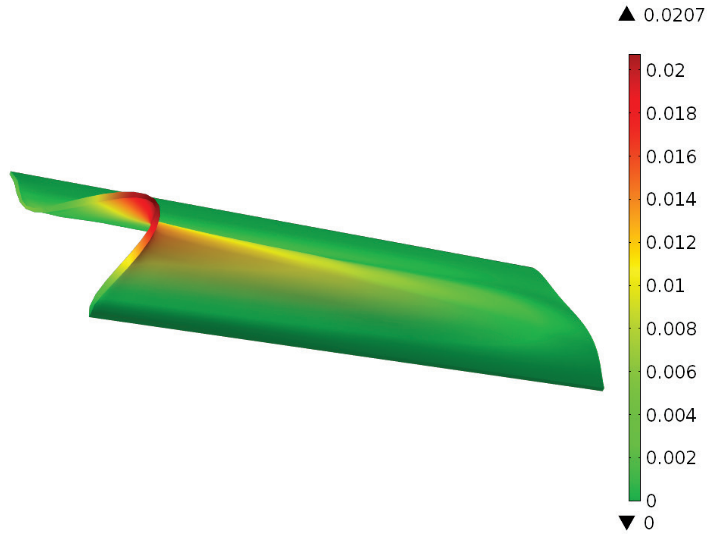


FIGURE 4. Leading edge deflection of the involute fuel plate. Eigenfrequency analyses predicts the "S" shape deflection of the involute fuel plate of the ANSR and HFIR.

thickness in the core. However, because of their unique shape, the HFIR requires that special attention be paid to the new fuel and core design in order to allow the reactor to maintain the needed flux of neutrons."

To understand the mechanical FSI taking place within the COMSOL model, a single-plate, two-channel model was developed. The initial analyses first examined flat plates, and the increased complexity of the involute shape of the fuel plates was later analyzed. The resulting model accurately predicted the FSI and resulting deformations of the ANSR fuel plate experiments along the plate's length (see Figure 4).

Current FSI simulations include a turbulent CFD analysis of the coolant channels and the fluid-structure deflections of the fuel plates. Previous attempts to solve the FSI problem at ORNL used a weakly coupled approach where the fluid domain was solved first and then the information was used in the structural analysis. "However, this approach was met with an unstable solution and limited success," says Curtis. "In our current analysis, we instead use the fully-coupled study available in COMSOL Multiphysics and have found that this improved both the stability and accuracy of the ANSR model." Using this fully-coupled approach, Curtis found that simulations at different flow rates showed excellent agreement with the experimental results (see Figure 5).

Currently, a model of the inner fuel plates of the HFIR using LEU fuel is being developed based off of the analysis techniques used for the ANSR model (see Figure 6). "We're

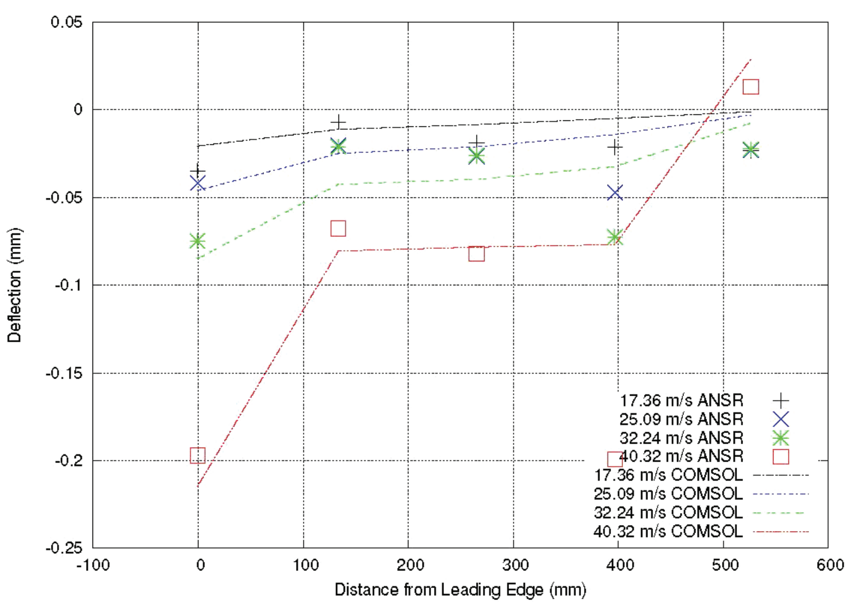


FIGURE 5. Experimental results of the fuel plate deflection of the ANSR flow tests compared against simulation results for different fluid flow rates.

very happy with the preliminary results that we've obtained from this model," says Curtis. "Over the next few months, we'll continue to improve upon this model to contribute toward a safety basis case for ultimate fuel conversion." The model will later be combined with other COMSOL models being developed at ORNL that couple multidimensional conduction of heat along the plate, thermal-structure deflections of the fuel plate, and other physics such as fuel defects, corrosion, and flow blockages.

VERIFICATION AND VALIDATION IS KEY

When designing something as complex as a nuclear reactor, engineers must take every precaution in order to ensure the safety of the design. This requires extensive validation of the simulations being created, as well as the verification of the code itself. "Other simulations of past experiments at ORNL have validated the thermal, structural, and turbulence modeling capabilities of COMSOL Multiphysics," says Curtis. "Our recent studies have verified the FSI tools of COMSOL, which will allow us to design and optimize the new HFIR core with confidence." ■

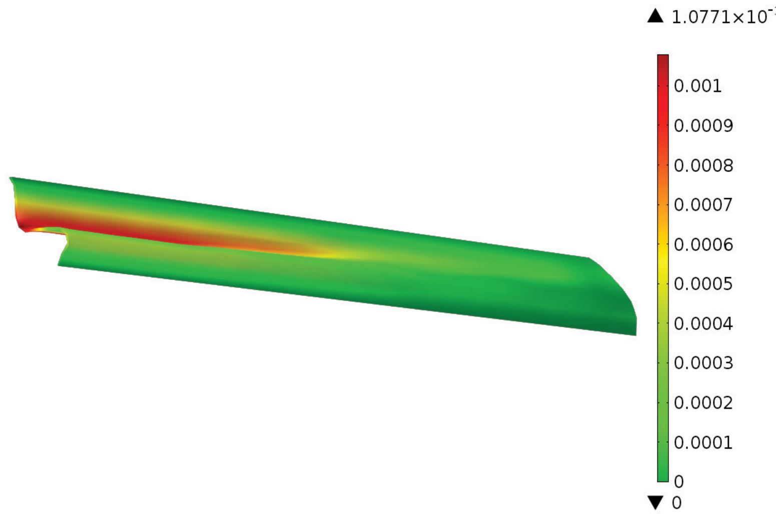


FIGURE 6. Deflection of the leading edge of a HFIR fuel plate.

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[1] Swinson, W. F., Battiste, R. L., Luttrell, C. R. & Yahr, G. T. *Fuel-Plate Stability Experiments and Analysis for the Advanced Neutron Source*, Symposium on Flow-Induced Vibration and Noise, 1992, (5) 133-143.

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