Continued Verification of MOOSE Structural Mechanics Tools for Modeling Core Bowing Phenomena in Fast Reactors

Nuclear Science and Engineering Division
About Argonne National Laboratory

Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. The Laboratory's main facility is outside Chicago, at 9700 South Cass Avenue, Argonne, Illinois 60439. For information about Argonne and its pioneering science and technology programs, see www.anl.gov.

DOCUMENT AVAILABILITY


Reports not in digital format may be purchased by the public from the National Technical Information Service (NTIS):

U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Rd
Alexandria, VA 22312
www.ntis.gov
Phone: (800) 553-NTIS (6847) or (703) 605-6000
Fax: (703) 605-6900
Email: orders@ntis.gov

Reports not in digital format are available to DOE and DOE contractors from the Office of Scientific and Technical Information (OSTI):

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
www.osti.gov
Phone: (865) 576-8401
Fax: (865) 576-5728
Email: reports@osti.gov

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor UChicago Argonne, LLC, nor any of their employees or officers, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of document authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, Argonne National Laboratory, or UChicago Argonne, LLC.
Continued Verification of MOOSE Structural Mechanics Tools for Modeling Core Bowing Phenomena in Fast Reactors

prepared by
Nicholas Wozniak\textsuperscript{1} and Emily Shemon\textsuperscript{2}

\textsuperscript{1}Experimental Operations and Facilities Division, Argonne National Laboratory
\textsuperscript{2}Nuclear Science and Engineering Division, Argonne National Laboratory

July 31, 2022
Abstract

Under the U.S. Department of Energy Office of Nuclear Energy’s Advanced Modeling and Simulation (NEAMS) Program, an integrated multiphysics approach is being developed to model the core bowing phenomena important to liquid metal-cooled fast reactors. Core bowing is an important passive safety mechanism whereby increased power (which leads to temperature and flux gradients) influences the core to bow into less reactive configurations when the restraint system is properly designed. The phenomenon includes a complex interplay of radiation transport, duct temperature calculations involving fluid flow and heat transfer, and thermo-mechanical responses to the induced temperature and flux gradients. Structural material properties are also important to determining inelastic response to longer term flux gradients which cause irradiation creep and swelling. While core bowing provides a strong negative reactivity feedback when the restraint system is designed properly, it also results in additional forces between assemblies which increase the loads required to extricate them during refueling or control rod movement. Therefore, the restraint system must be designed with these tradeoffs in mind.

The first stage of the work, which commenced in FY21 and continues through FY22, assesses thermo-mechanical modeling tools for producing core bowing predictions consistent with conventional tools. The Multiphysics Object Oriented Simulation Environment (MOOSE) Tensor Mechanics and Contact Modules are employed. This status report describes work on additional thermo-mechanical benchmark verification problems with increased complexity from the examples demonstrated in FY21.

Several benchmark verification examples were selected from the IAEA verification and validation report. These examples involve clusters of ducts representative of a sector of a hexagonal reactor core which bow into each other and cause contact and load pad elevations, as well as single ducts subjected to irradiation fields undergoing swelling and subsequent bowing. The MOOSE-based results were compared to both IAEA benchmark participants’ results, analytic equations as available, and NUBOW-3D, a beam model code developed by Argonne National Laboratory. In every case, the MOOSE results agreed with other simulations results, providing additional verification basis of the tools for this particular physics application.
Contents

Abstract ................................................................................................................................................. i
Contents ................................................................................................................................................... ii
List of Figures ........................................................................................................................................... iii
List of Tables ........................................................................................................................................... v
1 Introduction ......................................................................................................................................... 1
2 Verification Problems ............................................................................................................................. 2
  2.1 Thermo-Mechanical Bowing in a Sector of a Core: IAEA Verification Problem 3A (VP3A) .... 3
    2.1.1. VP3A Symmetric Sector .......................................................................................................... 5
    2.1.2. VP3A Full Sector ..................................................................................................................... 8
  2.2 Thermo-Mechanical Bowing in a Sector of a Core: IAEA Verification Problem 3B (VP3B)
      Symmetric ....................................................................................................................................... 13
  2.3 Irradiation Swelling: IAEA Verification Problem 7 (VP7) ............................................................. 16
    2.3.1. VP7A Duct 67 ....................................................................................................................... 17
    2.3.2. VP7B Duct 100 .................................................................................................................... 19
  2.4 Irradiation Swelling with More Complex Material Definition ..................................................... 21
  2.5 Summary of Examples .................................................................................................................... 24
3 Future Work .......................................................................................................................................... 27
  3.1 IAEA Verification Problem 3B Full Sector .................................................................................... 27
  3.2 IAEA Verification Problem 4 (VP4) ............................................................................................... 27
  3.3 IAEA Verification Problem 5 (VP5) ............................................................................................... 28
  3.4 MOOSE Physics Module Development ......................................................................................... 29
  3.5 Assessment of Additional Physics ................................................................................................. 29
4 Summary .............................................................................................................................................. 30
5 Acknowledgements .............................................................................................................................. 31
6 References ............................................................................................................................................ 31
List of Figures

Figure 2-1. IAEA VP3A (left) core layout showing the free boundary around the sector with red dashed lines and the bowing direction with a blue arrow, (right) sector removed from the full core (adapted from [6] © IAEA) ................................................................. 4

Figure 2-2. Schematic representing the axial thermal gradient.................................................................................. 4

Figure 2-3. VP3A symmetric model mesh, with the (left) top-down view at the ACLP elevation and (right) isometric view showing the top portion of the ducts ........................................................................................................ 5

Figure 2-4. Visualization for the (left) temperature gradient and (right) displacement results........................... 6

Figure 2-5. VP3A duct deflection results comparing MOOSE with NUBOW and IAEA results ...................... 7

Figure 2-6. Example of duct 3 ACLP sidesets showing (left) all faces of the ACLP grouped into one sideset and (right) a single face assigned to its own sideset ..................................................................................... 8

Figure 2-7. VP3A symmetric model mesh, with the (left) top-down view at the ACLP elevation and (right) isometric view showing the top portion of the ducts ................................................................. 9

Figure 2-8. Visualization for the (left) temperature gradient and (right) displacement results ................... 10

Figure 2-9. Comparison of the bowing displacement values between ducts 3 and 4 for the (left) X direction and (right) Y direction ................................................................................................................. 10

Figure 2-10. Comparison of the bowing displacement values between ducts 10 and 12 for the (left) X direction and (right) Y direction ............................................................................................................. 11

Figure 2-11. VP3A duct deflection results comparing MOOSE with NUBOW and IAEA ............................... 11

Figure 2-12. IAEA VP3B (left) core layout showing the free boundary around the sector with red dashed lines and the bowing direction with a blue arrow, (right) sector removed from the full core (adapted from [6] © IAEA). ........................................................................................................ 13

Figure 2-13. VP3A symmetric model mesh, with the (left) top-down view at the ACLP elevation and (right) isometric view showing the top portion of the ducts ................................................................. 14

Figure 2-14. Visualization for the (right) temperature gradient and (left) displacement results................. 15

Figure 2-15. VP3B duct deflection results comparing MOOSE with NUBOW and IAEA .............................. 15

Figure 2-16. IAEA verification problem 5, 6, and 7 core, showing the damage dose field with a blue circle and the ducts examined in VP7A and VP7B circled in red. (Adapted from [6] © IAEA) .............................................................................................................. 17

Figure 2-17. VP7A damage dose distribution (left) around cross section at the core mid height location and (right) along the entire duct in the axial direction .......................................................... 18

Figure 2-18. VP7A duct displacement for X and Y directions comparing MOOSE, Analytical, and IAEA results ........................................................................................................................................ 19

Figure 2-19. VP7B damage dose distribution (left) around cross section at the core mid height location and (right) along the entire duct in the axial direction ........................................................................ 20

Figure 2-20. VP7B duct displacement for X and Y directions comparing MOOSE and IAEA results ....... 21

Figure 2-21. Neutron flux distribution along the axial location of the duct ....................................................... 22

Figure 2-22. Irradiation free bowing displacement comparing MOOSE with NUBOW results .................. 23

Figure 3-1. IAEA VP4 core layout showing the restraint ring in black, symmetry boundary with red dashed lines, and the bowing direction with blue arrows (adapted from [6] © IAEA) ........ 28
Figure 3-2. IAEA VP5 core layout showing the radius for the damage dose with a circle around the core (Adopted from [6] © IAEA)
List of Tables

Table 2.1. Common duct geometry used in IAEA verification problems 3A and 3B ......................... 3
Table 2.2. VP3A symmetric model resultant duct deflection (mm) at the ACLP and TLP for ducts 1, 3, and 10.......................................................................................................................... 7
Table 2.3. VP3A full sector model resultant duct deflection (mm) at the ACLP and TLP for ducts 1, 3, and 10...................................................................................................................................... 12
Table 2.4. VP3B symmetric model resultant duct deflection (mm) at the ACLP and TLP for ducts 1, 2, 8, 9, and 20....................................................................................................................................... 16
Table 2.5. VP7A model duct deflection (mm) at the ACLP and TLP comparing MOOSE with the IAEA results and analytical solution results ......................................................................................................................... 19
Table 2.6. VP7B model duct deflection (mm) at the TLP comparing MOOSE with the IAEA results .... 21
Table 2.7. Irradiation swelling example bowing results (mm) at the top of the active core, the ACLP, and TLP locations after 1157.4 days................................................................................................................................. 23
Table 2.8. Summary of the example problems for MOOSE assessment ................................................ 25
1 Introduction

Under the U.S. Department of Energy Office of Nuclear Energy’s Advanced Modeling and Simulation (NEAMS) Program [1], an integrated multiphysics approach is being developed to model the core bowing phenomena important to liquid metal-cooled fast reactors. Core bowing is an important passive safety mechanism whereby increased power (which leads to temperature and flux gradients) influences the core to bow into less reactive configurations when the restraint system is properly designed. The phenomenon includes a complex interplay of radiation transport, duct temperature calculations involving fluid flow and heat transfer, and thermo-mechanical responses to the induced temperature and flux gradients. Structural material properties are also important to determining inelastic response to longer term flux gradients which cause irradiation creep and swelling. While core bowing provides a strong negative reactivity feedback when the restraint system is designed properly, it also results in additional forces between assemblies which increase the loads required to extricate them during refueling or control rod movement. Therefore, the restraint system must be designed with these tradeoffs in mind.

The first stage of the work, which commenced in FY21 [2] and continues through FY22, assesses thermo-mechanical modeling tools for producing core bowing predictions consistent with conventional tools. The Multiphysics Object Oriented Simulation Environment (MOOSE) [3] Tensor Mechanics [4] and Contact Modules [5] are employed. This status report describes work on additional thermo-mechanical benchmark verification problems with increased complexity from the examples demonstrated in FY21.

Later stages of this work (to follow verification of the thermo-mechanical physics modules for handling contact and irradiation effects which have not yet been robustly verified on large scales), will incorporate additional MOOSE-based fluid flow, heat transfer, and reactor physics into a multiphysics workflow to address the coupling feedback inherent in this phenomenon.
2 Verification Problems

Several core bowing benchmarks are taken from the International Working Group on Fast Reactors (IWGFR) verification and validation report which was organized and openly published by the International Atomic Energy Agency (IAEA) [6]. These benchmarks are limited to thermo-mechanical response calculation only (other parameters are provided as fixed input) but include thermal gradients, irradiation-induced creep and swelling, and contact phenomena. The IAEA examples provide a database ranging from simple to increasingly complex problems which can be systematically analyzed and used to verify MOOSE-based thermo-mechanical physics solvers. Numerous benchmark participants contributed solutions using a variety of codes and approaches.

The benchmark problems selected for this report were intended to exercise larger scale problems with contact as well as small problems with irradiation swelling, neither of which had been examined in detail in FY21. The MOOSE simulation results are compared with NUBOW-3D [7], which is a fast reactor core modeling code using beam element formulation, IAEA participants’ results, and analytical results where available. Beam element formulation results calculate the displacement at the beam centerline, and usually do not consider cross-section distortion or twisting, whereas the 3D solid model in MOOSE can account for all those factors. Thus, comparing the results presents slight complications. To keep results consistent, the effective centerline displacement is found by taking an average of the 6 corner displacements around the duct, since the solid model meshes only the duct wall and not the interior of the duct. Therefore, some differences in the results are expected since the MOOSE results consider cross-section distortion and twisting effects when outputting the duct corner displacements.

The verification problems (VPs) studied in this work follow:

- VP3A and VP3B, which include core sectors undergoing thermal bowing of a duct into the core and include duct-to-duct contact interactions,
- VP7A and VP7B, which examine a single duct undergoing free bowing due to irradiation swelling with a simple material,
- A free bowing example due to irradiation swelling with a thermal and flux gradient and a more complex swelling material property.

Common geometric parameters were used for the duct sizes and gaps among the verification problems and are shown in Table 2.1.
Table 2.1. Common duct geometry used in IAEA verification problems 3A and 3B

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duct Corner-to-corner</td>
<td>150</td>
</tr>
<tr>
<td>Assembly Length</td>
<td>4000</td>
</tr>
<tr>
<td>Wall Thickness</td>
<td>3</td>
</tr>
<tr>
<td>Gap</td>
<td>6</td>
</tr>
<tr>
<td>Load pad Pad Thickness (ACLP)</td>
<td>2.75</td>
</tr>
<tr>
<td>Pad Thickness (TLP)</td>
<td>N/A</td>
</tr>
<tr>
<td>Gap</td>
<td>0.5</td>
</tr>
<tr>
<td>Axial Position Core Bottom</td>
<td>1500</td>
</tr>
<tr>
<td>Core Top</td>
<td>2500</td>
</tr>
<tr>
<td>Above Core Load Pad (ACLP)</td>
<td>3000</td>
</tr>
<tr>
<td>Top Load Pad (TLP)</td>
<td>4000</td>
</tr>
</tbody>
</table>

2.1 Thermo-Mechanical Bowing in a Sector of a Core: IAEA Verification Problem 3A (VP3A)

IAEA Verification Problem 3A examined a 60° sector of a hexagonal-assembly core. In this configuration, the center duct thermally bows into the top 1/6 sector and has a free boundary around the sector as shown in red dashed lines in Figure 2-1. The center duct has a thermal gradient identical to VP1 [2] while all the other ducts remain at 400 °C. The gradient is shown schematically here for reference in Figure 2-2. The duct dimensions and load pad elevations are given in Table 2.1. To summarize, the ducts are 4000 mm long, with above core load pads (ACLPs) located 3000 mm above the nozzle (located at 0 mm), and top load pads (TLPs) located at 4000 mm. The active core for duct 1 starts at 1500 mm and extends to 2500 mm. The duct pitch was set to 138.9 mm with 6 mm gap between duct walls and 0.5 mm gap between the ACLPs. The TLPs had the same 6 mm gap as the duct wall.
Figure 2-1. IAEA VP3A (left) core layout showing the free boundary around the sector with red dashed lines and the bowing direction with a blue arrow, (right) sector removed from the full core (adapted from [6] © IAEA).

Figure 2-2. Schematic representing the axial thermal gradient
Since the dimensions were provided at room temperature, the model was created with dimensions at 400 °C to consider the initial warm up phase from 20 °C and grid plate expansion, which increases the pitch and gaps. The core sector was meshed using CUBIT v15.5 [8]. To reduce computational expense, a symmetric model was set up with symmetry along the YZ plane; the symmetric sector model and results are shared in Section 2.1.1. A full sector model was also created to test the effects of contact and to ensure the symmetry results held in the full model, which are shared in Section 2.1.2.

2.1.1. VP3A Symmetric Sector

The VP3A symmetric sector model was created by cutting the full sector model in half along the YZ-plane and removing some ducts as shown in the mesh in Figure 2-3. Only ducts 1, 3, 10, and 11 were modeled because the IAEA report results show contact only between 1 and 3 at the TLP and between 3 and 10 at the ACLP. For computational efficiency, the ducts beyond 10, 11, and 12 were not included since they are at constant 400 °C, and ducts 10, 11, and 12 should not deflect far enough to close the gap between the outside ducts. The MOOSE Tensor Mechanics and Contact Modules were used to solve the problem. Contact was enforced at the ACLP and TLP with node-face contact using a frictionless, penalty contact. The model was defined as a transient simulation with the temperature applied incrementally over the pseudo-time steps from 0 to 1 incremented by 0.1s. The results were checked to confirm the assumption that certain ducts could be removed from the model without impact.

Figure 2-3. VP3A symmetric model mesh, with the (left) top-down view at the ACLP elevation and (right) isometric view showing the top portion of the ducts
The VP3A symmetric model results were imported to ParaView for visualization and shown along with the temperature gradient in Figure 2-5. Due to the larger temperature gradient across duct 1, duct 1 deflects toward duct 3 and makes contact at the TLP plane, which causes duct 3 to deflect towards and contact duct 10 at the ACLP due to the small gap. The resultant centerline deflections for ducts 1, 3, and 10 are plotted in Figure 2-5 by taking an average of the corner displacements around each duct. These deflections are compared with the calculation results from NUBOW-3D and the participant code results from the IAEA report [6]. The values of the displacements at the ACLP and TLP for the MOOSE, NUBOW and IAEA results along with the percentage difference between the MOOSE and NUBOW results are shown in Table 2.2. The values are all in good agreement, with MOOSE giving the maximum displacement of 8.60 mm at the TLP for duct 1 and NUBOW and the IAEA giving 8.55 mm and 8.54, respectively. The largest percentage difference is 3.3% at the duct 1 ACLP, with the overall TLP displacement matching exactly.

![Visualization for the (left) temperature gradient and (right) displacement results](image)

Figure 2-4. Visualization for the (left) temperature gradient and (right) displacement results
Figure 2-5. VP3A duct deflection results comparing MOOSE with NUBOW and IAEA results

Table 2.2. VP3A symmetric model resultant duct deflection (mm) at the ACLP and TLP for ducts 1, 3, and 10

<table>
<thead>
<tr>
<th>Location</th>
<th>Duct</th>
<th>IAEA</th>
<th>NUBOW</th>
<th>MOOSE</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACLP</td>
<td>1</td>
<td>0.88</td>
<td>0.90</td>
<td>0.93</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.94</td>
<td>0.93</td>
<td>0.92</td>
<td>-1.1</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.43</td>
<td>0.42</td>
<td>0.42</td>
<td>0</td>
</tr>
<tr>
<td>TLP</td>
<td>1</td>
<td>8.54</td>
<td>8.55</td>
<td>8.60</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.51</td>
<td>1.49</td>
<td>1.48</td>
<td>-0.7</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.65</td>
<td>0.63</td>
<td>0.63</td>
<td>0</td>
</tr>
</tbody>
</table>

This benchmark verifies the MOOSE physics modules (Tensor Mechanics, Contact) for a small cluster of assemblies undergoing thermal bowing along the corner direction of the hexagonal
assembly and contacting at load pads. Notable, reflective boundary conditions and a prior knowledge about which ducts would contact were used to substantially reduce the computational cost of the full sector problem. The next section describes attempts to perform the same simulation for the full sector (non-contacting ducts still removed).

2.1.2. VP3A Full Sector

The full sector mesh consists of all “important” ducts in the sector rather than cutting a symmetry plane along the YZ-axis. Analogous to the symmetric sector model, ducts which did not influence the bowing were removed from the model to reduce computational expense. In this model, ducts 1, 3, 4, 10, 11, and 12 were fully included. The mesh is shown in Figure 2-7. An additional complexity was encountered in meshing and defining sidesets for contact compared with the symmetry model in the previous subsection. Initially, the exterior faces of the ACLP and TLP were all combined into a single sideset for each load pad, as shown in Figure 2-6 where all the ACLP faces are grouped together. Instead, each load pad face was individually assigned to a sideset to avoid conflicting definitions between primary and secondary contact sidesets. For example, contact between duct 1 and 3 ACLP was defined with duct 1 as the primary and duct 3 as the secondary, while contact between duct 3 and 10 was defined with duct 3 as the primary and duct 10 as the secondary. Therefore, it seemed there was a conflict in the primary/secondary sideset definitions results in computational errors overriding contact pressure results. There also seemed to be an issue with sideset nodes defined in multiple contact pairs, such as duct 1 having a contact defined between ducts 3 and 4.

Figure 2-6. Example of duct 3 ACLP sidesets showing (left) all faces of the ACLP grouped into one sideset and (right) a single face assigned to its own sideset
The VP3A full sector model results were imported to ParaView for visualization and shown along with the temperature gradient in Figure 2-8. Due to the larger temperature gradient across duct 1, duct 1 deflects toward duct 3 and 4 making contact at the TLP plane. This contact causes ducts 3 and 4 to deflect towards and contact ducts 10 and 12, respectively, at the ACLP due to the small gap. A comparison of the duct bowing displacements in the X and Y axis directions is shown for ducts 3 and 4 in Figure 2-9 and ducts 10 and 12 in Figure 2-10. These figures show identical bowing behavior which preserves the symmetric bowed displacements assumed by the symmetric geometry and temperature distribution.

The resultant centerline deflections for ducts 1, 3, and 10 are plotted in Figure 2-11 by taking an average of the corner displacements around each duct. These deflections are compared with the calculation results from NUBOW-3D and the participant code results from the IAEA report [6]. The values of the displacements at the ACLP and TLP for the MOOSE, NUBOW and IAEA results along with the percentage difference between the MOOSE and NUBOW results are shown in Table 2.2. The values are all in good agreement, with MOOSE giving the maximum displacement of 8.60 mm at the TLP for duct 1 and NUBOW and the IAEA giving 8.55 mm and 8.54,
respectively. The percentage differences match the symmetric sector model since the displacements match between the full sector and the symmetric sector.

Figure 2-8. Visualization for the (left) temperature gradient and (right) displacement results

Figure 2-9. Comparison of the bowing displacement values between ducts 3 and 4 for the (left) X direction and (right) Y direction
Figure 2-10. Comparison of the bowing displacement values between ducts 10 and 12 for the (left) X direction and (right) Y direction.

Figure 2-11. VP3A duct deflection results comparing MOOSE with NUBOW and IAEA.
Table 2.3. VP3A full sector model resultant duct deflection (mm) at the ACLP and TLP for ducts 1, 3, and 10

<table>
<thead>
<tr>
<th>Location</th>
<th>Duct</th>
<th>IAEA</th>
<th>NUBOW</th>
<th>MOOSE</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACLP</td>
<td>1</td>
<td>0.88</td>
<td>0.90</td>
<td>0.93</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.94</td>
<td>0.93</td>
<td>0.92</td>
<td>-1.1</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>0.92</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.43</td>
<td>0.42</td>
<td>0.42</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>-</td>
<td>-</td>
<td>0.42</td>
<td>-</td>
</tr>
<tr>
<td>TLP</td>
<td>1</td>
<td>8.54</td>
<td>8.55</td>
<td>8.59</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.51</td>
<td>1.49</td>
<td>1.47</td>
<td>-1.3</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>1.47</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.65</td>
<td>0.63</td>
<td>0.63</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>-</td>
<td>-</td>
<td>0.63</td>
<td>-</td>
</tr>
</tbody>
</table>

This benchmark verifies the MOOSE physics modules (Tensor Mechanics, Contact) for a small cluster of assemblies undergoing thermal bowing along the corner direction of the hexagonal assembly and contacting at load pads. Notable results include matching the duct bowing behavior in the X and Y axis directions between ducts 3 and 4 and ducts 10 and 12, which should have the same Y direction bowing and symmetric X direction bowing based on the geometric definition of the benchmark. This is an important result because it shows MOOSE can preserve the assumed symmetric behavior of the bowing as duct 1 contacts ducts 3 and 4 without a symmetry boundary condition, showing that contact between multiple objects can be enforced accurately.

A very important finding regarding the node-to-face contact definition was discovered. Each contact definition required individual sidesets on each load pad face to be defined to avoid conflicts between nodes in sidesets which were defined in multiple contact pairs. Specifically, this means each duct requires a different sideset for each face of the load pad, i.e. 6 sidesets each for the ACLP and TLP for a total of 12 sidesets per duct. While this requirement did not pose issues for this benchmark, larger clusters of ducts and full core problems would require a much larger number of sidesets and contact pair definitions since prior knowledge about the load pad contact will not necessarily be known and should not be assumed for accurate simulation results. Future development work on the node-to-face contact algorithm should address this limitation and prevent the issues associated with the conflict that occurs currently when assigning a sideset to multiple contact pairs, specifically when assigning a sideset as a primary sideset in one pair and a secondary sideset in another. It is not currently known if this limitation exists within the Mortar contact method and will be examined in future studies. Development of a general contact capability, which would allow self-contact to be enforced between a single sideset and itself, would greatly facilitate
the setup of this type of problem, because this would allow the analyst to define a single sideset for all load pads and a single contact interaction involving that sideset.

2.2 Thermo-Mechanical Bowing in a Sector of a Core: IAEA Verification Problem 3B (VP3B) Symmetric

IAEA Verification Problem 3B examined a 120° sector of a core with the center duct thermally bowing into the sector and a free boundary around the sector, Figure 2-12. The center duct has a thermal gradient similar to VP3A but the orientation is rotated such that the duct bows across the flats. All the other ducts remain at 400 °C. The duct dimensions and load pad locations were the same as VP3A and are listed in Table 2.1.

![Figure 2-12. IAEA VP3B (left) core layout showing the free boundary around the sector with red dashed lines and the bowing direction with a blue arrow, (right) sector removed from the full core (adapted from [6] © IAEA).](image)

The core sector was meshed using CUBIT. Like VP3A, the model was created with dimensions at 400 °C to consider the initial warm up phase from 20 °C and grid plate expansion, which increases the pitch and gaps. The VP3B symmetric sector model was created by cutting the full model in half along the XZ-plane and removing ducts which do not have temperature gradients and are not contacted by other bowing ducts. Only ducts 1, 2, 8, 19, and 20 were modeled because the IAEA report results show contact only between 1 and 2 at the TLP and between 2, 8, 20 and 19 at the ACLP. For computational efficiency, the ducts beyond those mentioned were not included since they are at constant 400 °C and ducts 2, 8, 19, and 20 should not deflect far enough to close the gap between the outside ducts. The mesh is shown in Figure 2-13.
Contact was enforced at the ACLP and TLP with node-face contact using a frictionless, penalty contact. The model was defined as a transient simulation with the temperature applied incrementally over the pseudo-time steps from 0 to 1 incremented by 0.1s. The results were checked to confirm that removal of ducts in the sector was a valid assumption.

![Figure 2-13. VP3A symmetric model mesh, with the (left) top-down view at the ACLP elevation and (right) isometric view showing the top portion of the ducts](image)

The VP3A symmetric model results were imported to ParaView for visualization and shown along with the temperature gradient in Figure 2-14. Again, the temperature gradient across duct 1 causes deflection toward duct 2 and results in contact at the TLP plane. This contact causes duct 2 to deflect towards and contact duct 8 at the ACLP due to the small gap. Duct 8 deflects toward duct 20 and contacts at the ACLP. The resultant centerline deflections for ducts 1, 2, 8, and 20 are plotted in Figure 2-15 by taking an average of the corner displacements around each duct. The deflections are compared with the calculation results from NUBOW-3D and the participant code results from the IAEA report [6]. The values of the displacements at the ACLP and TLP for the MOOSE, NUBOW and IAEA along with the percentage difference between the MOOSE and NUBOW results are shown in Table 2.4. The values are all in good agreement, with MOOSE giving the maximum displacement of 8.09 mm at the TLP for duct 1 and NUBOW and the IAEA giving 8.08 mm and 8.10 mm, respectively. The largest difference between MOOSE and the NUBOW and IAEA results is the displacement of the ACLP at duct 1, with MOOSE giving a displacement of 0.68 mm and NUBOW and the IAEA giving 0.58 mm and 0.61 mm, respectively. While the difference is about 17%, the magnitude of the displacement is small, less than 1 mm. Another large visible difference is the displacement of duct 20 TLP, with MOOSE giving the maximum displacement of 0.45 mm and NUBOW and the IAEA giving 0.51 mm and 0.50 mm, respectively. The difference is about 10% but the magnitude of the displacement is only 0.05 mm. One possible cause for the large percent differences could be small differences in displacements at the contact regions which aren’t captured in the beam element codes but are in the solid model.
Another potential cause could be the mesh density and number of elements at the contact region being relatively small compared with VP3A, since the flat face in VP3B is cut in half at the symmetry plane. A full sector model and finer mesh at the contact region will be studied to provide a better insight into the contact behavior.

Figure 2-14. Visualization for the (right) temperature gradient and (left) displacement results

Figure 2-15. VP3B duct deflection results comparing MOOSE with NUBOW and IAEA
Table 2.4. VP3B symmetric model resultant duct deflection (mm) at the ACLP and TLP for ducts 1, 2, 8, 9, and 20

<table>
<thead>
<tr>
<th>Location</th>
<th>Duct</th>
<th>IAEA</th>
<th>NUBOW</th>
<th>MOOSE</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACLP</td>
<td>1</td>
<td>0.61</td>
<td>0.58</td>
<td>0.68</td>
<td>17.2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.34</td>
<td>1.32</td>
<td>1.29</td>
<td>-2.3</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.84</td>
<td>0.83</td>
<td>0.80</td>
<td>-3.6</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>0.17</td>
<td>0.17</td>
<td>0.15</td>
<td>-11.8</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0.33</td>
<td>0.34</td>
<td>0.31</td>
<td>-8.5</td>
</tr>
<tr>
<td>TLP</td>
<td>1</td>
<td>8.10</td>
<td>8.05</td>
<td>8.09</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.20</td>
<td>2.16</td>
<td>2.12</td>
<td>-1.9</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1.25</td>
<td>1.24</td>
<td>1.20</td>
<td>-3.2</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>0.25</td>
<td>0.26</td>
<td>0.23</td>
<td>-11.5</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0.50</td>
<td>0.51</td>
<td>0.46</td>
<td>-9.8</td>
</tr>
</tbody>
</table>

This benchmark verifies the MOOSE physics modules (Tensor Mechanics, Contact) for a small cluster of assemblies undergoing thermal bowing along the flat-to-flat direction of the hexagonal assembly and contacting at load pads. It should be noted that reflective boundary conditions and a prior knowledge about the bowing were used to substantially reduce the computational cost of the full sector problem. No attempts were made to perform the full sector simulation.

2.3 Irradiation Swelling: IAEA Verification Problem 7 (VP7)

VP7 examines the free bowing of ducts 67 and 100 from the same core as VP3A, with irradiation induced swelling replacing the thermal gradient. The core is shown in Figure 2-16. The damage dose field is indicated by the interior of the blue circle and defined in dpa by a parabolic distribution in the radial direction:

\[
D = D_0 \left(1 - \frac{r^2}{a^2}\right) \sin\left(\frac{\pi \bar{Z}}{L}\right) \quad 0 \leq \bar{Z} \leq L
\]

\(D_0\) is the center dose at 100 dpa, \(r\) is the radial location of any point on a duct at 20 °C, \(a\) is the radius at zero swelling equal to 697 mm, \(\bar{Z}\) is the distance from the core bottom, and \(L\) is the length of the core region. The damage dose for any point beyond the radius is 0 dpa. VP7A examines
duct 67 and VP7B examines duct 100, which will be discussed in the subsections below. The swelling strain is given as a volumetric fraction increase based on the equation:

\[ S(\%) = 0.03 \left( \frac{D}{100} \right) \]

The swelling strain is calculated in MOOSE with the `ComputeVolumetricEigenstrain` and a `ParsedMaterial` property value with the equation for the swelling strain added as the function. The damage dose was calculated with a `ParsedFunction` with spatial parameters for the locations of the duct element nodes in radial and axial direction.

Figure 2-16. IAEA verification problem 5, 6, and 7 core, showing the damage dose field with a blue circle and the ducts examined in VP7A and VP7B circled in red. (Adapted from [6] © IAEA)

2.3.1. VP7A Duct 67

VP7A examines the free bowing behavior of duct 67 due to swelling induced by the damage dose field shown in Figure 2-16. Due to its location on the dose field boundary, Duct 67 has 180° symmetry behavior across the diagonal corners. Also due to the symmetry, an analytical solution for the damage dose exists and is provided by the IAEA report [6]. Figure 2-17 shows the damage
dose distribution at the core mid height location cross-section as well as the axial view of the
distribution along the whole duct. The damage dose is present only between 1500 mm and 2500
mm (active core region) and is 0 above and below the core region.

Figure 2-17. VP7A damage dose distribution (left) around cross section at the core mid
height location and (right) along the entire duct in the axial direction.

The centerline deflection for duct 67 due to irradiation dose is plotted in Figure 2-18 by taking
an average of the corner displacements around each duct and is compared with the calculation
results from the analytical solution and the participant code results from the IAEA report [6]. Due
to the large damage dose along the lower left corner, the duct deflects in the positive X and Y
directions across the flats. The values of the displacements at the ACLP and TLP for the MOOSE,
Analytical, and IAEA results are shown in Table 2.5. The IAEA report only provided values for
the TLP displacement. The values are all in good agreement, with MOOSE giving the maximum
resultant displacement of duct 67 as 17.86 mm at the TLP which agrees well with the analytical
solution (17.40 mm) and the IAEA result (17.92 mm).
Figure 2-18. VP7A duct displacement for X and Y directions comparing MOOSE, Analytical, and IAEA results

Table 2.5. VP7A model duct deflection (mm) at the ACLP and TLP comparing MOOSE with the IAEA results and analytical solution results

<table>
<thead>
<tr>
<th>Location</th>
<th>Direction</th>
<th>MOOSE</th>
<th>IAEA</th>
<th>Analytical</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACLP</td>
<td>X (mm)</td>
<td>4.46</td>
<td>-</td>
<td>4.34</td>
</tr>
<tr>
<td></td>
<td>Y (mm)</td>
<td>7.73</td>
<td>-</td>
<td>7.53</td>
</tr>
<tr>
<td></td>
<td>Resultant (mm)</td>
<td>8.93</td>
<td>-</td>
<td>8.69</td>
</tr>
<tr>
<td>TLP</td>
<td>X (mm)</td>
<td>8.93</td>
<td>8.96</td>
<td>8.70</td>
</tr>
<tr>
<td></td>
<td>Y (mm)</td>
<td>15.47</td>
<td>15.52</td>
<td>15.07</td>
</tr>
<tr>
<td></td>
<td>Resultant (mm)</td>
<td>17.86</td>
<td>17.92</td>
<td>17.40</td>
</tr>
</tbody>
</table>

This benchmark verifies the MOOSE physics modules (Tensor Mechanics) for a single duct undergoing irradiation induced swelling bowing along the flat-to-flat direction of the hexagonal assembly with a swelling material property using the ComputeVolumetricEigenstrain class. The natural symmetry of the problem description and damage dose distribution allowed comparison to an analytical solution for verification. It should be noted that the symmetry was not enforced in MOOSE with any boundary conditions, to ensure accurate calculation of the bowing could be achieved.

2.3.2. VP7B Duct 100

VP7B examines the free bowing behavior of duct 100 due to swelling induced by the damage dose field shown in Figure 2-16. Duct 100 has no symmetry behavior due to the damage dose
radius, so it deflects mostly along the Y direction, but also a bit in the X direction. Because there is no symmetry, an analytical solution is not available. Figure 2-19. shows the damage dose distribution at the core mid height location cross-section as well as the axial view of the distribution along the whole duct. The damage dose is present only between 1500 mm and 2500 mm (active core region) and is 0 above and below the core region.

Figure 2-19. VP7B damage dose distribution (left) around cross section at the core mid height location and (right) along the entire duct in the axial direction.

The centerline deflection for duct 100 is plotted in Figure 2-20 by taking an average of the corner displacements around each duct. The deflection is compared with the participant code results from the IAEA report [6]. The values of the displacements at the TLP for the MOOSE and IAEA results are shown in Table 2.6. The values are in good agreement, with MOOSE giving the maximum resultant displacement of 5.77 mm at the TLP and the IAEA giving 5.64 mm.
Figure 2-20. VP7B duct displacement for X and Y directions comparing MOOSE and IAEA results

Table 2.6. VP7B model duct deflection (mm) at the TLP comparing MOOSE with the IAEA results

<table>
<thead>
<tr>
<th>Direction</th>
<th>MOOSE (mm)</th>
<th>IAEA (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>1.16</td>
<td>1.17</td>
</tr>
<tr>
<td>Y</td>
<td>5.65</td>
<td>5.51</td>
</tr>
<tr>
<td>Resultant</td>
<td>5.77</td>
<td>5.64</td>
</tr>
</tbody>
</table>

This benchmark verifies the MOOSE physics modules (Tensor Mechanics) for a single duct undergoing irradiation induced swelling bowing along an arbitrary axis direction of the hexagonal assembly with a swelling material property using the ComputeVolumetricEigenstrain class. The lack of symmetry of the damage dose distribution allowed for calculation and comparison of the orthogonal X and Y directions of the bowing to ensure an accurate estimation of the true bowing direction was achieved.

2.4 Irradiation Swelling with More Complex Material Definition

This example evaluates bowing due to irradiation swelling induced by a fast flux axial gradient and thermal displacement with a more complex material definition for volumetric swelling. Specifically, this is a single duct free bowing problem with geometry and temperature gradient equivalent to Duct 1 from VP3B described above and irradiated over 1e8 seconds (1157.4 days). A simple fast flux distribution is applied which varies in the axial direction based on a normalized flux distribution multiplied by the maximum fast flux:
\[
\phi_f(z) = \phi_f^{max} f(z),
\]

Relative Flux = \[ f(z) = \frac{1}{e^{\frac{z-2}{0.5}}} \],

Maximum Fast Flux = \[ \phi_f^{max} = 4.0 \times 10^{15} \text{ n/cm}^2/\text{s}, \]

where \( z \) is the axial location along the duct. The value of the flux is the maximum fast flux multiplied by the relative flux value and is shown in Figure 2-21.

![Figure 2-21. Neutron flux distribution along the axial location of the duct](image)

The material swelling property is specified as the volumetric swelling strain percentage from the literature reference [9]

\[
S(\%) = 0.0275 \times 10^{-22} \cdot \phi_t \cdot t \cdot e^{-3.45 \times 10^{-4} \cdot (T-439.85)^2}.
\]

Where \( S \) is the volumetric percentage increase, \( \phi_t \) is the fast neutron flux in \( \text{n/cm}^2/\text{s} \), \( t \) is the irradiation time in seconds, and \( T \) is the temperature in °C. The swelling strain is calculated in MOOSE with the ComputeVolumetricEigenstrain and a ParsedMaterial property value with the equation for the swelling strain added as the function value, dependent on the temperature distribution and fast flux distribution. The fast flux distribution was specified with a ParsedFunction.
The duct centerline deflection (average of the corner displacements around each duct) is plotted in Figure 2-22 along with NUBOW results. The displacements at the top of the active core, ACLP, and TLP for the MOOSE and NUBOW along with the percentage difference between the MOOSE and NUBOW results are shown in Table 2.7. The values are all in good agreement, with MOOSE giving the TLP elevation maximum displacement of 3.91 mm and NUBOW giving 3.83 mm. The largest percentage difference is 9.4% at the ACLP, but the magnitude of the difference is less than 0.05 mm, so it’s expected this would not change the results much even in a multiple duct contact problem.

![Figure 2-22. Irradiation free bowing displacement comparing MOOSE with NUBOW results](image)

Table 2.7. Irradiation swelling example bowing results (mm) at the top of the active core, the ACLP, and TLP locations after 1157.4 days

<table>
<thead>
<tr>
<th>Location</th>
<th>MOOSE</th>
<th>NUBOW</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Core Top</td>
<td>-0.27</td>
<td>-0.28</td>
<td>3.7</td>
</tr>
<tr>
<td>ACLP</td>
<td>-0.32</td>
<td>-0.35</td>
<td>9.4</td>
</tr>
<tr>
<td>TLP</td>
<td>3.91</td>
<td>3.83</td>
<td>-2.0</td>
</tr>
</tbody>
</table>

This benchmark verifies the MOOSE Tensor Mechanics Module for a single duct undergoing irradiation induced swelling bowing with a more complex material property as a function of both the fast flux gradient and temperature distribution around the duct. This example leverages ParsedMaterial to add a more complex material property rather than creating a new material class to apply to the duct. ParsedMaterial is a dynamic method to change material properties without writing code.
2.5 Summary of Examples

Table 2.8 summarizes the examples for the updated assessment with simple descriptions of each of the examples and the main physics assessed in each. The range of examples extends the previous work [2] by adding duct-to-duct contact and irradiation swelling material properties, showing good agreement between IAEA, NUBOW-3D, and analytical results. These examples indicate that the MOOSE Tensor Mechanics and Contact modules will be able to accurately model clusters of ducts and small core problems with and without symmetry behavior and estimate the bowing deflection taking into account contact interactions. Future work will be done to increase the computational effort by including more ducts and contact regions to assess if successive contact between ducts causes any issues in accurately estimating contact stiffness, or if there are any calculation instability issues.
<table>
<thead>
<tr>
<th>Problem</th>
<th>Description</th>
<th>Physics</th>
<th>MOOSE Run Completed?</th>
<th>Code or Analytical Comparison</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. IAEA Verification Problem 3A (symmetric)</td>
<td>Fixed-end cantilever ducts with prescribed thermal gradient. Single duct bowing into cluster of ducts across corners (symmetry)</td>
<td>Deflection due to the differential thermal expansion induced by thermal gradient. Contact interaction between the cluster of ducts</td>
<td>Yes</td>
<td>IAEA VP3A results NUBOW-3D</td>
<td>Good agreement with NUBOW-3D and IAEA results</td>
</tr>
<tr>
<td>2. IAEA Verification Problem 3A (full sector)</td>
<td>Fixed-end cantilever ducts with prescribed thermal gradient. Single duct bowing into cluster of ducts across corners (full sector)</td>
<td>Deflection due to the differential thermal expansion induced by thermal gradient. Contact interaction between the cluster of ducts</td>
<td>Yes</td>
<td>IAEA VP3A results NUBOW-3D</td>
<td>Good agreement with NUBOW-3D and IAEA results</td>
</tr>
<tr>
<td>3. IAEA Verification Problem 3B (symmetric)</td>
<td>Fixed-end cantilever ducts with prescribed thermal gradient. Single duct bowing into cluster of ducts across flats (symmetry)</td>
<td>Deflection due to the differential thermal expansion induced by thermal gradient. Contact interaction between the cluster of ducts</td>
<td>Yes</td>
<td>IAEA VP3B results NUBOW-3D</td>
<td>Good agreement with NUBOW-3D and IAEA results</td>
</tr>
<tr>
<td>4. IAEA Verification Problem 7A</td>
<td>Fixed-end cantilever duct with prescribed damage dose in dpa. Single duct, free bowing, symmetric bowing behavior</td>
<td>Deflection due to the differential damage dose, volumetric swelling.</td>
<td>Yes</td>
<td>IAEA VP7A results Analytical Equation</td>
<td>Good agreement with analytical and IAEA results</td>
</tr>
<tr>
<td>5. IAEA Verification Problem 7B</td>
<td>Fixed-end cantilever duct with prescribed damage dose in dpa. Single duct, free bowing, non-</td>
<td>Deflection due to the differential damage dose, volumetric swelling.</td>
<td>Yes</td>
<td>IAEA VP7B results</td>
<td>Good agreement with IAEA results</td>
</tr>
<tr>
<td>Problem</td>
<td>Description</td>
<td>Physics</td>
<td>MOOSE Run Completed?</td>
<td>Code or Analytical Comparison</td>
<td>Results</td>
</tr>
<tr>
<td>--------------------------</td>
<td>------------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>----------------------</td>
<td>-------------------------------</td>
<td>----------------------------------------------</td>
</tr>
<tr>
<td>6. Irradiation Swelling</td>
<td>Fixed-end cantilever duct with prescribed thermal gradient, and axial fast flux</td>
<td>Deflection due to the differential thermal expansion induced by thermal gradient. Deflection due to volumetric swelling, as a function of fast flux and temperature.</td>
<td>Yes</td>
<td>NUBOW-3D</td>
<td>Good agreement with NUBOW results</td>
</tr>
</tbody>
</table>
3 Future Work

This report expands on the single duct, thermal bowing behavior examples in [2] and includes clusters of ducts with contact at the load pads and irradiation material swelling behavior. Assessment is still needed on larger core configurations and full limited-free bow behavior including restraint rings. Additional verification problems with irradiation creep effects over time are also required for full core mechanics evaluation. The follow subsections describe some of the future work planned.

3.1 IAEA Verification Problem 3B Full Sector

Future work will be performed to convert the VP3B symmetric sector into a full sector example like VP3A. Due to the flat-to-flat bowing, the symmetric sector contact geometry is reduced and might be incorrectly estimating the contact behavior between the load pads. Unlike VP3A, where the symmetry plane is cut along the diagonal of the duct, the symmetry plane in the VP3B model cuts the face of the duct which undergoes contact in half, which might produce inaccurate contact results.

3.2 IAEA Verification Problem 4 (VP4)

VP4 examines a 30° sector of a full core, with a ring outside the core region bowing outwards due to thermal gradient. The full model is shown in Figure 3-1, with the black ring around the reactor representing the restraint ring at the ACLP and TLP elevations along the duct, with a clearance value of 0.5 mm. The red dashed lines represent the symmetry boundary, with the numbered ducts representing the ducts used for the analysis. Duct 42 has the same thermal gradient as Duct 1 from VP3B bowing along the across-flats direction and Ducts 43 and 44 have the same thermal gradient as Duct 1 from VP3A bowing along the across-corners direction.
3.3 IAEA Verification Problem 5 (VP5)

VP5 examines the same core restraint system and 30° symmetric region VP4. The thermal gradient is replaced with a damage dose field, which exists within a certain radius from the center of the reactor, and goes to 0 beyond that. Figure 3-2 shows the reactor with the damage dose field boundary with a blue circle. Swelling is activated on ducts 42, 43, and 44 (the same ducts as for the thermal bowing), with the purpose of the example to find displacements of the ducts and contact forces at the ACLP and TLP locations between the ducts in the same region as VP4, with a maximum center dose of 100 dpa. All the ducts are at 400 °C with the bowing displacements induced by an irradiation volumetric swelling and irradiation creep over time due to the contact stresses.
Figure 3-2. IAEA VP5 core layout showing the radius for the damage dose with a circle around the core (Adopted from [6] © IAEA)

3.4 MOOSE Physics Module Development

Additional work is needed to adapt the current mechanics solvers in MOOSE to large-scale core radial expansion problems, by addressing node-to-face contact definition when assigning sidesets to multiple contact pairs. The current working method for the full sector (and full core) geometry requires a separate sideset for each load pad face, to avoid “reusing” nodes/sidesets in multiple contact pairs. This could be computationally prohibitive or at the least, onerous for users to set up in large cores.

3.5 Assessment of Additional Physics

The verification work in this report is building the foundation to create an integrated multiphysics tool based on the MOOSE framework to model core radial expansion, including structural mechanics, thermal fluids, and reactor physics. The MOOSE framework provides a robust computational foundation for detailed physics computation and is based on an unstructured finite element mesh framework ideal for computing core deformations. The MOOSE-based neutronics and thermal fluids codes will begin being assessed in the near future. Development is expected to be needed for these codes as well, with neutronics capability to add sodium (or other liquid metal coolant) backfill and rehomogenize zones as deformation occurs being identified as a critical need. Finally, handling the load pad and restraining ring gap closures in the non-mechanics tools may prove to be challenging.
4 Summary

This report summarizes the assessment of the MOOSE Tensor Mechanics and Contact modules to compute the structural mechanical response in radial core expansion problems performed during FY22. It is critically important to correctly predict the deformations of reactor core ducts in order to estimate the bowed shape and the effect on radial core expansion to reactivity. The examples from the IAEA were continued, starting with VP3A and VP3B which include thermal bowing and duct-to-duct contact interactions using the Contact Module. Also, irradiation induced swelling due to damage dose and fast flux gradients was included, using a ParsedMaterial property and volumetric eigenstrain formulation, calculated with ComputeVolumetricEigenstrain, added to the thermal expansion eigenstrain. MOOSE compared well to both NUBOW results and IAEA benchmark participants as available for the problems analyzed. Further examples will be explored pursuing more complex duct-to-duct interactions with larger core configurations, grid plate expansion during start-up, restraint ring boundaries, and irradiation induced creep effects.
5 Acknowledgements

Argonne National Laboratory’s work was supported by the U.S. Department of Energy, Office of Nuclear Energy, Advanced Modeling and Simulation Program (NEAMS) under contract DE-AC02-06CH11357. The authors would like to thank Benjamin Spencer of Idaho National Laboratory for consultation on the MOOSE Tensor Mechanics and Contact Modules.

6 References


