Simulations help to design a new low-enriched nuclear fuel for materials testing, isotope production and neutron radiography for research that reduces proliferation threat.

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Research reactors are used for a variety of applications, including materials testing, neutron radiography and the production of radioisotopes for medicinal and industrial purposes. Canadian Nuclear Laboratories (CNL, formerly Atomic Energy of Canada Ltd.) — Canada’s premier nuclear science and technology laboratory — is developing a new low-enriched uranium (LEU) fuel designed for use in research reactors around the world. LEU fuel is favored for research reactors because it reduces proliferation risks in comparison to highly enriched uranium (HEU) fuels.

DEVELOPING A NEW REACTOR FUEL

Nuclear research reactors generate a neutron source for a wide variety of research and industrial purposes. HEU fuel is used in many research reactors because it allows a compact core and reasonably long times between refueling. As security concerns with the use of HEU fuel have grown within the international community, many research reactors have converted to LEU fuel.

CNL is designing and qualifying a new LEU fuel that can be used in research reactors to replace HEU and currently used LEU uranium-silicide fuels. Uranium–molybdenum (U-Mo) dispersion fuel is an attractive option for this next generation of fuels because of the ease of spent-fuel reprocessing and the potential for substantial density improvements over uranium silicide–based fuels. With any fuel design, the modeling of thermal–mechanical properties is key to concept evaluation. ANSYS software provides an effective toolset to perform these evaluations and guide more-detailed fuel design. Furthermore, numerical simulations help to guide the safety analyses of experiments by making it possible to study the thermal and fluid behaviors of candidate fuel designs before they are placed in the reactor for complete testing.

Microstructural modeling with ANSYS Mechanical finite element analysis (FEA) software helped CNL scientists to estimate the thermal conductivity of potential LEU fuels.
ANSYS Fluent simulated all three modes of heat transfer: convection, conduction and radiation.

the thermal conductivity of candidate LEU fuels, which is the most important material property in predicting fuel behavior. ANSYS Fluent computational fluid dynamics (CFD) software was used to perform solid-fluid conjugate heat transfer simulations of two candidate LEU fuels to establish how several design variables affected their operating temperature, pressure loss and power output. The simulation results helped to optimize the design of fuel elements that will be used for in-reactor testing scheduled for the near future.

FEA PREDICTS THERMAL CONDUCTIVITY

Determining thermal conductivity of fuel during irradiation is a critical first step in simulation, since both fuel performance and safety depend on its thermal behavior. Measuring the thermal conductivity of irradiated fuel is both difficult and expensive. Of particular importance in U-Mo fuels dispersed in an aluminum or magnesium matrix is capturing the impact of the low thermal conductivity interaction layer formed by a chemical reaction between U-Mo fuel particles and the matrix. CNL researchers used ANSYS Mechanical to model a representative region of the fuel rod as a prism-shaped unit cell made of brick elements. The elements within the unit cell were assigned the material properties of either the fuel or matrix, depending on their position, to represent randomly distributed fuel particles with a size distribution similar to the manufactured fuel.

The team simulated the presence of a fuel–matrix interaction layer by adding a third set of material properties assigned to the finite elements that surround each fuel particle. Researchers estimated the thermal conductivity of the interaction layer by choosing a value that best matched the observed degradation in thermal conductivity of the fuel sample as a function of the volume fraction of the interaction layer. Applying an appropriate heat flux across the unit cell made it possible to determine the effective thermal conductivity of the unit cell as a function of the volume fraction of the fuel particles. The effective thermal conductivity of the material was determined as a function of the volume fraction of the interaction layer.

CFD PREDICTS OVERALL FUEL PERFORMANCE

CNL researchers then used the simulated thermal conductivity values as input to CFD simulations of the proposed U-Mo dispersion fuels to optimize fuel design and ensure its safety in preparation for physical testing. Fluid flow and heat transfer of a fuel assembly were simulated in a 3-D geometry. Heat is generated by nuclear fission within the fuel, which is cladded entirely in aluminum. Together, the fuel and cladding are referred to as a fuel element. Eight concentric fins are attached to the cladding of each fuel element to enhance heat removal from the fuel to the surrounding coolant. The CFD software simulated all three modes of heat transfer: convection, conduction and radiation.

Simulations were performed in which inlet fluid velocity, fuel type and linear power were varied to calculate the relative sensitivity of the fuel, cladding and coolant temperatures to each design variable. In addition, CNL considered an alternate fuel geometry that replaced the straight
fins in the original design with helical fins — which does not greatly complicate the manufacturing process — to investigate the effect on heat transfer. Replacing straight fins with helical fins reduced the predicted cladding and fuel temperatures. Heat transfer between the fluid and solid regions was improved by the increased level of turbulence generated by the non-linear geometry, which promotes mixing of coolant near the hot cladding surface with the relatively cooler bulk fluid. Thus, the enhanced heat transfer with this design suggests that higher operating powers may be permitted. The numerical simulation predictions support performance and safety analyses of candidate fuel designs and guide physical experiments of U-Mo dispersion fuels. The trends seen in varying power and inlet flow conditions will be useful in optimizing performance and safety of the physical experiments. The temperature predictions provided by the model will help to determine the linear power for possible future use in a reactor. The benefits of the helical-finned cladding provided justification for manufacturing this unique design. In the end, this new fuel design may enable efficient and safe use in research and test reactors while reducing proliferation risks.

**Reference**

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