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INTRODUCTION

Fuel performance and whole core neutron transport codes are often used to analyze fuel behavior as it is depleted in a reactor. For fuel performance codes, internal models provide the local intra-pin power density, fast neutron flux, burnup, and fission rate density, which are needed for a fuel performance analysis [1,2,3]. The fuel performance internal models have a number of limitations, including direct coupling to the local neutron flux field, which is key to determining the intra-pin quantities needed for a fuel performance simulation.

In addition, whole core neutron transport codes need an accurate intra-pin temperature distribution in order to calculate neutron cross sections. Fuel performance simulations are able to model the intra-pin fuel displacement as the fuel expands and densifies and are thus able to provide a higher fidelity fuel temperature distribution than current methods.

Redwing is a MOOSE-based application that enables coupling between MPACT [4] and BISON [5] for transport and fuel performance coupling. MPACT is a 3D neutron transport and reactor core simulator based on the method of characteristics (MOC). The development of MPACT began at the University of Michigan (UM) and now is under the joint development of ORNL and UM as part of the DOE CASL Simulation Hub. BISON is a fuel performance application in the MOOSE framework that is under development at Idaho National Laboratory.

Redwing currently enables the coupling of MPACT/BISON for either single fuel pins (full or partial length) or small rectangular arrays of fuel pins. It is planned to extend this capability to multi-assembly or full-core applications. Redwing enables depletion simulations with two-way data transfer and a loose Gauss-Seidel coupling method which is expected to provide $O(\Delta t)$ accuracy, where Δt is MPACT's depletion time step size. The MPACT solution leads for each depletion time step and then BISON advances the fuel performance calculation with multiple implicit Euler time steps. Tighter coupling via a Picard iteration will be enabled in the future.

In coupled Redwing simulations, the MPACT to BISON data transfers include fission rate density, power density, and fast neutron flux. The BISON to MPACT data transfers include temperature in any region of the BISON domain and an axially-dependent coolant density for each fuel pin. For this coupling the internal BISON 1D coolant enthalpy rise model is applied to the cladding boundary.

Redwing currently has a limited capability to parallelize a simulation using MPI by decomposing the MOC solve by angle in MPACT. Redwing can be run with either a 2D RZ , 2D R-Theta, or 3D mesh of each fuel pin. Further details on Redwing and the coupling of MPACT/BISON are provided in the Redwing User's Manual.

DESCRIPTION OF THE ACTUAL WORK

The current coupling capabilities of Redwing can be demonstrated with a simple simulation of a single fuel pellet depleted using both coupled MPACT/BISON with Redwing, as well as BISON "standalone." Here the internal power profile model is used for the BISON standalone calculations. As shown in Fig. 1, the coupled Redwing depletion simulation had a separate mesh for MPACT and BISON. A two-way data transfer was enabled for the coupled simulation. Through the use of utilities provided by MOOSE, BISON is able to calculate the temperature for each volumetric region of the MPACT mesh. BISON is able to calculate and provide temperature feedback with the MOOSE based PostProcessor system and coolant density feedback with the LayeredAverage utility. The same BISON mesh was used for both simulations.

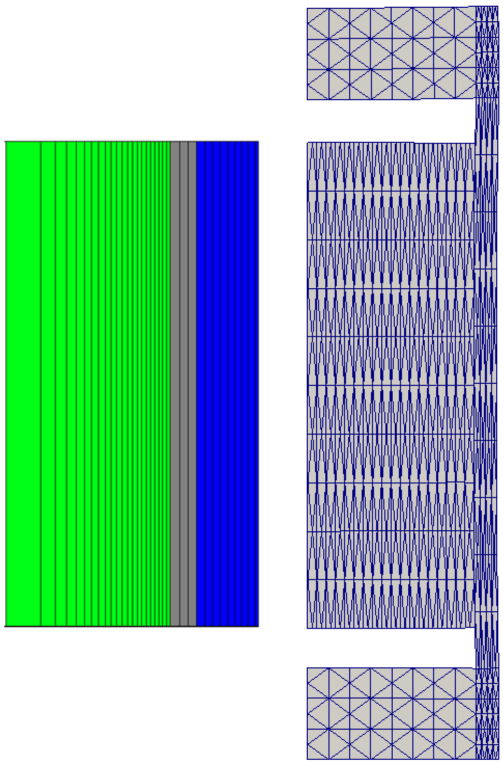

Fig. 1. A 2D slice of the fuel pellet mesh in the MPACT domain (on left) and the entire BISON 2D mesh (on right). From left to right, the MPACT mesh regions are fuel, clad, and coolant.

The MPACT mesh was not discretized azimuthally or axially; it consisted of a circular fuel region, surrounded by cladding, in a square coolant channel; the fuel-clad gap was not modeled. Based on previous studies [6], the radial mesh was refined in both domains in an effort to realistically capture the neutronic “rim” effect. The BISON mesh was a 2D axisymmetric finite element mesh with a separate mesh block for the fuel and the cladding; each finite element was quadrilateral with quadratic basis functions. As shown in Fig. 1, the BISON model had cladding end caps even though it was a single pellet; BISON needed a finite plenum volume in order to calculate the pressure of the gas in the plenum for this particular axisymmetric case. The detailed specifications for the single pellet simulation are shown in Table I.

TABLE I. Specifications for the Single Pellet Simulation

Property	Value
Active fuel height	1.1894 cm
Fuel pellet radius	0.41 cm
Radial divisions (MPACT)	22
Radial divisions (BISON)	18
Initial gap thickness (BISON)	0.0085 cm
Cladding thickness (BISON)	0.0561 cm
Cladding thickness (MPACT)	0.0646 cm
Initial temperature	580 K
U^{235} enrichment	3.1 wt%
Initial heavy metal mass	5.66 g
Full power	212.67 W
Simulation time	3 years
Final burnup	45.2 MWD/kgHM
Resonance shielding interval	0.5 MWD/kgHM

The MPACT simulation was performed with reflective boundary conditions and each domain was decomposed over 16 processes using MPI. The MPACT depletion time step size was 2 days. BISON started with a time step of 200s at $t = 0$, and was allowed to increase its time step; however, the BISON time step was constrained to synchronize data exchange with MPACT at the end of each MPACT depletion time step.

The full pellet power was determined using the specifications for the Watts Bar Nuclear Plant Unit 2 [7] for which the average linear is given as 17.88 kW/m. In an attempt to simulate two fuel cycles, the pellet was initially set to 120% full power, burned for 1.5 years, stepped down to 100% full power, and then burned for another 1.5 years as depicted in Fig. 2.

BISON Fuel Performance Models in Both Simulations

1. Heat conduction
2. Solid mechanics
    a. Thermal expansion
    b. Swelling (fuel)
    c. Creep
    d. Fuel/clad mechanical contact
3. Gap heat transfer
4. 1D enthalpy rise for coolant channel
5. Fission gas creation and release into plenum with Sifgrs [3]
    a. Plenum pressure
6. Neutron damage to cladding
7. Gravity

The BISON model for the cladding creep requires the fast neutron flux as an input. A 47 energy group HELIOS library was used to provide the neutron cross sections to MPACT for this simulation. The lower energy cutoff for the fast flux was group 5 (0.82 MeV) for the coupled Redwing depletion simulation. In the BISON standalone simulation, the fast flux and the power density distribution during burnup were based on semi-empirical correlations.

RESULTS

The change in the k_{∞} vs. burnup for the coupled Redwing depletion case is shown in Fig. 2. The reactivity decrease with burnup is consistent with a 3.1 wt% fuel pellet depletion.

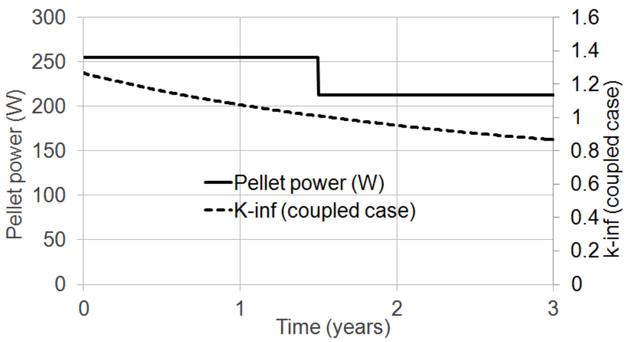

Fig. 2. The pellet power used in each simulation and k_∞ vs. time for the coupled Redwing depletion simulation.

Fig. 3 shows the radial fission rate density distribution in the coupled Redwing depletion case and the BISON standalone case at the end of the simulation at *t=3* years. This figure shows a significant peak in the fission rate density near the surface of the fuel pellet. This is the neutronic rim effect; it occurs due to the buildup of plutonium near the fuel surface during burnup.

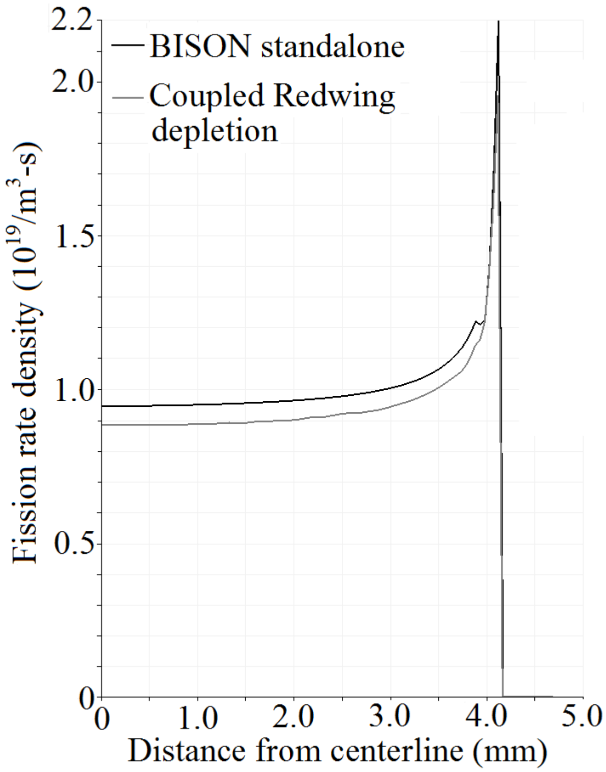

Fig. 3. The fission rate density at $t = 3$ years on a line segment extending from the fuel centerline to the fuel surface along the fuel pellet midplane in the BISON domain.

Fig. 3 shows that the fission rate density is significantly higher in the BISON standalone case, which is attributable to differences in the energy production per fission because of differences in the isotopics used in the BISON standalone and MPACT/BISON coupled case. BISON standalone does not account for the change in average energy per fission as plutonium is created in the fuel.

Several other interesting differences can be seen when comparing the behavior of coupled Redwing depletion and BISON standalone. Fig. 4 shows the change in the gap conductance over time. Over the course of the both simulations, the fuel-clad gap slowly closed. As indicated in Fig. 4, the gap closed faster in the coupled Redwing depletion case, with the average gap conductance starting to level off at about 1 year, indicating that the gap had mostly closed by this point. For the BISON standalone case, the average gap conductance did not start to level off until about 1.2 years.

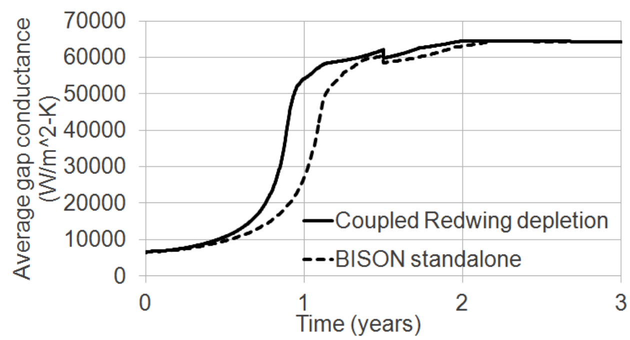

Fig. 4. Average gap conductance vs. time for the single pellet simulation.

Figs. 5 and 6 show the changes in the maximum centerline and cladding surface temperatures over time. As expected, the maximum fuel centerline temperature decreased slowly as the gap closed and then decreased abruptly when the pellet power was decreased at 1.5 years. As indicated in Fig. 5, the maximum centerline temperature in BISON standalone was slightly higher than in coupled Redwing depletion, which is likely attributable to the differences in the power density shape and gap conductance. The differences in the average temperature on the cladding inner surface in Fig. 6 are consistent with the gap closure starting at about 1 year for coupled Redwing depletion and at about 1.2 years for BISON standalone simulation.

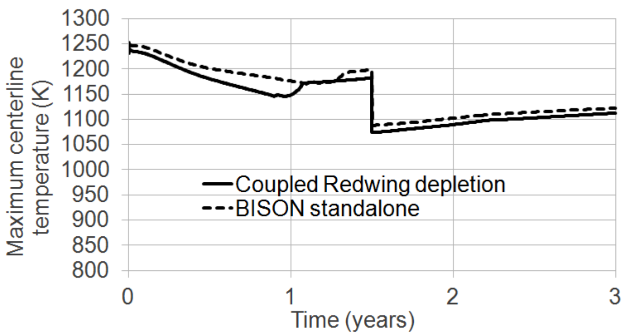

Fig. 5. Maximum fuel centerline temperature vs. time for the single pellet simulation

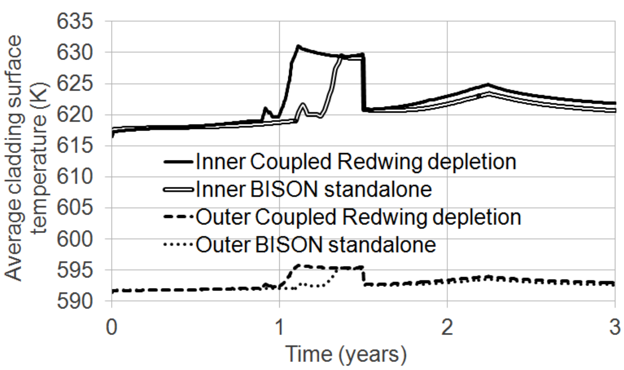

Fig. 6. Average inner and outer cladding surface temperature vs. time for the single pellet simulation.

Conclusions and Future Work

The Redwing application was developed to couple MPACT and BISON, and a single pellet depletion simulation was used to provide a preliminary assessment of the coupled solution by comparing it to a standalone BISON simulation. Some explainable differences were observed in the results, but the overall consistency provided confidence in the coupled results.

Although this preliminary work was not intended to provide a thorough assessment, the coupled and standalone results provide some insights that can help prioritize continued development of the code coupling.

The following improvements to Redwing are currently being implemented or are planned:

1. Tighter coupling via a Picard iteration for single-pin and multi-pin simulations should be a high priority.
2. Additional data should be exchanged between MPACT and BISON, such as burnup, density, and certain nuclide concentrations.
3. The parallelization of Redwing should be improved.
4. A more sophisticated method should be implemented for the spatial mapping of data between the MPACT and BISON meshes.
5. A formal test suite should be developed for Redwing to be included with the current validation used in BISON and MPACT.

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