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Heat deposition analysis for the High Flux Isotope Reactor's HEU and LEU core models

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HIGHLIGHTS

- HFIR models were developed for heat deposition analyses of HEU and LEU cores.
- Calculated energy released per fission, power and volumetric heating rates.
- Compared results from HEU and LEU cores at the beginning and end of a reactor cycle.

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ABSTRACT

The High Flux Isotope Reactor at Oak Ridge National Laboratory is an 85 MW_{th} pressurized light-water-cooled and -moderated flux-trap type research reactor. The reactor is used to conduct numerous experiments, advancing various scientific and engineering disciplines. As part of an ongoing program sponsored by the US Department of Energy National Nuclear Security Administration Office of Material Management and Minimization, studies are being performed to assess the feasibility of converting the reactor's highly enriched uranium fuel to low-enriched uranium fuel. To support this conversion project, reference models with representative experiment target loading and explicit fuel plate representation were developed and benchmarked for both fuels to (1) allow for consistent comparison between designs for both fuel types and (2) assess the potential impact of low-enriched uranium conversion. These high-fidelity models were used to conduct heat deposition analyses at the beginning and end of the reactor cycle and are presented herein.

This paper (1) discusses the High Flux Isotope Reactor models developed to facilitate detailed heat deposition analyses of the reactor's highly enriched and low-enriched uranium cores, (2) examines the computational approach for performing heat deposition analysis, which includes a discussion on the methodology for calculating the amount of energy released per fission, heating rates, power and volumetric heating rates, and (3) provides results calculated throughout various regions of the highly enriched and low-enriched uranium core at the beginning and end of the reactor cycle.

These are the first detailed high-fidelity heat deposition analyses for the High Flux Isotope Reactor's highly enriched and low-enriched core models with explicit fuel plate representation. These analyses are used to compare heat distributions obtained for both fuel designs at the beginning and end of the reactor cycle, and they are essential for enabling comprehensive thermal hydraulics and safety analyses that require detailed estimates of the heat source within all of the reactor's fuel element regions.

1. Introduction

The High Flux Isotope Reactor (HFIR) operating at the Oak Ridge National Laboratory (ORNL) is an 85 MW_{th} pressurized light-water-cooled and -moderated flux-trap type research reactor. It is fueled with highly enriched uranium (HEU) (~93 wt% ^{235}U) in the form of uranium oxide dispersed in aluminum powder (U_3O_8-Al). HFIR produces one of the highest steady-state neutron fluxes in the world, with a peak thermal neutron flux of $\sim 2.5 \times 10^{15}$ neutrons/$cm^2 \cdot s$. HFIR has four primary missions: neutron scattering, isotope production, materials irradiation, and neutron activation analysis. These missions ensure that numerous experiments can be conducted to benefit various scientific and engineering disciplines.

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An ongoing program sponsored by the US Department of Energy (DOE) National Nuclear Security Administration Office of Material Management and Minimization studies the feasibility of converting HFIR (and other HEU-based reactors) from the use of HEU fuel to low-enriched uranium (LEU) fuel. The LEU fuel under consideration is a high-density molybdenum-uranium (U-Mo) monolithic alloy (10 wt% Mo and 90 wt% U) with an enrichment of 19.75 wt% ^{235}U. Several performance goals and constraints were set for the design and development of a new LEU fuel for HFIR (Renfro et al., 2014), including maintaining the current fuel safety margins and reliability for use in the reactor, maintaining the scientific performance of the reactor, ensuring fuel affordability, preserving the current physical dimensions of the fuel and core geometry, and minimizing the LEU conversion impacts to reactor safety systems or other infrastructure.

To assess the viability of any proposed LEU fuel design and the impact of the LEU conversion on reactor performance, comparisons of relevant metrics must be performed between the proposed LEU core model and the reference HEU core model. The metrics assessed in this paper include spatial and temporal heat deposition rates. Obtaining the heat deposition distribution is especially important in the fuel regions of the reactor due to the impact on the thermal-hydraulics (T/H) analyses performed to determine safety margins and safety limits. The models used for T/H analysis require accurate, spatially dependent estimates of the heat source within the fuel element regions. Heat deposition in regions outside the fuel region is also important, but the spatial resolution required in these regions is coarser when compared to that needed within the fuel region. The T/H analyses are not within the scope of this work; however, T/H analyses making use of the data presented in this paper may be the subject of future publications.

The HFIR models (Chandler et al., 2016; Betzler et al., 2017) were analyzed in this study using the Monte Carlo N-Particle (MCNP) code (Monte Carlo Team, 2003) versions 5-1.60 and 5-1.51. MCNP is a radiation transport analysis tool that simulates coupled neutron-gamma transport. The end-of cycle (EOC) configurations used in this work were obtained via Monte Carlo-based depletion simulations for the HFIR core. These simulations included fuel, control elements, and experiment targets (Chandler et al., 2016; Betzler et al., 2017), and they were performed using VESTA (Haeck, 2009), a depletion tool. MCNP5 was used in the current study instead of MCNP6 because it has been thoroughly verified and validated for HFIR analysis and because for depletion simulations, VESTA couples MCNP5's capabilities as a neutron transport solver and ORIGEN 2.2's (Computer Code Collection CCC-371, 2002) capabilities as a point depletion and decay code.

The approach for calculating heat deposition in this study draws from similar work previously reported (Peterson and Ilas, 2012; Yesilyurt et al., 2010; Betzler et al., 2011). There are two methods discussed—the *pikmt* and *ratio* methods (Yesilyurt et al., 2010; Betzler et al., 2011)—for performing heat deposition analysis with MCNP models. The *ratio* method applies if the MCNP model does not change during the analysis. In the application discussed for the *pikmt* and *ratio* methods (Yesilyurt et al., 2010; Betzler et al., 2011), the same MCNP models were used to converge on temperature and powers in a loose coupling of neutronics and T/H codes (e.g., MCNP-RELAP Yesilyurt et al., 2010; Betzler et al., 2011). The *ratio* method is fast, but it requires the user to precalculate fractions of delayed gamma heating over prompt gammas heating to account for the delayed gamma heating in order to avoid performing the extra *pikmt* run during the analysis. These precalculated fractions vary if the MCNP models are altered, especially if modifications are made to the fuel design or isotopic compositions. For HFIR core heat deposition analysis, multiple LEU fuel designs must be analyzed, and the control elements must continuously move outward during operation. Therefore, the more rigorous *pikmt* method (Yesilyurt et al., 2010; Betzler et al., 2011) is applicable for this study.

This paper presents a methodology for detailed heat deposition analysis for a HFIR core model, summarizes the computational approach, and provides results obtained for various regions of HEU and LEU HFIR models at beginning-of-cycle (BOC) and EOC. The heat deposited in various regions of the fuel elements in the HEU model is compared with the corresponding values in the LEU model. In-depth heat deposition analyses of the HFIR HEU and LEU models with explicit fuel plate representation have not been conducted prior to this work.

2. HFIR MCNP Models

The HFIR HEU and LEU core models (Chandler et al., 2016; Betzler et al., 2017) analyzed in this study account for the explicit representation of the HFIR involute plate geometry, with various regions within the fuel plate defined in the MCNP models. Both the HFIR HEU and LEU models have the same experiment loadings in the flux trap target and reflector regions to keep the heat deposition analysis consistent. The experiment loading in the HEU and LEU MCNP models are based on an analysis of recent, typical cycle loadings and details on the loadings in these models are presented in Chandler et al. (2016). Typical perturbations on the experiment loadings, from cycle to cycle, are not expected to change the heat deposition in the fuel significantly. Prior to loading an experiment into HFIR, safety evaluations are performed to ensure that the perturbation does not increase a local fission rate by greater than 9% with respect to nominal values. A power uncertainty factor is utilized in follow-on thermal-hydraulics calculations to account for experiment loading variations and uncertainty in the heat deposition calculations.

The detailed regions within the fuel plate in the HFIR HEU model are based on the HFIR Cycle 400 model (Ilas et al., 2015). The HEU HFIR Cycle 400 MCNP model was validated against experimental data for various metrics from the HFIR HEU core during Cycle 400 and are documented in Ilas et al. (2015). The results from the validation gave confidence in the results from the MCNP model with explicit representation of the HFIR fuel plates. After validating the HFIR Cycle 400 model, a more general representation of the materials within the experiment region in the HEU core was modeled and is documented in Chandler et al. (2016). The same representative target region from the HEU model was modeled in the corresponding LEU model and is documented in Betzler et al. (2017).

The HEU core operates at a power of 85 MW_{th}, whereas the prospective LEU core is evaluated at 100 MW_{th}. This increase in power for the LEU core model was necessary to approximately maintain the HEU HFIR core fluxes in all relevant experimental locations with the LEU core (Ilas et al., 2009).

Fig. 1 shows a mockup of different regions in the HFIR core. The MCNP model for the HFIR core contains the following six regions for both HEU and LEU cores to accurately represent the physical HFIR configuration: flux trap target (FTT), inner fuel element (IFE), outer fuel element (OFE), control element (CE), removable and semi-permanent beryllium (RB and SPB) reflectors, and permanent beryllium (PB) reflector.

The FTT region in the model is radially bounded by the inner radius of the IFE inner side plate/sidewalls. The IFE region consists of all cells in the model that are radially bounded by the inner and outer radii of the IFE's inner and outer side plates/sidewalls. Similarly, the OFE region consists of all cells that are radially bounded by the inner and outer radii of the OFE inner and outer side plates/sidewalls. The CE region lies outside the OFE's outer side plates/