Black Rabbit Ejection Studies and COMSOL Kinetics Modeling Development at HFIR

David Chandler[1], G. Ivan Maldonado[1], R. T. Primm, III[2], and R. W. Hobbs[2]

[1]*Nuclear Engineering Department, The University of Tennessee, Knoxville, TN 37996-2300*
chandlerd@ornl.gov, Ivan.Maldonado@utk.edu
[2]*Research Reactors Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831-6399*
primmrtiii@ornl.gov, hobbsrw@ornl.gov

INTRODUCTION

The High Flux Isotope Reactor (HFIR) is a multipurpose research reactor located at the Oak Ridge National Laboratory (ORNL). It is a pressurized, light water-cooled and –moderated reactor designed with an over-moderated flux-trap (FT) in the center of the core and a large beryllium reflector on the outside of the core in order to produce a large thermal flux-to-power ratio. The FT consists of 37 target rod locations including a hydraulic tube (HT) that is used for inserting and ejecting rabbits during operation. The core consists of two concentric fuel annuli, an inner fuel element (IFE) and an outer fuel element (OFE), each constructed of aluminum involute fuel plates. The high-enriched-uranium (HEU) fuel is enriched to ~93 wt% in $^{235}U/U$ in the form of U_3O_8 in an aluminum matrix and is non-uniformly distributed along the arc of the involute plate. Two control elements are located between the fuel and the reflector and are utilized for regulation and safety purposes. The neutron field produced in this 85 MW_{th} reactor is utilized for cold and thermal neutron scattering, materials irradiation, isotope production, and neutron activation analysis.

The DOE-NE Fuel Cycle R&D Program has requested HFIR assistance in irradiating nuclear fuel samples to study the microstructural evolutionary changes due to irradiation of fuel materials, fuel-clad chemical interactions, and etc. "Black" rabbits containing thermal neutron absorbing shields (Gd, GdO_2, and Eu_2O_3) and transmission electron microscopy (TEM) discs have been designed for irradiation in the HFIR HT. The insertion or ejection of these "black" rabbits will lead to negative or positive reactivity insertions, respectively, which have the potential of initiating power transients, engaging the safety system, and causing unplanned shutdowns.

In order to meet safety and technical requirements, rabbit ejection tests and calculations are being performed and planned. Cadmium shielded rabbits ($\rho \approx 8¢$) have been ejected at the beginning-of-cycle (BOC) from various HT axial positions at low power ($P \approx 12$ MW_{th}) and gadolinium shielded rabbits ($10¢ \leq \rho \leq 16¢$) have been fabricated for near-future ejection tests. During these tests the reset flux, rate network output voltage, and control rod position are being monitored and recorded via a high speed multichannel data recorder.

Similar experiments involving the ejection of cadmium shielded rabbits of lesser worth ($\rho \leq 6¢$) at low power and BOC conditions were performed over 40 years ago in 1967 [1]. Although the results are insightful, no attempt was made to check the reproducibility of the results and the data cannot be reliably extrapolated to predict the response to rabbits of higher worth at full power and at BOC or end-of-cycle (EOC) conditions. Thus, new experiments are being conducted at a range of power levels at both BOC and EOC in order to obtain more precise and reproducible results, which are being and will be used to develop and validate new kinetics methodologies and to define worth and axial position limits on the rabbits being ejected.

Currently, point-kinetics are being implemented in PARET [2] and COMSOL [3] to predict HFIR's response to the reactivity-induced transients caused by ejecting "black" rabbits. Under the point-kinetics assumption, the properties of the reactor are rapidly changed uniformly throughout the entire system when reactivity is introduced by ejecting a "black" rabbit. However, in actuality, these transients are induced by spatially-dependent reactivity insertions because the rabbit is ejected from the core axial midplane and moves upward and away from the core. Consequently, a time- and spatially-dependent reactor kinetics model is being developed to study the spatial effects caused by reactivity-induced transients.

METHODOLOGY

The PARET code couples neutronic (point-kinetics), hydrodynamic (1-D), and heat transfer (1-D) equations to study non-destructive accidents caused by transients in research reactors with plate- or pin-type fuel elements. The PARET input developed in Ref. 4 was modified as needed for modeling the rabbit ejection transient. In order to represent an accurate power distribution, the plates were discretized into 19 axial regions and by dividing the IFE and OFE into 8 and 9 radial regions, respectively. The main inputs include the external reactivity insertion, the thermal properties for the clad and fuel, the neutronic parameters (6 delayed precursor groups), the operational parameters, and the control system response data.

The ejection transient has also been modeled with an input developed in the COMSOL v3.5 built-in ODE solver. COMSOL is a finite-element-based multiphysics

software package used to solve physics-based systems of differential equations. Fifteen ODEs were derived and coded into COMSOL including the point-kinetics equations, the rate trip output voltage equation, and various equations needed to employ temperature and voiding reactivity feedback effects.

Due to the limitations and assumptions associated with point-kinetics, a HFIR time- and spatially-dependent reactor kinetics model is being developed to study the spatial effects caused by reactivity-induced transients. COMSOL was selected for this study because it is a powerful finite-element-based simulation tool with numerous built-in physics modules and solvers and has been adopted at HFIR for thermal hydraulic analyses. A COMSOL v4.1 neutronics study has been performed as a first step by creating a 2-D, two-group, neutron diffusion model to analyze the BOC, spatially-dependent fast ($E > 3$ eV) and thermal ($E < 3$ eV) neutron fluxes. The two-group diffusion equations were implemented in the COMSOL coefficient form PDE application mode and were solved via eigenvalue analysis and the Direct (UMFPACK) linear system solver.

The 238-group ENDF/B-VII neutron cross section library and NEWT, a 2-D, discrete-ordinates neutron transport code within the SCALE 6 code package [5], were used to calculate the two-group neutron cross sections required to solve the diffusion equations. The NEWT input was constructed by modifying the input prepared in Ref. 6 by replacing the low-enriched-uranium fuel with HEU fuel and by inserting the control elements.

RESULTS

Measurement data from a cadmium rabbit ejection was obtained and the PARET and COMSOL point-kinetics models were used to calculate the time-dependent reactor power during the ejection. The rabbit worth was determined to be about 8 cents and the ejection occurred at BOC conditions and at a power of 12 MW_{th}. The rate network (volts) and change in reactor power [$1 + \Delta P$ (MW_{th})] are shown for the measured (M) results and the COMSOL (C) and PARET (P) calculations in Fig. 1.

NEWT calculations were performed to obtain the cross sections associated with the annular gadolinium shielded rabbit that will be ejected from the HT in the near future. The gadolinium rabbit was inserted into the COMSOL diffusion model at different axial locations to observe the spatial impact it has on the neutron flux. The thermal ($E < 3$ eV) flux distributions are shown in Fig. 2 for the rabbit at the fuel axial midplane, three quarters the way up the fuel, at the top of the active fuel, and removed from the core. The flux distributions calculated by means of COMSOL compare well with those calculated with benchmarked 3-D MCNP and KENO models.

CONCLUSIONS

Rabbit ejection tests of various worths are being performed in order to define the operating space for irradiating nuclear fuel samples in HFIR's HT. These samples will be used to study the temperature- and irradiation-dependent microstructural evolution of certain fuel types. The samples will be shielded by thermal neutron absorbing materials and thus when ejected will insert positive reactivity into the system. Point-kinetics studies have been used to aid in these experiments and to develop a transient power response prediction methodology. Due to the limitations and assumptions associated with point-kinetics, a time- and spatially-dependent kinetics model is being developed to study the spatial effects of transients such as HT rabbit ejections and control cylinder ejections.

A 2-D, two-group, neutron diffusion theory model of HFIR was developed via COMSOL as a first step approach in creating a spatially-dependent reactor kinetics model. This model is currently being updated by creating a more detailed geometry and by expanding from two neutron energy groups to three in order to incorporate an epithermal group. Once this model is complete, a multiphysics model will be developed by adding fluid flow and heat transfer physics. A time-dependent solver will then be setup and spatially-dependent reactivity-induced transients will be studied and compared to previous methodologies employing point-kinetics.

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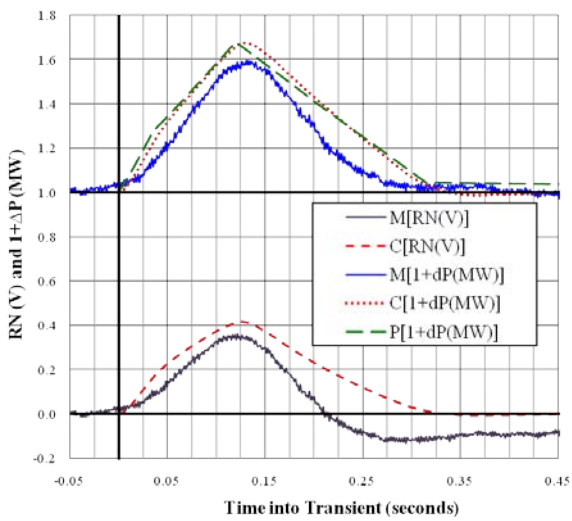

Fig. 1. Rate Network (V) and Reactor Power [1 + ΔP (MW_{th})] Response.

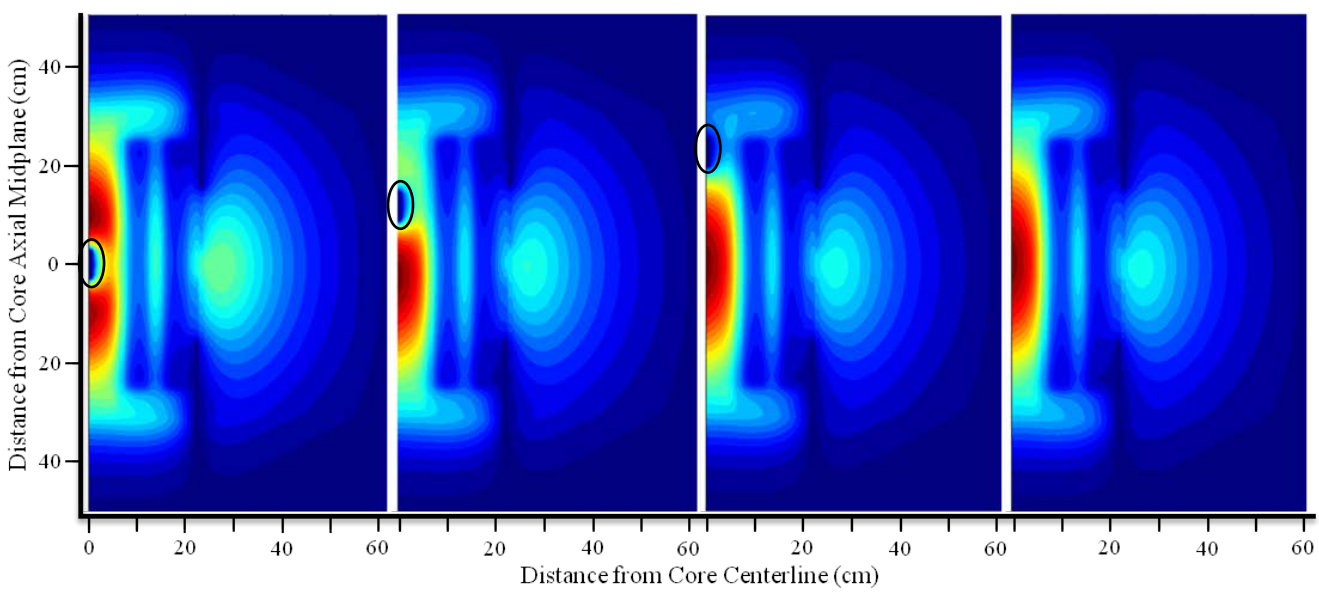

Fig 2. Thermal Flux (E < 3 eV) Contour Plots During Gadolinium Rabbit Ejection.