Modeling the IFR-1 Metal Fuel Experiment in Bison through the NEAMS Workbench

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INTRODUCTION

The United States Department of Energy Office of Nuclear Energy (DOE-NE) Versatile Test Reactor (VTR) project is studying a possible new fast spectrum test reactor. The mission of the VTR would be to further the development and deployment of nuclear energy technologies by providing a modern, fast-spectrum facility for testing advanced nuclear materials, sensors, instruments, and fuels. The proposed VTR driver fuel concept is a uranium-plutonium-zirconium (UPuZr) ternary alloy metallic fuel cladded in HT9.

In 1985, the Integral Fast Reactor (IFR)-1 experiment was performed in the Fast Flux Test Facility (FFTF). There were three IFR-1 fuel slug compositions: U-10Zr, U-8Pu-10Zr, and U-19Pu-10Zr [1]. All of these were cladded in D9. The U-19Pu-10Zr fuel rods are of greatest interest to the VTR project. As a result, Oak Ridge National Laboratory (ORNL) recently used the Bison fuel performance code to model, simulate, and analyze a U-19Pu-10Zr IFR-1 fuel pin. Bison is a thermomechanical finite element code with material models and other capabilities that enable the study of how various types of nuclear fuel would perform under given operating conditions [2].

For this work, ORNL used the Bison code through the Nuclear Energy Advanced Modeling and Simulation (NEAMS) Program's Workbench analysis environment. The NEAMS Program's goal is to develop, apply, deploy, and support a predictive modeling and simulation toolkit for the design and analysis of current and future nuclear energy systems using computing architectures ranging from laptops to leadership class facilities [3]. The NEAMS Workbench is a software actively being developed to provide a common graphical user interface (GUI) and analysis environment for creating, reviewing, executing, and visualizing models for integrated codes [3]. In addition to the GUI, the NEAMS Workbench provides an analysis sequence processor [4] that enables code integration and workflow encapsulation, as demonstrated with the Argonne Reactor Computation (ARC) suite of codes used for neutronics modeling of VTR [5]. The NEAMS Workbench enabled ORNL to successfully develop, analyze, and visualize the IFR-1 U-19Pu-10Zr fuel pin model from a Windows, Mac, or Linux operating system through one consistent user interface.

By creating a benchmark model of IFR-1, ORNL can further assess the use of Bison for analyzing metallic fuel while simultaneously testing the NEAMS Workbench to evaluate its capabilities in supporting the integrated use of the Bison fuel performance code.

The work reported in this summary is the result of R&D studies supporting a VTR concept, cost, and schedule estimate for DOE-NE. The technology and location for the VTR have not been selected, as this is part of a formal DOE process. As such, all information provided herein must be considered preliminary.

COMPUTATIONAL MODEL

A two-dimensional (2D) axisymmetrical (r-z) model of the IFR-1 fuel pin was constructed for Bison using NEAMS Workbench. A similar input model found in the Bison examples directory for a metallic fuel experiment (x441) performed in the Experimental Breeder Reactor II (EBR-II) was used as a starting template.

IFR-1 fuel pins contained 16.5-cm-long axial blankets of depleted uranium (DU) U-10Zr above and below the main fuel column [6]. However, for simplification, the model in this work ignores those axial blankets in order to comply with current limits in Bison's internal mesh generation script and avoids having to use external mesh generation resources. This modeling approximation therefore ignores the mechanical and thermal impacts of the axial blankets by assuming that 100% of power production occurs in the main fuel column; this should be conservative for thermal analysis due to concentrating power production into a smaller region. The mechanical impacts of this approximation should be small and are considered acceptable for this current work. Future work will explicitly model the axial blankets and incorporate their effects, to include axial power distribution and mechanical effects.

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Mesh parameters include 6 fuel elements in the radial direction, 260 fuel elements in the axial direction, 4 cladding elements in the radial direction, and 260 cladding elements in the axial direction. The upper and lower end plugs on the cladding tube were both modeled using 3 cladding elements in the axial direction. A smeared mesh was used to model the fuel column.

Input values and parameters required to model the IFR-1 experiment were collected from various sources [6–9] and are summarized in Table I. Some of these parameters are assumed or estimated and may be subject to change. The rod-average linear heat generation rate (LHGR) was input at specific timesteps using data from previous work [7] and is summarized in Figure 1. Most coolant channel parameters required for this IFR-1 model are currently taken from the x441 input provided in the BISON code due to difficulty in obtaining specific values for IFR-1; however, the actual FFTF coolant inlet temperature, 633 K, is used based on values found in the literature [10]. In addition, HT9 material models are currently used in this IFR-1 model because Bison currently lacks most material models for D9. As they are eventually added, this IFR-1 model will need to be updated accordingly. All of these approximations should be updated at a later point to improve accuracy of the model.

TABLE I. Summary of input parameters for Bison model of IFR-1 experiment

Parameter	Value	Source
Cladding Thickness	0.056 cm	[7,8]
Fuel Slug Outer Radius	0.249 cm	[7]
Initial Na Bond Gap Thickness	0.038 cm	x441.i
Plenum Height	106.2 cm	[6]
Gap Conductivity	61 W/m-K	x441.i
Rod Diameter	0.686 cm	[7,8]
Fuel Slug Height	91.4 cm	[6]
Zr Weight Fraction	0.10	[7,8]
Pu Weight Fraction	0.19	[7,8]

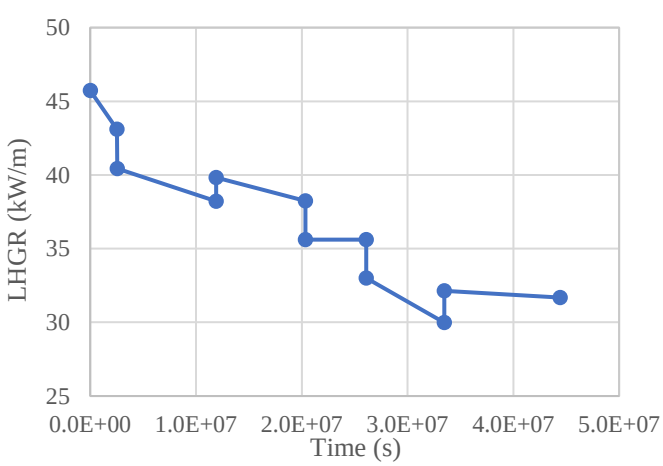

Fig. 1. Calculated LHGR values in kW/m used to define power history over time in seconds for IFR-1 model.

Figure 2 illustrates the creation of the model using the listed values through NEAMS Workbench, as well as the visual depiction of the generated model's mesh. Note that different length units were used on the X-axis and the Y-axis.

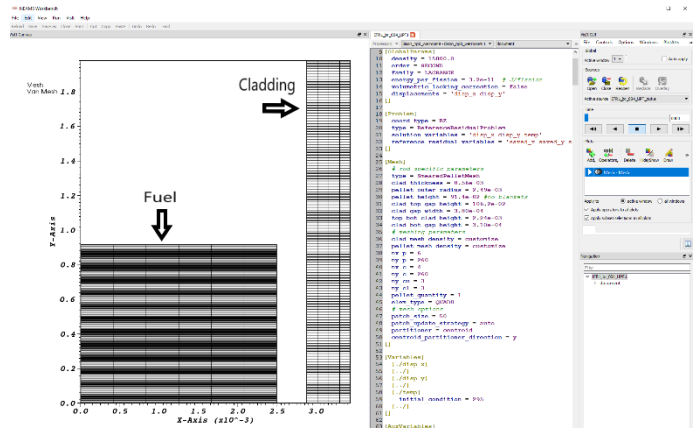

Fig. 2. NEAMS Workbench screenshot depicting the 2D IFR-1 mesh on the left, Bison input in the center, and the VisIt GUI on the right.

RESULTS

Simulations were performed to analyze and visualize numerous parameters at the beginning of life (BOL) and end of life (EOL) of the fuel pin. These parameters include temperature (Fig. 3), burnup (Fig. 4), cumulative damage fraction (CDF) in the cladding, total hoop strain in the cladding, and other items of interest to understand the behavior and performance of the fuel cladding system.

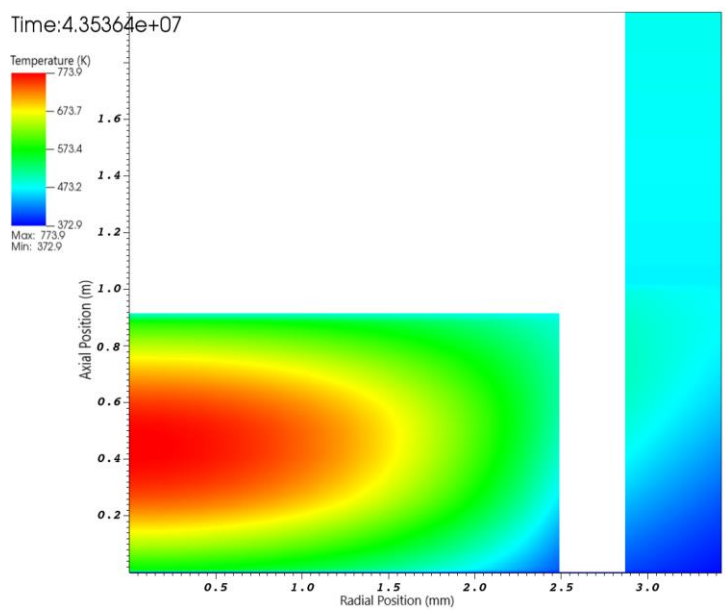

Fig. 3. Display of temperature distribution in fuel and cladding at EOL in NEAMS Workbench VisIt GUI.

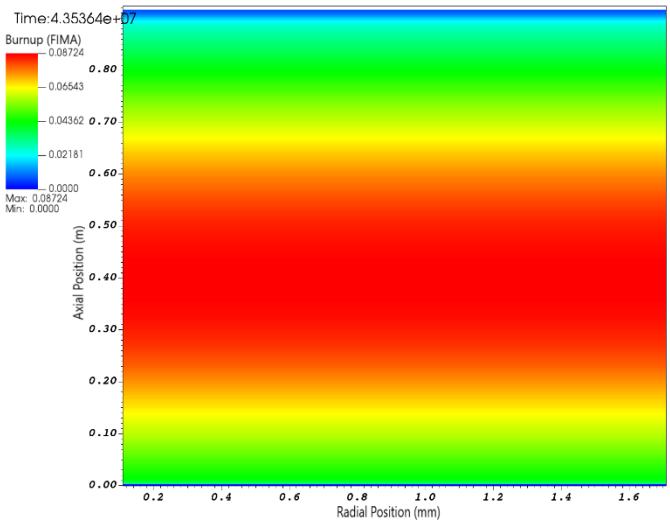

Fig. 4. Display of burnup distribution at EOL in NEAMS Workbench VisIt GUI. Cladding was omitted from this figure, as burnup only occurs in the active fuel.

Table III summarizes several key parameters of interest at EOL from the IFR-1 simulation in Bison. The maximum hoop stress of 62.1 MPa occurred at approximately 0.51 m from the bottom of the active fuel column (x/L=0.6). The peak burnup of 8.7% fissions per initial metal atoms (FIMA) was reached at approximately 0.42 m above the bottom of the fuel column (x/L=0.5).

TABLE III. Output Values

Parameter	Value
Peak Fuel Temperature (at 142 d)	1080 K
Peak Cladding Temperature (at 1 hr)	816 K
Maximum Average Fuel Surface Temperature During Operation (at 1 hr)	792 K
Maximum Average Inner Cladding Temperature During Operation (at 1 hr)	781 K
EOL Average Burnup	6.6 %
EOL Peak Burnup	8.7 %
EOL Plenum Pressure	3.3 MPa
EOL Maximum Hoop Stress	62.1 MPa
EOL Maximum Cladding Creep Strain	1.36×10^{-5}
EOL Fission Gas Release	91.6 %
EOL Maximum Cladding Damage Factor	2.77×10^{-8}

Fuel temperature appeared to generally increase, peak, and then decrease as burnup increased, as illustrated in Fig. 5. Gap thickness gradually decreases as burnup occurs, as is seen in Fig. 6. The gap completely closes, achieving contact with cladding at approximately 6.6% average burnup. The results in both figures match the overall qualitative behaviors expected, though gap closure (Fig. 6) was expected to occur sooner.

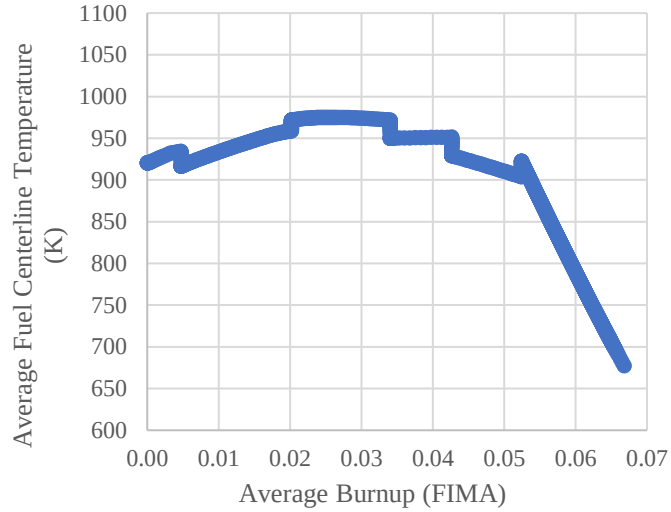

Fig. 5. Plot of change in average fuel centerline temperature as burnup occurs.

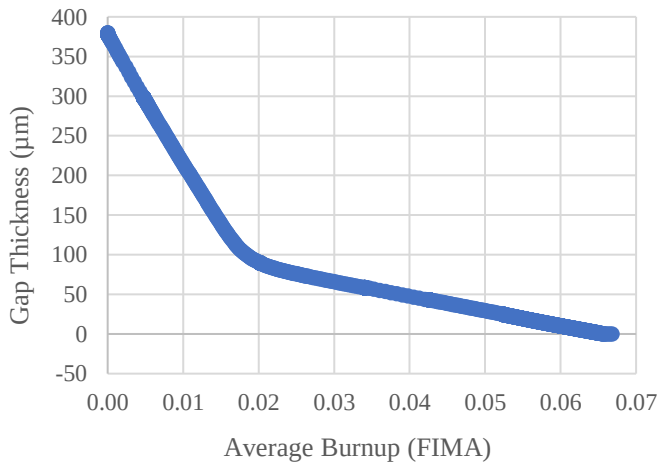

Fig. 6. Plot of change in minimum gap thickness between cladding and fuel as burnup occurs.

Table IV illustrates the accuracy of the model. The peak percent burnup was calculated for the IFR-1 experiment at EOL for the first four irradiation cycles in one of the IFR UPuZr pins [7]. In Table IV, these values are compared to the output peak burnup from the created model at the same time steps. The relative error for each was calculated by subtracting the actual value from the simulation value and then dividing that quantity by the simulation value. The average was 2.91% relative error.

TABLE IV. Burnup Results Comparison

Cycle	Time (EFPD)	Experimental Peak EOL BU (%FIMA) [7]	IFR Model Peak EOL BU (%FIMA)	Relative % Error
9A	138	2.61%	2.68%	2.6%
9B	244	4.44%	4.67%	5.2%
9C	342	6.12%	6.27%	2.4%
10A1	408	7.18%	7.28%	1.4%

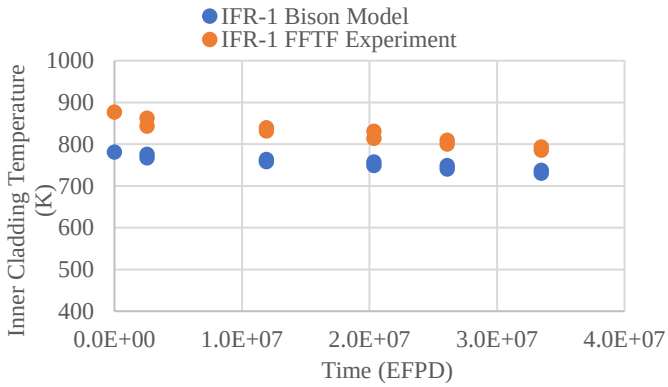

Fig. 7. Comparison of simulation-generated and original experiment [7] temperature values as time progresses.

As shown in Fig. 7, the simulation generated a cladding inner temperature distribution within 100 K of the actual experimental values. This is potentially due to the use of the x441 input coolant channel parameters among other potential factors and must be further investigated to improve the accuracy of the model

CONCLUSION

A 2D axisymmetric model of the IFR-1 experiment was built in Bison through NEAMS Workbench to provide a benchmark model of metallic fuel analysis for the VTR project.

In the future, this IFR-1 model needs to be revised to correct or improve current approximations and assumptions, including treatment of the U-10Zr axial blankets, coolant channel parameters, and axial power distributions. In addition, future efforts are needed to continue to expand the benchmark suite of metallic fuel models in Bison. Future work should include explicit representation of the U-10Zr axial blankets in the model. Furthermore, results from this IFR-1 analysis can be used to examine possible areas of improvement in Bison material models or other input sections for metallic fuel models.

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