INTRODUCTION

Nuclear engineering is reaching a domain space in which computational power and methods are starting to surpass the models that are used to simulate nuclear fuel rods. As these models are updated, simulations utilizing different compositions, operating conditions, fabrication techniques, and geometries can provide core designers with an important first step towards fuel qualification. Due to the cost associated with fuel irradiations, it can be expected that time and money spent building better fuel models may provide an attractive return during initial studies of advanced fuels, especially with regards to fuels beyond the extensively studied uranium oxide system.

In general, the primary U.S. experience with irradiated fuel rods beyond traditional oxide fuel is with binary (U-Zr) and ternary (U-Pu-Zr) metal fuels. The bulk of the experimental data for metal fuels is obtained from rods irradiated in the EBR-II sodium fast reactor (SFR), thus many of the correlations developed for metal fuels comes from the post-irradiation (PIE) examination of EBR-II rods.

One of the unique characteristics that set U-Pu-Zr fuels apart from traditional oxide fuels is the presence of different phases that develop in the fuel during irradiation. Each of these different phases has unique thermal, mechanical, and diffusive behavior. The transitions between these phases are not static as the initially homogenous zirconium diffuses towards the center and edge of the fuel rod, resulting in a low-Zr, high-U ring. Along with the differing material properties that occur in each phase, the increase in uranium corresponds to an increase in localized fission and power production. The direct coupling between the thermal and diffusion solves highlights one of the many examples of tightly coupled phenomenon that are present in nuclear fuel, and motivation for the development of codes that simultaneously solve each piece of physics in a fully-coupled manner.

SIMULATIONS

New models to simulate U-Pu-Zr fuel have been implemented in BISON [1]. Much of the thermo-mechanical physics is provided by the MOOSE/BISON backbone, including heat conduction, volumetric swelling, and contact, and has been described elsewhere [1, 2]. In addition, unique physics such as zirconium redistribution and phase-dependent properties that have been added to BISON [3, 4].

The fuel rod T179 is a typical U-19Pu-10Zr fuel rod irradiated in EBR-II in 1985. The rod is of interest due to the PIE results that provided micrographs at several locations, as well as microprobe examinations near the top of the fuel. As a result, it has been utilized in previous studies for calibration of zirconium diffusion coefficients [3-8]. The rod was simulated using the best available operating conditions, and provides the baseline case for which variations in composition or initial conditions can be modified. Although the assembly containing the T179 rod experienced slightly different flow rates and power ratings during the course of irradiation, the changes were slight enough that a daily weighted linear heat generation and flow rate were utilized in the simulations.

Two cases were run to compare with the baseline T179 simulation. The “Axial shift” case utilizes an axial fission rate distribution that mimics the behavior that may be expected in advanced fast reactor concepts being proposed for power generation, in which the power profile shifts from the bottom of the core to the top [6]. For this case, the peak fission rate location will shift from the lower section of the rod to the upper, as displayed in Fig. 1. In addition, the integral rod power will also shift from high to low from beginning of life (BOL) to end of life (EOL). At the middle of life (MOL), the power profile will exactly match the baseline T179 case.

The second case represents changing the fabrication of the fuel rod in an effort to address operational concerns. One of the primary apprehensions with ternary metal fuel is the existence of a low temperature Pu-Fe eutectic that may form between the fuel and cladding. In addition, fuel/cladding chemical interaction (FCCI) has been observed to occur at the locations of highest fuel temperatures. This is due to enhanced presence of lanthanides near the top third of the rod due to higher diffusivity, as well as more prevalent cracking that provides pathways for the lanthanides to
diffuse to the fuel. In general, plutonium fuels experience greater cracking, thus limiting the plutonium content in the top third of the fuel may reduce the consequences of FCCI, both through preventing the Pu-Fe eutectic, which has been shown to accelerate FCCI [7], and by reducing the source term of lanthanide on the fuel. By linearly varying the concentration of plutonium as a function of axial height, the impact on fuel performance can be explored. For the second comparative case, the plutonium atom fraction was varied from 20 a/o at the bottom of the rod to 0 a/o at z/L = 0.67 (Fig. 1).

The temperature and zirconium distribution for each of the three cases were compared at EOL in Fig. 2. In addition, local power, thermal conductivity, phase distribution, and temperature distribution is plotted in Fig. 3 at EOL. The baseline “T179” case shows similar behavior as was modeled previously [2, 6].

The “Axial shift” simulation, which experienced initially higher integral power peaking lower in the rod, and ending with a lower final power peaked at the top of the rod, showed that the maximum redistribution effectively followed the movement of the power peak. As the power shifted towards the upper portions of the rod, the gamma phase tended to grow axially, rather than creating a radially large gamma zone, as observed in the T179 rod at the EOL. Temperatures for the axial shift case were similar to the T179 case, albeit the peak centerline fuel temperature tended to follow the peak axial power shift.

The “Pu ramp” case showed the most deviation from the baseline T179 case, presenting a much more subdued zirconium redistribution. In general, increasing plutonium content results in a lower thermal conductivity of U-Pu-Zr fuels [5]. As a result of axially decreasing the concentration of plutonium in the rod, the temperature profile maintains a flattened arc, and avoids the highly peaked temperature profile. This in turn slows zirconium redistribution such that evidence of movement is not apparent until near the end of irradiation. In addition, the zirconium redistribution radially extends only half as much as the T179 case.

The variation in temperature distributions becomes most evident when comparing the thermal conductivity, power, temperature, and phase distribution of the different cases, as exemplified in Fig. 3, which displays various conditions at the EOL. Following methods described in [3] in which the power is scaled by the zirconium concentration, the power distribution mimics the zirconium in Fig. 2, resulting in localized power region in the center of the rod that is half as much as in the corresponding surface power. The variation in thermal conductivity follows the phase distribution, as evident when comparing the T179 and Axial shift simulations. In addition, the axial decrease in plutonium content vastly increases the thermal conductivity at the top of the rod. As a result of the deviations in thermal conductivity and power, it is clear that the temperature distribution closely follows the zirconium redistribution, and results in a much cooler rod if the plutonium concentration is decreased axially.

**DISCUSSION AND CONCLUSIONS**

These simulations only attempted to address the thermal-diffusion problem utilizing the models in BISON. The fuel is assumed to swell due to both solid and gaseous contributions, of which the later affect the thermal conductivity through the introduction of gas bubbles. This contribution is accounted for in the simulations here, but is
included using only a simple model, thus further discussion should be limited to future simulations when advanced models become available. In the meantime, it should be recognized that fission gas modifications to the temperature distribution will likely affect all rods in a similar fashion to the simulation comparisons here are for the exact same irradiation conditions (e.g. rod power, flow rate, irradiation time).

In addition, the diffusion coefficients and phase diagram utilized to model the zirconium redistribution are only formulated assuming 16.3 at.% plutonium concentrations, and are not necessarily directly applicable to binary fuels. However, the transition temperatures for binary fuels are higher and decrease as a function of plutonium [5], thus the zirconium redistribution will only be further reduced if U-Zr coefficients are utilized.

Due to the adaptability of BISON and the recent inclusion of flexible models, it is clear that small changes in either the operating or fabrication procedures produce vastly different results. This is especially clear as the traditionally constant plutonium concentration is allowed to vary. With only simple axial changes, the temperature profile is flattened, and the peak temperature is nearly 50 K less than the baseline case. In addition, by avoiding the plutonium concentration at locations of high cladding temperatures that occur in the upper region of the rod, the Pu-Fe eutectic can be avoided.

As previously discussed, U-Pu-Zr fuel presents a complicated system due to the different phases present in the fuel during irradiation. The differing material properties for each phase result in complex interactions as stresses due to thermal cycling combined with fission gas bubble growth may serve to produce the large cracks observed in ternary fuels. By limiting the volume of the gamma region, it may be possible to suppress the consequences of sharp phase transitions. While the shifting axial power peak results in a axially smaller gamma region in the fuel, the decreasing plutonium concentration results in a much smaller radial gamma accumulation. By tailoring the Pu axially, it may be possible to suppress the total volume of the gamma phase, thus reducing the stresses introduced by differing material properties across sharp phase transitions.

The power deviations and corresponding zirconium redistribution displayed in Fig. 3 highlights the importance of coupling the thermal and diffusion simulation to the power distribution. This can be done either through a tight coupling of MCNP/BISON runs, or more simply through a correlation developed independent of the BISON runs, as was done in [3].

Despite some of the simplifications in these simulations, it is clear that the coupled thermo-diffusion problem can be solved for different model parameters by leveraging the adaptability of BISON to new parameters, and the flexibility of the material models to handle different simulation conditions. Following this baseline, advances in other models such as phase-dependent properties and gaseous swelling rates will further enhance the ability of fuel designers to utilize fuel performance codes as a predictive code to study advanced fuel types and reactor conditions.

REFERENCES