Metallic Fuel Performance Benchmarks for Versatile Test Reactor Applications

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Abstract — The U.S. Department of Energy Office of Nuclear Energy’s Versatile Test Reactor (VTR) project is designing a new fast-spectrum test reactor. The VTR reference driver fuel design is sodium-bonded U-20Pu-10Zr (wt%) metallic fuel and HT-9 cladding. The BISON fuel performance code is being used to model the VTR driver fuel pin to evaluate the effects of differences between its design and the legacy designs that preceded it. This work summarizes ongoing efforts at Oak Ridge National Laboratory to benchmark BISON for VTR driver fuel analyses, including establishing metallic fuel performance code requirements for VTR applications and benchmarking BISON for VTR driver fuel analyses. Integral fuel pin predictions are compared to legacy calculations and post-irradiation examination data for 261 fuel pins irradiated at Experimental Breeder Reactor II and the Fast Flux Test Facility. The BISON predictions exhibit trends that are generally consistent with the legacy data. Burnup and temperature predictions were found to be more accurate than mechanical predictions such as radial cladding dilation, axial fuel elongation, and plenum pressure. Likely sources of error were identified for evaluation in future work.

Keywords — Versatile Test Reactor, U-Pu-Zr, metallic fuel, BISON, benchmarking.

Note — Some figures may be in color only in the electronic version.

I. INTRODUCTION

The U.S. Department of Energy (DOE) has directed a team of national laboratories, universities, and private industry partners to design a fast-spectrum test reactor called the Versatile Test Reactor (VTR) (Ref. 1). VTR will provide the experimental capabilities necessary to test advanced nuclear reactor fuel and coolant concepts with the high fast-neutron flux needed to study long-term radiation damage.

The reference VTR driver fuel design, which is sodium-bonded U-20Pu-10Zr fuel (compositions in this work are given in weight percent unless specifically noted otherwise) and HT-9 cladding, is summarized in Table I (Refs. 2 and 3).

The United States has considerable experience with U-Zr and U-Pu-Zr metallic fuels in sodium-cooled fast reactors (SFRs). Tens of thousands of metallic fuel pins were irradiated in Experimental Breeder Reactor II (EBR-II), including those irradiated during the Integral Fast Reactor (IFR) program of the 1980s and 1990s (Ref. 4). These developments and design evolutions were responsible for numerous major design and material improvements,5-7 thus establishing the foundation for current metallic fuel pin designs. Irradiation experiments were also conducted at the Fast Flux Test Facility8 (FFTF) and the Transient REActor Test (TREAT) Facility.9,10
TABLE I
Nominal Design Parameters for the Reference VTR Driver Fuel

| Parameter                  | Value       |
|----------------------------|-------------|
| Fuel composition           | U-20Pu-10Zr |
| Cladding composition       | HT-9        |
| Cladding outer diameter (cm)| 0.625      |
| Plenum–to–fuel volume ratio| 1.0         |
| Fuel length (cm)           | 80          |

*References 2 and 3.

The fuel performance design basis for the VTR driver fuel will be based on past operational experience from driver fuel and irradiation experiments in EBR-II and FFTF (Ref. 11). While the VTR driver fuel design deviates from the designs tested in EBR-II, FFTF, and the TREAT Facility in small ways, the available data sufficiently envelop the VTR driver fuel design parameters and intended operating conditions. Therefore, experience from these tests is directly relevant when determining expected VTR driver fuel behavior and reliability. VTR fuel design criteria have been proposed.11 As with the EBR-II Mark-V and Mark-VA fuel design criteria12 on which they are based, the VTR fuel design criteria minimize the risk of bulk fuel melting and cladding rupture by establishing limits on fuel and cladding temperatures, cladding strain, cladding hoop stress, and cladding cumulative damage function.

BISON fuel performance simulations will be conducted to provide support for the VTR driver fuel design basis by assessing the expected behavior of the VTR driver fuel and indicating the margin to fuel failure. BISON is maintained by Idaho National Laboratory (INL) and is under continuous development by contributors from numerous institutions.13 It is based on the Multiphysics Object-Oriented Simulation Environment (MOOSE) framework,14,15 and its modular design and use of the finite element method make it one of the most modern and flexible fuel performance codes available.16–20 Demonstrating BISON’s ability to accurately predict the behavior of fuel pins from past metallic fuel irradiation experiments will increase confidence in its VTR driver fuel predictions. These fuel performance simulations are the focus of this work.

The accuracy of BISON predictions can be evaluated using several types of data available for fuel pins irradiated at EBR-II, FFTF, and the TREAT Facility. Predictions can be validated against post-irradiation examination (PIE) measurements including radial cladding dilation, axial fuel elongation, plenum pressure, and cladding corrosion. Direct temperature measurements are limited, but BISON predictions can be benchmarked against coolant outlet, peak cladding, and peak fuel temperatures calculated using the SE2-ANL thermal-hydraulic code, which was applied to support experiments at EBR-II and FFTF (Ref. 21). Temperature predictions could also be compared to temperatures inferred from fuel melt tests and phase boundaries observed in fuels that have undergone constituent redistribution. Supporting calculations such as average burnup, peak burnup, fission gas release (FGR), and cladding failure probability are also available. BISON predictions are compared with all three types of data in this work. For simplicity, comparisons made to this mixed dataset are referred to as “benchmarking against legacy data and analyses.”

Associated work at Oak Ridge National Laboratory (ORNL) includes an assessment of the metallic fuel performance models available in the BISON fuel performance code,22 the metallic fuel performance code requirements established for VTR applications,23 and a plan for benchmarking BISON for VTR driver fuel analyses. Results from the X430 and IFR-1 benchmarks covered in Sec. IV were previously published in Refs. 24 through 28. The present work provides a comprehensive view of this body of work, including a concise summary of the above benchmarking activities and updated BISON results.

Metallic fuel behaviors and the metallic fuel performance code requirements established for VTR applications are summarized in Sec. II. Overviews of the past metallic fuel irradiation experiments and the plan developed to benchmark BISON for VTR driver fuel analyses are provided in Sec. III. Results from a curated set of benchmarks are presented in Sec. IV. Results from an extended set of benchmarks developed from the EBR-II Fuels Irradiation and Physics Database (FIPD), an irradiation database maintained by Argonne National Laboratory29 (ANL), are presented in Sec. V. Broader trends based on these results are discussed in Sec. VI. Finally, conclusions and suggestions for future work are covered in Sec. VII.

II. METALLIC FUEL PERFORMANCE CODE REQUIREMENTS

Metallic fuel performance code requirements were established to ensure that the code is capable of (1) calculating the parameters used in defining the VTR driver fuel design criteria and (2) modeling all thermo-mechanical and irradiation behaviors that impact those parameters.23 Brief overviews of metallic fuel pin materials, structure, and in-core behaviors are provided in Sec. II.A to provide context for the code requirements that follow.
II.A. Fuel Pin Thermomechanical and Irradiation Behaviors

The metallic fuel pin designs relevant to this work have (1) U-Pu-Zr alloy fuels with plutonium contents between 0 and 26 wt%; (2) ferritic-martensitic HT-9 cladding and, to a limited extent, cold-worked austenitic D9 and Type 316 stainless steel (316SS) claddings; (3) fuel smeared density (the ratio of the cross-sectional area of the as-fabricated fuel to the inner cross-sectional area of the as-fabricated cladding) of approximately 75%; and (4) liquid sodium bonds. Metallic fuel pins exhibit a number of irradiation behaviors resulting from interactions among the fuel pin materials, neutrons, and fission fragments. These include gaseous and solid fission product swelling in the fuel, porosity formation and evolution in the fuel, fuel-cladding mechanical interaction (FCMI), FGR from the fuel into the open fuel pin volume, thermal and irradiation creep in the fuel and cladding, irradiation-induced swelling and embrittlement in the cladding, fuel-cladding chemical interaction (FCCI), and fuel constituent redistribution. Each behavior is discussed in further detail in this section, and more in-depth reviews are available in the open literature.6,30–32

When a fresh metallic fuel pin is irradiated in a reactor, gaseous and solid fission products begin to accumulate within the fuel lattice, causing it to swell.33 The gaseous fission products—primarily xenon and krypton, which are insoluble in the fuel matrix—combine to form pores or bubbles, which grow and eventually interconnect to form channels that allow fission gases to migrate toward the surface of the fuel. A large portion of the fission gases is ultimately released into the fuel-cladding gap and fuel pin plenum, where they increase the plenum pressure and contribute to cladding hoop stress. While some isolated fission gas bubbles remain in the fuel, the interconnected pores continue to vent most new gaseous fission products to the plenum, largely limiting additional gaseous swelling.

Radial fuel swelling leads to contact between the fuel and cladding, causing FCMI. The fuel pin’s smeared density is carefully chosen so that gap closure and porosity interconnection occur concurrently, thus limiting FCMI (Ref. 34). This approach avoids a portion of the stress in the cladding that might otherwise contribute to cladding rupture at low burnup. Solid fission products continue to accumulate within the fuel lattice, but contact with the cladding opposes further fuel swelling in the radial dimension. The combined effects of FCMI and solid swelling produce compressive stress in the fuel, which provides a driving force for the collapse of some of the existing fuel porosity via thermal and irradiation creep (i.e., hot pressing) up to about 10% burnup for fuel pins with smeared densities of approximately 75%, and additional axial fuel elongation thereafter.35 The risks to the cladding associated with FCMI increase with burnup due to the accumulation of solid fission products, reduction in fuel porosity, increased fission gas pressure in isolated and interconnected pores, and increased radiation damage to the cladding.

The binary fuels irradiated in EBR-II generally exhibited greater swelling and axial elongation than the ternary fuels.36,37 It is generally agreed that U-Zr and U-Pu-Zr fuels swell preferentially in the radial direction (i.e., anisotropically),33 but the available experimental data are insufficient to describe the swelling behavior of the stable multiphase microstructures that are dispersed throughout these fuels. Because the porous fuel is notably more plant than the cladding under in-core conditions, radial constraints on the fuel from the cladding may force fuel to swell in the axial dimension, driving further fuel elongation; however, it is also possible that fuel-cladding contact will cause frictional resistance against fuel elongation.

Porosity and low-conductivity fission gas bubbles degrade heat transfer through the fuel. Interconnected pores also provide pathways for high-conductivity liquid bond sodium to enter the fuel from the gap, but questions remain about when sodium infiltration occurs and how deeply the sodium penetrates the fuel. Sodium infiltration is particularly difficult to characterize because metallographic sample preparation used in PIE can disrupt the sodium content of the fuel. Studies based on the average fission gas and sodium contents of irradiated fuels suggest that their combined effects lower the effective thermal conductivity of the fuel, thus increasing fuel temperature.35 Other studies have shown that the magnitudes of the effects of porosity evolution and sodium infiltration on fuel temperature are much smaller than the margin to fuel melting.38

In prior metallic fuel designs, HT-9, D9, and 316SS were all used as cladding materials, and all exhibit varying degrees of thermal and irradiation creep and irradiation-induced swelling. The alloys also vary in strength and in their susceptibility to irradiation hardening from the accumulation of irradiation-induced defects, radiation-induced segregation, and formation of secondary precipitates.39 Of these materials, ferritic-martensitic HT-9 exhibits significantly less void swelling than austenitic D9 and 316SS when subjected to high fast-neutron fluxes at SFR-relevant temperatures.40,41 All three cladding materials may be considered as part of the benchmarking effort, but HT-9 is the cladding material selected for VTR driver fuel and is the focus of VTR driver fuel analyses.
Mechanical contact between the fuel and cladding also enables FCCI, in which chemical interactions and diffusive processes effectively thin the load-bearing thickness of the cladding wall. HT-9 is susceptible to carbon depletion, which contributes to reduction of the cladding’s load-carrying capacity. Austenitic D9 and 316SS are also susceptible to nickel depletion via FCCI. These diffusive processes form interdiffusion layers that are conservatively considered wastage and assumed to be incapable of bearing mechanical load. Lanthanide diffusion into the cladding can also form a brittle wastage layer, further reducing the margin to cladding rupture and also forming low melting temperature phases at the fuel-cladding interface. Diffusion of iron into the fuel causes the accumulation of a eutectic or eutectic-like phase containing uranium and/or plutonium on the fuel side of the fuel-cladding interface, which also has a low melting temperature (about 650°C to 720°C). Melting of these interdiffusion regions and phases can enhance interdiffusion into the cladding and further degrade cladding integrity through a process commonly referred to as eutectic liquefaction. FCCI is most often observed in the upper half of the fuel column, where higher fuel and cladding temperatures enhance interdiffusion.

Metallic fuels have multiphase structures at room temperature and during operation. Temperature and chemical potential gradients between those regions with different phase compositions drive the redistribution of fuel constituents. Constituent redistribution impacts the phase composition of the fuel and therefore its local melting temperature, porosity evolution, and other thermomechanical properties. Phases with low zirconium content have the lowest melting temperatures. Currently, most of the property and behavior correlations used in BISON analyses of metallic fuels are expressed in terms of bulk constituent composition, temperature, and/or burnup. However, some models are capable of accounting for local variations in properties and composition. Benchmarking studies such as those contained in the current work will be used to determine whether the code can predict integral fuel performance behaviors with sufficient accuracy, despite its inability to completely resolve all of the structural heterogeneities in the fuel.

II.B. Code Requirements

The technical metallic fuel performance code requirements established for VTR applications and additional features that are desired to extend a code’s functionality are summarized in Table II (Ref. 23). In addition to ensuring that the code can model the required behaviors and calculate the parameters needed to compare to the design criteria, these requirements address other modeling concerns such as simulation dimensionality, spatial and temporal discretization and resolution, and code-to-code coupling capabilities. The minimum requirements are based on satisfying the fuel design criteria and correspond to a code that could be used for trend analysis to inform design decisions. Incorporation of one or more desired features would make the code more useful from a research perspective by enabling it to simulate increasingly more detailed and realistic phenomena.

III. BENCHMARKING PLAN

Benchmarking of a fuel performance code is essential to build confidence in its predictions. A plan was developed to benchmark BISON for VTR driver fuel analyses. The available historical data; criteria applied to select experiments for development into benchmarks; benchmark selections; and plans for benchmark development, usage, and maintenance are discussed in Secs. III.A through III.D.

III.A. Historical Data

Data from historical metallic fuel irradiation experiments are available for development into BISON fuel performance benchmarks. Nominal design and performance parameters from metallic fuel irradiation experiments that involved U-xPu-10Zr (0 ≤ x ≤ 26) fuels, HT-9, D9, and 316SS are summarized in Tables III and IV. The tables were derived from EBR-II, FFTF, and TREAT Facility data compiled by Crawford et al., Chang, and Bauer et al. Nominal fuel lengths for EBR-II and FFTF were taken from the paper by Porter and Tsai. Crawford et al. noted that the peak cladding temperature and peak linear heat generation rate (LHGR) values were estimated for the beginning of life (BOL). A value of 9.38 × 10²⁵ W/m²/kg per GWd/tonne of heavy metal (calculated from approximate atomic mass and fission energy yield values of 238 g/mol and 200 MeV, respectively) was used to convert some of the burnup values.

Some data are missing from Tables III and IV, and the geometries of the fuel pins used in the experiments differ slightly from those listed in Tables III and IV because of variations in fabrication. However, a preliminary search showed that the data in the tables are generally representative of what is available in the open literature. In-depth literature searches constitute a significant part of the effort needed to develop fuel performance benchmarks, so experiments for which the table entries are sparse are unlikely to be good candidates
for rapid benchmark development. However, the data in the tables were deemed sufficient for the purposes of the current work.

Many historical documents refer to the plenum–fuel volume ratio, which is an indicator of the plenum volume available in a fuel design to accommodate FGR and the associated increase in plenum pressure. In practice, the plenum–fuel volume ratio $r_{PFV}$ is calculated using

\[ r_{PFV} = \frac{h_{\text{plenum}}}{h_{\text{fuel}} + h_{\text{sodium}}}, \]  

(1)

where $h_{\text{plenum}}$, $h_{\text{fuel}}$, and $h_{\text{sodium}}$ are the heights of the gas space in the plenum, the fuel, and the bond sodium above the top of the fuel at the BOL, respectively.

Benchmark development is ongoing for experiments X421 and X425, and benchmarks have been completed for experiments X430 (Ref. 28) and IFR-1.
### TABLE III
Nominal Design and Performance Parameters from Past Metallic Fuel Irradiation Experiments*

| Experiment | Fuel | Cladding | Fuel Smeared Density (%) | Plenum–to–Fuel Volume Ratio | Cladding Thickness (cm) | Fuel Length (cm) | Peak LHGR (kW/m) | Peak Cladding Temperature (°C) | Peak Burnup (%) | Peak Fast-Neutron Fluence (10^{22} n·cm^{-2}) |
|------------|------|----------|--------------------------|-----------------------------|------------------------|------------------|----------------|---------------------------------|----------------|-------------------------------------|
| X419       | U-10Zr | D9       | 75                       | 1.0                         | 0.038                  | 0.584            | 34.3           | 39.4                            | 560            | 11.9                                 |
|            | U-8Pu-10Zr |         |                           |                             |                        |                  |                |                                 |                |                                     |
|            | U-19Pu-10Zr |         |                           |                             |                        |                  |                |                                 |                |                                     |
| X420       | U-10Zr | D9       | 75                       | 1.0                         | 0.038                  | 0.584            | 34.3           | 36.1                            | 590            | 18.4                                 |
|            | U-8Pu-10Zr |         |                           |                             |                        |                  |                |                                 |                |                                     |
|            | U-19Pu-10Zr |         |                           |                             |                        |                  |                |                                 |                |                                     |
| X421       | U-10Zr | D9       | 75                       | 1.0                         | 0.038                  | 0.584            | 34.3           | 39.4                            | 560            | 17.1                                 |
|            | U-8Pu-10Zr |         |                           |                             |                        |                  |                |                                 |                |                                     |
|            | U-19Pu-10Zr |         |                           |                             |                        |                  |                |                                 |                |                                     |
| X423       | U-10Zr | 316SS    | 75                       | 1.0                         | 0.038                  | 0.737            | 34.3           | 42.7                            | 522            | 4.9                                  |
|            | U-3Pu-10Zr |         |                           |                             |                        |                  |                |                                 |                |                                     |
|            | U-8Pu-10Zr |         |                           |                             |                        |                  |                |                                 |                |                                     |
|            | U-19Pu-10Zr |         |                           |                             |                        |                  |                |                                 |                |                                     |
|            | U-22Pu-10Zr |         |                           |                             |                        |                  |                |                                 |                |                                     |
|            | U-26Pu-10Zr |         |                           |                             |                        |                  |                |                                 |                |                                     |
| X425       | U-10Zr | HT-9    | 75                       | 1.0                         | 0.038                  | 0.584            | 34.3           | 48.2                            | 590            | 3.0 to 19.3                         |
|            | U-8Pu-10Zr |         |                           |                             |                        |                  |                |                                 |                |                                     |
|            | U-19Pu-10Zr |         |                           |                             |                        |                  |                |                                 |                |                                     |
| X427       | U-10Zr | 316SS    | 75                       | 1.0                         | 0.038                  | 0.440            | 34.3           |                                 | 600            | 7.7 to 14.4                         |
| X429       | U-10Zr | HT-9    | 75                       | 1.0                         | 0.038                  | 0.584            | 34.3           | 42.7                            |                | 11.5                                 |
|            | U-8Pu-10Zr |         |                           |                             |                        |                  |                |                                 |                |                                     |
|            | U-19Pu-10Zr |         |                           |                             |                        |                  |                |                                 |                |                                     |
|            | 316SS |         |                           |                             |                        |                  |                |                                 |                |                                     |
| X430 | U-10Zr | U-19Pu-10Zr | U-22Pu-10Zr | U-26Pu-10Zr | 75 | 1.4 | 0.041 | 0.737 | 34.3 | 49.2 | 540 | 11.5 | 20.6 |
|------|--------|-------------|-------------|-------------|----|-----|-------|-------|------|------|-----|------|------|
| XY24 | U-10Zr | 316SS       | 0.440       | 34.3        | 7.6 |
| XY27 | U-10Zr | 316SS       | 0.440       | 34.3        | 6.6 |
| X397 | U-10Zr | D9          | 1.290       | 34.3        | 2.0 |
| X431 | U-10Zr | D9          | 0.038 to 0.051 | 0.940  | 34.3 | 39.4 | 507 | 3.9 | 15.4 |
| X432 | U-10Zr | D9          | 0.038 to 0.051 | 0.940  | 34.3 | 39.4 | 507 | 4.5 | 16.6 |
| X435 | U-10Zr | D9          | 0.038       | 0.584       | 34.3 | 49.2 | 591 | 19.8 | 22.8 |
| X436 | U-10Zr | D9          | 0.038       | 0.584       | 34.3 | 34.4 | 596 | 8.5  |
| X437 | U-10Zr | D9          | 0.038       | 0.584       | 34.3 | 37.7 | 597 | 10.0 |
| X438 | U-10Zr | D9          | 0.038       | 0.584       | 34.3 | 32.8 | 623 | 9.5  |
| X441 | U-19Pu-10Zr | D9 | 0.038       | 0.584       | 34.3 | 45.9 | 600 | 12.7 | 10.1 |

*References 4, 45, and 46.*
### TABLE IV
Nominal Design and Performance Parameters from Past Metallic Fuel Irradiation Experiments

| Experiment | Fuel  | Cladding | Fuel Smeared Density (%) | Plenum–to–Fuel Volume Ratio | Cladding Thickness (cm) | Cladding Outer Diameter (cm) | Fuel Length (cm) | Peak LHGR (kW/m) | Peak Cladding Temperature (°C) | Peak Burnup (%) | Peak Fast-Neutron Fluence (10\(^{22}\) n-cm\(^{-2}\)) |
|------------|-------|----------|--------------------------|----------------------------|------------------------|-------------------------------|-----------------|----------------|-------------------------------|----------------|---------------------------------|
| X447       | U-10Zr| HT-9     | 75                       | 1.4                        | 0.046                  | 0.584                         | 34.3            | 36.1           | 660                          | 10.0           | 9.2                             |
| X448       | U-10Zr| HT-9     | 75                       | 1.4                        | 0.046                  | 0.584                         | 34.3            | 45.9           | 552                          | 14.6           | 14.9                            |
| X449       | U-10Zr| HT-9     | 75                       | 1.4                        | 0.046                  | 0.584                         | 34.3            | 29.5           | 578                          | 11.3           | 17.7                            |
| X450       | U-10Zr| HT-9     | 75                       | 1.4                        | 0.046                  | 0.584                         | 34.3            | 36.1           | 576                          | 10.2           | 13.1                            |
| X451       | U-10Zr| HT-9     | 75                       | 1.4                        | 0.046                  | 0.584                         | 34.3            | 32.8           | 623                          | 13.7           | 13.7                            |
| X452       | U-10Zr| D9       | 75                       | 1.4                        | 0.038                  | 0.584                         | 34.3            | 34.4           | 596                          | 6.1            | 5.4                             |
| X453       | U-10Zr| D9       | 75                       | 1.4                        | 0.038                  | 0.584                         | 34.3            | 49.2           | 596                          | 8.5            | 8.5                             |
| X454       | U-10Zr| D9       | 75                       | 1.4                        | 0.038                  | 0.584                         | 34.3            | 49.2           | 547                          | 8.3            | 9.1                             |
| X455       | U-10Zr| D9       | 75                       | 1.4                        | 0.038                  | 0.584                         | 34.3            | 49.2           | 547                          | 10.3           | 9.2                             |
| X481       | U-19Pu| D9       | 75                       | 1.4                        | 0.038                  | 0.584                         | 34.3            | 49.2           | 579                          | 10.0           | 11.3                            |
| X482       | U-19Pu| D9       | 75                       | 1.4                        | 0.038                  | 0.584                         | 34.3            | 49.2           | 579                          | 10.0           | 11.3                            |
| X483       | U-10Zr| 316SS    | 75                       | 1.4                        | 0.038                  | 0.584                         | 34.3            | 49.9           | 552                          | 14.8           | 15.7                            |
| X484       | U-10Zr| 316SS    | 75                       | 1.4                        | 0.038                  | 0.584                         | 34.3            | 36.1           | 576                          | 11.7           | 11.9                            |
| X485       | U-10Zr| 316SS    | 75                       | 1.4                        | 0.038                  | 0.584                         | 34.3            | 39.7           | 576                          | 10.5           | 10.7                            |
| X486       | U-10Zr| 316SS    | 75                       | 1.4                        | 0.038                  | 0.584                         | 34.3            | 37.1           | 623                          | 13.9           | 13.9                            |
| X489       | U-19Pu| HT-9     | 75                       | 1.4                        | 0.046                  | 0.584                         | 34.3            | 36.1           | 606                          | 5.4            | 4.8                             |
| X496       | U-10Zr| HT-9     | 75                       | 3.0                        | 0.056                  | 0.686                         | 34.3            | 63.3           | 536                          | 8.3            | 6.9                             |
| X501       | U-10Zr| HT-9     | 75                       | 1.4                        | 0.046                  | 0.584                         | 34.3            | 44.9           | 540                          | 7.6            | 6.4                             |
| X510       | U-10Zr| HT-9     | 75                       | 1.4                        | 0.046                  | 0.584                         | 34.3            | 36.1           | 606                          | 5.4            | 4.8                             |
| X521       | U-10Zr| HT-9     | 75                       | 1.4                        | 0.046                  | 0.584                         | 34.3            | 36.1           | 606                          | 5.4            | 4.8                             |
| IFR-1      | U-10Zr| D9       | 75                       | 1.2                        | 0.056                  | 0.686                         | 91.4            | 49.2           | 604 to 615                    | 8.8\(^a\)       | 15.4                            |
III.B. Benchmark Selection Criteria

Engineering judgment was applied to identify general design and operating parameters that factor into integral metallic fuel pin behavior. These parameters include materials, geometry, operating conditions, and duty cycle (i.e., burnup, fast-neutron fluence, and operational transient conditions). Criteria were then established for the selection of a set of experiments that would envelop the design space defined by the reference VTR driver fuel design. Additional criteria were defined to allow the comparison of predicted and observed failure behaviors, prioritize the selection of experiments for which benchmarks are already available or under development for VTR applications using a consistent modeling approach, and prioritize experiments for which design and PIE data are available in the FIPD (Ref. 29). The criteria are summarized in Table V.

The criteria call for a diverse set of experiments that cover ranges of design parameters and operating conditions. These ranges are included to ensure that BISON models do not deliver unstable or anomalous predictions in the design space around the reference VTR driver fuel design. Although variations in manufacturing tolerances and operating conditions can also contribute to uncertainties in fuel performance predictions, the ranges included in the criteria are more focused on evaluating BISON’s behavioral models and material properties. Therefore, the ranges of parameters represented by the benchmarks may be larger than the variations and tolerances expected with VTR driver fuel fabrication and operation.

Several of the criteria in Table V require further explanation. The reference VTR driver fuel design calls for U-20Pu-10Zr alloy fuel with HT-9 cladding. However, irradiation experiments were conducted with numerous combinations of U-Pu-Zr fuels, HT-9, D9, and 316SS, all of which can be modeled by BISON. Modeling these additional materials increases the robustness of the benchmarking plan and the ability to address alternative material types that might be used as backup options for VTR driver fuel cladding (e.g., advanced austenitic stainless steels). Including additional materials also takes advantage of the overlap between experiments and greatly increases the number of experiments that can be used as benchmarks.

Criterion 2 refers to the cladding pressure-vessel ratio, which is the ratio of cladding mid-radius $r_m$ to
cladding thickness $t_c$. The ratio is used to estimate how much hoop stress can develop in the cladding as a result of internal fission gas pressure, according to the thin-wall pressure vessel approximation

$$\sigma_h = \frac{P r_m}{t_c},$$

where $\sigma_h$ is the hoop stress in the cladding and $P$ is the internal pressure.

Criterion 3 ensures that the selected experiments encompass a range of LHGRs and peak cladding temperatures. Temperature has a strong influence on key behaviors such as thermal creep, fuel melting, and FCCI. Cladding temperatures are good reference points for fuel pin thermal behaviors because they can be estimated from the coolant temperature, coolant flow, and power output. Fuel temperature estimates, on the other hand, must account for uncertainties in porosity development, porosity evolution, and sodium infiltration. One temperature value (the maximum cladding temperature) is expected to be sufficient for selecting experiments for development into benchmarks in this work.

Criterion 4 ensures that the selected experiments cover a range of burnups and irradiation damage conditions. Simulating a range of burnups and comparing predictions to legacy data will exercise BISON’s behavioral models and help confirm that they adequately capture the burnup dependence of metallic fuel irradiation behaviors. Criterion 5 allows for evaluation of BISON’s damage and failure models by selecting experiments with breached fuel pins or fuel pins that exhibited behaviors that otherwise indicate the end of fuel lifetime.

Criterion 6 makes the benchmarking effort more efficient by using benchmarks that have been completed or are under development for VTR applications using a consistent modeling approach. Metallic fuel benchmarks have been developed at ANL for the LIFE-METAL code,$^{16}$ at the Central Research Institute of Electric Power Industry for the ALFUS code,$^{17}$ at INL for the BISON code,$^{47}$ and at other institutions, but the modeling approaches used differ significantly. This lack of consistency makes it difficult to determine whether differences in modeling results are caused by the differences in the fuel pin designs, the experimental conditions, or the models being applied to simulate them. Applying a consistent modeling approach is critical to establishing confidence in VTR driver fuel predictions and quantifying the uncertainties associated with those predictions. Only ORNL benchmarks using BISON are considered in the current work, but benchmarks from other institutions may be incorporated into the benchmarking plan in the future. Finally, Criterion 7 will further enhance consistency and quality by maximizing the use of design and PIE data from the FIPD.

| Number | Category                  | Criterion                                                                 |
|--------|---------------------------|---------------------------------------------------------------------------|
| 1      | Materials                 | Selections shall prioritize experiments with fuel and cladding materials that can be modeled by BISON and are relevant to benchmarking the proposed VTR driver fuel design. |
| 2      | Geometry                  | Selections shall prioritize a set of experiments with a range of smeared densities, plenum–to–fuel volume ratios, cladding thicknesses, fuel diameters, fuel lengths, and cladding pressure-vessel ratios (cladding mid-radius–to–thickness ratios) that are less than, similar to, and greater than those called for in the proposed VTR driver fuel design. |
| 3      | Operating conditions      | Selections shall prioritize a set of experiments with a range of peak LHGRs and peak cladding temperatures that are less than, similar to, and greater than those called for in the proposed VTR driver fuel design. |
| 4      | Duty cycle                | Selections shall prioritize a set of experiments with a range of peak burnups and peak fast-neutron fluences that are less than, similar to, and greater than those called for in the proposed VTR driver fuel design. |
| 5      | Failure behaviors         | Selections shall prioritize a set of experiments that allows for comparison of predicted and observed failure behaviors (or behaviors that otherwise indicate the end of fuel lifetime, such as reaching the maximum allowable cladding strain). |
| 6      | Benchmark availability     | Selections shall prioritize experiments that have already been or are being developed into benchmarks for VTR applications using a consistent modeling approach. |
| 7      | Data availability         | Selections shall prioritize experiments for which design and PIE data are accessible in the FIPD or open literature. |
III.C. Benchmark Selections

A Python script was developed and applied to parse the data from the historical experiments, apply the selection criteria defined in Sec. III.B, and identify high-priority experiments for development into benchmarks. Parameter values related to geometry, operating conditions, duty cycle, and materials are shown in Fig. 1. Values from the metallic fuel irradiation experiments selected as BISON benchmarks are marked with bars. Overlapping bars are used when an experiment involved fuel pins with multiple parameter values. The results show that the selected experiments represent a range of parameters and take advantage of overlap among the materials used in the experiments. Simulating multiple fuel and/or cladding materials within the same

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**Fig. 1.** (a) through (j) Nominal design and performance parameters from the metallic fuel irradiation experiments selected for development into BISON benchmarks. (k) and (l) The fuel and cladding materials used in those experiments. Overlapping bars are used when the experiment included multiple fuel pin designs.
experiment may help reduce uncertainties in operating conditions and material behaviors.

The design and operating parameters considered in this work are assumed to be completely independent. This assumption is not completely realistic, but it is necessary because the metallic fuel irradiation experiments did not test all permutations of parameters. Sensitivity analysis (SA) and uncertainty quantification (UQ) will be conducted in future work to evaluate the fuel pin design space and characterize uncertainties. These studies will be examined alongside benchmark results to identify gaps in the available data and, if necessary, make recommendations for risk mitigation.

As the benchmarking plan is executed, modifications and additions to the plan may be necessary to ensure that the plan provides adequate coverage for (1) transient behaviors; (2) different failure mechanisms, such as those that contribute to cladding breach in the fuel and plenum regions; (3) interrelated design and performance parameters; (4) behaviors associated with fuel and/or fuel pin length; (5) behaviors associated with the location of a pin within a subassembly and the location of a subassembly within the core; and (6) specific fuel and cladding materials.

### III.D. Development, Usage, and Maintenance

The process being applied to develop each BISON benchmark is shown in Fig. 2. Optional steps and components are marked with dashed lines, and those that should fall under a quality assurance program are outlined in gray. The process of developing each benchmark will vary depending on the availability, quality, and source of experimental data; the experimental conditions; the intended use of the benchmark; and more.

In general, benchmark development begins with a literature survey to collect (1) the experiment geometry and operating conditions needed to construct BISON simulations (e.g., fuel dimensions, LHGR, inlet coolant flux, coolant inlet temperature, and material composition) and (2) the PIE data (e.g., axial fuel elongation, radial cladding dilation, and plenum pressure) and other legacy calculations (e.g., average burnup, peak burnup, and fuel pin temperatures) needed to make quantitative comparisons with the simulation results. Experiment geometry and operating conditions are then used to construct a BISON input file. Simulations are then run, and results are compared with the legacy data to evaluate BISON’s ability to accurately model fuel performance in the region(s) of the design space defined by that experiment.

Benchmarks developed for VTR applications should use a consistent modeling approach and model parameters. Doing so helps ensure that differences in BISON predictions for various benchmarks can be attributed to differences in fuel designs and operating conditions—not to the methods being applied by different analysts. Maintenance and quality assurance procedures are needed to ensure that fuel

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**Fig. 2.** The process being applied to develop each BISON benchmark. Optional steps and components are marked with dashed lines, and those that should be controlled under a quality assurance program are outlined in gray.
performance benchmarks satisfy the requirements of the VTR project. A BISON repository with an integrated input file templating system is being established to simplify the application of a consistent modeling approach, to maintain records of BISON versions used, to store benchmarks, to facilitate updating benchmarks when new data become available or the underlying BISON models are changed, and to archive copies of input files used to produce results for publications and key decisions.

Benchmark maintenance and quality assurance procedures are expected to evolve as work on the repository continues, and they will be documented as part of future work. Benchmarking efforts will be thoroughly documented to allow for independent review and future reference. BISON input files could also be committed to the main BISON repository to facilitate software quality maintenance and further code developments. Benchmark results will be evaluated on a case-by-case basis for inclusion in the main BISON repository.

Calibration could be applied to account for uncertainties in behavioral models and material properties, potentially improving agreement between the predicted and the observed results. However, it is important that model parameters not be calibrated to improve the results of one benchmark at the expense of others, or in a way that results in different physics being applied to different experiments or fuel pins within an experiment. Some amount of error in model predictions is expected; however, although calibrating BISON for individual experiments and fuel pins may appear to improve its performance, there is no way to determine which set of calibration parameters should be used to simulate VTR driver fuel performance. If calibration is used, the best approach to maximizing the accuracy and reliability of VTR driver fuel simulations is to conduct calibrations with the goal of improving the overall accuracy of a large set of diverse benchmarks. Also, SA and UQ studies may be conducted to provide input for separate effects tests, manufacturing process refinements, and design and safety decisions.

IV. CURATED BENCHMARK SET

Benchmarks have been completed for the X430 and IFR-1 experiments using a consistent modeling approach. In this work, these benchmarks are referred to as “curated” because the data used in their development have been thoroughly reviewed for use in VTR applications. The experiments, the modeling approach used to develop the benchmarks, and selected benchmark results are presented in Secs. IV.A, IV.B, and IV.C.

IV.A. Experiment Descriptions

The X430 experiment was conducted to test the performance of wide-diameter fuel pins and was documented in a publicly available report by Hayes et al.26 The experimental subassembly contained a hexagonal array of 37 wide-diameter pins. The pins included U-10Zr, U-19Pu-10Zr, U-22Pu-10Zr, and U-26Pu-10Zr fuels, and all were clad in HT-9. After selected bumup increments, the subassembly was dismantled for nondestructive PIE. Some of the pins were removed for destructive examination and replaced, other pins were repositioned in the subassembly, and the subassembly was reconstituted for the next experiment. In total, 52 pins were irradiated. X430 was irradiated in EBR-II between 1987 and 1992 to a peak bumup of 12%. Initially, two pin-specific simulations were developed; but subsequent work has expanded the benchmark case to include every pin for which PIE data could be located, for a total of 25 pins.28

Documentation of the IFR-1 experiment can be found in the literature.46,48,49 It was one of only seven test assemblies containing “full-length” fuel pins irradiated as part of the IFR program. The IFR-1 fuel pins were similar in size to those intended for deployment in fast reactors. The EBR-II subassemblies contained a smaller number of shorter fuel pins. Of the seven full-length subassemblies irradiated in FFTF, IFR-1 was the only one to contain U-19Pu-10Zr. The purpose of the experiment was to validate data from the shorter EBR-II subassemblies used for the majority of the IFR program with a full-length subassembly, ensuring that there were no unanticipated dimensional effects.

Between September 1986 and October 1988, IFR-1 was irradiated to a target bumup of 10% in FFTF. Of the 169 pins used, 18 were U-19Pu-10Zr, 19 were U-8Pu-10Zr, and the remainder were U-10Zr. All the pins were clad in D9 and included depleted U-10Zr blankets. PIE included a wide range of measurements from a considerable number of fuel pins, but no single pin was subjected to a full set of PIE measurements. Benchmark development for the IFR-1 experiment began in 2019 (Refs. 24 and 27). Because of the large number of pins, complete simulations were not developed for all 169 pins. Rather, a representative U-19Pu-10Zr pin was simulated and compared against all the PIE data from the U-19Pu-10Zr pins. The benchmark was recently expanded to include representative U-8Pu-10Zr and U-10Zr pins.

IV.B. Modeling Approach

After a critical assessment of the metallic fuel performance models available in BISON was performed,22
a metallic fuel modeling approach was devised for use in all VTR applications. A thorough review of the established BISON capabilities used in this work is beyond the scope of this text, but a brief overview of its governing equations and key behavioral models is provided below. Readers are encouraged to refer to the comprehensive BISON documentation distributed by INL online for detailed descriptions of the BISON objects discussed in this work and references to the underlying works from which each was derived. BISON solves two coupled partial differential equations to model conservation of energy and conservation of momentum in a fuel pin. The heat transport equation, Eq. (3), governs conservation of energy and is used to calculate the temperature $T$ throughout the fuel pin:

$$\rho c_p \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) - e_f \dot{F} = 0,$$  \hspace{1cm} (3)

where

$T =$ temperature  
$\rho =$ density  
$c_p =$ specific heat capacity  
$t =$ time  
$k =$ thermal conductivity  
$e_f =$ energy per fission  
$\dot{F} =$ fission rate density.

The physics described by the heat transport equation are implemented in the HeatConductionTimeDerivative, HeatConduction, and FissionRateHeatSource BISON objects.

Cauchy’s equation, Eq. (4), governs conservation of momentum and is used to calculate fuel pin displacements:

$$\nabla \cdot \sigma + \rho f = 0,$$  \hspace{1cm} (4)

where

$\sigma =$ Cauchy stress tensor  
$f =$ body force per unit mass; in this case, the body force is gravity.

The physics described by Cauchy’s equation are provided by the TensorMechanicsMasterAction and Gravity BISON objects. The TensorMechanicsMasterAction relates the stress tensor to fuel pin displacements using strain tensors that account for thermal expansion, elasticity, swelling, and creep.

Burnup $\beta$ is calculated by the UPuZrBurnup BISON object using Eq. (5):

$$\beta(t + \Delta t) = \beta(t) + \frac{[\dot{F}(t) + \dot{F}(t + \Delta t)] \Delta t}{2N_f^0},$$  \hspace{1cm} (5)

where

$\Delta t =$ length of a time step  
$N_f^0 =$ initial density of heavy metal atoms in the fuel.

The fission rate density $\dot{F}$, which also appears in Eq. (3), is calculated from a prescribed LHGR using the UPuZrFissionRate BISON object. UPuZrBurnup, UPuZrFissionRate, and the other BISON objects needed to model the physical behaviors and material properties introduced in Eqs. (3), (4), and (5) are summarized below.

The physical behaviors and material properties included in the modeling approach are summarized in Table VI along with the names of the BISON objects being used. Readers are encouraged to refer to the BISON documentation for a complete description of each object, including background information, governing equations, default parameter values, and references to underlying models and data. Additional background information and discussion can be found in assessment reports released by INL (Ref. 51) and ORNL (Ref. 22). Instances when the selected modeling approach deviates from BISON’s default behaviors and parameter values are discussed in the paragraphs that follow. Operational data were used to define the average LHGRs and axial power profiles needed to model heat generation and calculate burnup. Inlet coolant fluxes and coolant inlet temperatures were used to define boundary conditions at the outer surface of the cladding. All simulations in this work were conducted using a two-dimensional (2-D) axisymmetric coordinate system with an adaptive time stepping scheme.

The BISON objects used to model gaseous swelling and porosity evolution in the fuel do not account for compressive stress in the material that would contribute to hot pressing. An empirical hot pressing approximation was implemented using generic functions in the input file to overcome this limitation. The approximation is applied in conjunction with UPuZrGaseousEigenstrain to model fuel deformation due to the combined effects of gaseous swelling and the compressive stresses that result from its mechanical interaction with the cladding. The approximation assumes that after porosity interconnection and FGR, solid fuel swelling is accommodated by porosity closure. Porosity closure is assumed to continue until some minimum porosity, interconnection_porosity_min, is reached.
TABLE VI
Summary of the Physical Behaviors and Material Properties Included in the Metallic Fuel Performance Simulations and the BISON Object(s) Used for Each

| Physical Behavior or Material Property                                      | BISON Object(s)                                                                 |
|----------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| Conservation of energy                                                    | HeatConductionTimeDerivative, HeatConduction, FissionRateHeatSource             |
| Conservation of momentum                                                  | TensorMechanicsMasterAction, Gravity                                            |
| Fuel-cladding mechanical contact                                           | Frictionless                                                                   |
| Fuel-cladding thermal contact                                              | GapHeatTransfer                                                                |
| Convective heat transfer at cladding surface                               | CoolantChannel                                                                 |
| Fuel fission rate                                                          | UPuZrFissionRate                                                              |
| Fuel burnup                                                                | UPuZrBurnup                                                                    |
| Fuel and cladding density                                                  | Density                                                                        |
| Fuel sodium infiltration                                                  | UPuZrSodiumLogging                                                            |
| Fuel thermal conductivity and specific heat capacity                       | UPuZrThermal (LANL and Savage correlations)                                     |
| Fuel elasticity tensor                                                    | UPuZrElasticityTensor                                                         |
| Fuel creep                                                                | UPuZrCreepUpdate                                                              |
| Fuel gaseous swelling                                                      | UPrZrGaseousEigenstrain                                                       |
| Fuel solid swelling                                                        | BurnupDependentEigenstrain                                                    |
| Fuel FGR                     Fast-neutron flux                             | UPuZrFissionGasRelease                                                        |
| Fuel thermal expansion                                                    | UPuZrThermalExpansionEigenstrain                                              |
| Cladding thermal conductivity and specific heat capacity                   | UPuZrFastNeutronFlux                                                          |
| Cladding swelling                                                         | ThermalX (X = HT9, D9, 316)                                                    |
| Cladding swelling                                                         | XVolumetricSwellingEigenstrain (X = HT9, D9, 316SS)                           |
| Cladding thermal expansion                                                | XThermalExpansionEigenstrain (X = HT9, D9, 316SS)                             |
| Cladding elasticity tensor                                                | XElasticityTensor (X = HT9, D9, 316SS)                                        |
| Cladding creep                                                            | XCReepUpdate (X = HT9, D9, 316SS)                                             |

*References 22, 50, and 51.

Values for interconnection_porosity_min were manually estimated so that it would be reached at 8% to 10% burnup for both binary and ternary fuels. After that, fuel porosity is held constant, and additional solid fuel swelling contributes to increases in fuel volume. The overall trends in fuel volume changes predicted by this empirical approximation are consistent with experimental observations.35

The approximation cannot be generalized to drastically different metallic fuel pin designs because it does not mechanistically capture the physical processes that contribute to gaseous swelling and hot pressing. However, researchers at other institutions are working to implement gaseous swelling models into BISON that account for hot pressing effects by modeling viscoplasticity. Those models will be assessed for possible incorporation into benchmarks and VTR driver fuel analyses as soon as they are available.

The model parameters used in these BISON objects and the hot pressing approximation are summarized in Table VII. References to the literature containing the values or the information from which the values were calculated are provided. In some cases, different values are used for binary and ternary fuels to account for their different swelling and FGR behaviors. The porosities used in the fuel gaseous swelling models were manually estimated to deliver volume changes consistent with the average values observed in binary and ternary X430 fuels. More precise estimates will be made in the future using fuel swelling measurements from fuel in multiple experiments reflecting a range of fuel compositions.

IV.C. Simulation Results

Integral results from the 25 X430 and 3 IFR-1 benchmarks performed in BISON are compared with results from legacy calculations and PIE data in Fig. 3 (Refs. 24, 27, 28, 36, 46, 48, and 49). For X430, simulations were performed for each pin and then compared directly with legacy values for that pin. For IFR-1, simulations were performed for only three pins, each with a different fuel composition, and then compared with all legacy values available for IFR-1 pins with the same fuel composition. Therefore, the IFR-1 comparisons may not fully capture pin-to-pin variations in power, burnup, and temperature. The transparencies of the
data points in the plots in Fig. 3 were adjusted to more clearly illustrate where they overlap, and the number of points in each comparison varies owing to the limited availability of legacy data. The average absolute error $\bar{\xi}_{abs}$ and average relative error $\bar{\xi}_{rel}$ were calculated to estimate the quality of fit for each result.

Average and peak burnup comparisons are shown in Figs. 3a and 3b, respectively. BISON slightly overpredicts the burnups of X430 pins and underpredicts the burnups of IFR-1 pins. Both comparisons have $\bar{\xi}_{abs}$ values of about 0.3%. This is a satisfactory level of agreement given that studies conducted to validate the SE2-ANL thermal-hydraulic code estimated that the uncertainties associated with subassembly powers in EBR-II were about 10% (Ref. 21). Coolant outlet, cladding, and fuel temperatures are shown in Figs. 3c, 3d, and 3e. BISON underpredicts the temperatures of X430 pins and overpredicts the temperatures of IFR-1 pins. The $\bar{\xi}_{abs}$ values are about 30 K for all three metrics. This is comparable to the results of a previous study conducted to validate SE2-ANL coolant temperature predictions against subassemblies instrumented with dummy pins, which identified root-mean-squared and maximum deviations of 8 and 20 K, respectively. 21 The value 30 K corresponds to $\bar{\xi}_{rel}$ values of 3% to 4%, which is comparable to the relative accuracy of the burnup predictions.

Peak radial cladding dilation and axial fuel elongation comparisons are shown in Figs. 3f and 3g, respectively. BISON underpredicts the radial cladding dilations of X430 pins, all of which used HT-9, and overpredicts the radial cladding dilations of IFR-1 pins, all of which used D9. Additional benchmarks are needed to determine whether these trends are correlated more strongly with the experiments or the cladding materials.

BISON overpredicts axial fuel elongation for almost all the X430 and IFR-1 pins. Overall, the X430 and IFR-1 mechanics predictions are less accurate than the temperature predictions. The two distinct groups of axial fuel elongation results from X430 include pins with 0 and $\geq 19\text{ wt}\%$ plutonium. The orientations of these groups confirm that plutonium composition should be considered when modeling fuel swelling. There are three less-distinct groups of axial fuel elongation results from IFR-1. These groups include pins with 0, 8, and 19 wt% plutonium. BISON predicts that pins with 8 and 19 wt% plutonium elongate by the same amount, which is consistent with the modeling approach being applied but inconsistent with experimental observations. Axial fuel elongation predictions are much more accurate for pins with 0 and 19 wt% plutonium than for those with 8 wt% plutonium. This finding suggests that
accuracy could be improved by correlating swelling to plutonium content, and its effect on phase stability in the fuel, rather than using only two sets of parameters for binary and ternary fuels. A similar set of benchmarks conducted without the hot pressing approximation yielded $\epsilon_{\text{abs}}$ and $\epsilon_{\text{rel}}$ values of 11.89% and 407%. Comparison with the values shown in Fig. 3g shows that use of the hot pressing approximation drastically improves accuracy.

Finally, FGR and plenum pressure comparisons are shown in Figs. 3h and 3i, respectively. There are fewer legacy values with which to make these comparisons, and as a result, the comparisons cannot be easily correlated to the experiments or any of the features of the fuel pin designs. BISON overpredicts plenum pressure, more so as plenum pressure increases. Although less accurate than desired, these results are useful for conservative estimates of allowable fuel lifetime because they conservatively overpredict cladding stress.

More detailed time-dependent results from three X430 pins simulated in BISON are compared with results from legacy calculations and PIE data for those pins in Fig. 4 (Refs. 28 and 36). The initial X430 and the X430A and X430B reconstitutions are shaded and labeled for reference. Pins T651 and T654 were included throughout, but Pin T684 was included only in the X430A and X430B reconstitutions. For each parameter with PIE data available, the agreement between the predicted and the legacy results is similar in magnitude to that shown in Fig. 3. The axial fuel elongation predictions in Fig. 4j for Pins T651 and T654 illustrate the swelling behaviors obtained from the hot pressing approximation. The fuels elongate until FGR occurs at about 1% burnup, remain

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Fig. 3. Results from the X430 (U-10Zr, U-19Pu-10Zr, U-22Pu-10Zr, and U-26Pu-10Zr fuels clad in HT-9) and IFR-1 (U-10Zr, U-8Pu-10Zr, and U-19Pu-10Zr fuels clad in D9) benchmarks performed in BISON compared with results from legacy calculations and PIE data. For X430, simulations were performed for each pin and then compared directly with legacy values for that pin. For IFR-1, simulations were performed for only three pins, each with a different fuel composition, and then compared with all legacy values available for IFR-1 pins with the same fuel composition.
essentially constant until 8% to 10% burnup, and then elongate thereafter.

More detailed time-dependent results from three IFR-1 pins simulated in BISON are compared with results from legacy calculations and PIE data for all pins that had the same fuel composition in Fig. 5 (Refs. 24, 27, 46, 48, and 49). The periods of time corresponding to FFTF operating cycles 9A, 9B, 9C, 10A1, 10A2, and 10B are shaded and labeled for reference. The three simulated pins were included in IFR-1 through all six cycles.

Fig. 4. Results from simulations of three X430 pins in BISON compared with results from legacy calculations and PIE data for those pins. The X430, X430A, and X430B subassemblies are shaded and labeled for reference. Pins T651 and T654 were included in all three subassemblies, but Pin T684 was included in the X430A and X430B reconstructions only.
Agreement between the predicted and the legacy results for IFR-1 is generally less than was observed for X430. This lower extent of agreement can be partly attributed to the simulation of one pin for each fuel composition instead of 169 individual pins.

V. EXTENDED BENCHMARK SET

An extended set of benchmarks was developed using data from the FIPD (Ref. 29). These benchmarks include the X419, X421, X447, X483, and X486 experiments conducted at EBR-II. These experiments were selected...
Numerical values and gridlines were intentionally omitted because the preliminary results are still under review. As before, the average relative error $\overline{\varepsilon}_{rel}$ was calculated to estimate the quality of fit for each result. Six of the comparisons made for the curated benchmark set are not calculated for the extended benchmark set because the legacy data needed to do so either are not available in the FIPD or are not stored in a way that facilitates automated analysis at this time. These parameters include average burnup, peak burnup, coolant outlet temperature, cladding temperature, fuel temperature, and FGR.

Peak radial cladding dilation results are shown in Fig. 6a with a $\overline{\varepsilon}_{rel}$ value of 44%. This value represents an improvement over the value obtained for the curated benchmark set (54%), but increased accuracy is desired. Improved accuracy over the curated set is promising, considering that the extended set includes fuel pins with all three cladding types. A similar trend is observed in the axial fuel elongation results shown in Fig. 6b, with a $\overline{\varepsilon}_{rel}$ value of 46%. This value again represents an improvement over that obtained for the curated benchmark set (119%). Without the hot pressing approximation, the extended benchmark set yields a $\overline{\varepsilon}_{rel}$ value of 69%. As was the case with the curated benchmark set, this result supports the use of the hot pressing approximation.

Finally, plenum pressure results are shown in Fig. 6c. As was observed for the curated benchmark set, the predicted plenum pressures are generally greater than the measured values, and the overprediction increases as the plenum pressure increases. The $\overline{\varepsilon}_{rel}$ values shown in Fig. 6 indicate poorer agreement for the extended benchmark set (36%) than for the curated benchmarks.
benchmark set (27%). Figure 6c shows that the predicted plenum pressures for the X421 pins are significantly less accurate than those obtained for the other four experiments in the extended set. The overall trends may be influenced by differences in the number of PIE data available for each benchmark set. The extended set also includes fuel pins that were irradiated to much higher burnups. Investigations focused on these observations are suggested for future work. Once completed, the benchmarks in the extended set will be combined with those in the curated set to thoroughly characterize the overall accuracy of the predictions.

More detailed time-dependent results from three X421 pins simulated in BISON are compared with results from PIE data in Fig. 7 (Ref. 29). As before, some values and gridlines were intentionally omitted from these preliminary results. The X421 subassembly and the X421A reconstitution are shaded and labeled for reference. All three pins were included in both subassemblies. Compared with the lower burnup results presented in Fig. 4j, the simulation results shown in Fig. 7g more clearly illustrate the expected increases in axial fuel elongation after about 10% burnup. These trends are in good agreement with those observed in the PIE measurements in Fig. 7g. All the results except for average burnup, peak burnup, and FGR (Figs. 7a, 7b, and 7h, respectively) exhibit vertical fluctuations. These features result from fluctuations in power and coolant flow captured by the high-fidelity FIPD data. Unfortunately, it is often impractical to include this level of detail in manually developed simulations such as those in the curated benchmark set.

![Fig. 7. Results from three X421 pins simulated in BISON compared with PIE data for those pins.](Ref. 29) Some values and gridlines were intentionally omitted from these preliminary results. Subassembly X421 and the reconstituted X421A are shaded and labeled for reference.
VI. DISCUSSION

In Secs. IV and V, BISON predictions were compared with legacy calculations and PIE data for 261 fuel pins. These included 28 pins from EBR-II experiment X430 and FFTF experiment IFR-1, which make up the curated benchmark set, and 233 pins from EBR-II experiments X419, X421, X447, X483, and X486, which make up the extended benchmark set. All simulations were conducted using the same modeling approach that is being applied to model VTR driver fuel. Analysis of a large, diverse set of fuel pin designs using a consistent modeling approach allows for meaningful evaluation of BISON’s accuracy over a broad design space, providing a better understanding of and increasing confidence in its VTR driver fuel predictions.

Comparisons with legacy burnup and temperature calculations were made only for the curated benchmark set at this time. BISON’s burnup and temperature predictions were generally accurate. Its coolant outlet, cladding, and fuel temperature predictions were off by an average of about 30 K. BISON generally underpredicted X430 temperatures and overpredicted IFR-1 temperatures. Collecting additional legacy temperature calculations and analyzing them more closely may help identify the source of these biases and improve the accuracy of temperature predictions.

BISON’s radial cladding dilation and axial fuel elongation predictions were less accurate than its burnup and temperature predictions. It is unclear whether errors in the radial cladding dilation predictions were related to the cladding type, fuel type, operating conditions, model form, or some combination thereof. It is likely that the frictionless contact formulation selected for the modeling approach does not adequately represent the physics of fuel-cladding contact in these systems. However, preliminary studies conducted early in the benchmark development process showed that use of a frictional contact formulation did not significantly improve accuracy. This topic may be revisited in future work.

The poorest agreement between the predictions and the legacy results was observed for axial fuel elongation. BISON overpredicted axial fuel elongation more for the curated benchmark set than for the extended benchmark set, but the results for the two sets exhibited comparable amounts of scatter. The results suggest that accuracy could be improved by refining how fuel plutonium content and its influence on phase stability is accounted for by the fuel swelling model. Future work could investigate this possibility and assess the hot pressing models currently under development for BISON.

BISON generally overpredicted plenum pressure predictions, more so as plenum pressure increased. This trend is helpful for conservative prediction of fuel lifetime because it delivers conservative cladding stress results, but better accuracy is desired. Further model refinements, such as incorporation of a nonideal gas model, are suggested for future work.

Time-dependent results for nine fuel pins were also presented in Secs. IV and V. The trends shown in the results were generally consistent with experimental observations. The high fidelity of the operational power and flow data in the FIPD produced significant fluctuations in the temperature, deformation, and plenum pressure predictions of the extended benchmark set. The use of high-fidelity data like these may have significant benefits if combined with mechanistic fuel performance models capable of accounting for the evolution of fuel pin materials and their microstructures over time.

VII. CONCLUSIONS AND FUTURE WORK

The DOE Office of Nuclear Energy VTR project is designing a new fast-spectrum test reactor, which will provide the experimental capabilities necessary to test advanced nuclear reactor fuel and coolant concepts with the high fast-neutron flux needed to study long-term radiation damage. The BISON fuel performance code is being used to assess the expected behavior of the VTR driver fuel and indicate the margin to fuel failure. This work has summarized ongoing efforts to benchmark BISON for VTR driver fuel analyses.

The metallic fuel performance code requirements for VTR applications and the plan developed to benchmark BISON for VTR driver fuel analyses were reviewed. Next, the modeling approach being applied to model historical metallic fuel irradiation experiments and VTR driver fuel was examined. Integral fuel pin predictions were compared with legacy calculations and PIE data for 28 pins from curated benchmarks derived from data for two experiments and 233 pins from extended benchmarks derived from data for five experiments. Time-dependent predictions were also examined for nine fuel pins to inspect fuel performance trends.

Analysis of a large, diverse set of fuel pin designs using a consistent modeling approach will ultimately allow for meaningful evaluation of BISON’s accuracy over a broad design space, increasing confidence in its VTR driver fuel predictions. Future work that would support this goal includes (1) developing new benchmarks, refining existing benchmarks, and revising the benchmarking plan; (2) developing benchmarks that target specific fuel pin phenomena such as transient behaviors; (3) calibrating models; (4) applying SA and UQ to characterize model performance, identify the most impactful material properties and physical...
behaviors, and quantify uncertainties; (5) implementing additional quality assurance measures; and (6) improving swelling and creep models and mechanics predictions through incorporation of hot pressing models for the fuel, different contact formulations, and so on.

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Disclosure Statement

No potential conflict of interest was reported by the author(s).

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