Standalone BISON Fuel Performance Results for Watts Bar Unit 1, Cycles 1-3

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REVISION LOG

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EXECUTIVE SUMMARY

The Consortium for Advanced Simulation of Light Water Reactors (CASL) is moving forward with more complex multiphysics simulations and increased focus on incorporating fuel performance analysis methods. The coupled neutronics/thermal-hydraulics capabilities within the Virtual Environment for Reactor Applications Core Simulator (VERA-CS) have become relatively stable, and major advances have been made in analysis efforts, including the simulation of twelve cycles of Watts Bar Nuclear Unit 1 (WBN1) operation. While this is a major achievement, the VERA-CS approaches for treating fuel pin heat transfer have well-known limitations that could be eliminated through better integration with the BISON fuel performance code.

Several approaches are being implemented to consider fuel performance, including a more direct multiway coupling with Tiamat, as well as a more loosely coupled one-way approach with standalone BISON cases. Fuel performance typically undergoes an independent analysis using a standalone fuel performance code with manually specified input defined from an independent core simulator solution or set of assumptions.

This milestone covers efforts to facilitate the use of VERA for core simulation and fuel performance to operate in this standalone mode of execution by using power distribution and moderator temperature data from VERA-CS. This approach can be used for several CASL fuel performance applications:

1) as a screening tool for the pellet-clad interaction (PCI) challenge problem to identify rods that require further analysis,

2) to analyze reactivity insertion accidents (RIAs) and departures from nucleate boiling (DNBs) which require time-dependent full core results to establish the boundary conditions for the high-fidelity BISON simulations, and

3) to improve fuel temperature models in VERA-CS by providing higher fidelity comparisons of core-wise temperature distributions.

4) as a high fidelity fuel performance methodology (using explicit rather than bounding core operating conditions) to evaluate and screen fuel and core design concepts for a comprehensive set of design criteria including pin powers, PCI, pin burnups, corrosion, oxidation, margin to fuel melt, and rod internal pressure.

This report summarizes the improvements made since the initial milestone to execute BISON from VERA-CS output. Many of these improvements were prompted through tighter collaboration with the BISON development team at Idaho National Laboratory (INL). A brief description of WBN1 and some of the VERA-CS data used to simulate it are presented. Data from a small mesh sensitivity study are shown, which helps justify the mesh parameters used in this work. The multi-cycle results are presented, followed by the results for the first three cycles of WBN1 operation, particularly the parameters of interest to PCI screening (fuel-clad gap closure, maximum centerline fuel temperature, maximum/minimum clad hoop stress, and cumulative damage index). Once the mechanics of this capability are functioning, future work will target cycles with known or suspected PCI failures to determine how well they can be estimated.
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A.2.1. Maximum Centerline Fuel Temperature

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<td>ANS</td>
<td>American Nuclear Society</td>
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<tr>
<td>BOC</td>
<td>beginning of cycle</td>
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<tr>
<td>CASL</td>
<td>Consortium for Advanced Simulation of Light Water Reactors</td>
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</tr>
<tr>
<td>CIPS</td>
<td>crud-induced power shift</td>
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<tr>
<td>CMFD</td>
<td>coarse mesh finite difference</td>
<td></td>
</tr>
<tr>
<td>COBRA</td>
<td>Coolant Boiling in Rod Arrays</td>
<td></td>
</tr>
<tr>
<td>CS</td>
<td>core simulator</td>
<td></td>
</tr>
<tr>
<td>CSV</td>
<td>comma separated value</td>
<td></td>
</tr>
<tr>
<td>CTF</td>
<td>COBRA two-phase flow</td>
<td></td>
</tr>
<tr>
<td>DNB</td>
<td>departure from nucleate boiling</td>
<td></td>
</tr>
<tr>
<td>DOE</td>
<td>US Department of Energy</td>
<td></td>
</tr>
<tr>
<td>EFPD</td>
<td>effective full power day</td>
<td></td>
</tr>
<tr>
<td>GWd/MT</td>
<td>gigawatt day per metric ton</td>
<td></td>
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<tr>
<td>HDF</td>
<td>hierarchical data format</td>
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<tr>
<td>IFBA</td>
<td>integral fuel burnable absorber</td>
<td></td>
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<tr>
<td>INF</td>
<td>infrastructure</td>
<td></td>
</tr>
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<td>INL</td>
<td>Idaho National Laboratory</td>
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<tr>
<td>JFNK</td>
<td>Jacobian Free Newton-Krylov</td>
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<td>LWR</td>
<td>light water reactor</td>
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<tr>
<td>MOC</td>
<td>Method of Characteristics</td>
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<tr>
<td>MOOSE</td>
<td>Multiphysics Object Oriented Simulation Environment</td>
<td></td>
</tr>
<tr>
<td>MW</td>
<td>megawatt</td>
<td></td>
</tr>
<tr>
<td>MWth</td>
<td>megawatt thermal</td>
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</tr>
<tr>
<td>NE</td>
<td>Office of Nuclear Energy</td>
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<tr>
<td>NEM</td>
<td>nodal expansion method</td>
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<td>ORNL</td>
<td>Oak Ridge National Laboratory</td>
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<tr>
<td>PCI</td>
<td>pellet-clad interaction</td>
<td></td>
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<tr>
<td>PETSc</td>
<td>Portable, Extensible Toolkit for Scientific Computation</td>
<td></td>
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<td>PWR</td>
<td>pressurized water reactor</td>
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<tr>
<td>RIA</td>
<td>reactivity-insertion accident</td>
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<tr>
<td>SP3</td>
<td>simplified P3</td>
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<tr>
<td>TH</td>
<td>thermal hydraulics</td>
<td></td>
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<tr>
<td>TPL</td>
<td>third party library</td>
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</tr>
<tr>
<td>TVA</td>
<td>Tennessee Valley Authority</td>
<td></td>
</tr>
<tr>
<td>UM</td>
<td>University of Michigan</td>
<td></td>
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<tr>
<td>VERA</td>
<td>Virtual Environment for Reactor Applications</td>
<td></td>
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<tr>
<td>WABA</td>
<td>wet annular burnable absorber</td>
<td></td>
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<tr>
<td>WBN1</td>
<td>Watts Bar Nuclear Unit 1</td>
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1. INTRODUCTION

1.1 Motivation
The Consortium for Advanced Simulation of Light Water Reactors (CASL) is moving forward with more complex multiphysics simulations, and there is increased focus on incorporating fuel performance analysis methods into the Virtual Environment for Reactor Applications Core Simulator (VERA-CS). The coupled neutronics/thermal-hydraulics (TH) capabilities within VERA-CS are relatively stable, and major advances have been made in analysis efforts, including the simulations of twelve cycles of Watts Bar Nuclear Unit 1 (WBN1) operation [1]. Several approaches are being implemented to consider fuel performance, including a more direct multiway coupling with Tiamat [2,3,4], as well as a more loosely coupled one-way approach with standalone BISON cases.

This milestone focuses on generating and executing BISON fuel performance cases using output power and temperature distributions produced by coupled neutronics/TH simulations with VERA-CS. While work is underway to develop Tiamat, the primary motivation for this approach is to provide quicker results without the need to rerun previous calculations. For example, output from the twelve cycles of WBN1 simulated with MPACT and CTF within VERA-CS [5] could be used as a basis for independent BISON cases to assess parameters of pellet-clad interaction or accuracy of global fuel temperature distributions. Additionally, the results can provide insights for evaluating a number of fuel and core design concepts such as corrosion, oxidation, margin to fuel melt, and rod internal pressure. However, it should be noted that the VERA-CS simulations producing the temperature and power distribution yield a different fuel temperature because it is using a simpler fuel temperature table produced by BISON.

1.2 VERA-CS Description
The VERA simulation environment being developed by CASL is comprised of codes collectively used for nuclear reactor modeling and simulation. This work uses the MPACT neutron transport solver, the CTF TH solver, and the BISON fuel performance code, all briefly described below. Figure 1.2.1 shows the components of VERA. At this writing, the components that make up the core simulator (VERA-CS) are the neutronics, TH, and fuel performance packages.
1.2.1 MPACT
The MPACT neutron transport solver, being developed collaboratively by Oak Ridge National Laboratory (ORNL) and the University of Michigan (UM), provides pin-resolved flux and power distributions [6]. To solve three-dimensional (3D) problems, it employs the 2D/1D method, which decomposes the problem into a 1D axial stack of 2D radial planes [7]. Typically, 2D Method of Characteristics (2D MOC) is used to solve each radial plane, and 1D nodal methods are used to solve axially along each rod. While there are a variety of axial solvers available, the nodal expansion method (NEM)-simplified P₃ (SP₃) solver is the default, which wraps a one-node NEM kernel [8]. These 2D and 1D solvers are coupled together through transverse leakage terms to ensure neutron conservation, and they are accelerated using 3D coarse mesh finite difference (CMFD).

1.2.2 CTF
CTF is a subchannel TH code being developed by ORNL and Pennsylvania State University (PSU) specifically for light water reactor (LWR) analysis [10]. It simulates two-phase flow with a three-field representation—liquid, droplet, and vapor—assuming that the liquid and droplet fields are in dynamic equilibrium, leaving two energy conservation equations.

CTF provides significantly higher resolution than internal thermal hydraulics solver (Simplified TH) in MPACT, but it is currently more limited in parallelization. Ongoing work is focused on increasing parallelization from the assembly level to the subchannel level, significantly alleviating runtime concerns for cases presented in this work.

1.2.3 BISON
The BISON fuel performance code is being developed by Idaho National Laboratory (INL) to provide single-rod fuel performance modeling capability so that users can assess best-estimate values of design and safety criteria and the impact of plant operation and fuel rod design on thermo-mechanical behavior such as pellet-cladding interaction (PCI) failures in pressurized water reactors (PWRs) [11,12]. PCI is controlled by the complex relationship between the mechanical, thermal, and
chemical behaviors of a fuel rod during operation. Consequently, modeling PCI requires an integral fuel performance code to simulate the fundamental processes of these behaviors. BISON is built on INL’s Multiphysics Object Oriented Simulation Environment (MOOSE) package [13,14], which use the finite element method for geometric representation and a Jacobian Free Newton-Krylov (JFNK) scheme to solve systems of partial differential equations [13]. For this work, BISON uses a 2D azimuthally symmetric (R-Z), smeared-pellet thermomechanical fuel pin model with output data from VERA-CS to generate the time-dependent power shape/history and moderator temperature inputs needed for BISON.

1.3 Milestone Objectives
There are a number of primary objectives in this milestone, several of which build upon work from the initial milestone [15]:

1) extend XML2MOOSE to accommodate fuel shuffling in quarter symmetry cases as quarter symmetry assumptions were used in both this work and the VERA-CS simulations;
2) develop a post-processor to collect the results from the individual BISON cases and consolidate them onto the VERAOut hierarchical data format (HDF) 5 file, particularly for use in VERAView;
3) consider the establishment of a driver program that will simplify usage by preprocessing, running, and gathering output all in one overarching executable;
4) determine an appropriate model for simulating integral fuel burnable absorber (IFBA) rods in BISON;
5) run several cycles of WBN1 using the VERA-CS output data available from Reference 1; and
6) assess temperatures, stresses, and other important parameters of interest to PCI screening.

With two additional stretch goals:
1) compare results to FRAPCON results obtained by Ryan Bratton [16], a student at Pennsylvania State University working remotely from ORNL, who obtained these results as part of his thesis work; and
2) perform a mesh sensitivity study to assess appropriate refinement level.

1.4 Acknowledgements
The authors wish to acknowledge the BISON development team for their continued support, as well as the CASL Infrastructure (INF) team, particularly Mark Baird and Ross Bartlett, for updating PETSc and MOOSE very quickly.

Many thanks are also due to Ron Lee for his expedient modifications to VERAView to allow for the new data structures being introduced with this work.

This work was supported by the Consortium for Advanced Simulation of Light Water Reactors (www.casl.gov), an energy innovation hub (http://www.energy.gov/hubs) for modeling and simulation of nuclear reactors under US Department of Energy (DOE) Contract No. DE-AC05-00OR22725.

This research used the resources of the High Performance Computing Center at INL, which is supported by DOE’s Office of Nuclear Energy (NE) under Contract No. DE-AC07-05ID14517.
2. RECENT UPDATES

Since completion of the initial milestone to generate BISON cases from VERA-CS output [15], several important modifications have been made to the BISON template, XML2MOOSE preprocessor, and general software configuration.

2.1 Template Updates
Meetings with the BISON development team and continued review have prompted a number of modifications to the BISON template file.

1) To help resolve some of the convergence issues observed during cycle outages, the BISON team recommended changing the problem type to what is termed a ReferenceResidual type. This has been more robust, particularly when there is not much change occurring to the input variables, as is the case during a cycle outage. As will be seen in the results, this change has been fairly successful overall, but there are still a couple of cases that fail to converge.

2) To address concerns with lengthy runtime, it was suggested to switch to the IterativeAdaptive scheme, which has proven to be invaluable.

3) As will be justified in the mesh sensitivity study in Section 3, a change was made from first order, QUAD4 elements to second order QUAD8. This resolves a significant portion of the power discrepancy that can build up during depletion.

4) A cumulative damage index post-processor [17] has been added.

5) Various default values have been updated, such as those pertaining to densification and relocation.

An updated BISON template file is available in Appendix B.

2.2 XML2MOOSE Preprocessor Updates
Because the Watts Bar output data file for some cycles is a conglomeration of several output files as a result of necessary restarts, it was found that many of the data typically available (such as input-related data echoed in the HDF5 output) were not guaranteed to be available. For this reason, modifications were made to pull the data from the input XML files for each cycle. This should avoid future problems in which the HDF5 data may be inconsistent, depending on how the data files are consolidated.

The shuffling capability has also been extended to better account for quarter-core symmetry shuffling. Ongoing work is aiming to better optimize how this is performed, but at present, the baseline shuffling capability is sufficient to produce meaningful results.

2.3 MOOSE/BISON/PETSc Updates
Consultation with the BISON team regarding many of the issues encountered in the initial milestone helped clarify that several issues were related to the VERA MOOSE/BISON configuration being out of date. This prompted updates to the MOOSE and BISON repositories and an upgrade of the VERA PETSc version to 3.5.4. Additionally, while SuperLU cannot be distributed as part of the official VERA third party libraries (TPLs), several builds were generated that allow the SuperLU options within PETSc to be enabled, which is the solver option recommended by the BISON team.
2.4 Unit Testing Additions
Two more unit tests to account for quarter symmetry shuffling with rotational (bison_from_vera_multi_qtr_shuffle_rot) and mirror (bison_from_vera_multi_qtr_shuffle_mir) symmetry have been added to the MOOSEExt repository.
3. WATTS BAR UNIT 1

3.1 General Description
The Watts Bar Nuclear Plant is a Westinghouse four-loop PWR operated by the Tennessee Valley Authority (TVA) and is currently operating in its thirteenth cycle, logging over 6,000 effective full power days (EFPD) of operation since 1996 [1]. It began with a 3,411 megawatt thermal (MWth) power rating, but had a 1.4% power uprate in 2001.

Figure 3.1.1 (left) shows a 2D slice of the WBN1 Cycle 1 full core layout, where the darker blue denotes moderator, lighter blue denotes 3.1% enriched rods, green denotes, 2.6% enriched rods, and red denotes 2.1% enriched rods. The structural components such as the core baffle, barrel, and pads are represented with a lighter gray whereas the vessel is shown with a darker gray. It has 193 Westinghouse 17 × 17 fuel assemblies which are 12 feet tall, each with 264 fuel rods and 25 guide/instrumentation tubes. On the right is a typical axial layout of a fuel assembly used in the nonproprietary model. It includes upper/lower core plate, nozzles, and gaps, with two Inconel and six Zircaloy spacer grids.

Fig. 3.1.1. Watts Bar Unit 1 – Cycle 1 Core diagram [1,18]

The left side of Fig. 3.1.2 shows a quarter core layout of the assembly configurations, including enrichment and the number of Pyrex rods for Cycle 1. The assemblies are color-coded based on the fuel enrichment. The right side of the figure shows the various control rod bank configurations, where operational banks are A-D and the safety banks at SA-SD, color-coded by bank.
3.2 Relevant Cycle Data
To provide a brief insight into some of the more cycle-specific data, the following subsections show the core power history used in the VERA-CS cases, along with the core layout, as appropriate.

3.2.1 Cycle 1
Figure 3.2.1 shows the power history for Cycle 1, which has a more gradual ramp to power than will be seen in subsequent cycles as this is the first cycle of operation during which additional startup tests (including flux maps at stages of power ramp as are typical during any startup) are completed. There is also a bit more variation, though still relatively minor, than in other cycles. While this illustration is simpler than the real operational history, it is what was used in VERA-CS. Shortly after 14 gigawatt days per metric ton (GWd/MT), VERA-CS imposes a step change to 86.9% power. This was reflected in the BISON inputs, allowing a one-day transition to 86.9% during the downramp, and then after an additional ~1GWd/MT back up to 100% power since an instantaneous power change would be problematic for BISON. At all other statepoints, BISON uses a linear interpolation of the power.

Fig. 3.1.2. Watts Bar Unit 1 – Cycle 1 core layout and rod bank configuration [1].
3.2.2 Cycle 2

Figure 3.2.2 shows the simulated power history for Cycle 2, which is very stable, with a more accelerated ramp to power, but with constant 100% power until a similar down-power ramp/coast down. The actual history was more complicated, including at least one trip.

Figure 3.2.3 shows the core layout in Cycle 2. Each assembly is color-coded based on enrichment, and fresh assemblies include data on the IFBA / wet annular burnable absorber (WABA) configuration, whereas others contain the corresponding location from Cycle 1.
3.2.3 Cycle 3

Figure 3.2.4 shows the simulated power history for Cycle 3, which is very similar to Cycle 2, and Fig. 3.2.5 shows the core layout in Cycle 3.
3.3 Remarks

It is important to note that BISON does not have the capability to simulate the IFBA coating on fuel pellets. This coating will affect the fuel performance physics, particularly the internal rod pressure. The results in this work neglect the IFBA coating, but a model to account for the coating is actively being developed at INL, and these results will be regenerated once it becomes available. Additionally, many IFBA rods use a combination of solid and annular fuel pellets (annular pellets at the axial extremities) to accommodate the additional helium generated by the IFBA coating. At present, BISON does not have an internal mesh capability that can accommodate this case, so annular pellets are also being represented as solid. The capability to do this is also actively under development, but it is worth noting that these pellets are at very low power anyway, and are likely not limiting in any way.

The BISON cases in this work used Zircaloy-4 material models as opposed to proprietary ZIRLO material models that would be necessary in these rods. Additionally, the oxide layer growth is only available in select boundary condition modes of BISON, which is not one used in this work. Extending the oxide layer growth capability (waterside and internal) is planned for future work by the BISON development team.
4. MESH SENSITIVITY STUDY

As work with BISON progressed, it became clear that an independent mesh sensitivity study would be beneficial to ensure that the mesh parameters being used were sufficiently tight for this application. An internal report on INL’s similar study [25] highlighted some potential issues with using a coarse mesh, particularly in the discrepancy between input and calculated rod power. In this study, eight different configurations were tested: four different mesh options (all equi-spaced) and two different quadrature options. These configurations were tested on a single rod from WBN1 Cycle 1 that was run on 12 processors on Falcon.

4.1 Mesh and Quadrature Description

Table 4.2.1 shows the mesh options that were used. Because the aspect ratio of each element is important to convergence (with the target in BISON of around 20 [25]), each of these meshes preserves the same aspect ratio, so if the radial mesh is doubled, so is the axial mesh.

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<th># Axial Mesh</th>
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<td>100</td>
</tr>
<tr>
<td>medium</td>
<td>12</td>
<td>200</td>
</tr>
<tr>
<td>fine</td>
<td>24</td>
<td>400</td>
</tr>
<tr>
<td>ultrafine</td>
<td>48</td>
<td>800</td>
</tr>
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</table>

Two different quadrature options were assessed: (1) linear, consisting of QUAD4 and first order elements, and (2) quad, consisting of QUAD8 and second order element options.

4.2 Results

Figures 4.2.1–4.2.3 show the maximum centerline fuel temperature, average fuel temperature, and minimum gap thickness for each of the eight different options. In the temperature plots, all but the coarse linear configuration agree well. All agree well for the gap thickness estimation.

Fig. 4.2.1. Mesh sensitivity study – maximum centerline fuel temperature (K).
However, for the difference between input (Watts) and calculated power (Watts), more substantial differences are observed, with coarse linear yielding at nearly a 20% difference by the end of the cycle. While the rod power history is specified as an input to BISON, various components of the solve can lead to a lack of conservation of power in the sense that the power calculated from the BISON mesh is not guaranteed to match the specified power exactly. Most of this discrepancy is well resolved with fine linear or medium quad. The radial mesh used here is equispaced. The same internal INL report [17] showed that a non-uniform biased mesh can significantly reduce this discrepancy even further. While the biased meshing option is currently not available with BISON’s internal mesh generator, it is under development and will be a useful addition.
Table 4.2.2 shows the timing results for the configurations. In general, going from linear to quad for a particular mesh refinement is more cost effective than doubling the mesh.

<table>
<thead>
<tr>
<th>Mesh</th>
<th>Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>linear</td>
<td></td>
</tr>
<tr>
<td>coarse</td>
<td>2.05</td>
</tr>
<tr>
<td>medium</td>
<td>5.23</td>
</tr>
<tr>
<td>fine</td>
<td>17.58</td>
</tr>
<tr>
<td>ultrafine</td>
<td>59.73</td>
</tr>
<tr>
<td>quad</td>
<td></td>
</tr>
<tr>
<td>coarse</td>
<td>4.73</td>
</tr>
<tr>
<td>medium</td>
<td>12.30</td>
</tr>
<tr>
<td>fine</td>
<td>43.48</td>
</tr>
<tr>
<td>ultrafine</td>
<td>179.12</td>
</tr>
</tbody>
</table>

For this reason, the coarse quad parameters were used in the remainder of the analysis and in this report since it (1) has a much improved discrepancy over coarse linear, (2) provides greater improvement than medium linear mesh with less computational burden, and (3) will likely be even better once biased meshing options are available, providing performance similar to that anticipated in the long-term option.
5. RESULTS

The available output data is briefly summarized here, and then the results for the first and last full power data points (near-BOC and near-EOC) of each cycle are presented for the following parameters of interest:

1) maximum centerline fuel temperature,
2) average fuel temperature,
3) minimum gap thickness,
4) minimum clad hoop stress, and
5) maximum clad hoop stress.

In addition, a more complete set of data for the maximum centerline fuel temperature and minimum gap thickness for each cycle is available in Appendix A. The results in this section and the appendix are shown at burnups that were used as VERA-CS statepoints. True BOC and true EOC cycle results for most parameters were omitted because they are at low or zero power. However, Appendix A includes BOC/EOC for the maximum centerline fuel temperature and minimum gap thickness.

To run these cases, a large number of 24-rod batch jobs were executed on Falcon on 12 processors each. This is primarily because the means to run all rods at once (such as MultiApps) is not yet available. To complete these jobs, a total of approximately 74,000 core-hours were used. Previous discrepancies reported in parallel execution of BISON in an earlier milestone report [15] have since been resolved, and consistency is observed.

5.1 Output Data

A variety of data is available from BISON in (1) comma-separated value (CSV) files, which typically contain maximum, minimum, and average values of quantities of interest (temperatures, stress, etc.) and (2) EXODUS files, which can contain higher resolution data such as axial and finite element-based distributions. At this point, only data from CSV files are currently accessible in the post-processing tool that consolidates that output data onto VERAOut. Work is underway to gather the data from the EXODUS files.

5.2 Cycle 1

Figures 5.2.1–5.2.5 show the results for several parameters of interest for Cycle 1. Figure 5.2.1 shows the maximum centerline fuel temperature, which peaks at roughly 1516 K (much lower than the melting temperature of UO$_2$). Not surprisingly, it is considerably higher early in the cycle and decreases as fuel densification and gap closure help bring it down as the cycle progresses. The distribution also flattens out along with the power profile as the higher enriched assemblies burn out more rapidly.
Figure 5.2.1 shows the maximum centerline fuel temperature for Cycle 1.

Figure 5.2.2 shows the average fuel temperature for Cycle 1, which exhibits similar trends as observed in the maximum centerline fuel temperature.
Figure 5.2.3 shows the minimum gap thickness for each rod, where it can be seen that none of the rods are in contact near BOC (as expected), but as the cycle progresses, nearly all rods have some contact by the end of the cycle.

Figure 5.2.3 shows the minimum clad hoop stress. There is very little interesting about these figures, but worth watching in future work.

Figure 5.2.4 shows the maximum clad hoop stress. The spike near the end of the cycle seems to result from the power transition to/from 86.9% power near the end of the cycle, which also includes a small movement of the Bank D rods, which are located at H-8, D-8, H-12, and D-12 and clearly stand out near EOC. However, these stresses (~30 MPa) are still low and are not very concerning.
5.3 Cycle 2

Figures 5.3.1–5.3.5 show results for several parameters of interest for Cycle 2. Based on the results, it is easy to identify the fresh and burned assemblies at beginning of cycle (BOC). For example, in Figures 5.3.1 and 5.3.2, the fresh assemblies have higher temperatures because the enrichments (and resultantly power) are higher. It can also been seen in Figure 5.3.3 as most of the burned assemblies have a substantial number of rods with contact at BOC, whereas the fresh assemblies have no contact present yet. Of the several thousand rods displayed, a couple encountered convergence problems, which seem to arise during cycle outages where the power is zero. However, this is a significant improvement over the results in the previous milestone [15], in which two rods out of several hundred had issues. In these plots, troubled rods show up just as guide tubes do, with zero value entries. For example, looking at H-15, there is one additional zero entry in the lower right quadrant.

Figures 5.3.1 and 5.3.2 show the maximum centerline and average fuel temperature distribution. Very few surprises and all temperatures are well below any cause for concern.
Fig. 5.3.1. Cycle 2 maximum centerline fuel temperature (K).

Fig. 5.3.2. Cycle 2 average fuel temperature (K).
Figure 5.3.3 show the minimum gap thickness. As in Cycle 1, the fresh assemblies do not exhibit any fuel-clad contact early in the cycle, though nearly all pins do by EOC.

Fig. 5.3.3. Cycle 2 minimum gap thickness (m).

Fig. 5.3.4. Cycle 2 minimum clad hoop stress (Pa).
Figure 5.3.5 shows the maximum hoop stress distribution for Cycle 2. The maximum hoop stresses are considerably higher than in Cycle 1 at roughly 250 MPa. Much of this spike is related to the ramp to power, which is much quicker than in Cycle 1. Based on the VERA-CS power input, the transition happened over about 7 days. However, as the cycle progresses, the stresses reduce considerably.

Figure 5.3.6 shows the cumulative damage index for the cycle. Interestingly, no CDI is registered at the 0.142 GWd/MT statepoint, which is the first full power statepoint, but is registered at the next statepoint (0.521 GWd/MT), as shown here. The CDI distribution tends to correspond well with the maximum clad hoop stress in the previous figure, which is a major component in the CDI equation [17]. Based on this, the maximum CDI is around 4% for a couple of rods, which is still relatively low.
5.4 Cycle 3
Figures 5.4.1–5.4.5 show the results for several parameters of interest for Cycle 3. In general, similar trends are observed as in Cycle 2. However, the higher enriched (4.401%) fresh assemblies dominate the maximum centerline fuel temperature distribution early in the cycle.

Fig. 5.4.1. Cycle 3 maximum centerline fuel temperature (K).

Fig. 5.4.2. Cycle 3 average fuel temperature (K).
Fig. 5.4.3. Cycle 3 minimum gap thickness (m).

Fig. 5.4.4. Cycle 3 minimum clad hoop stress (Pa).
It should also be noted that this core is rotationally symmetric, which accounts for some of the trends observed along the symmetry boundaries in Figure 5.4.5. Additionally, it appears that the maximum hoop stresses occur near BOC because of the ramp to power, as in Cycle 2.

Similarly, the CDI corresponds well with Figure 5.4.5, but with a slightly increased maximum CDI of nearly 5%.
6. CONCLUSIONS AND FUTURE WORK

6.1 Conclusions
In this report, a quarter-core standalone BISON capability has been demonstrated for the first three cycles of Watts Bar Unit 1. While the current output is limited to maximum, minimum, and average quantities of interest across each fuel rod, the insights that can be obtained are still very worthwhile. This capability could be very helpful in screening for potential PCI issues as part of the challenge milestone due next year.

6.2 Assessment of Milestone Objectives
The objectives listed in Sect. 1 are discussed below.

1) Extend XML2MOOSE to accommodate fuel shuffling in quarter symmetry cases.
Quarter symmetry shuffling appears to be functioning appropriately. Some improvements can still be made, but it is operating as expected.

2) Develop a post-processor to collect the results from the individual BISON cases and consolidate them onto the VERAOut HDF5 file, particularly for use in VERAView.
The post-processor, which is currently termed bison-post, has been created and collects the data from the output CSVs from BISON and consolidates them onto the VERAOut HDF5 file generated by VERA-CS. The data in this file can then be easily visualized using VERAView.

3) Consider the establishment of a driver program that will simplify usage by preprocessing, running, and gathering output all in one overarching executable
Because BISON cases are running in small batches using a large number of jobs on Falcon, it is not ideal to use a single driver program to handle these jobs. If MultiApps issues are resolved completely, then a driver program can be created to handle the jobs, simplifying things for the user.

4) Determine an appropriate model for simulating IFBA rods in BISON.
The BISON team is actively developing this model, and once complete, it will require Cycles 2 and 3 to be rerun. This development should provide more insights regarding the internal pressure of the IFBA rods.

5) Run several cycles of WBN1 using the VERA-CS output data available from Reference 1.
This capability was tested using these data on the first three cycles and is currently set up to generate BISON inputs from Cycles 1–X, depending on what is specified in the input. It may be useful to change how this works to allow users to specify that they only want results for Cycle X. This may lead to some redundancy if consecutive cycles are desired, but it could be accommodated.

6) Assess temperatures, stresses, and other important parameters of interest to PCI screening
A number of parameters of interest have been shown, including maximum centerline fuel temperature, average fuel temperature, clad hoop stresses, minimum gap thickness, and cumulative damage index. Data are also available for the clad temperatures, but they were not shown in this report.
Two additional stretch goals:

1) Compare these results to Bratton’s FRAPCON results [20].

No comparisons for full WBN1 simulations have been completed yet. However, as part of ongoing work to improve the fuel temperature tables, comparisons between FRAPCON and BISON have been completed as a function of linear heat rate and burnup, generally with good agreement.

2) Perform a mesh sensitivity study to assess the appropriate refinement level.

A simple mesh sensitivity study was performed to justify the use of a coarse quad configuration. In general, anything finer than the coarse linear parameters is sufficient for temperature, but the power discrepancy can be substantial, even in some of the slightly more refined cases. No study of time sensitivity was performed. BISON is using an adaptive time-stepping procedure that attempts to use the largest time step while still maintaining convergence (based on several parameters). Therefore, conducting a study to restrict the maximum timestep allowed would be useful.

6.3 Running on Leadership Class Clusters

Running a large number of BISON cases using the MultiApps capability has continued to encounter a number of errors that require some time to investigate. Additionally, the BISON team is actively working to resolve a bug with MultiApps in which all of the CSV output files are not generated appropriately. MultiApps may be necessary to use this capability on machines such as Titan and Eos, where the number of active jobs and jobs queued is considerably more restricted. For now, the current approach of running a number of small batches on Falcon has been sufficient to generate results, but it is clearly not ideal.

6.4 Future Work

6.4.1 Accounting for More Fuel Rod Types

The current BISON template is limited to use for standard UO$_2$ fuel pins. Additional work should be performed to generalize the input for other types of rods, such those with IFBA-coated fuel, and gadolinia or erbia burnable absorber rods.

6.4.2 Biased Meshing

An internal INL report on BISON mesh sensitivity showed that biased (non-uniform) meshes can significantly reduce the power discrepancy between the input and calculated powers. This is something the BISON team is working on, and it will be incorporated into this capability once it is completed.

6.4.3 Assess Effect of ZIRLO vs. Zircaloy-4

All results here used Zircaloy-4 cladding material properties instead of a proprietary ZIRLO model, which is currently unavailable. If possible, it would be useful to obtain a ZIRLO model for comparison purposes.

6.4.4 Oxide Layer Growth

Oxide layer growth is an important phenomenon currently only available in the CoolantChannel model of BISON. This is actively being extended to other models, such as the one used in this work that uses a Dirichlet boundary condition on the coolant temperature.

6.4.5 Processing More Detailed Output via EXODUS

Accessing the more resolved data on the EXODUS output files will be essential to gaining a better understanding of the rod conditions. The CSV output data are adequate to gain some insight, but having axially dependent data will provide significantly more information.
6.4.6 Extending Analysis to Include WBN1 Cycles 6 and 7

It was recently suggested that WBN1 Cycles 6 and 7 be tested with this capability to assess the potential for PCI failures. Cycle 7 is known to have substantial crud-induced power shift (CIPS) and will be an interesting test for this capability. It may be useful to allow the users to generate only inputs for Cycle X if desired. This may provide sufficient motivation to do that. Additionally, new fuel temperature tables have been obtained with both BISON and FRAPCON, and work is underway to reassess the temperatures in Watts Bar Cycles 1–12. It may be advantageous to wait until these new simulations have been completed before continuing BISON analysis for later cycles.

6.4.7 Assessing Power Ramp Procedures

One application for future work may be to assess the impact of ramping speed on potential rod failures. There may be other computational or experimental results that would provide a useful basis for comparison.
REFERENCES


[22] Hall, D. and Montgomery, R. Core Design Information including assembly and insert ID’s, core locations, and enrichments for Watts Bar Unit 1 Cycle 2. Technical Report, CASL-P-2012-0101-000-g, CASL. PROPRIETARY (TVA NPG L36 120731 803) July 31 (2012).


APPENDIX A – EXPANDED RESULTS

A.1. Cycle 1

A.1.1. Maximum Centerline Fuel Temperature

Fig. A.1.1. Cycle 1 maximum centerline fuel temperature (K) – 0.00 GWd/MT.

Fig. A.1.2. Cycle 1 maximum centerline fuel temperature (K) – 0.35 GWd/MT.
Fig. A.1.3. Cycle 1 maximum centerline fuel temperature (K) – 1.23 GWd/MT.

Fig. A.1.4. Cycle 1 maximum centerline fuel temperature (K) – 1.92 GWd/MT.
Fig. A.1.5. Cycle 1 maximum centerline fuel temperature (K) – 2.46 GWd/MT.

Fig. A.1.6. Cycle 1 maximum centerline fuel temperature (K) – 2.99 GWd/MT.
Fig. A.1.7. Cycle 1 maximum centerline fuel temperature (K) – 3.56 GWd/MT.

Fig. A.1.8. Cycle 1 maximum centerline fuel temperature (K) – 4.07 GWd/MT.
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Fig. A.1.9. Cycle 1 maximum centerline fuel temperature (K) – 4.64 GWd/MT.

Fig. A.1.10. Cycle 1 maximum centerline fuel temperature (K) – 5.14 GWd/MT.
**Fig. A.1.11.** Cycle 1 maximum centerline fuel temperature (K) – 5.70 GWd/MT.

**Fig. A.1.12.** Cycle 1 maximum centerline fuel temperature (K) – 6.27 GWd/MT.
Fig. A.1.13. Cycle 1 maximum centerline fuel temperature (K) – 7.46 GWd/MT.

Fig. A.1.14. Cycle 1 maximum centerline fuel temperature (K) – 8.49 GWd/MT.
Fig. A.1.15. Cycle 1 maximum centerline fuel temperature (K) – 9.60 GWd/MT.

Fig. A.1.16. Cycle 1 maximum centerline fuel temperature (K) – 10.8 GWd/MT.
Fig. A.1.17. Cycle 1 maximum centerline fuel temperature (K) – 12.00 GWd/MT.

Fig. A.1.18. Cycle 1 maximum centerline fuel temperature (K) – 13.40 GWd/MT.
Fig. A.1.19. Cycle 1 maximum centerline fuel temperature (K) – 14.3 GWd/MT.

Fig. A.1.20. Cycle 1 maximum centerline fuel temperature (K) – 15.10 GWd/MT.
Fig. A.1.21. Cycle 1 maximum centerline fuel temperature (K) – 15.30 GWd/MT.

Fig. A.1.22. Cycle 1 maximum centerline fuel temperature (K) – 15.80 GWd/MT.
Fig. A.1.23. Cycle 1 maximum centerline fuel temperature (K) – 16.30 GWd/MT.

Fig. A.1.24. Cycle 1 maximum centerline fuel temperature (K) – 16.90 GWd/MT.
A.1.2. Minimum Gap Thickness

Fig. A.1.25. Cycle 1 minimum gap thickness (m) – 0.00 GWd/MT..

Fig. A.1.26. Cycle 1 minimum gap thickness (m) – 0.35 GWd/MT..
Fig. A.1.27. Cycle 1 minimum gap thickness (m) – 1.23 GWd/MT.

Fig. A.1.28. Cycle 1 minimum gap thickness (m) – 1.92 GWd/MT.
Fig. A.1.29. Cycle 1 minimum gap thickness (m) – 2.46 GWd/MT.

Fig. A.1.30. Cycle 1 minimum gap thickness (m) – 2.99 GWd/MT.
Fig. A.1.31. Cycle 1 minimum gap thickness (m) – 3.56 GWd/MT.

Fig. A.1.32. Cycle 1 minimum gap thickness (m) – 4.07 GWd/MT.
Fig. A.1.33. Cycle 1 minimum gap thickness (m) – 4.64 GWd/MT.

Fig. A.1.34. Cycle 1 minimum gap thickness (m) – 5.14 GWd/MT.
Fig. A.1.35. Cycle 1 minimum gap thickness (m) – 5.70 GWd/MT.

Fig. A.1.36. Cycle 1 minimum gap thickness (m) – 6.27 GWd/MT.
Fig. A.1.37. Cycle 1 minimum gap thickness (m) – 7.46 GWd/MT.

Fig. A.1.38. Cycle 1 minimum gap thickness (m) – 8.49 GWd/MT.
Fig. A.1.39. Cycle 1 minimum gap thickness (m) – 9.60 GWd/MT.

Fig. A.1.40. Cycle 1 minimum gap thickness (m) – 10.8 GWd/MT.
Fig. A.1.41. Cycle 1 minimum gap thickness (m) – 12.00 GWd/MT.

Fig. A.1.42. Cycle 1 minimum gap thickness (m) – 13.40 GWd/MT.
Fig. A.1.43. Cycle 1 minimum gap thickness (m) – 14.3 GWd/MT.

Fig. A.1.44. Cycle 1 minimum gap thickness (m) – 15.10 GWd/MT.
Fig. A.1.45. Cycle 1 minimum gap thickness (m) – 15.30 GWd/MT.

Fig. A.1.46. Cycle 1 minimum gap thickness (m) – 15.80 GWd/MT.
Fig. A.1.47. Cycle 1 minimum gap thickness (m) – 16.30 GWd/MT.

Fig. A.1.48. Cycle 1 minimum gap thickness (m) – 16.90 GWd/MT.
A.2. Cycle 2

A.2.1. Maximum Centerline Fuel Temperature

Fig. A.2.1. Cycle 2 maximum centerline fuel temperature (K) – 0.00 GWd/MT.

Fig. A.2.2. Cycle 2 maximum centerline fuel temperature (K) – 0.14 GWd/MT.
Fig. A.2.3. Cycle 2 maximum centerline fuel temperature (K) – 0.52 GWd/MT.

Fig. A.2.4. Cycle 2 maximum centerline fuel temperature (K) – 1.00 GWd/MT.
Fig. A.2.5. Cycle 2 maximum centerline fuel temperature (K) – 1.48 GWd/MT.

Fig. A.2.6. Cycle 2 maximum centerline fuel temperature (K) – 2.07 GWd/MT.
Fig. A.2.7. Cycle 2 maximum centerline fuel temperature (K) – 2.48 GWd/MT.

Fig. A.2.8. Cycle 2 maximum centerline fuel temperature (K) – 3.13 GWd/MT.
Fig. A.2.9. Cycle 2 maximum centerline fuel temperature (K) – 4.02 GWd/MT.

Fig. A.2.10. Cycle 2 maximum centerline fuel temperature (K) – 5.53 GWd/MT.
Fig. A.2.11. Cycle 2 maximum centerline fuel temperature (K) – 6.53 GWd/MT.

Fig. A.2.12. Cycle 2 maximum centerline fuel temperature (K) – 8.22 GWd/MT.
Fig. A.2.13. Cycle 2 maximum centerline fuel temperature (K) – 9.29 GWd/MT.

Fig. A.2.14. Cycle 2 maximum centerline fuel temperature (K) – 10.36 GWd/MT.
Fig. A.2.15. Cycle 2 maximum centerline fuel temperature (K) – 11.43 GWd/MT.

Fig. A.2.16. Cycle 2 maximum centerline fuel temperature (K) – 12.54 GWd/MT.
Fig. A.2.17. Cycle 2 maximum centerline fuel temperature (K) – 13.54 GWd/MT.

Fig. A.2.18. Cycle 2 maximum centerline fuel temperature (K) – 14.62 GWd/MT.
Fig. A.2.19. Cycle 2 maximum centerline fuel temperature (K) – 15.76 GWd/MT.

Fig. A.2.20. Cycle 2 maximum centerline fuel temperature (K) – 16.32 GWd/MT.
Fig. A.2.21. Cycle 2 maximum centerline fuel temperature (K) – 16.90 GWd/MT.

Fig. A.2.22. Cycle 2 maximum centerline fuel temperature (K) – 17.48 GWd/MT.
Fig. A.2.23. Cycle 2 maximum centerline fuel temperature (K) – 18.06 GWd/MT.

A.2.2. Minimum Gap Thickness

Fig. A.2.24. Cycle 2 minimum gap thickness (m) – 0.00 GWd/MT.
Fig. A.2.25. Cycle 2 minimum gap thickness (m) – 0.14 GWd/MT.

Fig. A.2.26. Cycle 2 minimum gap thickness (m) – 0.52 GWd/MT.
Fig. A.2.27. Cycle 2 minimum gap thickness (m) – 1.00 GWd/MT.

Fig. A.2.28. Cycle 2 minimum gap thickness (m) – 1.48 GWd/MT.
Fig. A.2.29. Cycle 2 minimum gap thickness (m) – 2.07 GWd/MT.

Fig. A.2.30. Cycle 2 minimum gap thickness (m) – 2.48 GWd/MT.
Fig. A.2.31. Cycle 2 minimum gap thickness (m) – 3.13 GWd/MT.

Fig. A.2.32. Cycle 2 minimum gap thickness (m) – 4.02 GWd/MT.
Fig. A.2.33. Cycle 2 minimum gap thickness (m) – 5.53 GWd/MT.

Fig. A.2.34. Cycle 2 minimum gap thickness (m) – 6.53 GWd/MT.
Fig. A.2.35. Cycle 2 minimum gap thickness (m) – 8.22 GWd/MT.

Fig. A.2.36. Cycle 2 minimum gap thickness (m) – 9.29 GWd/MT.
Fig. A.2.37. Cycle 2 minimum gap thickness (m) – 10.36 GWd/MT.

Fig. A.2.38. Cycle 2 minimum gap thickness (m) – 11.43 GWd/MT.
Fig. A.2.39. Cycle 2 minimum gap thickness (m) – 12.54 GWd/MT.

Fig. A.2.40. Cycle 2 minimum gap thickness (m) – 13.54 GWd/MT.
Fig. A.2.41. Cycle 2 minimum gap thickness (m) – 14.62 GWd/MT.

Fig. A.2.42. Cycle 2 minimum gap thickness (m) – 15.76 GWd/MT.
Standalone BISON Fuel Performance Results for Watts Bar Unit 1, Cycles 1-3

### Fig. A.2.43. Cycle 2 minimum gap thickness (m) – 16.32 GWd/MT.

### Fig. A.2.44. Cycle 2 minimum gap thickness (m) – 16.90 GWd/MT.
Fig. A.2.45. Cycle 2 minimum gap thickness (m) – 17.48 GWd/MT.

Fig. A.2.46. Cycle 2 minimum gap thickness (m) – 18.06 GWd/MT.
A.3. Cycle 3

A.3.1. Maximum Centerline Fuel Temperature

Fig. A.3.1. Cycle 3 maximum centerline fuel temperature (K) – 0.00 GWD/MT.

Fig. A.3.2. Cycle 3 maximum centerline fuel temperature (K) – 0.20 GWD/MT.
Fig. A.3.3. Cycle 3 maximum centerline fuel temperature (K) – 0.69 GWd/MT.

Fig. A.3.4. Cycle 3 maximum centerline fuel temperature (K) – 1.17 GWd/MT.
Fig. A.3.5. Cycle 3 maximum centerline fuel temperature (K) – 1.70 GWd/MT.

Fig. A.3.6. Cycle 3 maximum centerline fuel temperature (K) – 2.24 GWd/MT.
Fig. A.3.7. Cycle 3 maximum centerline fuel temperature (K) – 2.77 GWd/MT.

Fig. A.3.8. Cycle 3 maximum centerline fuel temperature (K) – 3.30 GWd/MT.
Fig. A.3.9. Cycle 3 maximum centerline fuel temperature (K) – 3.96 GWd/MT.

Fig. A.3.10. Cycle 3 maximum centerline fuel temperature (K) – 4.91 GWd/MT.
Fig. A.3.11. Cycle 3 maximum centerline fuel temperature (K) – 6.44 GWd/MT.

Fig. A.3.12. Cycle 3 maximum centerline fuel temperature (K) – 8.13 GWd/MT.
Standalone BISON Fuel Performance Results for Watts Bar Unit 1, Cycles 1-3

Fig. A.3.13. Cycle 3 maximum centerline fuel temperature (K) – 9.72 GWd/MT.

Fig. A.3.14. Cycle 3 maximum centerline fuel temperature (K) – 11.35 GWd/MT.
Fig. A.3.15. Cycle 3 maximum centerline fuel temperature (K) – 12.94 GWd/MT.

Fig. A.3.16. Cycle 3 maximum centerline fuel temperature (K) – 14.56 GWd/MT.
Fig. A.3.17. Cycle 3 maximum centerline fuel temperature (K) – 16.70 GWd/MT.

Fig. A.3.18. Cycle 3 maximum centerline fuel temperature (K) – 18.14 GWd/MT.
Fig. A.3.19. Cycle 3 maximum centerline fuel temperature (K) – 18.79 GWd/MT.

Fig. A.3.20. Cycle 3 maximum centerline fuel temperature (K) – 19.32 GWd/MT.
A.3.2. Minimum Gap Thickness

Fig. A.3.21. Cycle 3 minimum gap thickness (m) – 0.00 GWd/MT.

Fig. A.3.22. Cycle 3 minimum gap thickness (m) – 0.20 GWd/MT.
Fig. A.3.23. Cycle 3 minimum gap thickness (m) – 0.69 GWd/MT.

Fig. A.3.24. Cycle 3 minimum gap thickness (m) – 1.17 GWd/MT.
Fig. A.3.25. Cycle 3 minimum gap thickness (m) – 1.70 GWd/MT.

Fig. A.3.26. Cycle 3 minimum gap thickness (m) – 2.24 GWd/MT.
Fig. A.3.27. Cycle 3 minimum gap thickness (m) – 2.77 GWd/MT.

Fig. A.3.28. Cycle 3 minimum gap thickness (m) – 3.30 GWd/MT.
Fig. A.3.29. Cycle 3 minimum gap thickness (m) – 3.96 GWd/MT.

Fig. A.3.30. Cycle 3 minimum gap thickness (m) – 4.91 GWd/MT.
Fig. A.3.31. Cycle 3 minimum gap thickness (m) – 6.44 GWd/MT.

Fig. A.3.32. Cycle 3 minimum gap thickness (m) – 8.13 GWd/MT.
Standalone BISON Fuel Performance Results for Watts Bar Unit 1, Cycles 1-3

Fig. A.3.33. Cycle 3 minimum gap thickness (m) – 9.72 GWd/MT.

Fig. A.3.34. Cycle 3 minimum gap thickness (m) – 11.35 GWd/MT.
Fig. A.3.35. Cycle 3 minimum gap thickness (m) – 12.94 GWd/MT.

Fig. A.3.36. Cycle 3 minimum gap thickness (m) – 14.56 GWd/MT.
Fig. A.3.37. Cycle 3 minimum gap thickness (m) – 16.70 GWd/MT.

Fig. A.3.38. Cycle 3 minimum gap thickness (m) – 18.14 GWd/MT.
Fig. A.3.39. Cycle 3 minimum gap thickness (m) – 18.79 GWd/MT.

Fig. A.3.40. Cycle 3 minimum gap thickness (m) – 19.32 GWd/MT.
APPENDIX B – UPDATED BISON INPUT TEMPLATE

# Bison-CASL Fuel Pin Input Template
# (see the bottom for uses and assumptions)
# --------------------------------------------------
# Nomenclature:
# -- #VERA_DEFINED = this value will be overwritten by xml2moose
# -- #VERA_MODIFIABLE = this value could be overwritten by xml2moose
# -- #VERA_PREPARED = this value is specified when created for Tiamat or from VERA-CS output; blank otherwise
# -- #TIAMAT = enabled for Tiamat
# -- #BISON_CASL = enabled for stand-alone Bison-CASL
# -- #CLAD_SURFACE = enabled when Dirichlet BCs on the clad surface are used.
# -- #COOLANT_TEMP = enabled when Dirichlet BCs for the bulk coolant temperature are used.
# -- #COOLANT_FLOW = enabled when Coolant Flow BCs are used.
# --------------------------------------------------

[GlobalParams]
density = disp_x = disp_x
disp_y = disp_y
disp_z = disp_x
disp = disp_y
order = SECOND
family = LAGRANGE
energy_per_fission = 3.2e-11 # J/fission
a_lower =
a_upper =
initial_porosity =

[Mesh]
displacements = 'disp_x disp_y'
file =
partitioner = centroid
centroid_partitioner_direction = y
patch_size = 10
patch_update_strategy = auto
type = SmearMesh
clad_mesh_density = customize
pellet_mesh_density = customize
clad_thickness =
pellet_outer_radius =
clad_bot_gap_height =
clad_top_gap_height =
pellet_quantity =
pellet_height =
clad_gap_width =
top_bot_clad_height =
nx_p = 6 # number of radial elements in the fuel
ny_p = 100 # number of axial elements in the fuel
nx_c = 3 # number of elements in the clad thickness
ny_c = 100 # number of elements in the axially in the clad
ny_cu = 1
intervals =
elem_type = QUADS

[Problem]
coord_type = RZ
type = ReferenceResidualProblem
solution_variables = 'disp_x disp_y temp'
reference_residual_variables = 'saved_x saved_y saved_t'

[Variables]
[../disp_x]
[../disp_y]
[../temp]
initial_condition = 300.0

[SolidMechanics]
[../solid]
temp = temp
save_in_disp_r = saved_x
save_in_disp_z = saved_y

[AuxVariables]
[../saved_x]
[../saved_y]
[../saved_t]

# Nodal Quantities

# COOLANT_TEMP = enabled when Dirichlet BCs for the bulk coolant temperature are used.
# CLAD_SURFACE = enabled when Dirichlet BCs on the clad surface are used.
# COOLANT_FLOW = enabled when Coolant Flow BCs are used.

# Nodal Quantities

# Standalone BISON Fuel Performance Results for Watts Bar Unit 1, Cycles 1-3

```plaintext
# ==============================================================#
[./htcl]
  initial_condition = 500.0 #VERA_MODIFIABLE as auxvariables_htcl_initial_condition
[../]
[./htcv]
  initial_condition = 0.0 #VERA_MODIFIABLE as auxvariables_htcv_initial_condition
[../]
[./Ti]
  initial_condition = 565.0 #VERA_MODIFIABLE as auxvariables_Ti_initial_condition
[../]
[./Tv]
  initial_condition = 565.0 #VERA_MODIFIABLE as auxvariables_Tv_initial_condition
[../]
[./fast_neutron_flux]
  block = 1
[../]
[./fast_neutron_fluence]
  block = 1
[../]
[./grain_radius]
  block = 3
  initial_condition = 2.50e-06 #VERA_MODIFIABLE as auxvariables_grain_radius_initial_condition
[../]
[./casl_fission_rate] #>> PURGED FROM STANDALONE CASES
  initial_condition = 0.0
[../]
[./casl_old_fission_rate]
  initial_condition = 0.0
[../]
[./casl_new_fission_rate]
  initial_condition = 0.0
[../]
[./casl_clad_surface_temperature] #>> PURGED FROM STANDALONE CASES
  Hot-Zero Power coolant temperature.
  initial_condition = 565.0 #VERA_MODIFIABLE as auxvariables_casl_clad_surface_temperature
[../]
[./casl_old_clad_temperature] #>> ONLY FOR TIAMAT-INLINE CASES
  initial_condition = 565.0
[../]
[./casl_new_clad_temperature] #>> ONLY FOR TIAMAT-INLINE CASES
  initial_condition = 565.0
[../]
# ==============================================================#
# Constant Monomial Quantities (Mechanics)
# ==============================================================#
[./hydrostatic_stress]
  order = CONSTANT
  family = MONOMIAL
[../]
[./radial_stress]
  order = CONSTANT
  family = MONOMIAL
[../]
[./axial_stress]
  order = CONSTANT
  family = MONOMIAL
[../]
[./hoop_stress]
  order = CONSTANT
  family = MONOMIAL
[../]
[./hoop_strain]
  order = CONSTANT
  family = MONOMIAL
[../]
[./radial_strain]
  order = CONSTANT
  family = MONOMIAL
[../]
[./axial_strain]
  order = CONSTANT
  family = MONOMIAL
[../]
[./vonmises]
  order = CONSTANT
  family = MONOMIAL
[../]
[./creep_strain_mag]
  order = CONSTANT
  family = MONOMIAL
[../]
[./creep_strain_radial]
  order = CONSTANT
  family = MONOMIAL
[../]
[./creep_strain_axial]
  order = CONSTANT
  family = MONOMIAL
[../]
[./creep_strain_hoop]
  order = CONSTANT
  family = MONOMIAL
[../]
[./cumulative_damage_index]
  order = CONSTANT
  family = MONOMIAL
[../]
```

# Constant Monomial Quantities (Non-Mechanics)

```
#pellet_id
order = CONSTANT
family = MONOMIAL
block = 3

#axial_fission_rate
order = CONSTANT
family = MONOMIAL

#axial_burnup
order = CONSTANT
family = MONOMIAL

#axial_temperature
order = CONSTANT
family = MONOMIAL

#gap_conductivity
order = CONSTANT
family = MONOMIAL

#fuel_conductivity
order = CONSTANT
family = MONOMIAL

#porosity
order = CONSTANT
initial_condition =

#gap_distance
order = CONSTANT
initial_condition =

#fuel_volume_ratio = 1.0
#VERA_MODIFIABLE as burnup_burnup_fuel_volume_ratio

#fuel_outer_radius =
#VERA_MODIFIABLE as burnup_burnup_fuel_outer_radius

#fuel_inner_radius = 0.0
#VERA_MODIFIABLE as burnup_burnup_fuel_inner_radius

#num_axial = 100
#VERA_MODIFIABLE as burnup_burnup_num_axial

#num_radial = 80
#VERA_MODIFIABLE as burnup_burnup_num_radial

#axial_power_profile =
#VERA_MODIFIABLE as burnup_burnup_axial_power_profile

#rod_ave_lin_pow = linear_heat_rate_profile
#VERA_MODIFIABLE as burnup_burnup_rod_ave_lin_pow

#block = 3

#functions = 'linear_heat_rate_profile axial_peaking_factors'
#VERA_MODIFIABLE as burnup_burnup_functions

#y = '0 1.0'
#VERA_MODIFIABLE as functions_linear_heat_rate_profile_y

#x = '

#scale_factor = 1
#VERA_MODIFIABLE as functions_linear_heat_rate_profile_scale_factor

#format = columns
#BISON_CASL as functions_linear_heat_rate_profile_format

#data_file =
#VERA_MODIFIABLE as functions_linear_heat_rate_profile_data_file

#y = '0 0 25000'
#VERA_MODIFIABLE as functions_linear_heat_rate_profile_y

#x = '

#type = PiecewiseLinear
#TiAMAT/BISON_CASL as functions_linear_heat_rate_profile_type (defaults

#initial_condition =
#VERA_DEFINED

family = MONOMIAL
order = CONSTANT

family = MONOMIAL
order = CONSTANT

family = MONOMIAL
order = CONSTANT

family = MONOMIAL
order = CONSTANT

family = MONOMIAL
order = CONSTANT

block = 3

family = MONOMIAL
order = CONSTANT
```

# Time- and Space-Dependent Source and BCs

```
[./linear_heat_rate_profile] #>> replaced power_history and power_profile

type = PiecewiseLinear

x = '-100 0 5000'

y = '0 0 25000'

file =

format = columns

scale_factor = 1

[./axial_peaking_factors]

type =

to ParsedFunction if TiAMAT, PiecewiseBilinear if BISON_CASL (data_file necessary)

value = 1

data_file =

BISON_CASL

axis = 1

file =

BISON_CASL

scale_factor = 1

[./coolant_temperature]

type = PiecewiseLinear

PiCewiseBilinear if BISON_CASL (data_file necessary)

data_file = user_coolant_temp.csv

otherwise:

x = '-100 0'

data_file (included)

y = '293 365'

data_file (included)

axis = 1

[./coolant_pressure_ramp]

# used in coolantPressure BC

type = PiecewiseLinear

scale_factor = 1

y = '0 1.0'

[./g]

# type = CompositeFunction

functions = 'linear_heat_rate_profile axial_peaking_factors' #VERA_MODIFIABLE as burnup_burnup_q_functions

[./Burnup]

block = 3

rod_ave_lin_pow = linear_heat_rate_profile

axial_power_profile = axial_peaking_factors

num_radial = 80

num_axial = 100

fuel_inner_radius = 0.0

fuel_outer_radius =

fuel_volume_ratio = 1.0

enrich = '3.100e-02 9.690e-01 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00'

#VERA_DEFINED (overridable) or VERA_MODIFIABLE as

Burnup.burnup_i_enrich

RFP = RFP
```

Standalone BISON Fuel Performance Results for Watts Bar Unit 1, Cycles 1-3
Standalone BISON Fuel Performance Results for Watts Bar Unit 1, Cycles 1-3

CASL - CASL I 2015 - 1010 - 001

# Coolant Channel Equation Set (#COOLANT_FLOW)

# [CoolantChannel]
#
# [./convective_clad_surface]
# boundary = Y1 z 3
# variable = temp
# inlet_temperature = $VERA_DEFINED$ TODO: check units
# inlet_pressure = $VERA_DEFINED$ TODO: check units
# inlet_massflux = $VERA_DEFINED$ TODO: check units
# rod_diameter = $VERA_DEFINED$ TODO: check units
# rod_pitch = $VERA_DEFINED$ TODO: check units
# linear_heat_rate = linear_heat_rate_profile
# coolchannel_convective_clad_surface_linear_heat_rate_profile
# axial_power_profile = axial_peaking_factors
# coolchannel_convective_clad_surface_axial_power_profile
# [.../]
#
# Primary Kernels used in Heat Transfer

# [Kernels]
[../gravity]
type = Gravity
variable = disp_y
value = -9.81
[../]
[../heat]
# gradient term in heat conduction equation
# type = HeatConduction
variable = temp
save_in = saved_t
[../]
[../heat_ie]
# time term in heat conduction equation
# type = HeatConductionTimeDerivative
variable = temp
save_in = saved_t
[../]
[../heat_source]
type = NeutronHeatSource
fission_rate = fission_rate
aux_var = auxvar
variable = temp
block = 3
save_in = saved_t
[../]

# AuxKernels]

# Pre-Defined Types

# [./pelletid]
type = PelletIdAux
block = 3
variable = pellet_id
number_pellets = 1
execute_on = initial
[../]

[../fast_neutron_flux]
type = FastNeutronFluxAux
variable = fast_neutron_flux
block = 1
rod_ave_lin_pow = linear_heat_rate_profile
axial_power_profile = axial_peaking_factors
auxkernels_fast_neutron_flux_rod_ave_lin_pow
auxkernels_fast_neutron_flux_axial_power_profile
factor = 4.29768x13 # (n/m2 - s per W/m)
exeexute_on = timestep_begin
[../]

[../fast_neutron_fluence]
type = FastNeutronFluenceAux
variable = fast_neutron_fluence
block = 1
fast_neutron_flux = fast_neutron_flux
execute_on = timestep_begin
[../]

[../fuel_porosity]
type = PorosityAuxUO2
block = 3
variable = porosity
execute_on = linear
[../]

[../grain_radius]
type = GrainRadiusAux
block = 3
variable = grain_radius
temp = temp
execute_on = linear
[../]

[../gap_conductance]
type = MaterialRealAux
property = gap_conductance
variable = gap_conductivity
boundary = 10  # fuel radially-outer surface

[./fuel_conductance]
type = MaterialRealAux
property = thermal_conductivity
variable = fuel_conductivity
block = 3

# General Mechanics Types
# ==============================================================

[./hydrostatic_stress]
block = 3
type = MaterialTensorAux
tensor = stress
variable = hydrostatic_stress
quantity = hydrostatic
execute_on = timestep_begin  # VERA_MODIFIABLE as auxkernels_hydrostatic_stress_execute_on

[./hoop_stress]
type = MaterialTensorAux
tensor = stress
variable = hoop_stress
index = 2
execute_on = timestep_begin  # VERA_MODIFIABLE as auxkernels_hoop_stress_execute_on

[./radial_stress]
type = MaterialTensorAux
tensor = stress
variable = radial_stress
index = 0
execute_on = timestep_begin  # VERA_MODIFIABLE as auxkernels_radial_stress_execute_on

[./axial_stress]
type = MaterialTensorAux
tensor = stress
variable = axial_stress
index = 1
execute_on = timestep_begin  # VERA_MODIFIABLE as auxkernels_axial_stress_execute_on

[./radial]
type = MaterialTensorAux
tensor = stress
variable = radial_strain
quantity = radial
point1 = '0, 0, 0'
point2 = '1, 0, 0'
execute_on = timestep_begin  # VERA_MODIFIABLE as auxkernels_radial_execute_on

[./axial]
type = MaterialTensorAux
tensor = stress
variable = axial_strain
quantity = axial
# what is this and why are all three the same.
point1 = '0, 0, 0'
point2 = '0, 1, 0'
execute_on = timestep_begin  # VERA_MODIFIABLE as auxkernels_axial_execute_on

[./hoop]
type = MaterialTensorAux
tensor = stress
variable = hoop_strain
quantity = hoop
# what is this and why are all three the same.
point1 = '0, 0, 0'
point2 = '0, 0, 1'
execute_on = timestep_begin  # VERA_MODIFIABLE as auxkernels_hoop_execute_on

[./elastic_radial_strain]
type = MaterialTensorAux
tensor = elastic_strain
variable = radial_strain
index = 0
execute_on = timestep_end

[./elastic_axial_strain]
type = MaterialTensorAux
tensor = elastic_strain
variable = axial_strain
index = 1
execute_on = timestep_end

[./elastic_hoop_strain]
type = MaterialTensorAux
tensor = elastic_strain
variable = hoop_strain
index = 2
execute_on = timestep_end

[...]
[/vonmises]
type = MaterialTensorAux
tensor = stress
variable = vonmises
quantity = vonmises
execute_on = timestep_begin

#VERA_MODIFIABLE as auxkernels_vonmises_execute_on

[...]
[/creep_strain_mag]
type = MaterialTensorAux
tensor = creep_strain
time = creep_strain_mag
variable = creep_strain_mag
quantity = plastic strainmag
execute_on = timestep_begin
# block = 1

#VERA_MODIFIABLE as auxkernels_creep_strain_mag_execute_on

[...]
[/creep_strain_radial]
type = MaterialTensorAux
tensor = creep_strain
variable = creep_strain_radial
index = 0
execute_on = timestep_end

#VERA_MODIFIABLE as auxkernels_creep_strain_radial_execute_on

[...]
[/creep_strain_axial]
type = MaterialTensorAux
tensor = creep_strain
variable = creep_strain_axial
index = 1
execute_on = timestep_end

#VERA_MODIFIABLE as auxkernels_creep_strain_axial_execute_on

[...]
[/creep_strain_hoop]
type = MaterialTensorAux
tensor = creep_strain
variable = creep_strain_radial
index = 2
execute_on = timestep_begin

# ==============================================================
# CASL Tiamat - Inline
# ==============================================================
[/casl_interpolated_power]
type = CASL_MOOSE_AK_TimeInterpolatedFissionRate
old_power_name = casl_old_fission_rate
ew_power_name = casl_new_fission_rate
casl_time_values = casl_time_values
multiplier = 1.0
print_debug = false
execute_on = timestep_begin

# ==============================================================
# Other General Types
# ==============================================================
[/axial_burnup]
type = SpatialUserObjectAux
block = 3
variable = axial_burnup
execute_on = timestep_begin
user_object = axial_burnup

[/axial_temperature]
type = SpatialUserObjectAux
block = 3
variable = axial_temperature
execute_on = timestep_begin
user_object = axial_temperature

[/gap_distance]
type = PenetrationAux
variable = gap_distance
boundary = 10
paired_boundary = 5

[/cumulative_damage_index]
type = CumulativeDamageIndex
variable = cumulative_damage_index
burnup = burnup
temp = temp
hoop_stress = hoop_stress
yield_stress = 240e6
clad_type = 'Zr4'
block = 1
execute_on = timestep_end
[/]
[#] # ==================================================== #
[#] # Mechanical and Thermal Contact #
[#] # ==================================================== #
[Contact]
{/pellet_clad_mechanical}
master = 5
slave = 10
penalty = 1e14
normalize_penalty = true
normal_smoothing_distance = 0.1
model = frictionless
formulation = kinematic
system = Constraint
[/]
[ThermalContact]
{/thermal_contact}
type = GapHeatTransferLWR
variable = temp
master = 5
slave = 10
roughness_coef = 3.2
roughness_fuel = 1.8e-06
roughness_clad = 8.0e-07
jump_distance_model = KENNARD
plenum_pressure = plenum_pressure
contact_pressure = contact_pressure
initial_moles = initial_moles
initial_gas_fraction = '1.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00' #VERA_MODIFIABLE as thermalcontact_initial_gas_fraction
gas_released = fis_gas_released
tangential_tolerance = 1.0e-6
normal_smoothing_distance = 0.1
quadrature = true
order = SECOND
[/]
[BCs]
{/no_x_all}
type = DirichletBC
variable = disp_x
boundary = 12
value = 0.0
[/]
{/no_y_fuel_bottom}
type = DirichletBC
variable = disp_y
boundary = 1020
value = 0.0
[/]
{/no_y_clad_bottom}
type = DirichletBC
variable = disp_y
boundary = 1
value = 0.0
[/]
{/clad_coolant_surface}
type = ConvectiveFluxFunction
coefficient = 1e5
coefficient_function = 1.0e6
T_infinity = coolant_temperature
aux_var = 'casl_clad_surface_temperature'
boundary = '2'
variable = temp
[/]
{/convective_clad_surface_bottom} # apply convective boundary to clad outer
type = ConvectiveFluxBC
boundary = '1 3'
variable = temp
rate = 38200.0 #convection coefficient (h)
initial = 565.0
final = 585.0
duration = 1.0e4 #duration of initial power ramp
[/]
{/Pressure}
{/coolantPressure}
boundary = '1 2 3'
factor = 15.5132e6
function = coolant_pressure_ramp
[/]
{/PlenumPressure}
boundary = '9'
initial_pressure = 1.0e5
startup_time = 0
R = 8.314462
output_initial_moles = initial_moles
temperature = ave_temp_interior
volume = gas_volume
material_input = fis_gas_released
output = plenum_pressure

Standalone BISON Fuel Performance Results for Watts Bar Unit 1, Cycles 1-3

`#> CLAD_SURFACE
[./right] #>PURGED FROM STANDALONE CASES
  type = CASL_MOOSE_MK_AuxVarDirichletBC
  variable = Temp
  boundary = 2
  aux_var = 'casl_clad_surface_temperature'

# Specification of Material Properties

[Material]
[./fuel_thermal]
  type = UO2Therm
  block = 3
  temp = Temp
  burnup = burnup

[./fuel_swelling]
  type = VSwellingUO2
  block = 3
  temp = Temp
  burnup = burnup
  total_densification = 0.005

[./fuel_mech]
  type = MechUO2
  block = 3
  temp = Temp
  burnup = burnup
  fission_rate = casl_fission_rate for TIAMAT, fission_rate for BISON_CASL
  youngs_modulus = 2.e11
  poissons_ratio = .345
  thermal_expansion = 10e-6
  grain_radius = 2.50e-06
  oxy_to_metal_ratio = 2.0
  max_its = -
  output_iteration_info = false
  model_thermal_expansion = true
  model_swelling = true
  name_swelling_model = fuel_swelling
  otherwise
    model_relocation = true
    name_relocation_model = fuel_relocation
    model_craw = false
    matpro_youns_modulus = true
    matpro_poissons_ratio = true
    dep_matl Props = deltat_v0_bd

[./fuel_relocation]
  type = RelocationUO2
  model = ESCORE
  block = 3
  burnup = burnup
  q = q
  diameter = 0.008192
  gap = 0.000168
  relocation_activation1 = 16404
  burnup_relocation_stop = 0.03

[./clad_thermal]
  type = ThermalZry
  block = 1
  temp = Temp

[./clad_solid_mechanics]
  type = MechZry
  block = 1
  temp = Temp
  fast_neutron_flux = fast_neutron_flux
  fast_neutron_fluence = fast_neutron_fluence
  youngs_modulus = 7.5e10
  poissons_ratio = 0.3
  thermal_expansion = 5.0e-6
  max_its = 50
  material_type = 0
  absolute_tolerance = 1e-12
  relative_tolerance = 1e-5

[./clad_solid_mechanics]
  stress_free_temperature = 523
  materials_clad_solid_mechanics_stress_free_temperature (omitted if BISON_CASL)
  model_primary_creep = true
  materials_clad_solid_mechanics_model_primary_creep (omitted otherwise)
  model_thermal_creep = true
  materials_clad_solid_mechanics_model_thermal_creep (omitted otherwise)
  model_thermal_growth = true
  materials_clad_solid_mechanics_model_thermal_growth (omitted otherwise)
  model_thermal_expansion = true
  materials_clad_solid_mechanics_model_thermal_expansion (omitted otherwise)
  output_iteration_info = false
  model_elastic_modulus = true
  materials_clad_solid_mechanics_model_elastic_modulus

#VERA_MODIFIABLE as materials_fuel_swelling_total_densification
#VERA_DEFINED as materials_fuel_mech_grain_radius
#VERA_MODIFIABLE as materials_fuel_mech_max_its (omitted otherwise)
#VERA_MODIFIABLE as materials_fuel_mech_output_iteration_info
#VERA_MODIFIABLE as materials_fuel_mech_model_swelling
#VERA_MODIFIABLE as materials_fuel_mech_model_relocation
#VERA_MODIFIABLE as materials_fuel_mech_model_craw
#VERA_MODIFIABLE as materials_fuel_relocation_q
#VERA_MODIFIABLE as materials_fuel_relocation_relocation_activation1
#VERA_MODIFIABLE as materials_fuel_relocation_burnup_relocation_stop
#VERA_MODIFIABLE as materials_clad_solid_mechanics_absolute_tolerance
#VERA_DEFINED as materials_clad_solid_mechanics_stress_free_temperature
#VERA_MODIFIABLE as materials_clad_solid_mechanics_model_primary_creep
#VERA_MODIFIABLE as materials_clad_solid_mechanics_model_thermal_creep
#VERA_MODIFIABLE as materials_clad_solid_mechanics_model_thermal_growth
#VERA_MODIFIABLE as materials_clad_solid_mechanics_model_thermal_expansion
#VERA_MODIFIABLE as materials_clad_solid_mechanics_model_elastic_modulus

---

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cold_work_factor = 4.812700e-02
#VERA_MODIFIABLE as materials_clad_solid_mechanics_cold_work_factor
(omitted otherwise)
oxxygen_concentration = 0.0
#VERA_MODIFIABLE as materials_clad_solid_mechanics_oxygen_concentration (omitted otherwise)

# ==============================================================
# User Objects for Output, Data Transfers, Time Marching...
# ==============================================================

[UserObjects]
[./casl_time_values]
type = CASL_MOOSE_GUO_TimeValues
initial_old_time = 0.0
initial_new_time = 1.0
[../]
[./pbz]
type = PelletBrittleZone
block = 3
pellet_id = pellet_id
temp = temp
pellet_radius = number_pellets = 1
extecution_on = linear
[../]
[./casl_average_fission_rate]
variable = casl_fission_rate
type = LayeredAverage
block = 3
direction = y
bounds =
[../]
[./axial_fission_rate]
variable = fission_rate
type = LayeredAverage
block = 3
direction = y
bounds =
[../]
[./axial_temperature]
variable = temp
type = LayeredAverage
block = 3
direction = y
bounds =
[../]
[./axial_burnup]
variable = burnup
type = LayeredAverage
block = 3
direction = y
bounds =
[../]
[./axial_surface_temperature]
variable = temp
type = LayeredSideAverage
boundary = 2
direction = y
bounds =
#VERA_DEFINED
use_displaced_mesh = 0
[../]

Standalone BISON Fuel Performance Results for Watts Bar Unit 1, Cycles 1-3

```
[./rod_avg_fast_fluence]
type = LayeredSideAverage
boundary = 2
variable = fast_neutron_fluence
direction = y
num_layers = 1
use_displaced_mesh = 0
[/]
[./casl_clad_surface_heat_flux]
type = LayeredSideFluxAverage
variable = temp
boundary = 2
direction = y
bounds =
  diffusivity = thermal_conductivity
[/]
[./integral_temperature]
type = LayeredAverage
block = 3
variable = temp
direction = y
num_layers = 1
[/]
[./integral_burnup]
type = LayeredAverage
block = 3
variable = burnup
direction = y
num_layers = 1
[/]

[]
[Dampers]
[./limitT]
type = MaxIncrement
max_increment = 20.0
variable = temp
[/]

# ===========
# Solver Options
# ====================================================
[Executioner]
type = Transient
solve_type = 'PJFNK'
petsc_options = '-pc_type_asm'  #VERA_MODIFIABLE as executioner_petsc_options (omitted otherwise)
petsc_options_iname = '-pc_type' - 'pc_factor_mat_solver_package'
petsc_options_value = 'lu' 'superlu_dist'  #VERA_MODIFIABLE as executioner_petsc_options_value #RECOMMENDED BY DANIELLE
line_search = 'none'  #VERA_MODIFIABLE as executioner_line_search
verbose = false  #VERA_MODIFIABLE as executioner_verbose

# controls for linear iterations
l_max_its = 100
l_tol = 8e-3  #VERA_MODIFIABLE as executioner_l_max_its
l_tol = 0.0001
l_abs_tol = 1e-10  #VERA_MODIFIABLE as executioner_l_tol

# controls for nonlinear iterations
nl_max_its = 15
nl_rel_tol = 0.0001
nl_abs_tol = 1e-10  #VERA_MODIFIABLE as executioner_nl_max_its
#VERA_MODIFIABLE as executioner_nl_rel_tol
#VERA_MODIFIABLE as executioner_nl_abs_tol

# ==============================================================
# Time Step Control
# ==============================================================
[start_time = -100
end_time = 6e+07
num_steps = 1
dtmax =
[/]
[./TimeStepper]
type = IterationAdaptiveDT
max_step = 100.0
optimal_iterations = 100
linear_iteration_ratio = 100
force_step_every_function_point = true
	timestep_limiting_function = linear_heat_rate_profile
[/]

# Quadrature block needs to be activated if you are using higher order elements (i.e. QUAD in 2D-RZ)
[./Quadrature]
order = FIFTH
side_order = SEVENTH
[/]

[]
# Postprocessors: for internal averages and output.
[Postprocessors]
# Required for Fission Gas Release Models
[./ave_temp_interior]
type = SideAverageValue
boundary = 9
variable = temp
execute_on = linear
outputs = 'exodus'
```

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...
fission_rate = casl_fission_rate
block = 3

[./rod_input_power]
  * Watts
  type = FunctionValuePostprocessor
  function = linear_heat_rate_profile
  scale_factor = 3.6576 # rod height

[./average_fission_rate]
  type = AverageFissionRate
  rod_ave_lin_pow = linear_heat_rate_profile
  outputs = 'exodus'

[./volume_casl_fission_rate] #>>> PURGED FROM STANDALONE CASES
  type = ElementIntegralVariablePostprocessor
  variable = 'casl_fission_rate'
  execute_on = custom

[./casl_max_rod_temperature] #>>> PURGED FROM STANDALONE CASES
  * for global convergence checking
  type = NodalMaxValue
  variable = temp
  block = 3

[./clad_hoop_stress_max]
  type = ElementExtremeValue
  value_type = MAX
  variable = hoop_stress
  block = 1
  outputs = 'csv'

[./clad_hoop_stress_min]
  type = ElementExtremeValue
  value_type = MIN
  variable = hoop_stress
  block = 1
  outputs = 'csv'

[./fuel_centerline_temp]
  type = NodalExtremeValue
  variable = temp
  boundary = 12
  outputs = 'csv'

[./gap_distance]
  type = ElementExtremeValue
  value_type = MAX
  variable = gap_distance
  outputs = 'csv'

[./average_clad_temp]
  type = ElementAverageValue
  block = 1
  variable = temp

[./max_clad_temp]
  type = ElementExtremeValue
  value_type = MAX
  variable = temp
  block = 1

[./min_clad_temp]
  type = ElementExtremeValue
  value_type = MIN
  variable = temp
  block = 1

[./CDI]
  type = ElementAverageValue
  variable = cumulative_damage_index
  outputs = 'csv'

[./burnup]
  type = ElementAverageValue
  variable = burnup

[ Outputs]
  output_initial = true
  csv = true
  exodus = true
  file_base = #BISON_CASL as outputs_file_base (omitted otherwise)
  interval = 1
  [./console]
- Stand-alone Bison-CASL with power history, shape, and clad temperatures from a VERA-CS HDF5 output file
- Stand-alone Bison-CASL with unspecified power history, shape, and clad temperature BCs
- Stand-alone Bison-CASL with unspecified power history, shape, and coolant channel BCs

Assumptions embedded in this input template

1. There is one fuel type:
   - UO2
     - single density (VERA_DEFINED)
     - single enrichment (VERA_DEFINED)
2. There is one clad type:
   - Zircaloy
     - single density (VERA_DEFINED)
     - single enrichment (VERA_DEFINED)
3. The fuel is modeled as a single smeared mesh
   - The axial edit bounds in the VERA input file define the minimum axial mesh and BOUNDS for post-processing
   - The internal mesh generator is used, but the axial and radial mesh in the fuel and cladding can be specified by the user (VERA_MODIFIABLE)
4. The current template is limited to 2D-RZ PWR standard fuel rod models. Future work will be necessary to include annular fuel, IFBA coating, and BWR rods.