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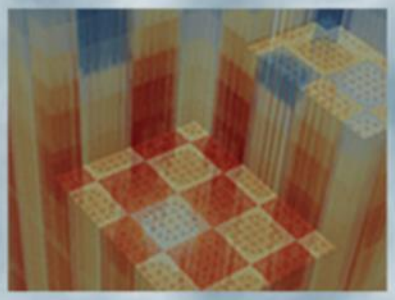

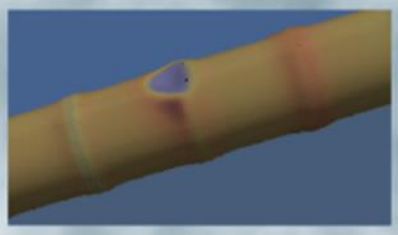

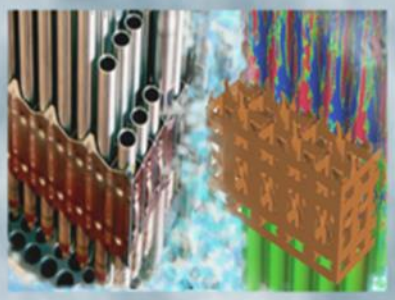

Standalone BISON Fuel Performance Results for Watts Bar Unit 1, Cycles 1-3

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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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ACRONYMS

ANS	American Nuclear Society
BOC	beginning of cycle
CASL	Consortium for Advanced Simulation of Light Water Reactors
CIPS	crud-induced power shift
CMFD	coarse mesh finite difference
COBRA	Coolant Boiling in Rod Arrays
CS	core simulator
CSV	comma separated value
CTF	COBRA two-phase flow
DNB	departure from nucleate boiling
DOE	US Department of Energy
EFPD	effective full power day
GWd/MT	gigawatt day per metric ton
HDF	hierarchical data format
IFBA	integral fuel burnable absorber
INF	infrastructure
INL	Idaho National Laboratory
JFNK	Jacobian Free Newton-Krylov
LWR	light water reactor
MOC	Method of Characteristics
MOOSE	Multiphysics Object Oriented Simulation Environment
MW	megawatt
MWth	megawatt thermal
NE	Office of Nuclear Energy
NEM	nodal expansion method
ORNL	Oak Ridge National Laboratory
PCI	pellet-clad interaction
PETSc	Portable, Extensible Toolkit for Scientific Computation
PWR	pressurized water reactor
RIA	reactivity-insertion accident
SP_3	simplified P_3
TH	thermal hydraulics
TPL	third party library
TVA	Tennessee Valley Authority
UM	University of Michigan
VERA	Virtual Environment for Reactor Applications
WABA	wet annular burnable absorber
WBN1	Watts Bar Nuclear Unit 1

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.

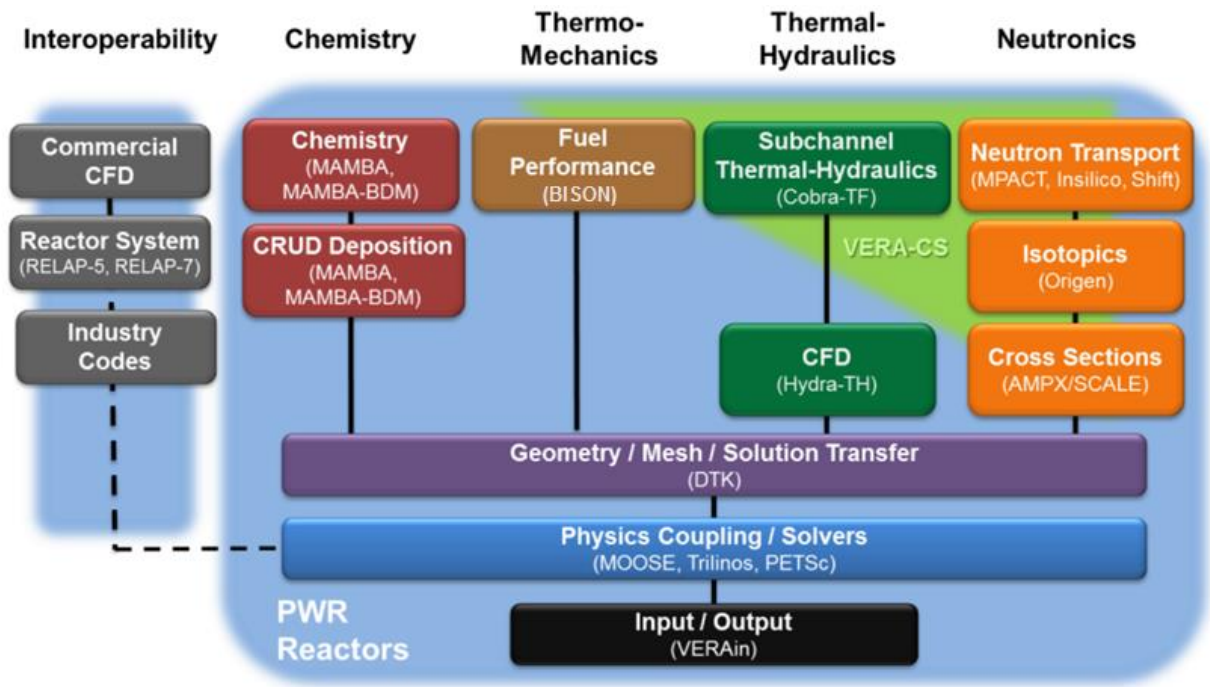

Fig. 1.2.1. VERA components.

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 P_3 (SP_3) 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 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.

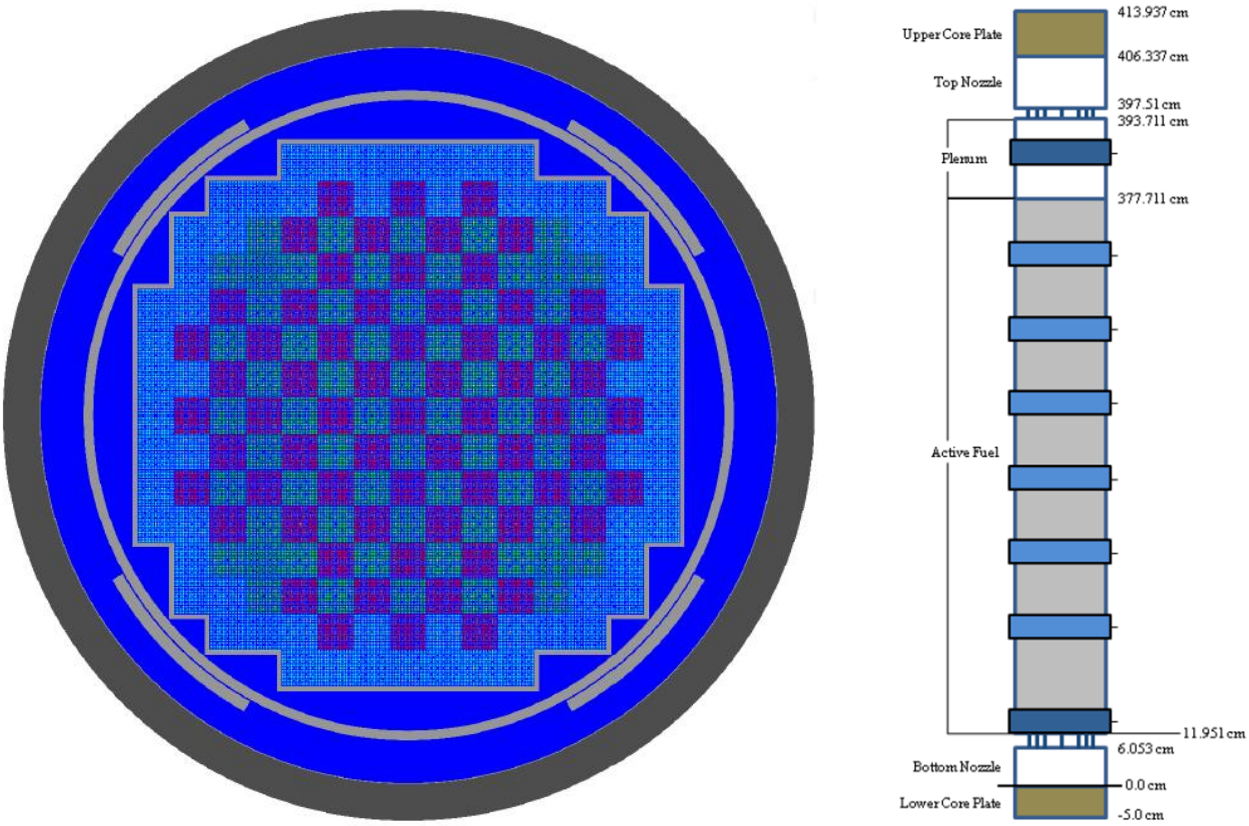

Fig. 3.1.1. Watts Bar Unit 1 – Cycle 1 Core diagram [1,18]

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.

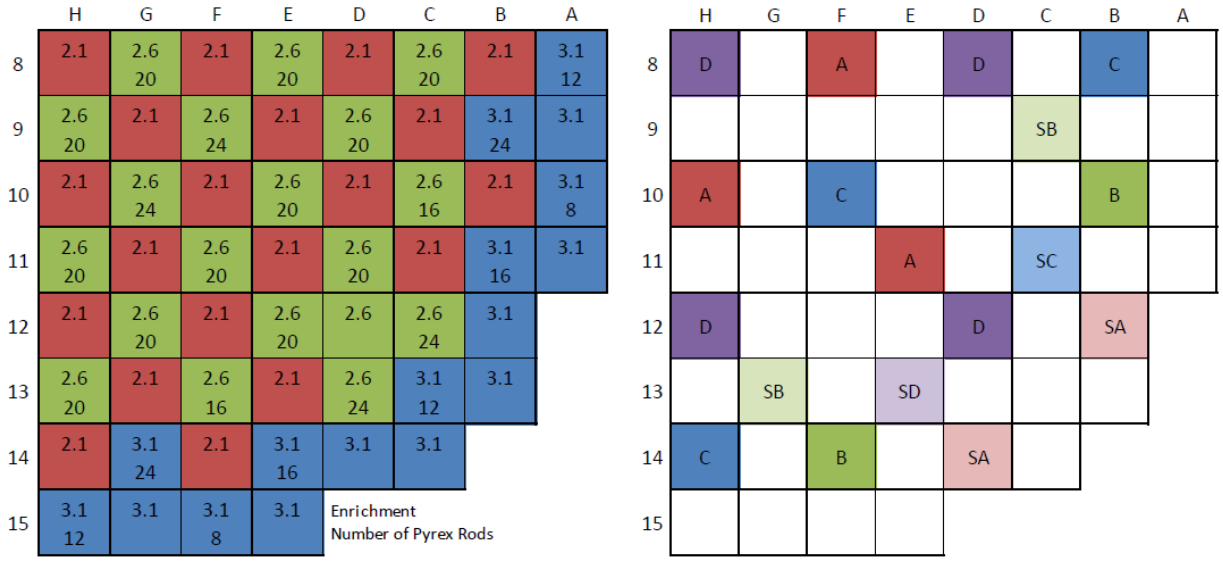

Fig. 3.1.2. Watts Bar Unit 1 – Cycle 1 core layout and rod bank configuration [1].

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 down-ramp, 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.

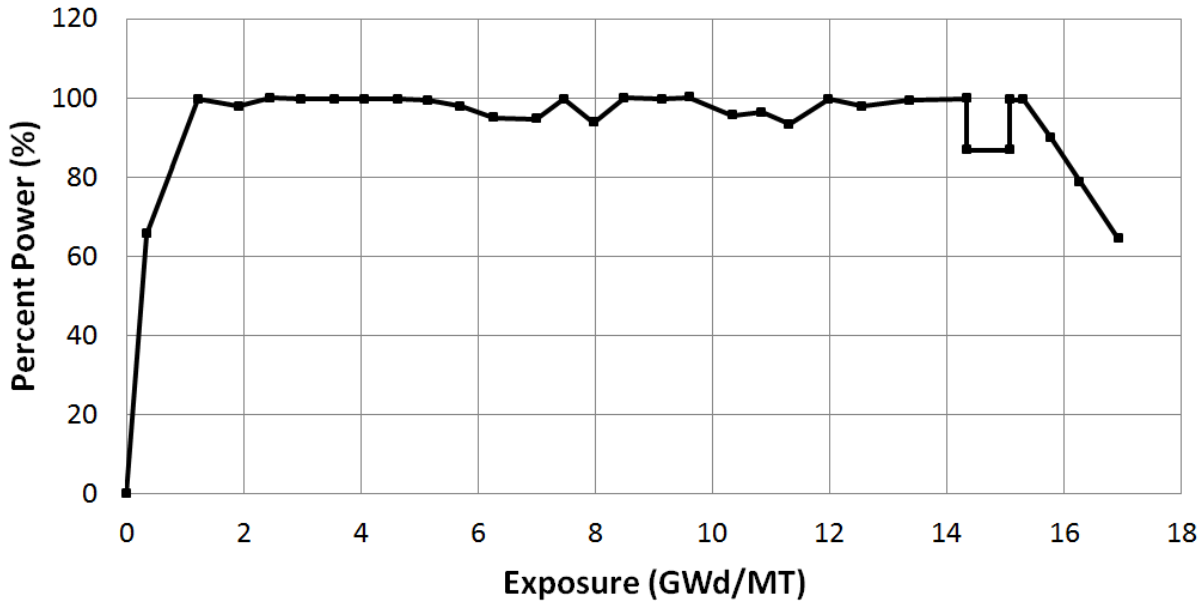

Fig. 3.2.1. Watts Bar Unit 1 – Cycle 1 power history [1,19,20].

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.

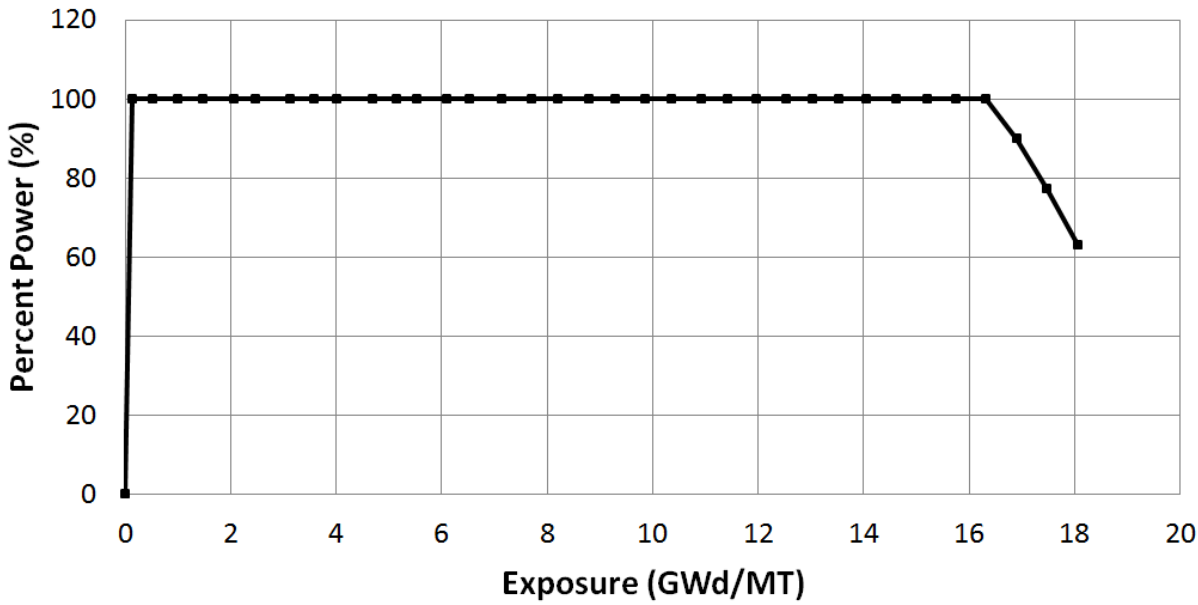

Fig. 3.2.2. Watts Bar Unit 1 – Cycle 2 power history [1,21,22]

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.

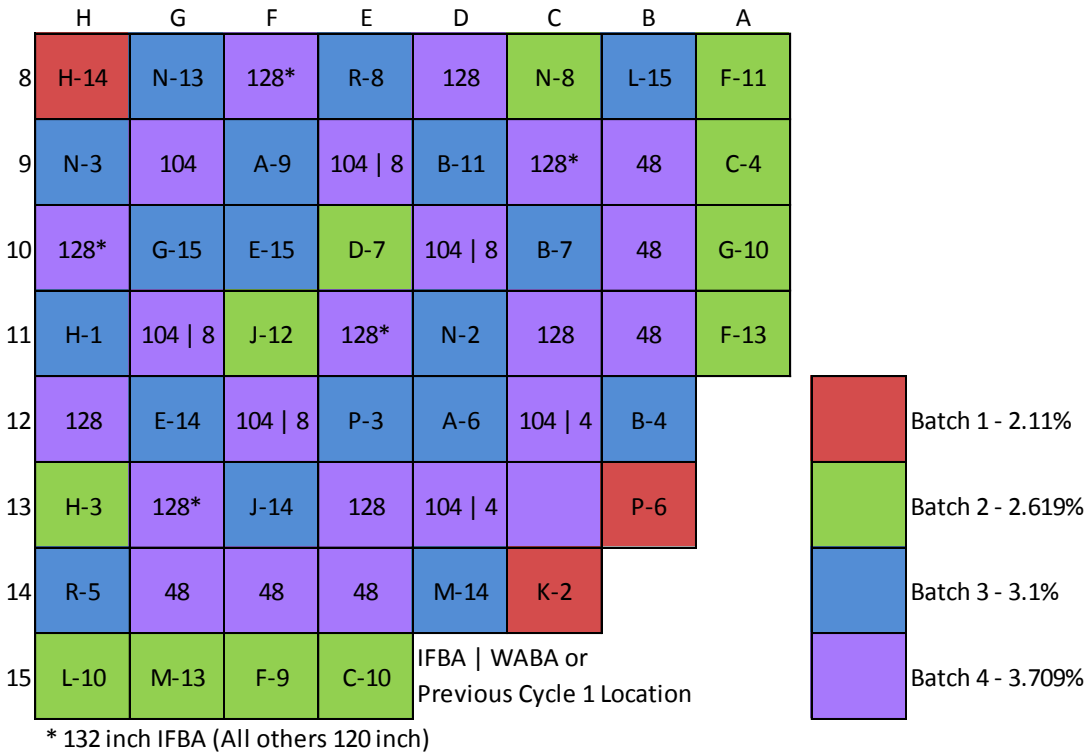

Fig. 3.2.3. Watts Bar Unit 1 – Cycle 2 core layout [18].

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.

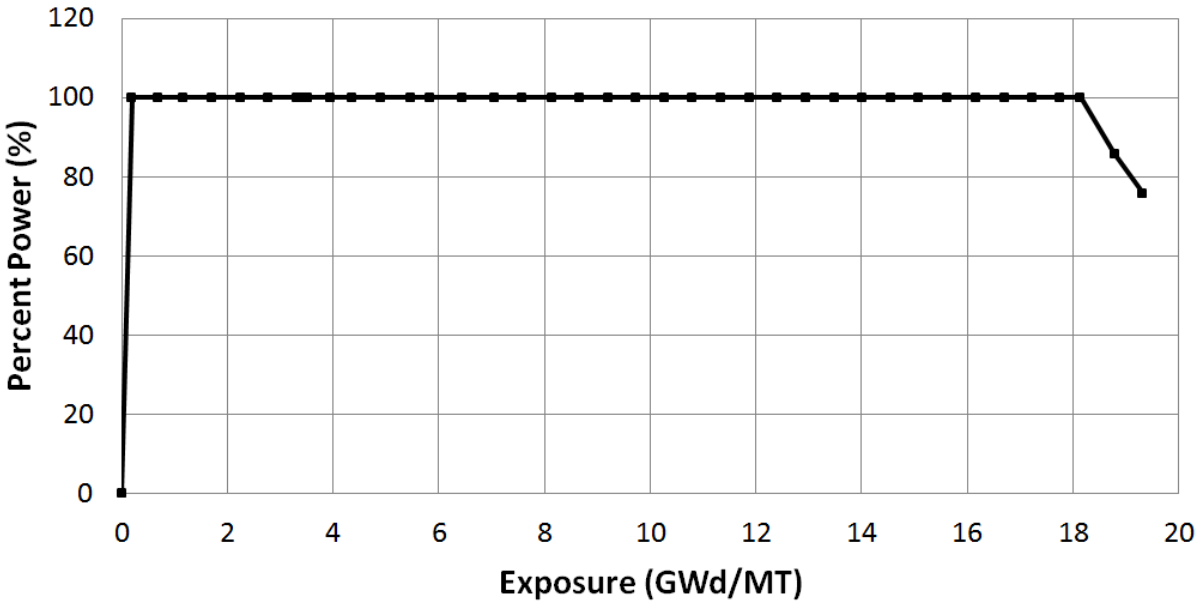

Fig. 3.2.4. Watts Bar Unit 1 – Cycle 3 power history [1,23,24].

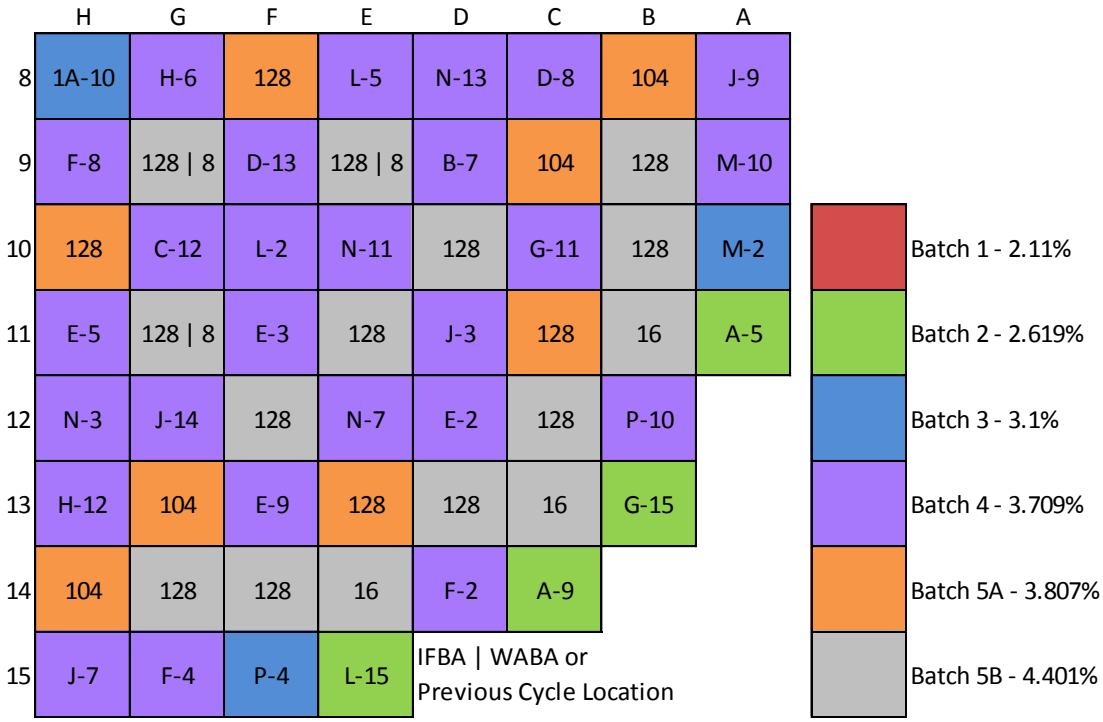

Fig. 3.2.5. Watts Bar Unit 1 – Cycle 3 core layout [23,24].

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.

Table 4.2.1. Fuel mesh parameters

	# Radial Mesh	# Axial Mesh
coarse	6	100
medium	12	200
fine	24	400
ultrafine	48	800

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.

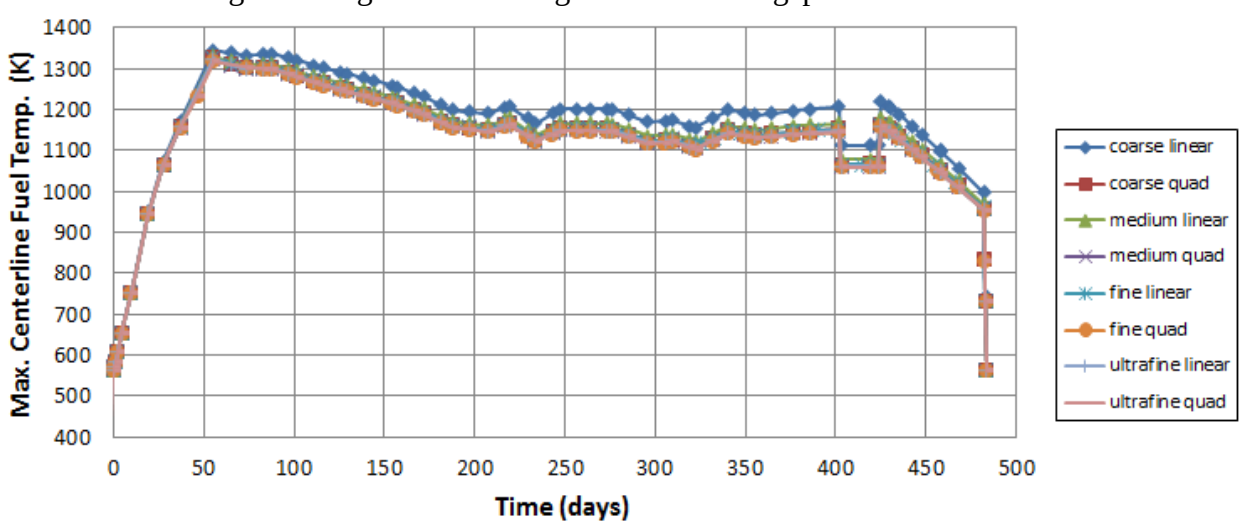

Fig. 4.2.1. Mesh sensitivity study – maximum centerline fuel temperature (K).

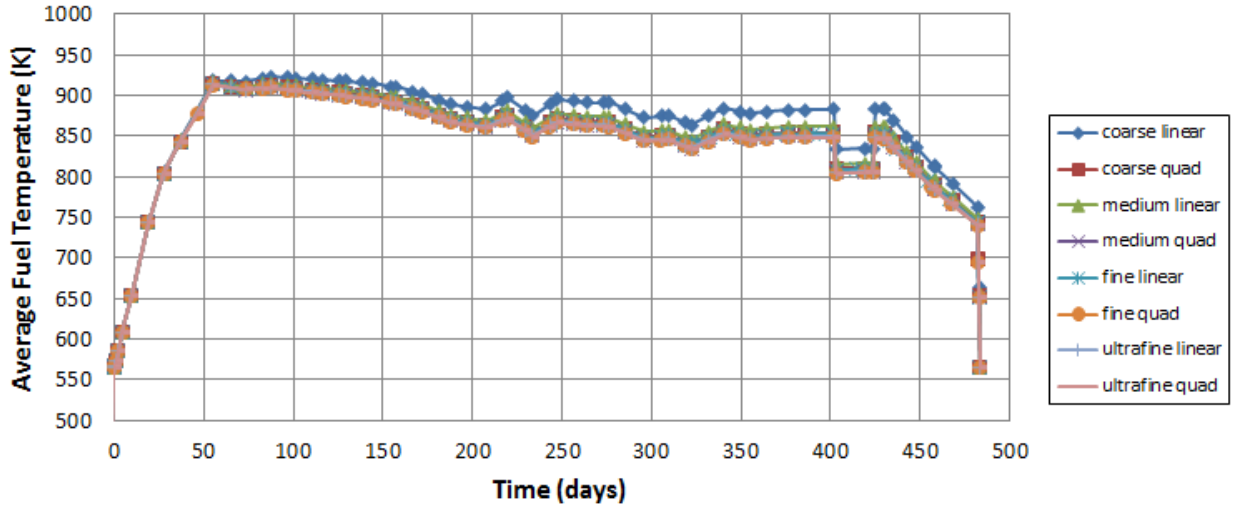

Fig. 4.2.2. Mesh sensitivity study – average fuel temperature (K).

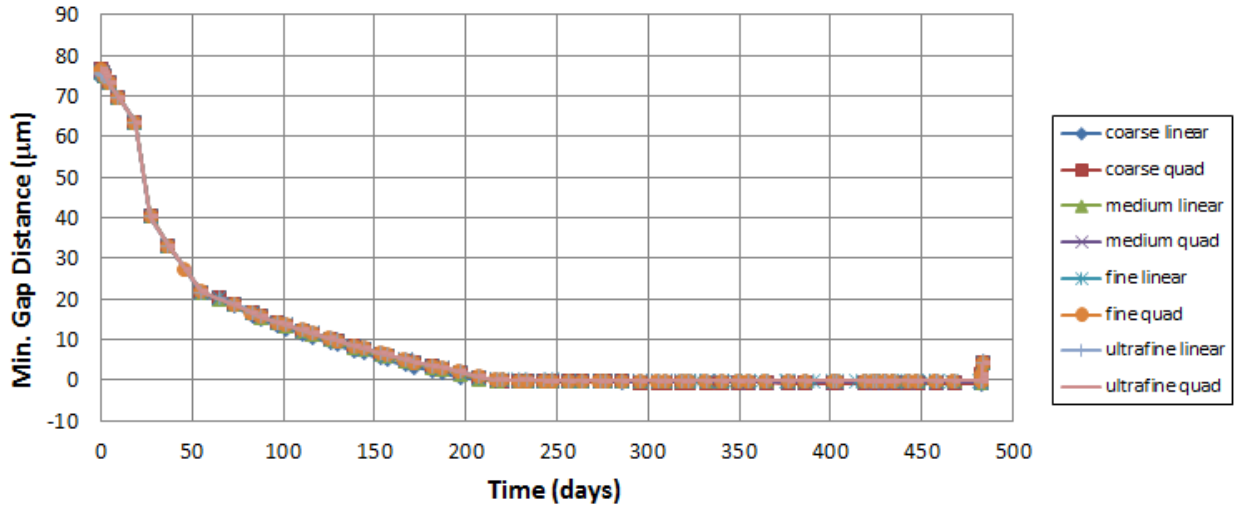

Fig. 4.2.3. Mesh sensitivity study – minimum gap thickness (µm).

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.

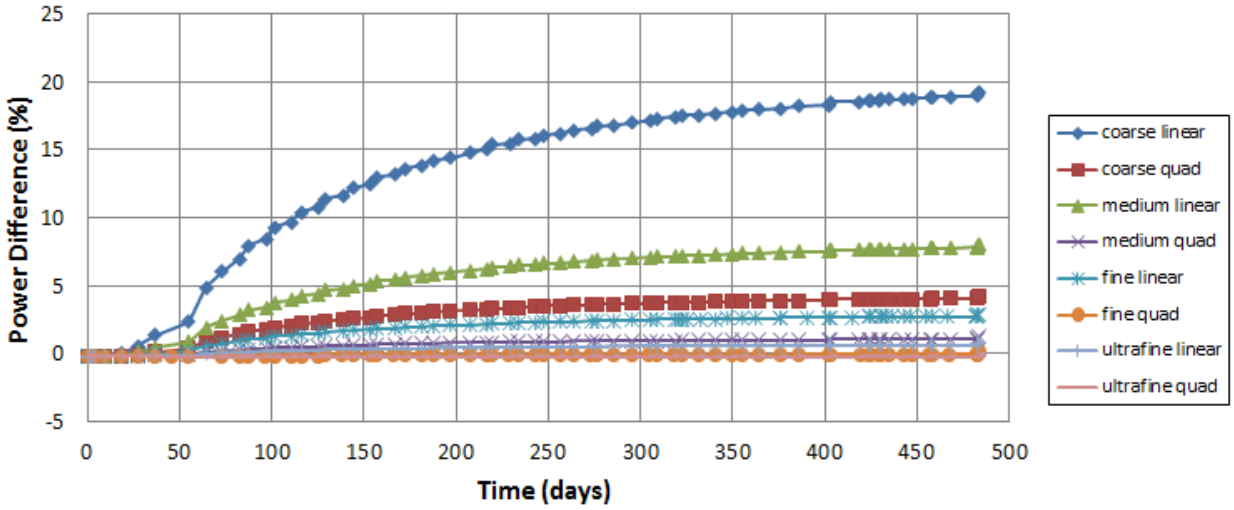

Fig. 4.2.4. Mesh sensitivity study – power difference (%).

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 4.2.2. Timing results for various meshes

	Time (min)	
	linear	**quad**
coarse	2.05	4.73
medium	5.23	12.30
fine	17.58	43.48
ultrafine	59.73	179.12

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.

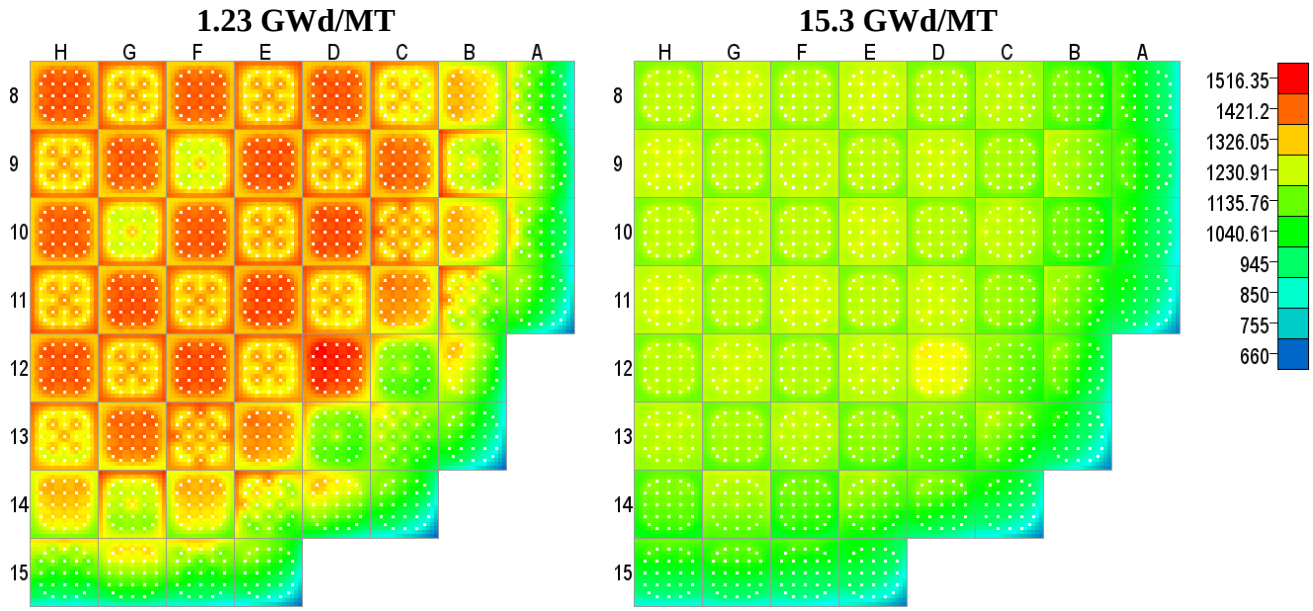

Fig. 5.2.1. Cycle 1 maximum centerline fuel temperature (K).

Figure 5.2.2 shows the average fuel temperature, which exhibits similar trends as observed in the maximum centerline fuel temperature.

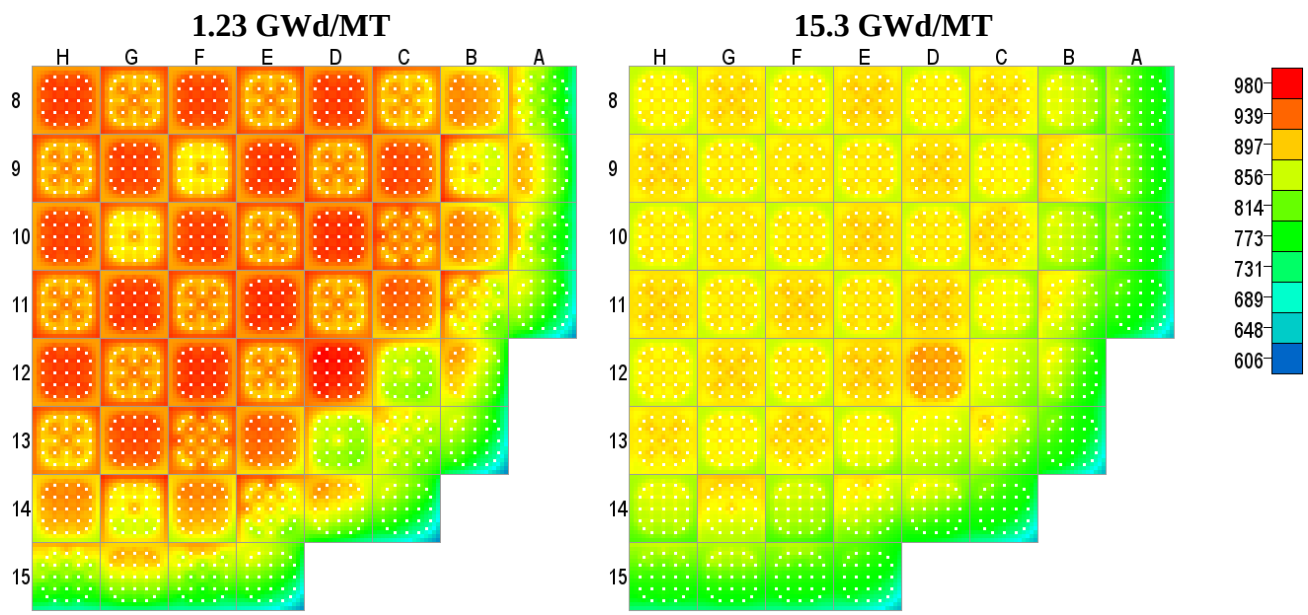

Fig. 5.2.2. Cycle 1 average fuel temperature (K).

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.

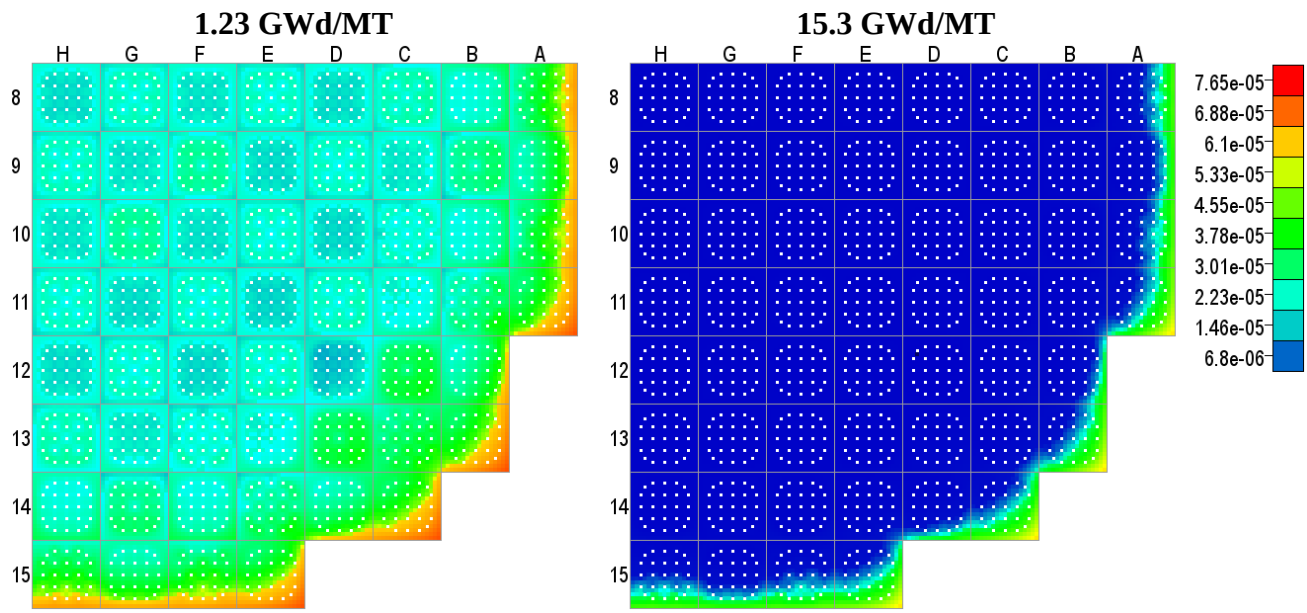

Fig. 5.2.3. Cycle 1 minimum gap thickness (m).

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

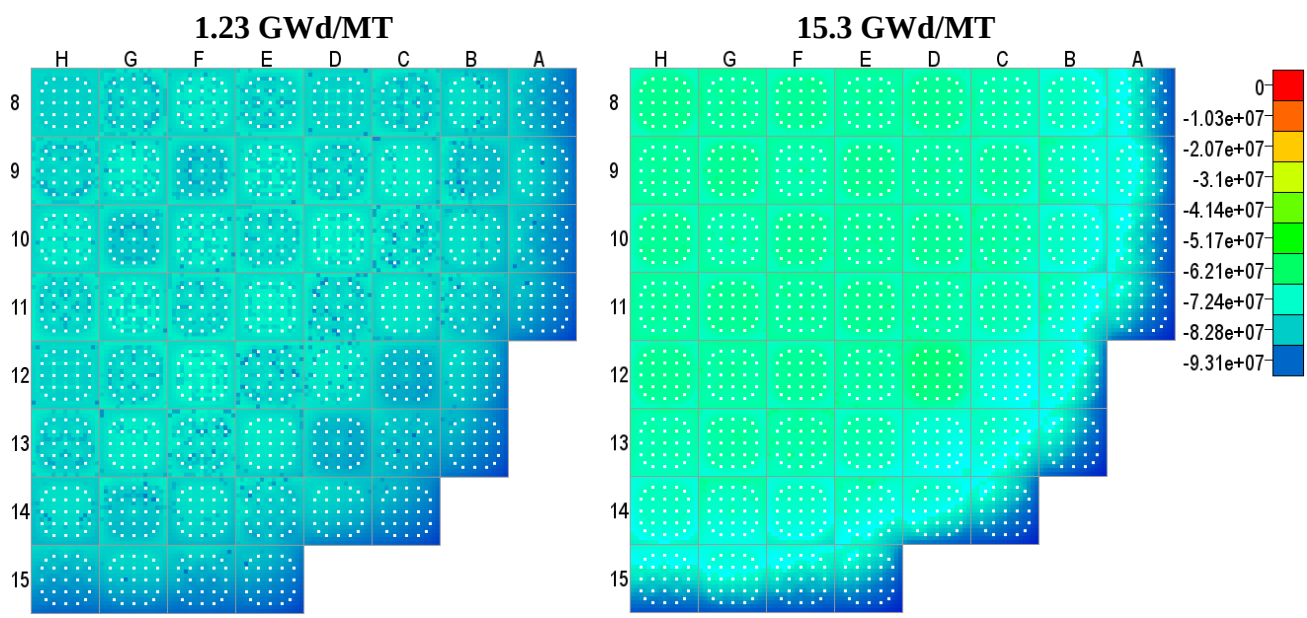

Fig. 5.2.4. Cycle 1 minimum clad hoop stress (Pa).

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.

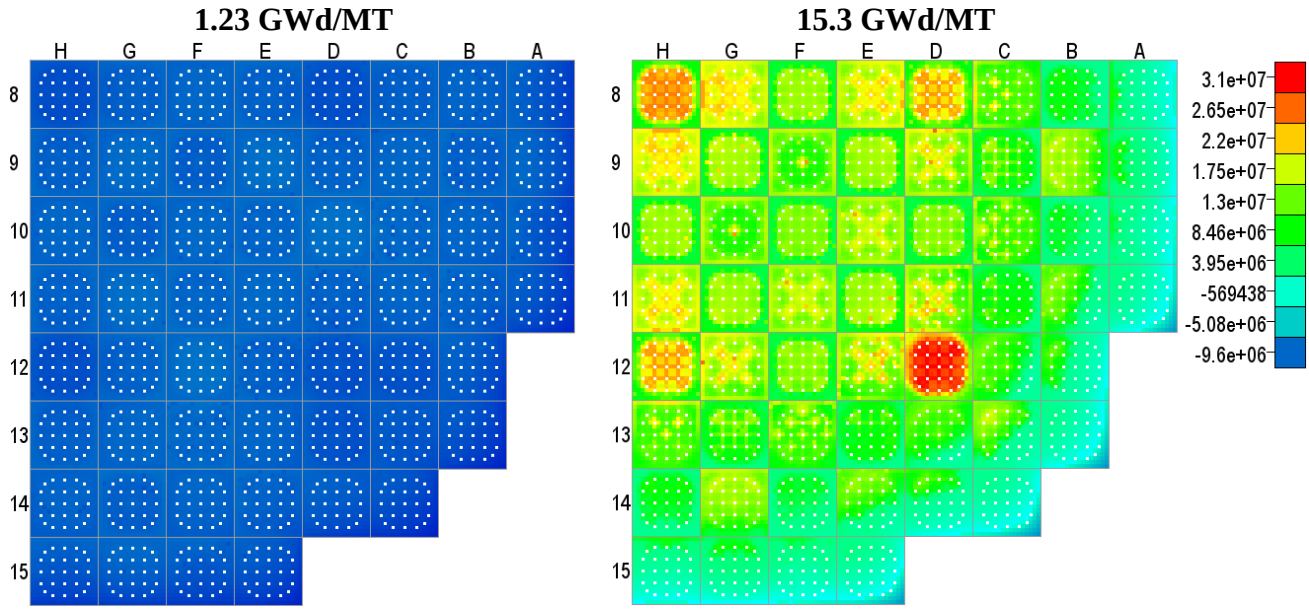

Fig. 5.2.5. Cycle 1 maximum clad hoop stress (Pa).

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.

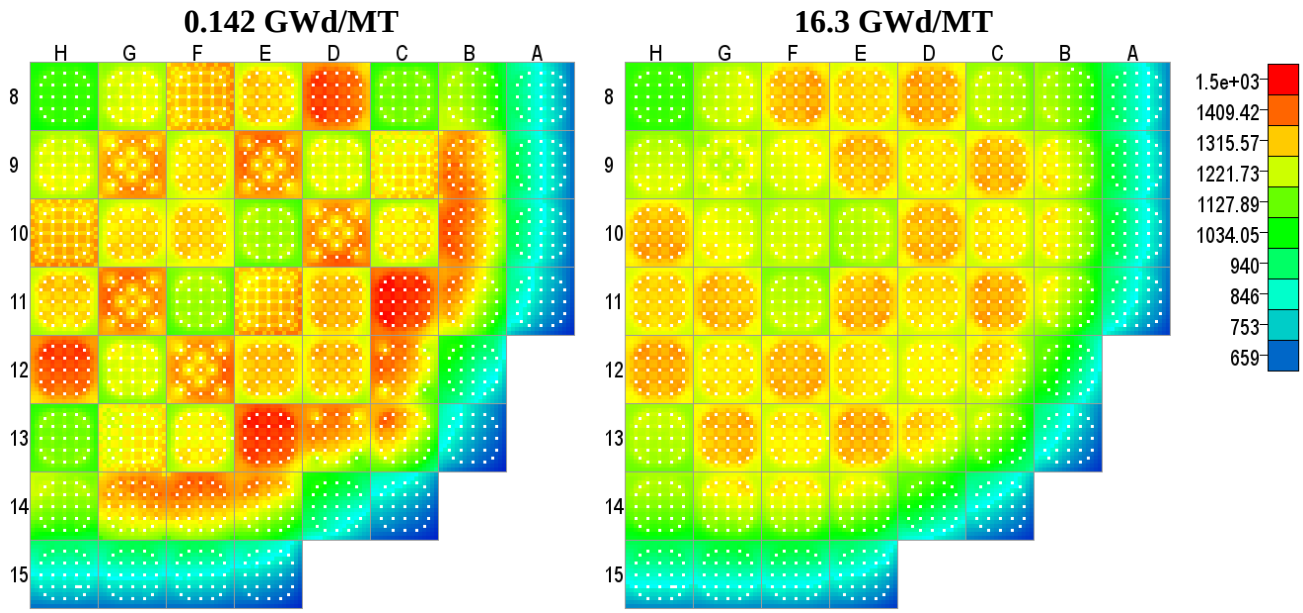

Fig. 5.3.1. Cycle 2 maximum centerline fuel temperature (K).

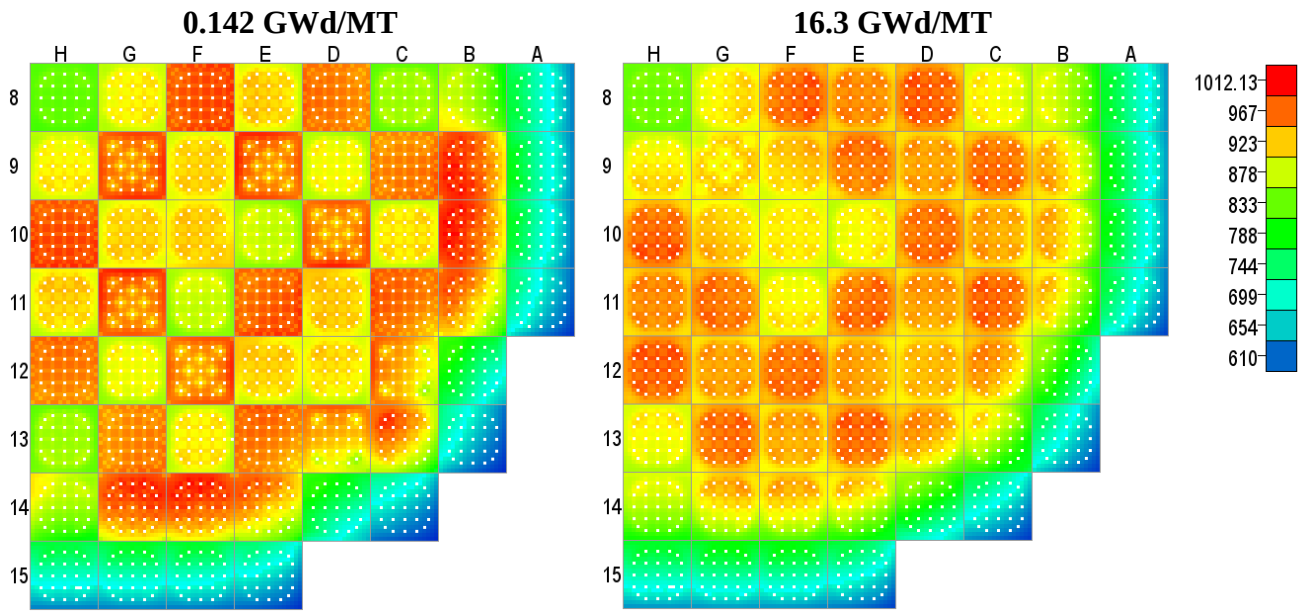

Fig. 5.3.2. Cycle 2 average fuel temperature (K).

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.

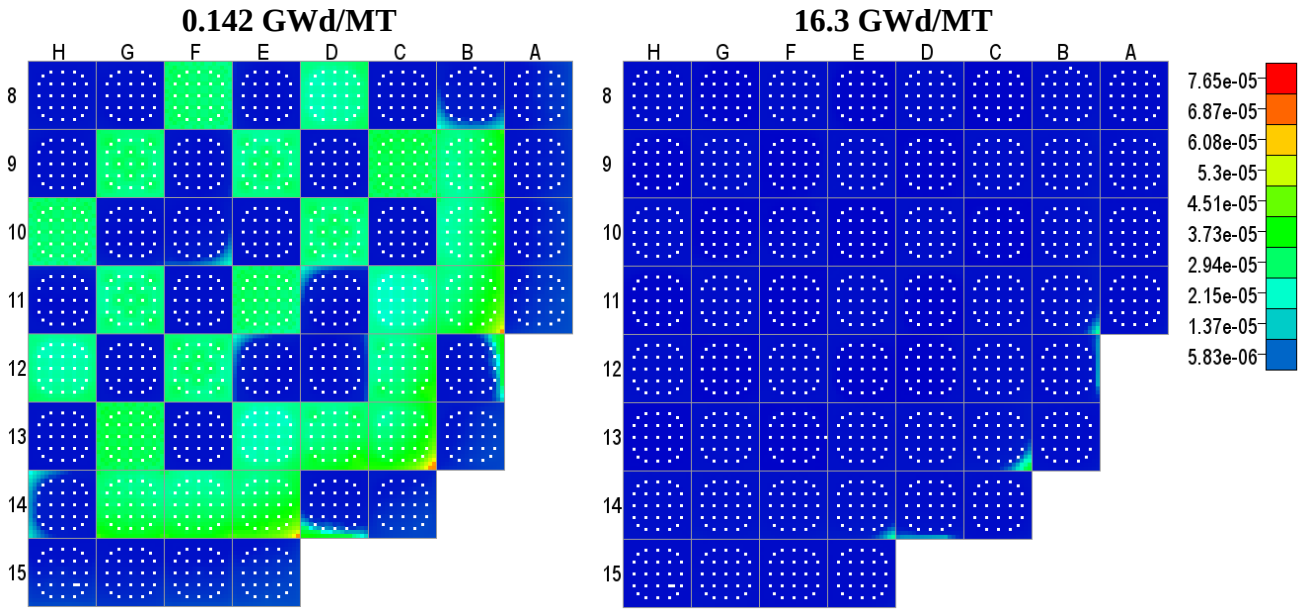

Fig. 5.3.3. Cycle 2 minimum gap thickness (m).

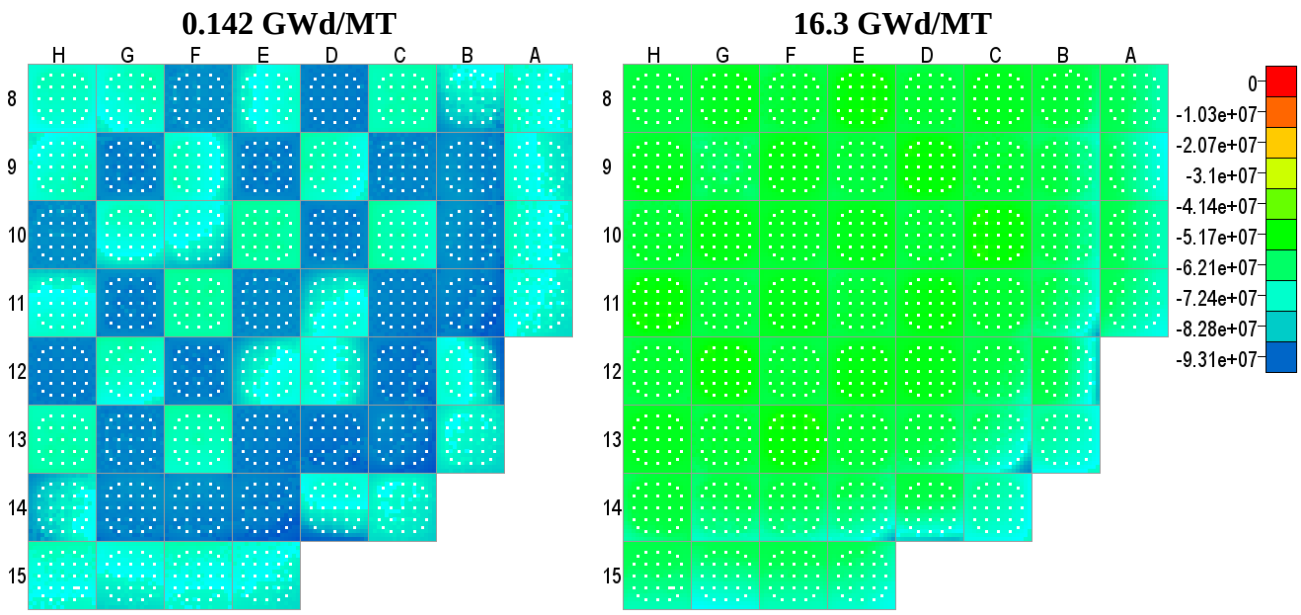

Fig. 5.3.4. Cycle 2 minimum clad hoop stress (Pa).

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.

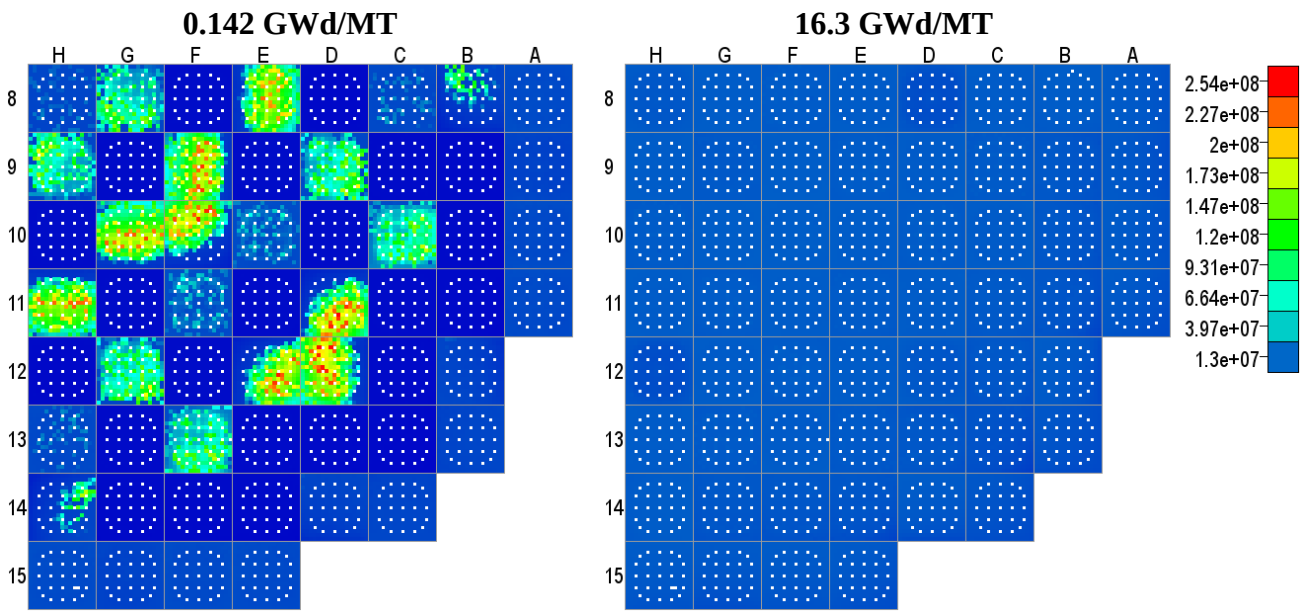

Fig. 5.3.5. Cycle 2 maximum clad hoop stress (Pa).

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.

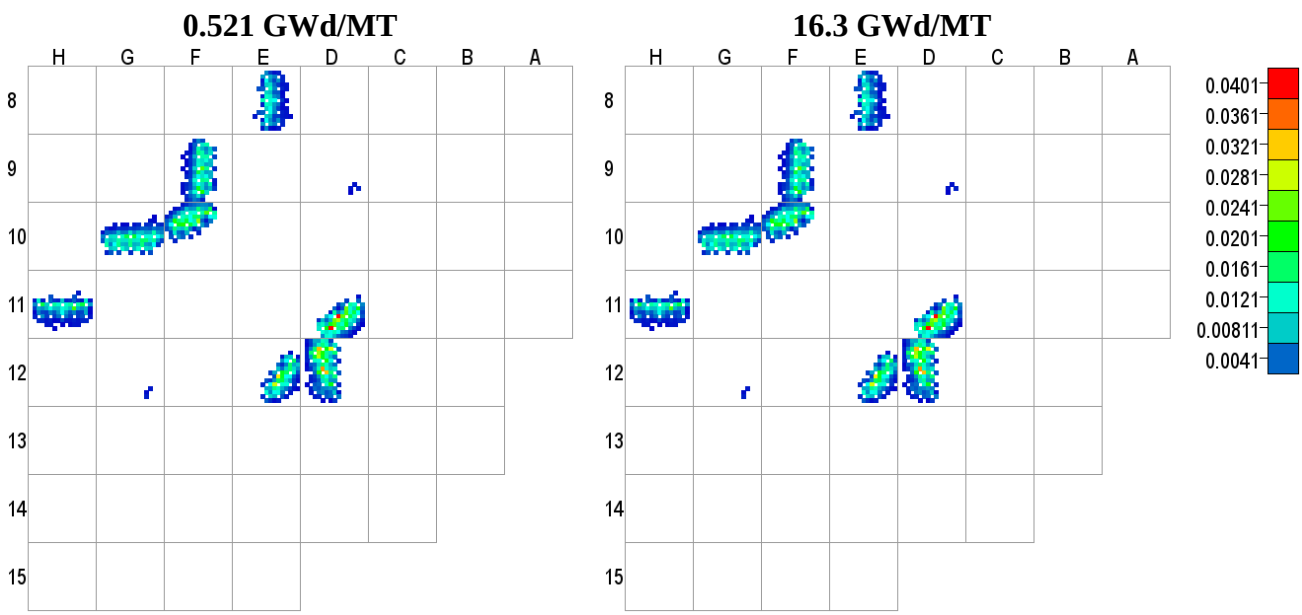

Fig. 5.3.6. Cycle 2 cumulative damage index.

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.

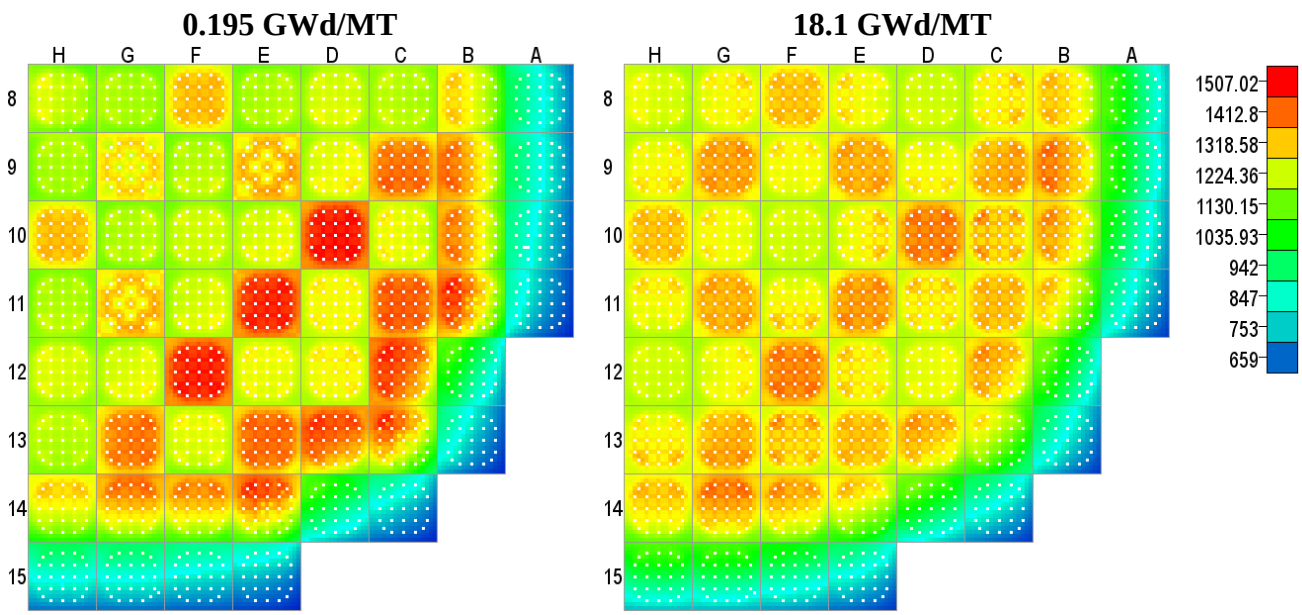

Fig. 5.4.1. Cycle 3 maximum centerline fuel temperature (K).

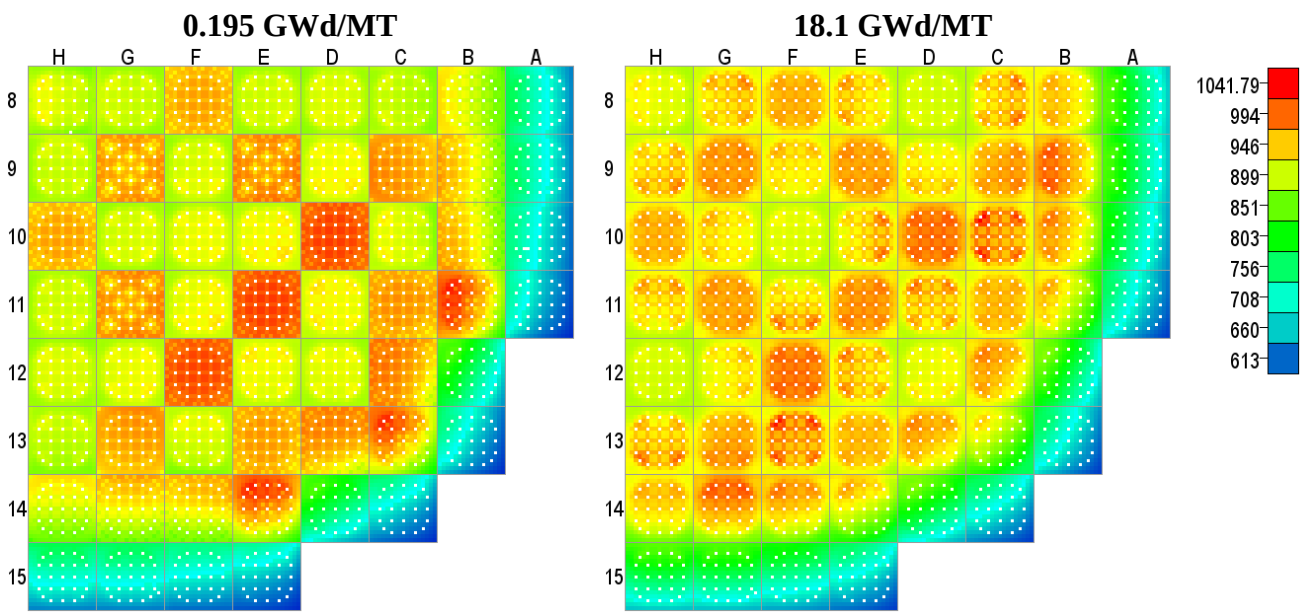

Fig. 5.4.2. Cycle 3 average fuel temperature (K).

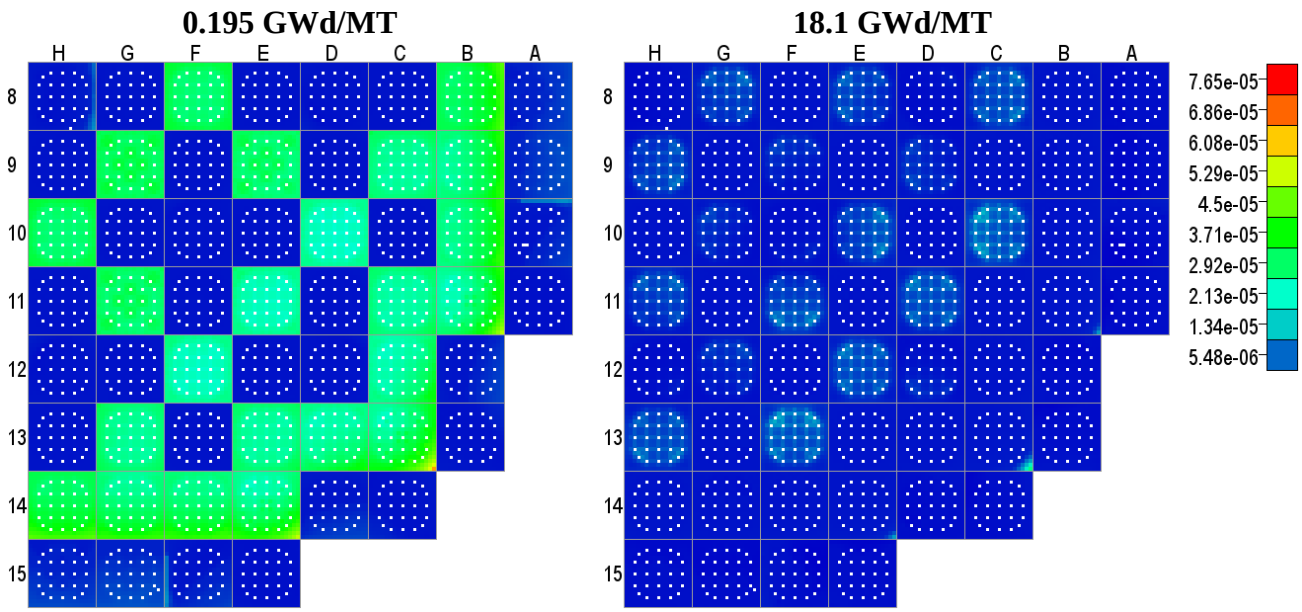

Fig. 5.4.3. Cycle 3 minimum gap thickness (m).

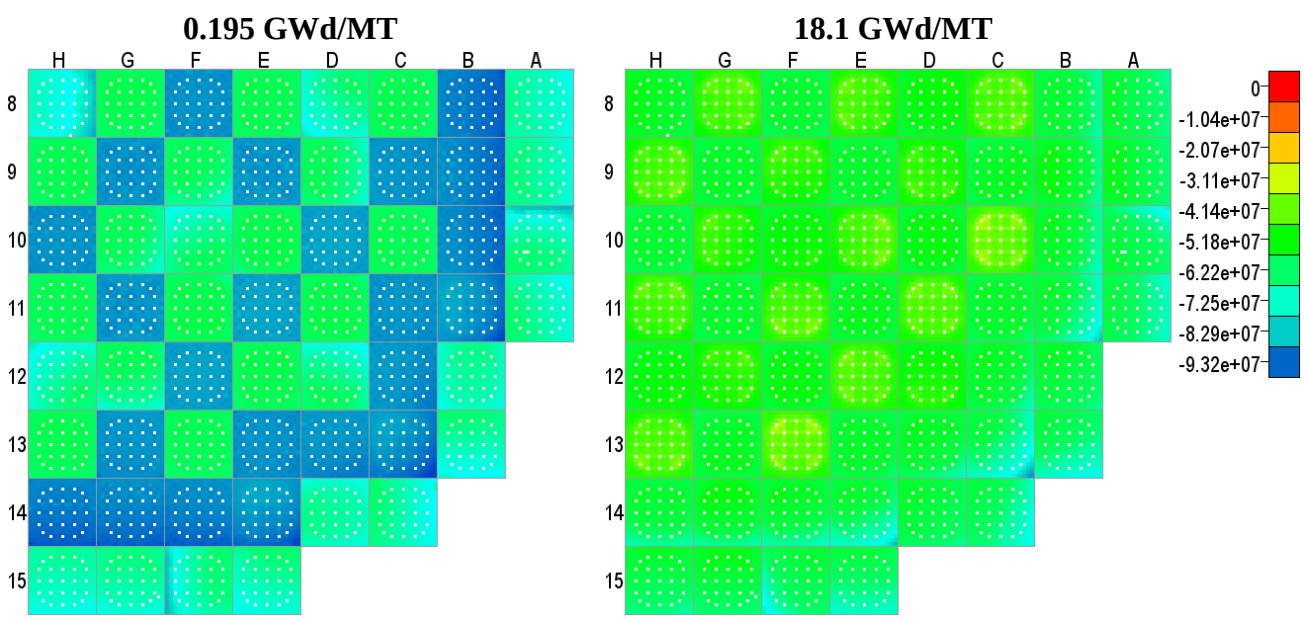

Fig. 5.4.4. Cycle 3 minimum clad hoop stress (Pa).

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.

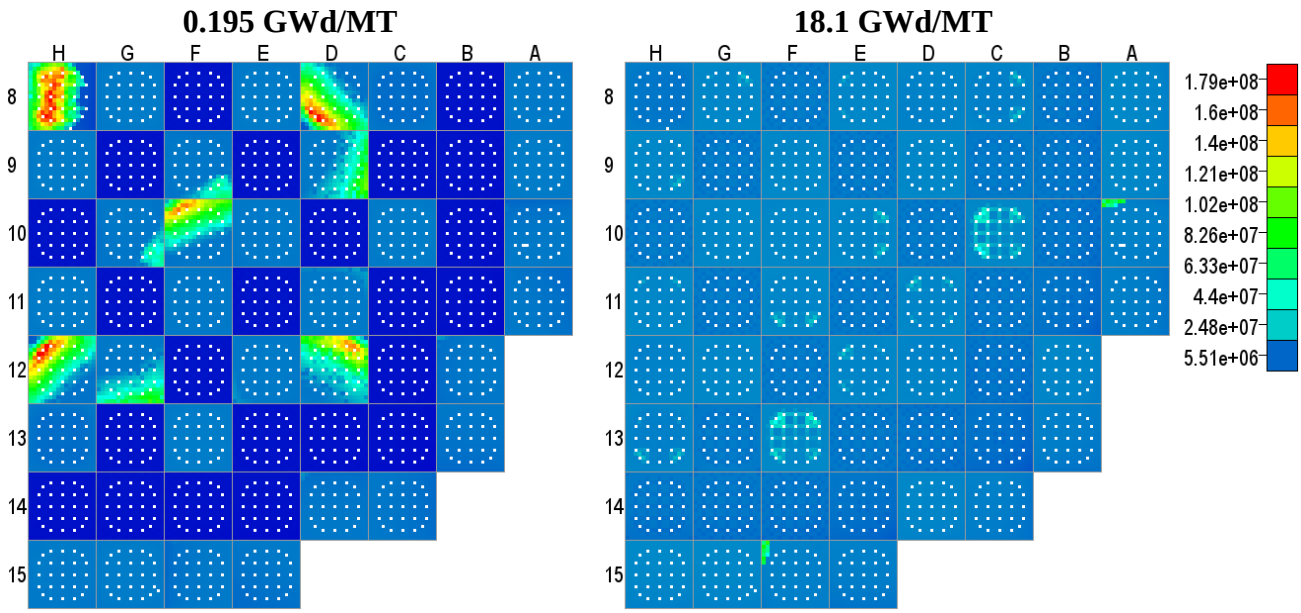

Fig. 5.4.5. Cycle 3 maximum clad hoop stress (Pa).

Similarly, the CDI corresponds well with Figure 5.4.5, but with a slightly increased maximum CDI of nearly 5%.

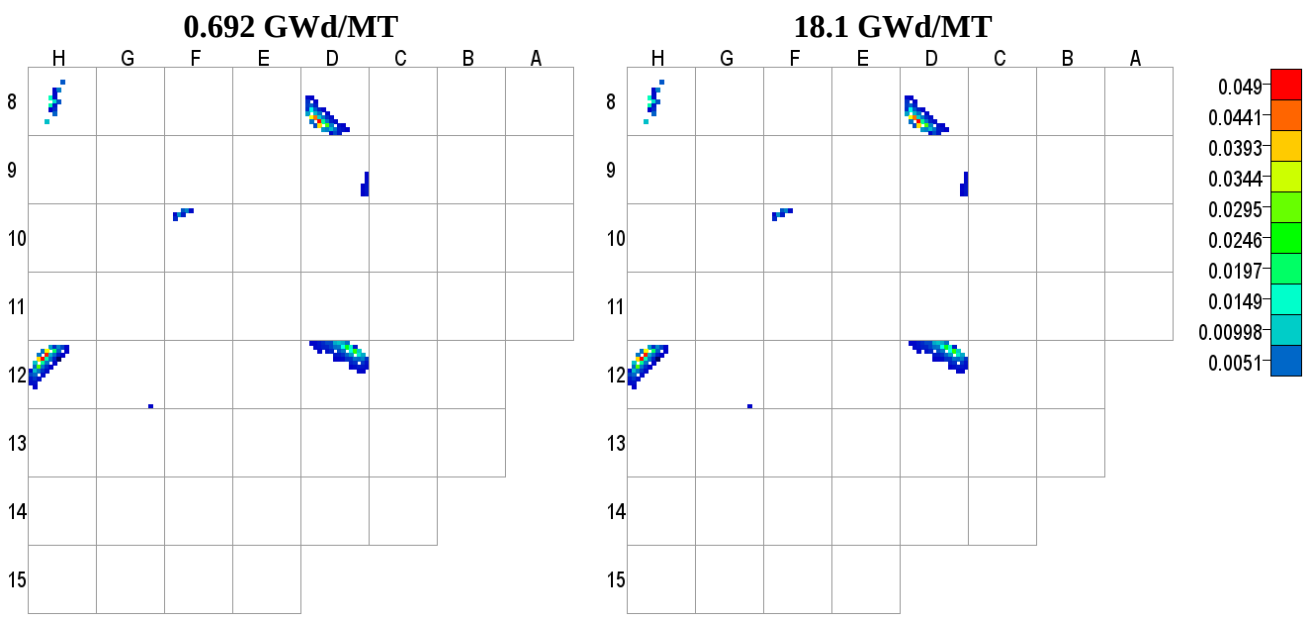

Fig. 5.4.6. Cycle 3 cumulative damage index.

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 temperate, 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.

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APPENDIX A – EXPANDED RESULTS

A.1. Cycle 1

A.1.1. Maximum Centerline Fuel Temperature

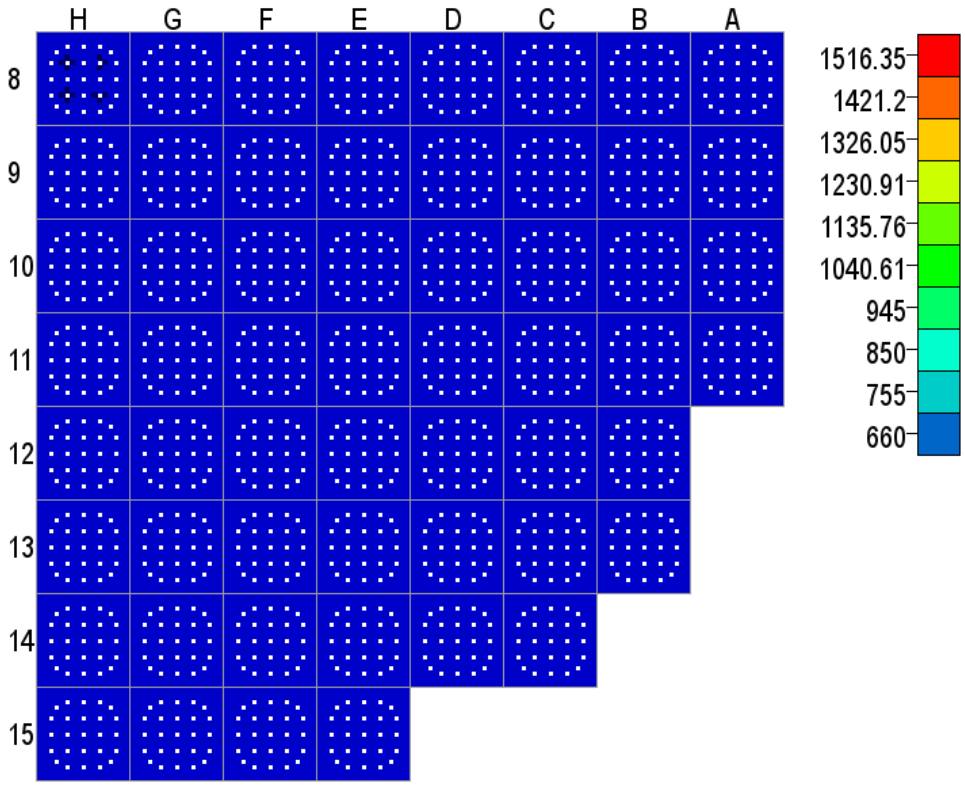

Fig. A.1.1. Cycle 1 maximum centerline fuel temperature (K) – 0.00 GWd/MT.

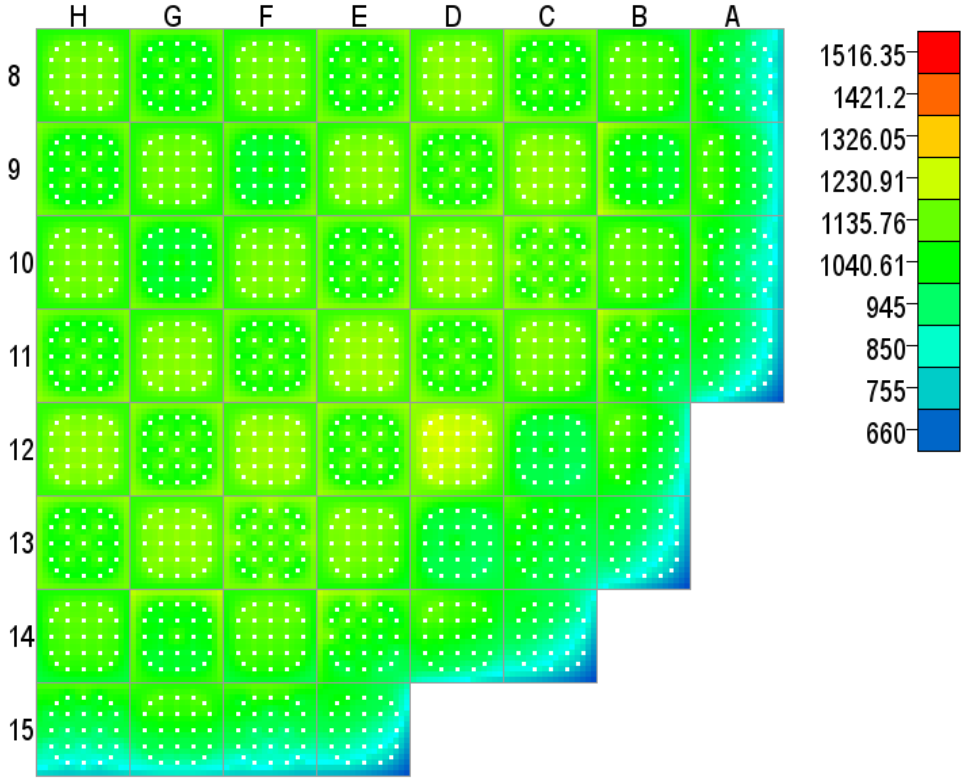

Fig. A.1.2. Cycle 1 maximum centerline fuel temperature (K) – 0.35 GWd/MT.

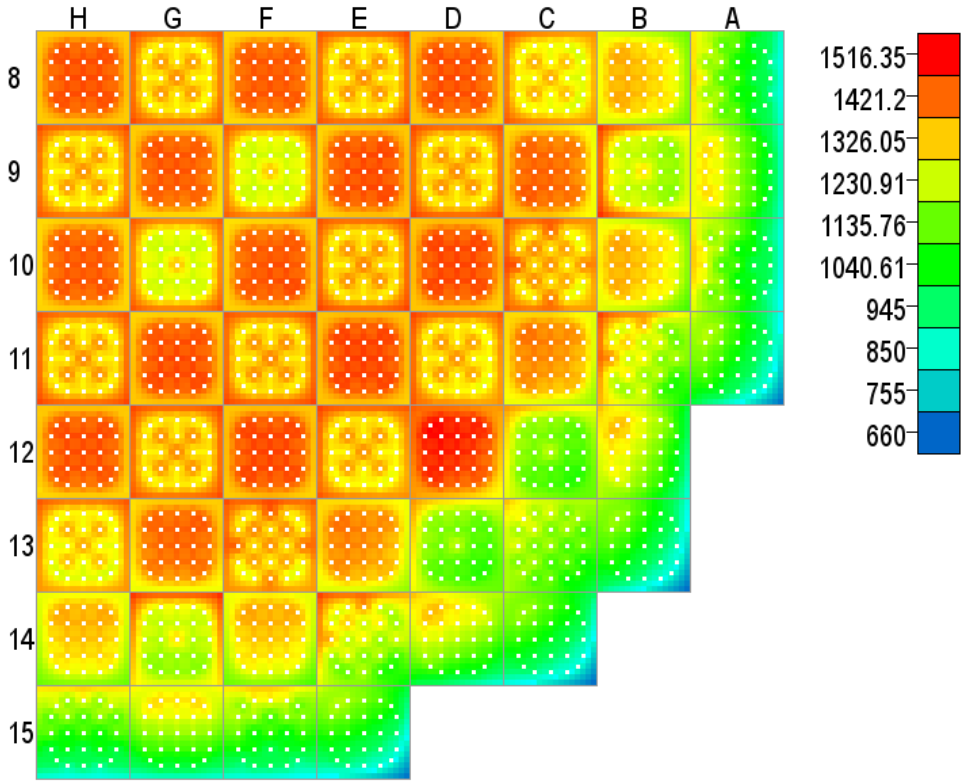

Fig. A.1.3. Cycle 1maximum centerline fuel temperature (K) – 1.23 GWd/MT.

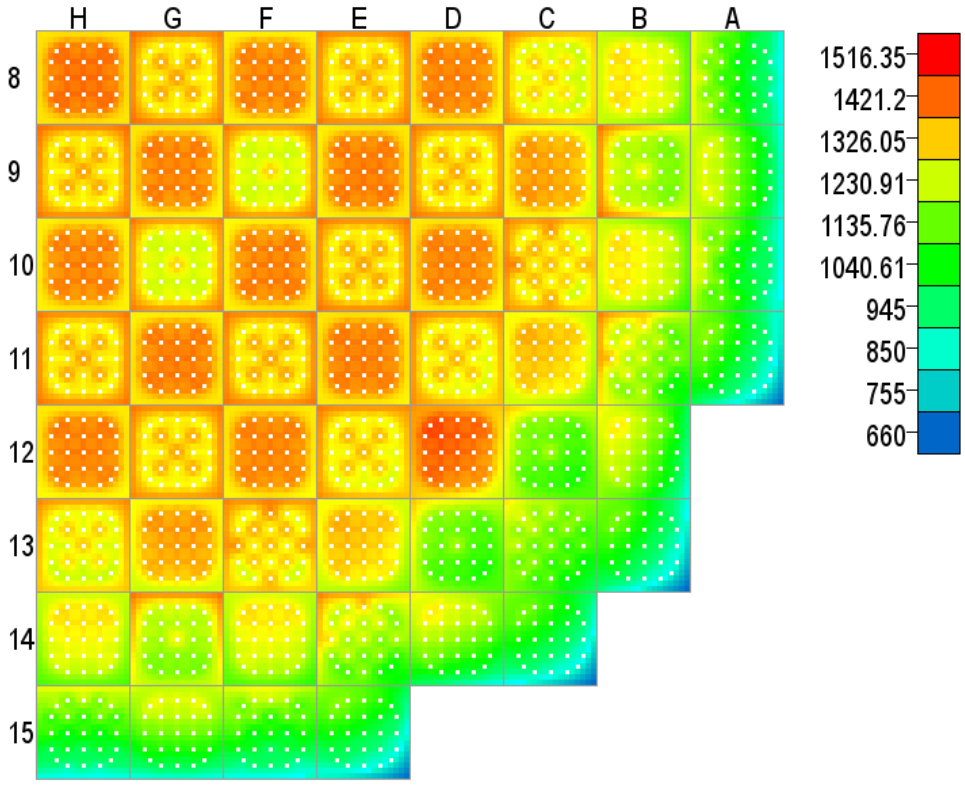

Fig. A.1.4. Cycle 1maximum centerline fuel temperature (K) – 1.92 GWd/MT.

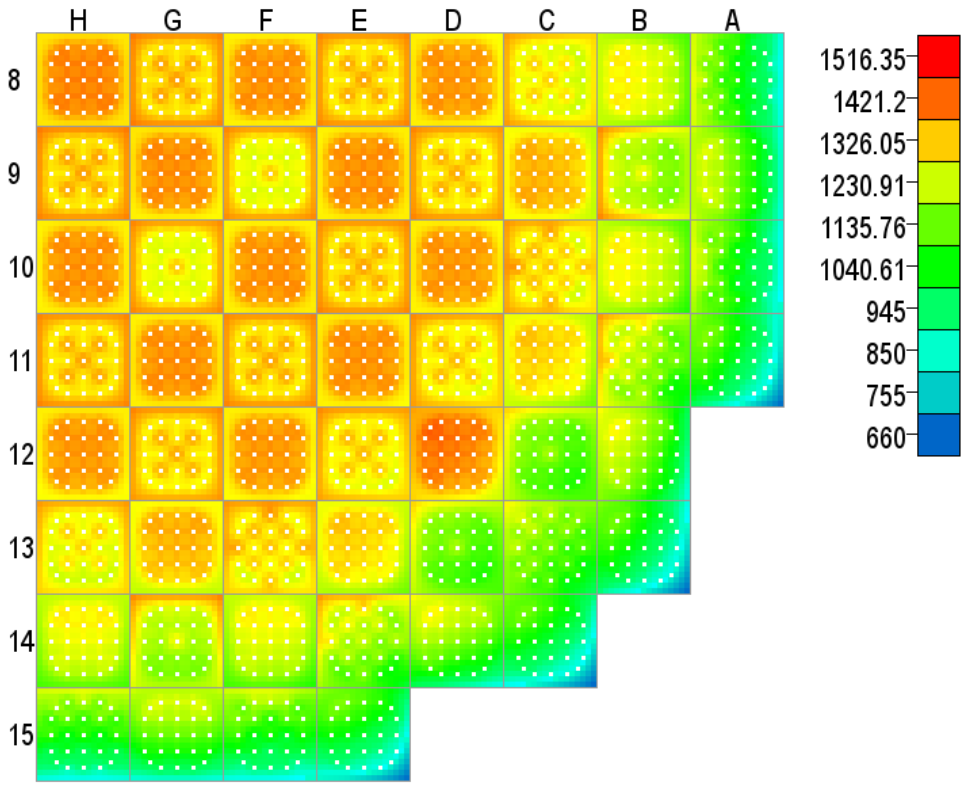

Fig. A.1.5. Cycle 1 maximum centerline fuel temperature (K) – 2.46 GWd/MT.

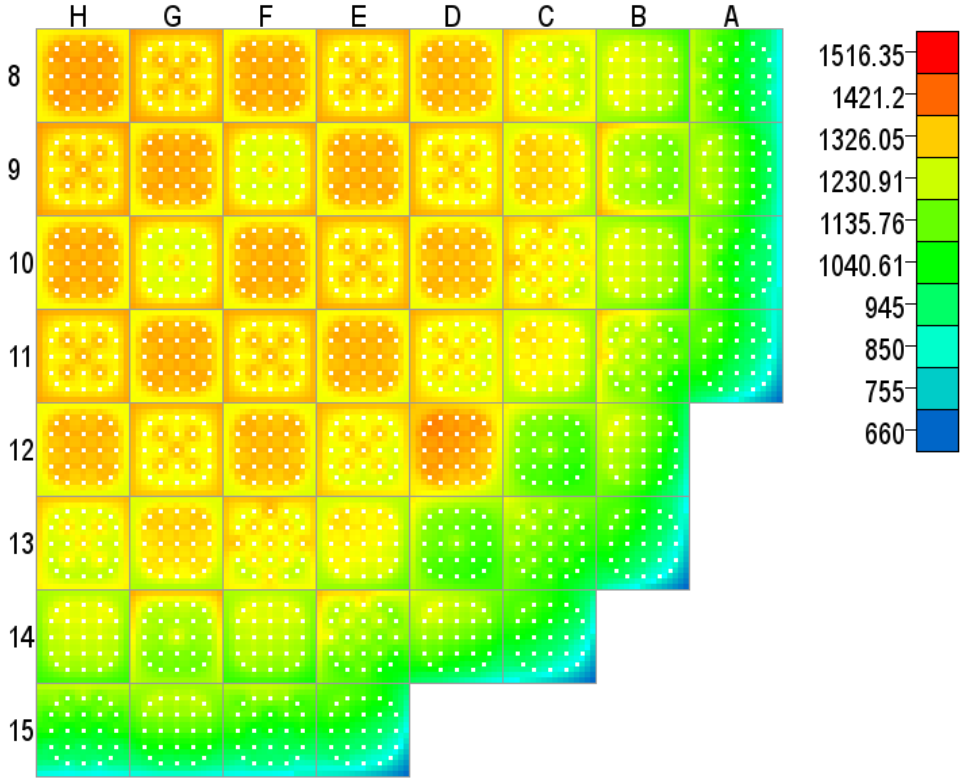

Fig. A.1.6. Cycle 1 maximum centerline fuel temperature (K) – 2.99 GWd/MT.

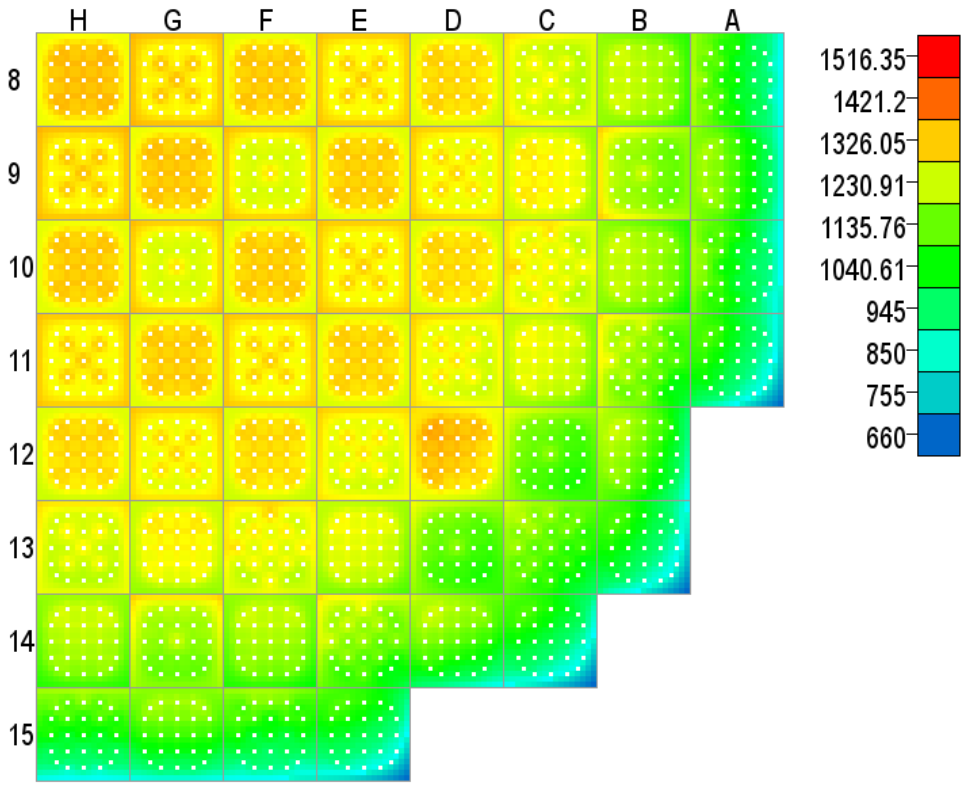

Fig. A.1.7. Cycle 1maximum centerline fuel temperature (K) – 3.56 GWd/MT.

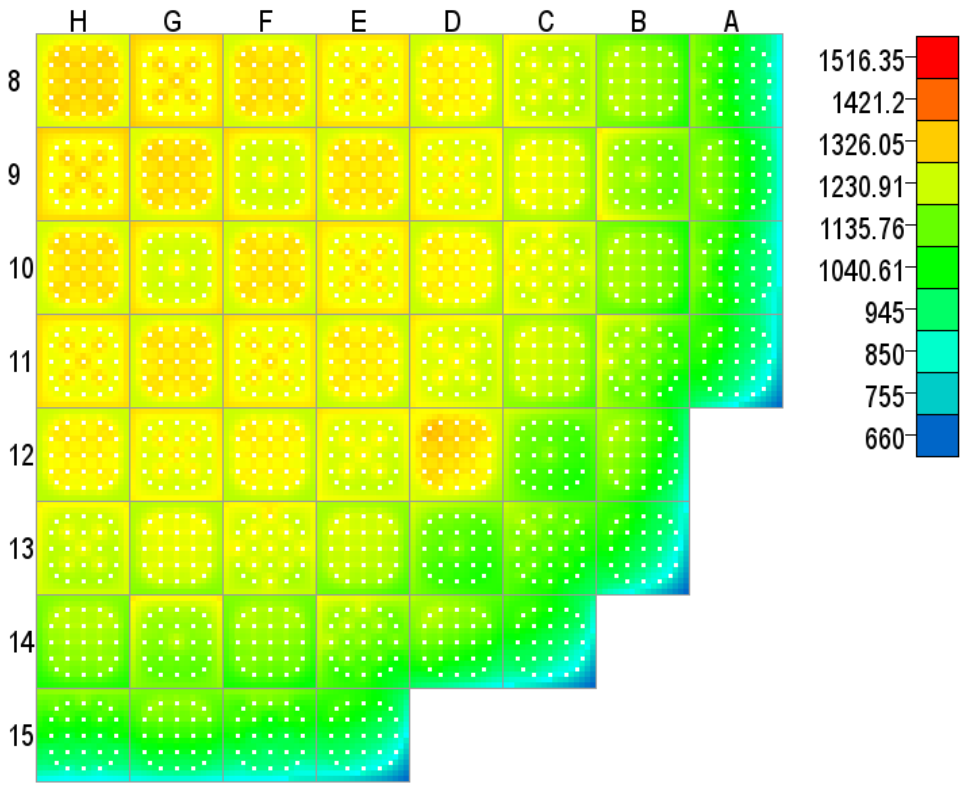

Fig. A.1.8. Cycle 1 maximum centerline fuel temperature (K) – 4.07 GWd/MT.

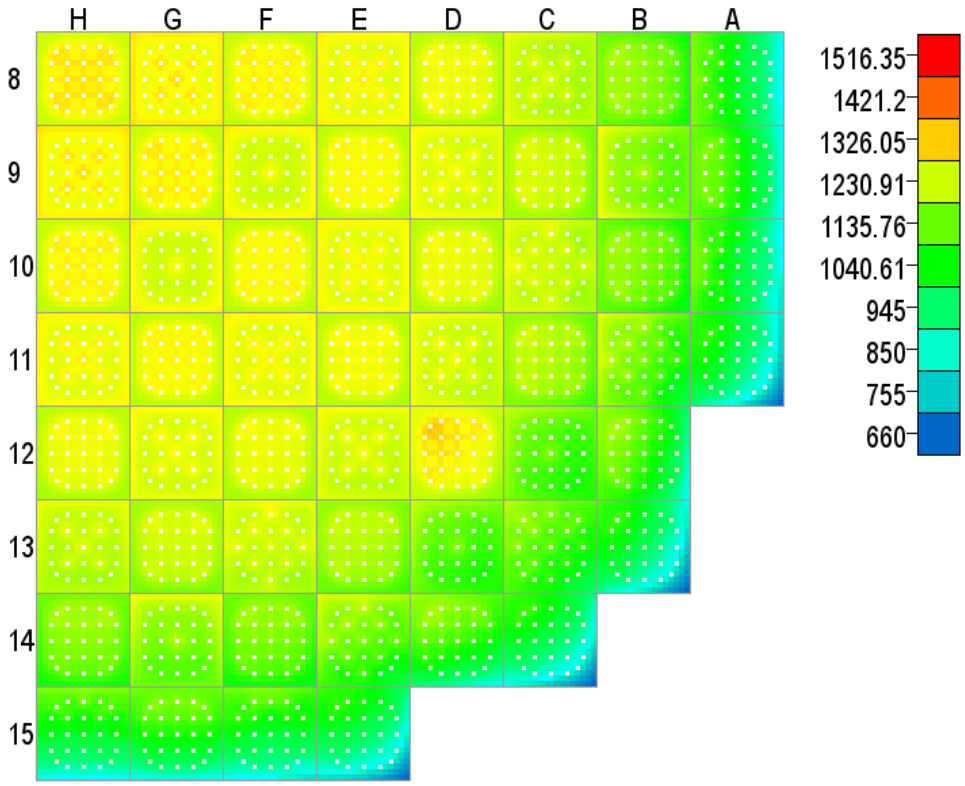

Fig. A.1.9. Cycle 1 maximum centerline fuel temperature (K) – 4.64 GWd/MT.

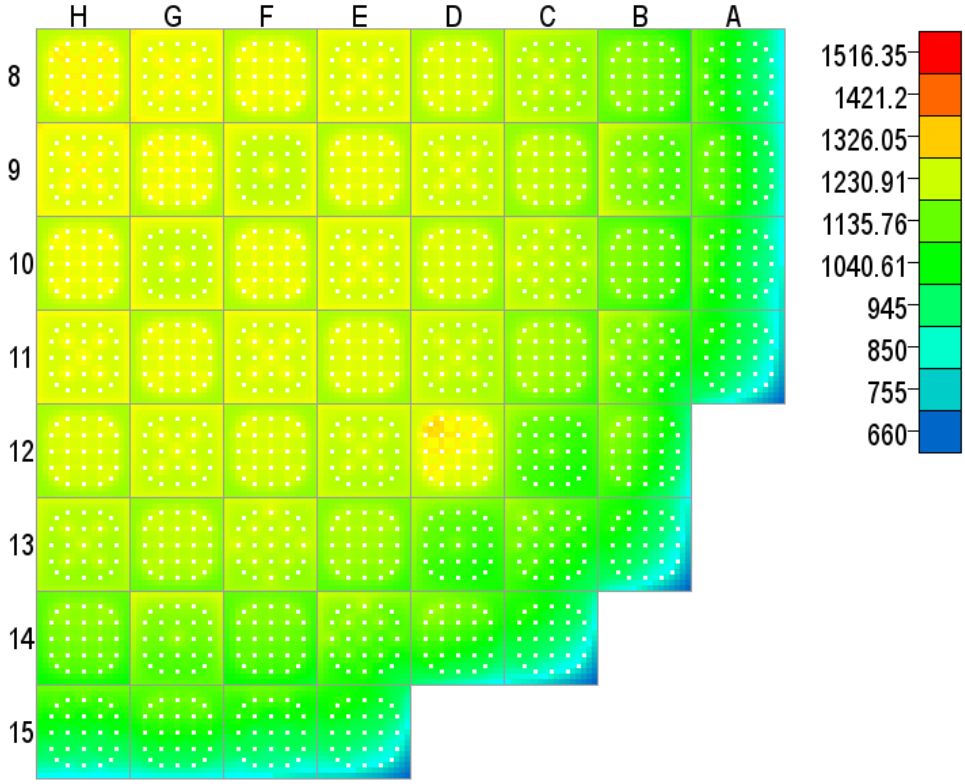

Fig. A.1.10. Cycle 1maximum centerline fuel temperature (K) – 5.14 GWd/MT.

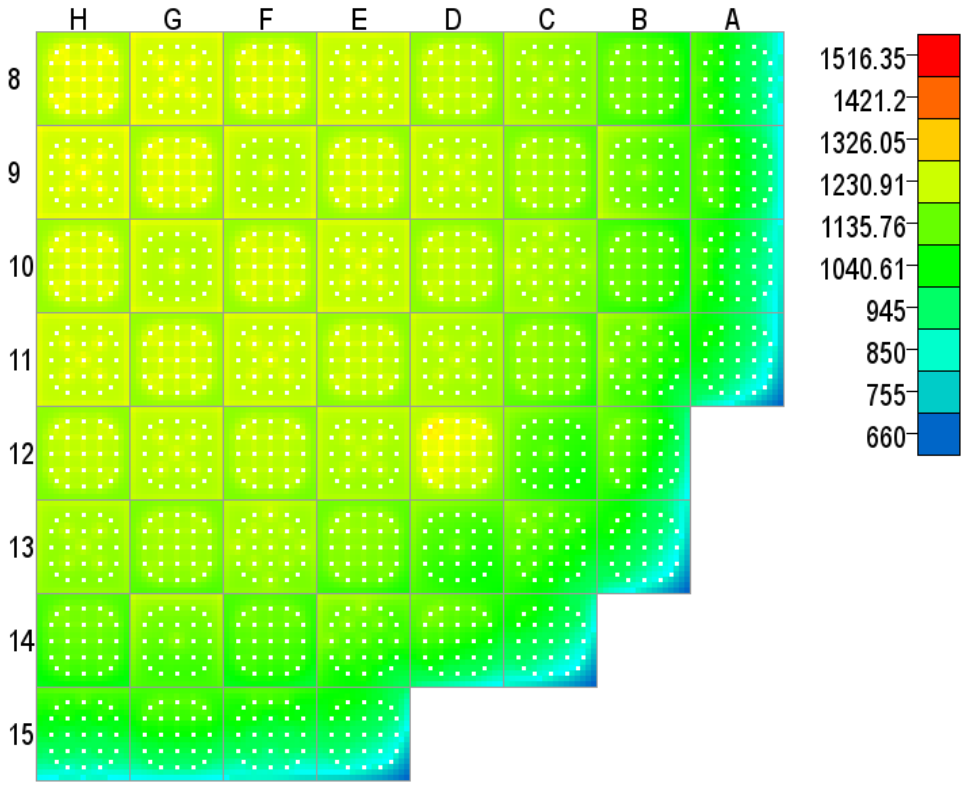

Fig. A.1.11. Cycle 1 maximum centerline fuel temperature (K) – 5.70 GWd/MT.

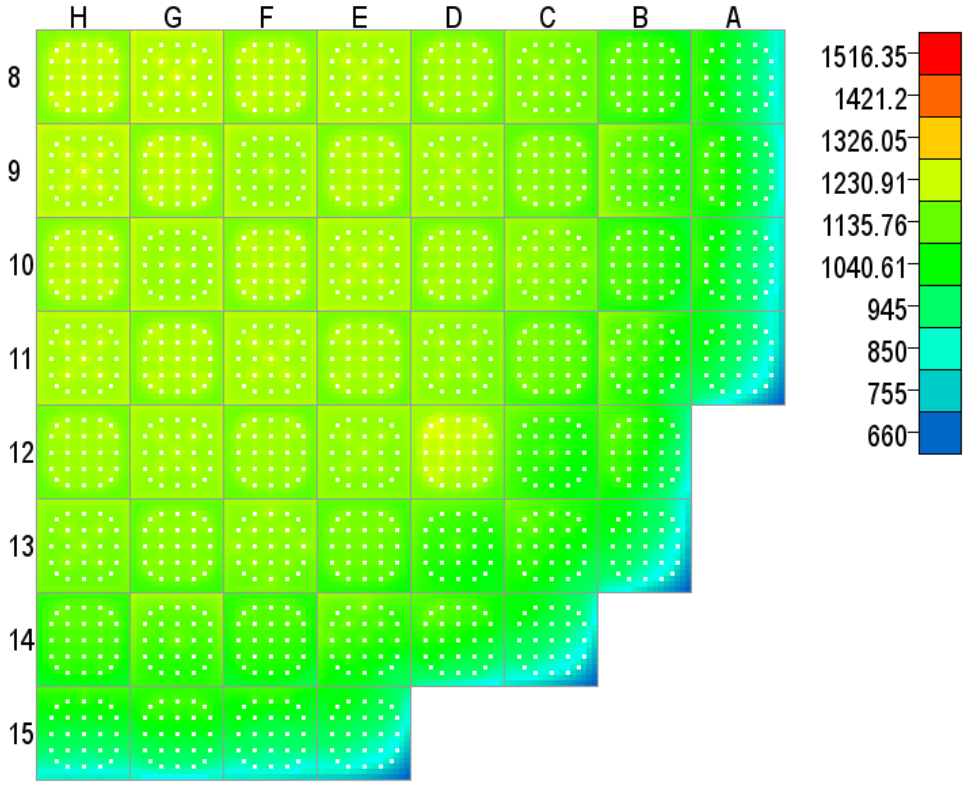

Fig. A.1.12. Cycle 1maximum centerline fuel temperature (K) – 6.27 GWd/MT.

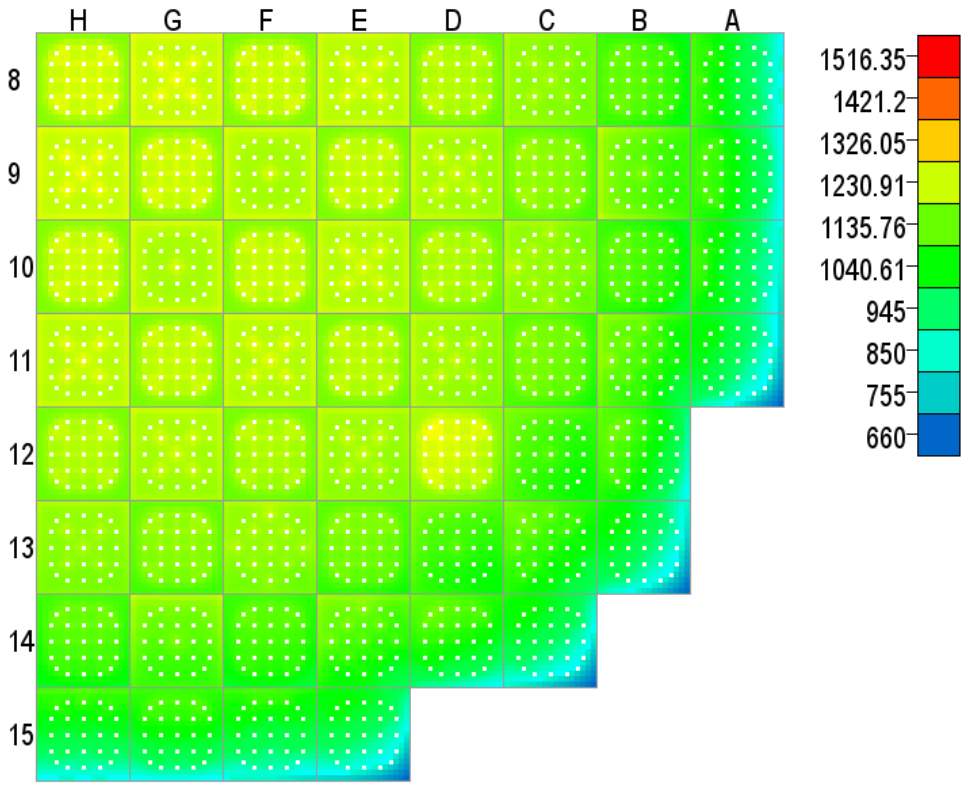

Fig. A.1.13. Cycle 1 maximum centerline fuel temperature (K) – 7.46 GWd/MT.

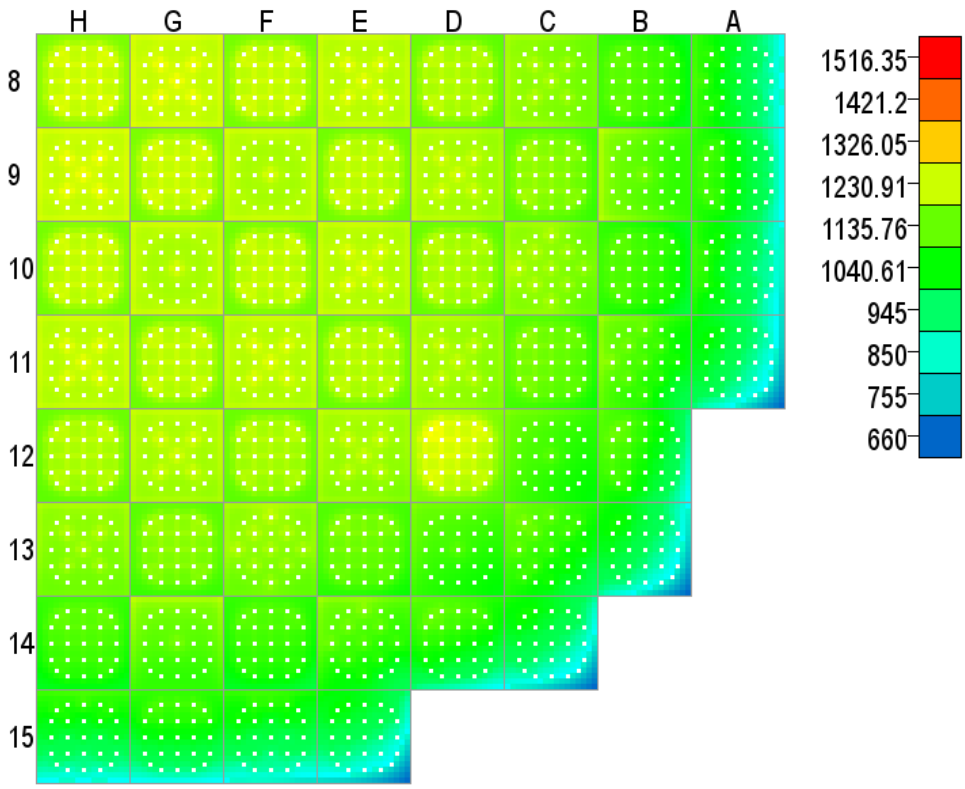

Fig. A.1.14. Cycle 1maximum centerline fuel temperature (K) – 8.49 GWd/MT.

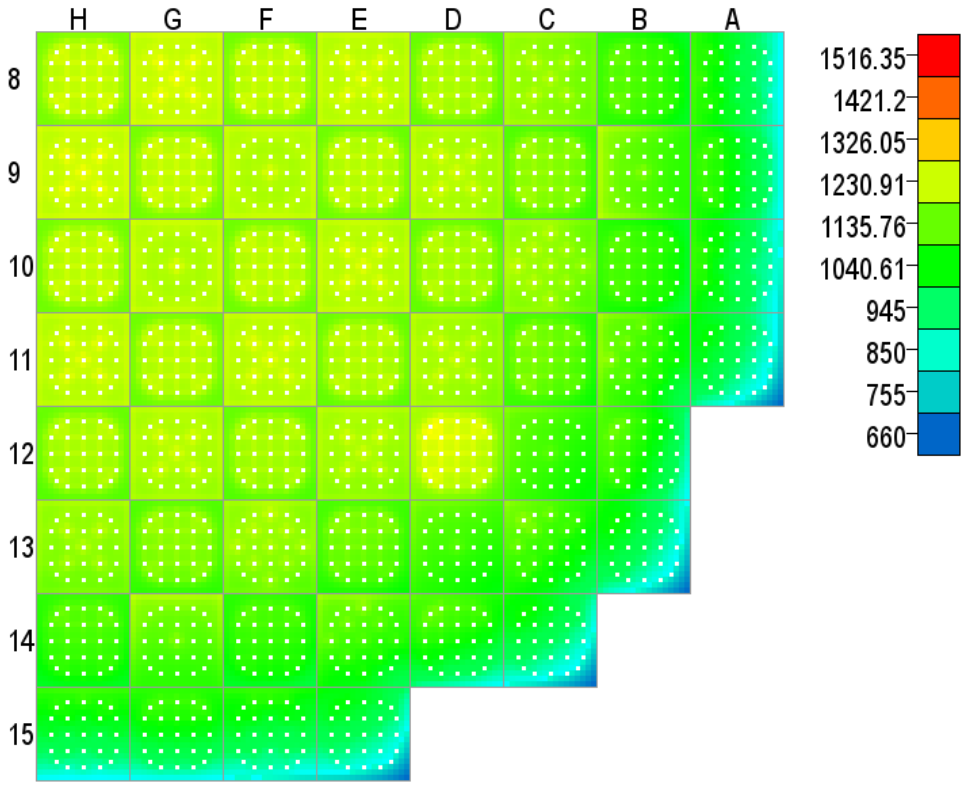

Fig. A.1.15. Cycle 1 maximum centerline fuel temperature (K) – 9.60 GWd/MT.

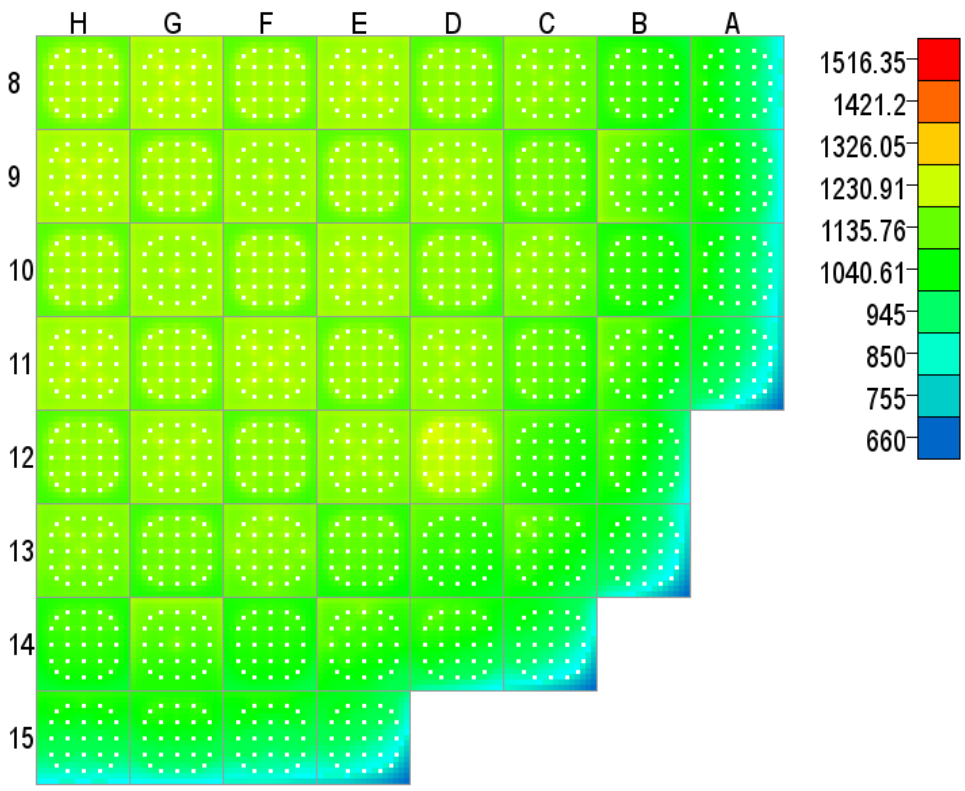

Fig. A.1.16. Cycle 1 maximum centerline fuel temperature (K) – 10.8 GWd/MT.

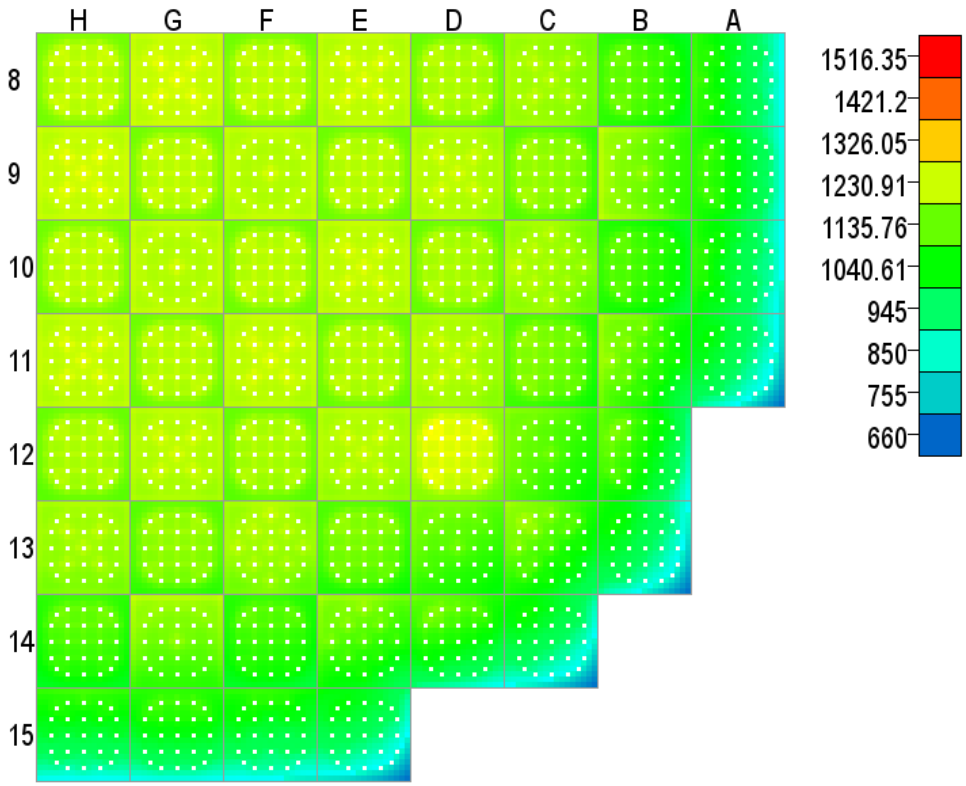

Fig. A.1.17. Cycle 1 maximum centerline fuel temperature (K) – 12.00 GWd/MT.

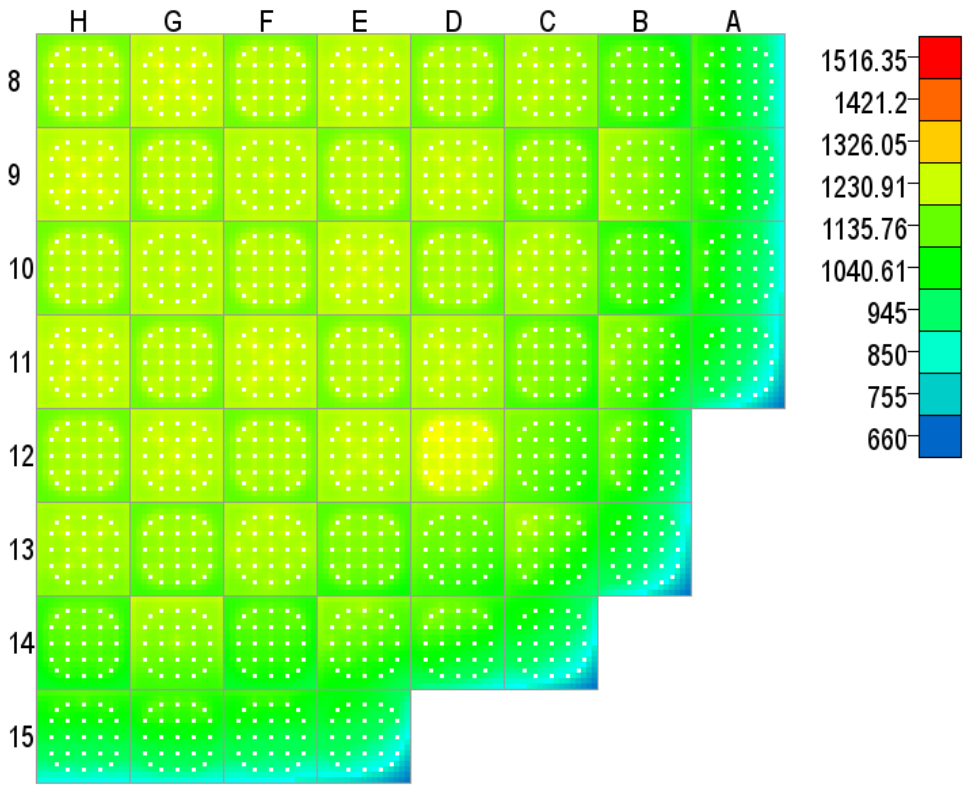

Fig. A.1.18. Cycle 1 maximum centerline fuel temperature (K) – 13.40 GWd/MT.

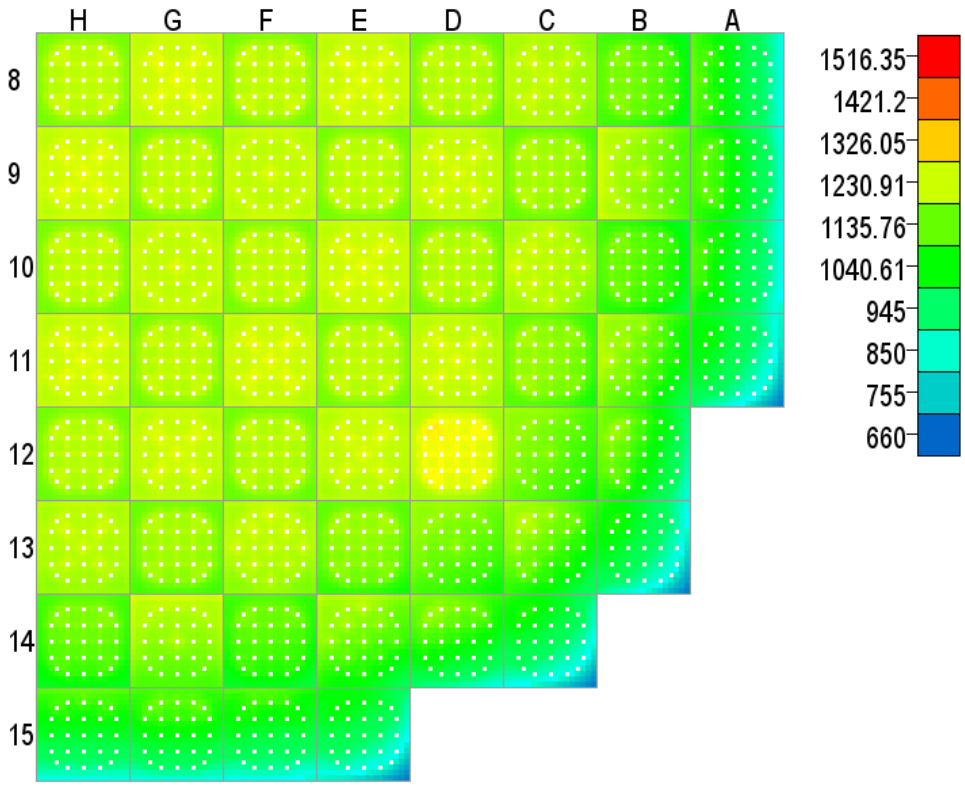

Fig. A.1.19. Cycle 1 maximum centerline fuel temperature (K) – 14.3 GWd/MT.

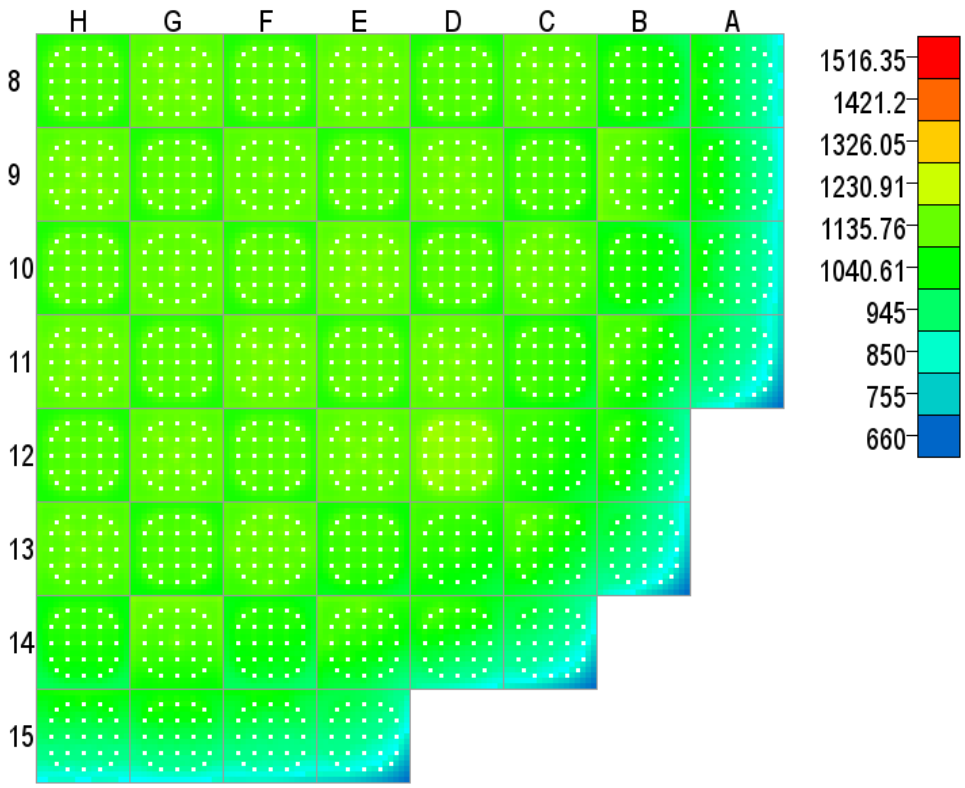

Fig. A.1.20. Cycle 1maximum centerline fuel temperature (K) – 15.10 GWd/MT.

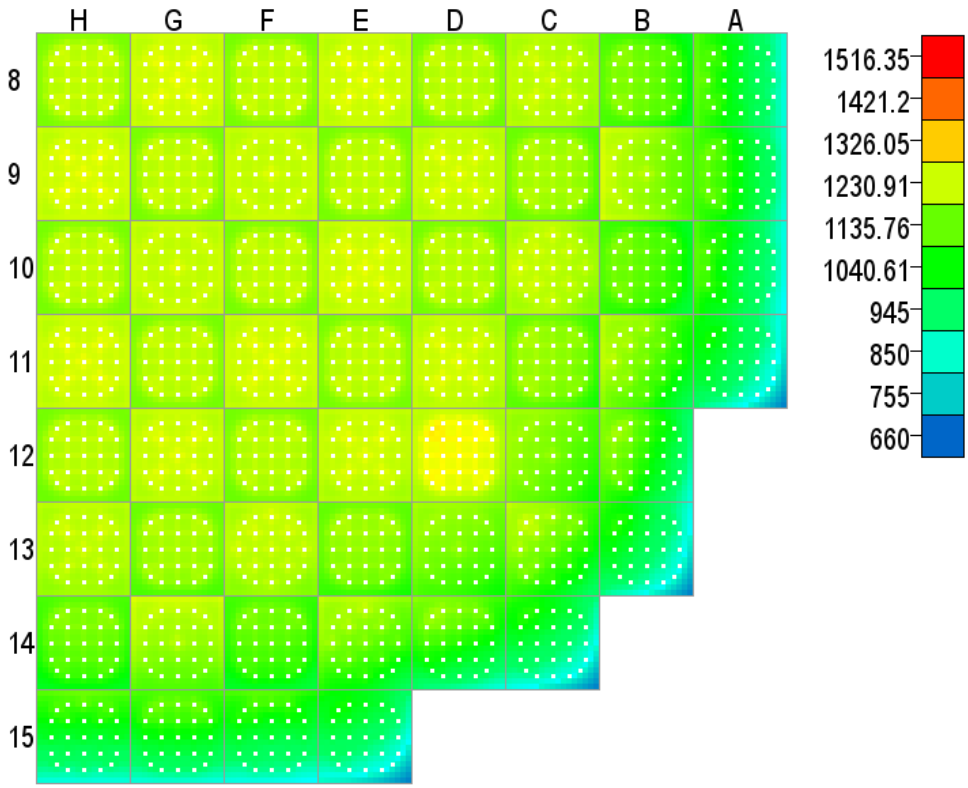

Fig. A.1.21. Cycle 1maximum centerline fuel temperature (K) – 15.30 GWd/MT.

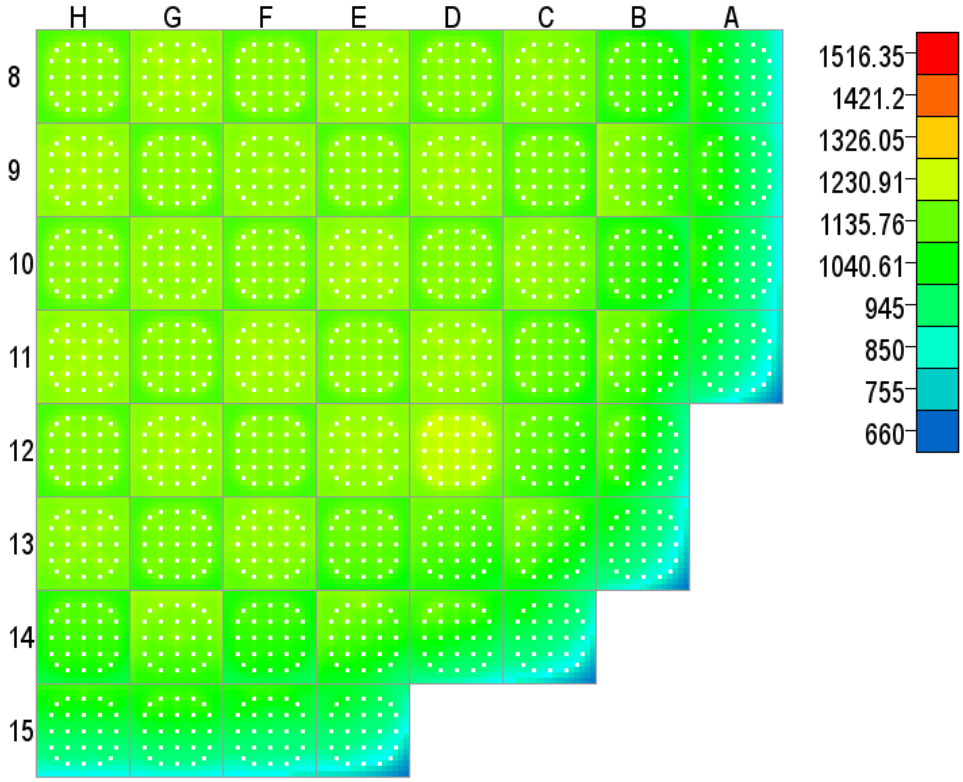

Fig. A.1.22. Cycle 1maximum centerline fuel temperature (K) – 15.80 GWd/MT.

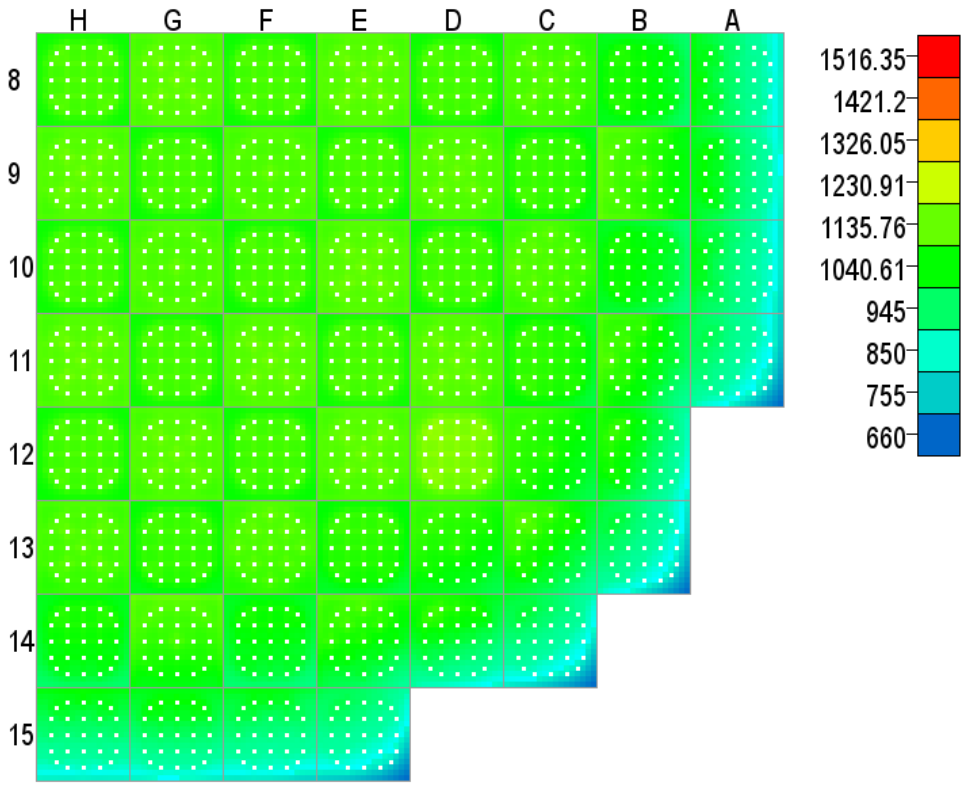

Fig. A.1.23. Cycle 1maximum centerline fuel temperature (K) – 16.30 GWd/MT.

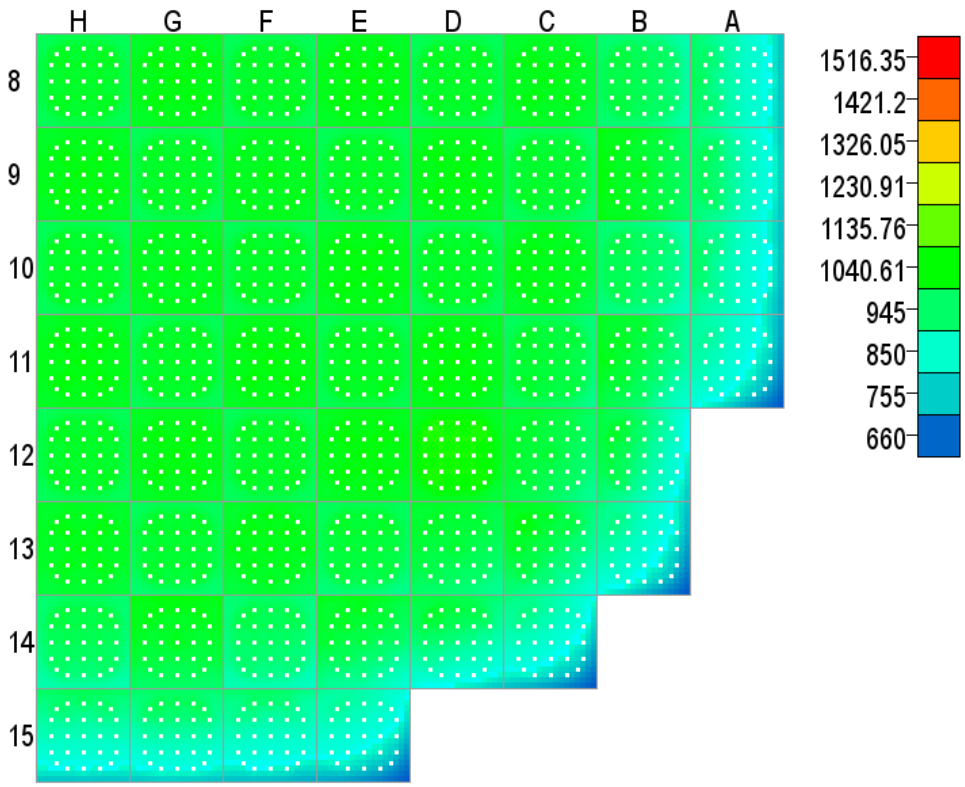

Fig. A.1.24. Cycle 1maximum centerline fuel temperature (K) – 16.90 GWd/MT.

A.1.2. Minimum Gap Thickness

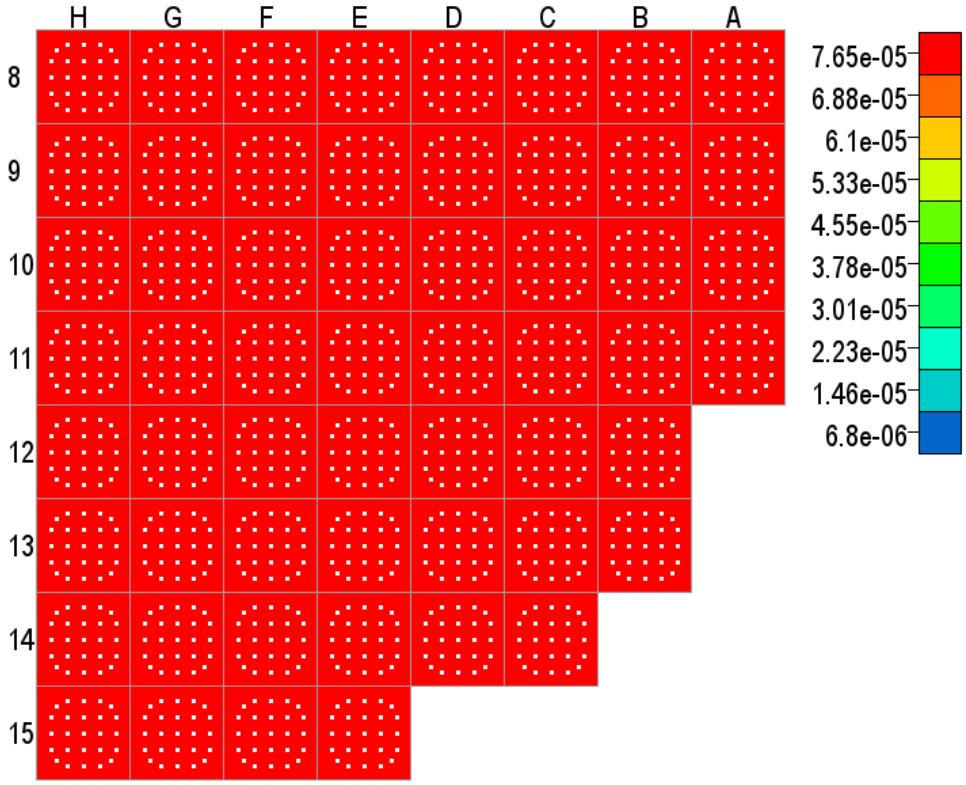

Fig. A.1.25. Cycle 1 minimum gap thickness (m) – 0.00 GWd/MT..

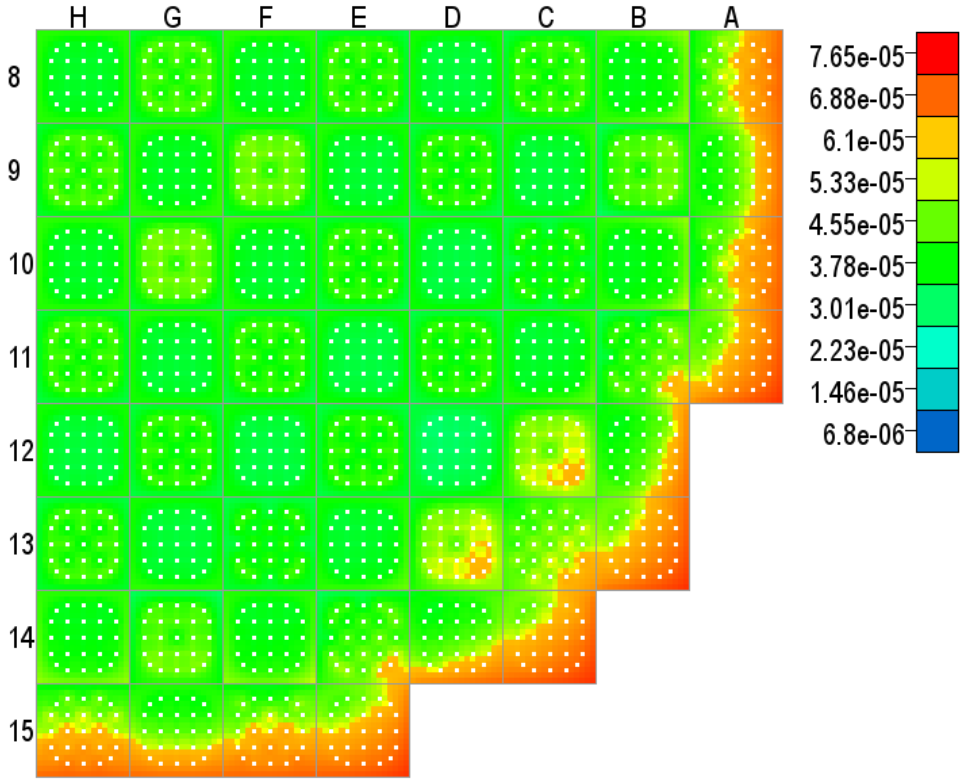

Fig. A.1.26. Cycle 1 minimum gap thickness (m) – 0.35 GWd/MT..

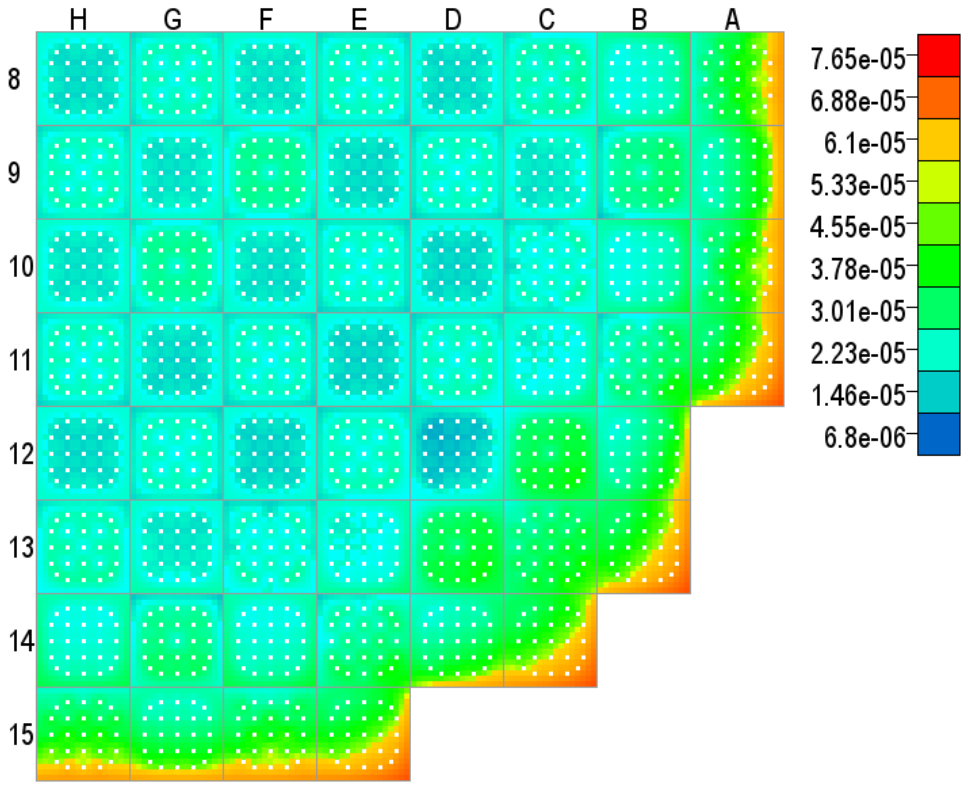

Fig. A.1.27. Cycle 1 minimum gap thickness (m) – 1.23 GWd/MT.

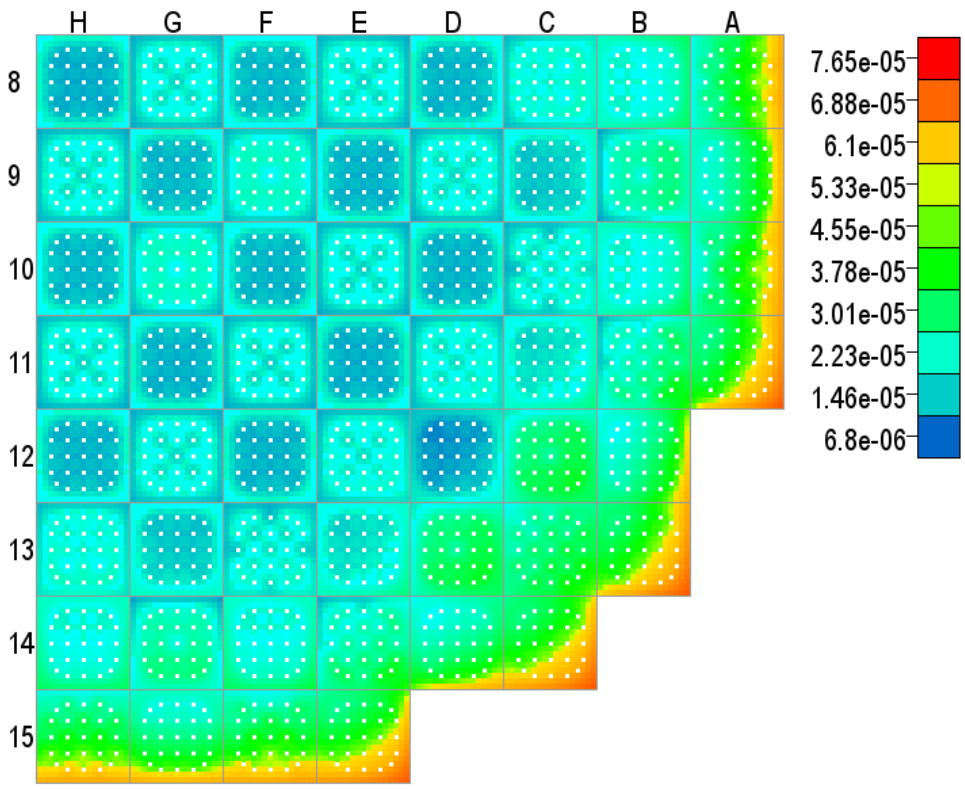

Fig. A.1.28. Cycle 1 minimum gap thickness (m) – 1.92 GWd/MT.

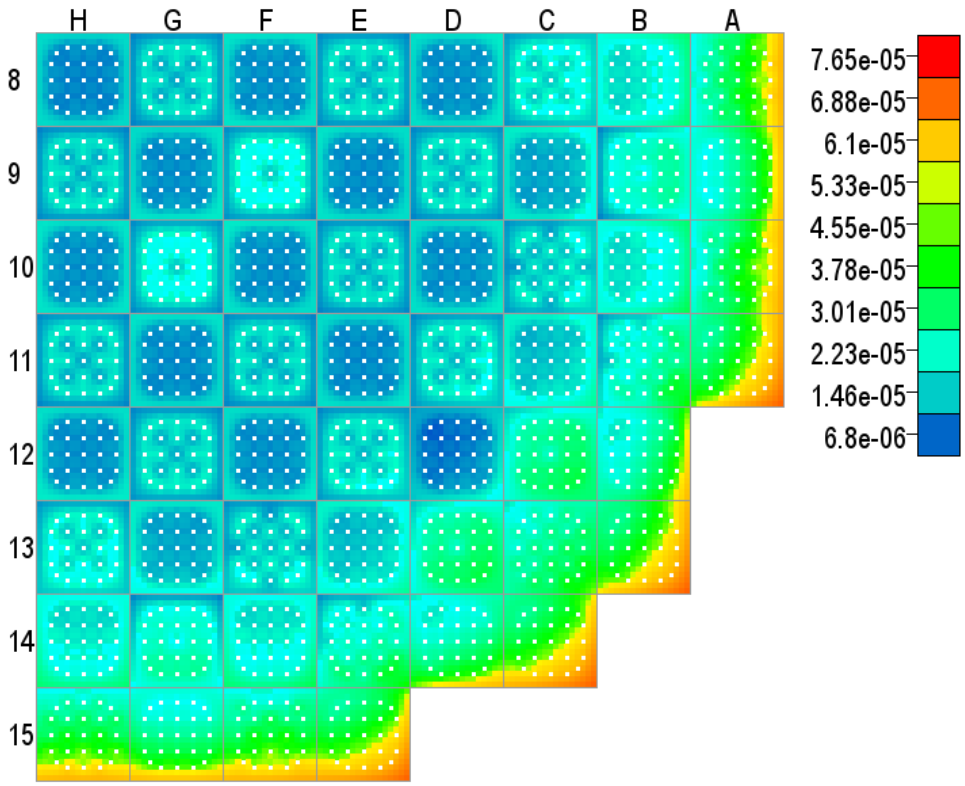

Fig. A.1.29. Cycle 1 minimum gap thickness (m) – 2.46 GWd/MT.

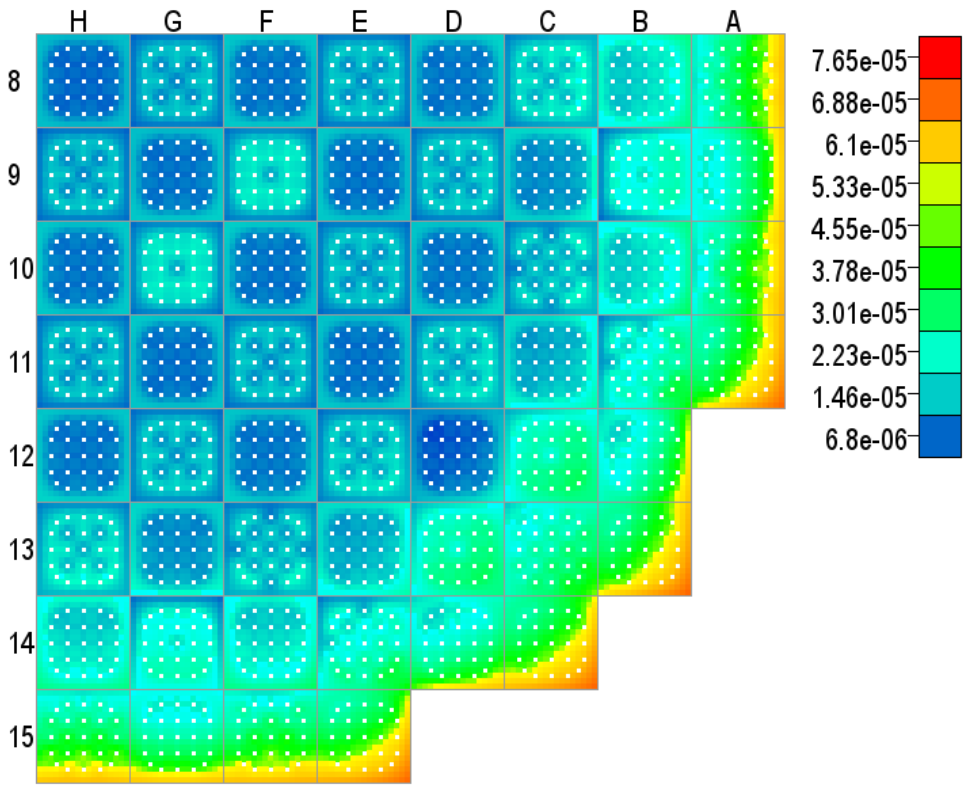

Fig. A.1.30. Cycle 1 minimum gap thickness (m) – 2.99 GWd/MT.

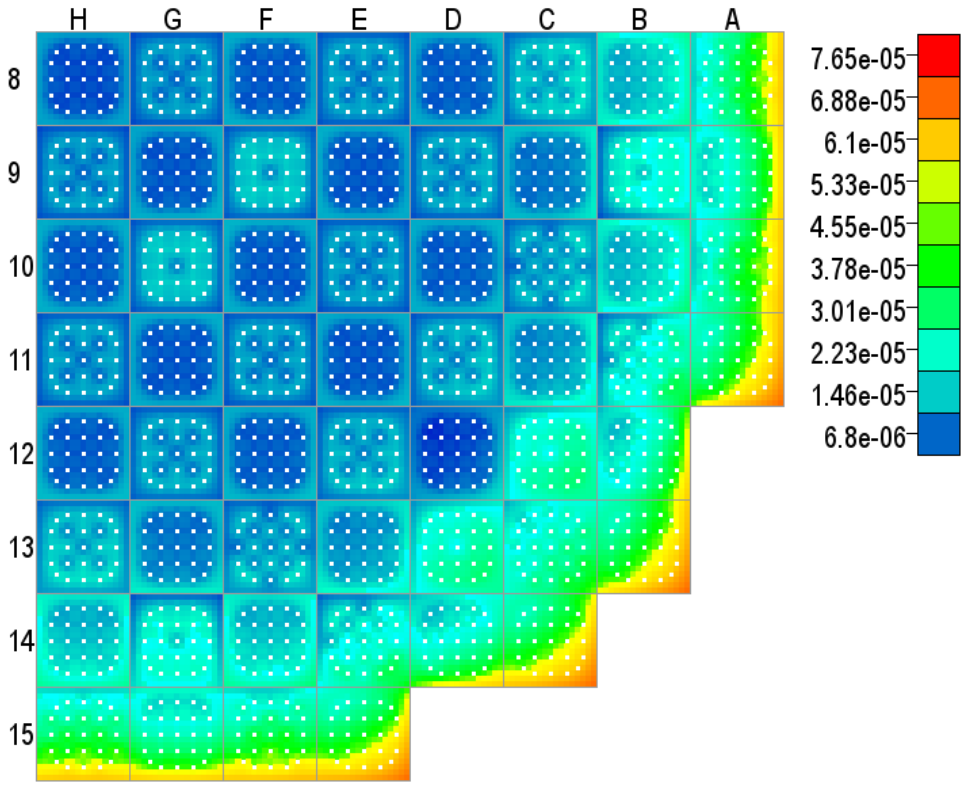

Fig. A.1.31. Cycle 1 minimum gap thickness (m) – 3.56 GWd/MT.

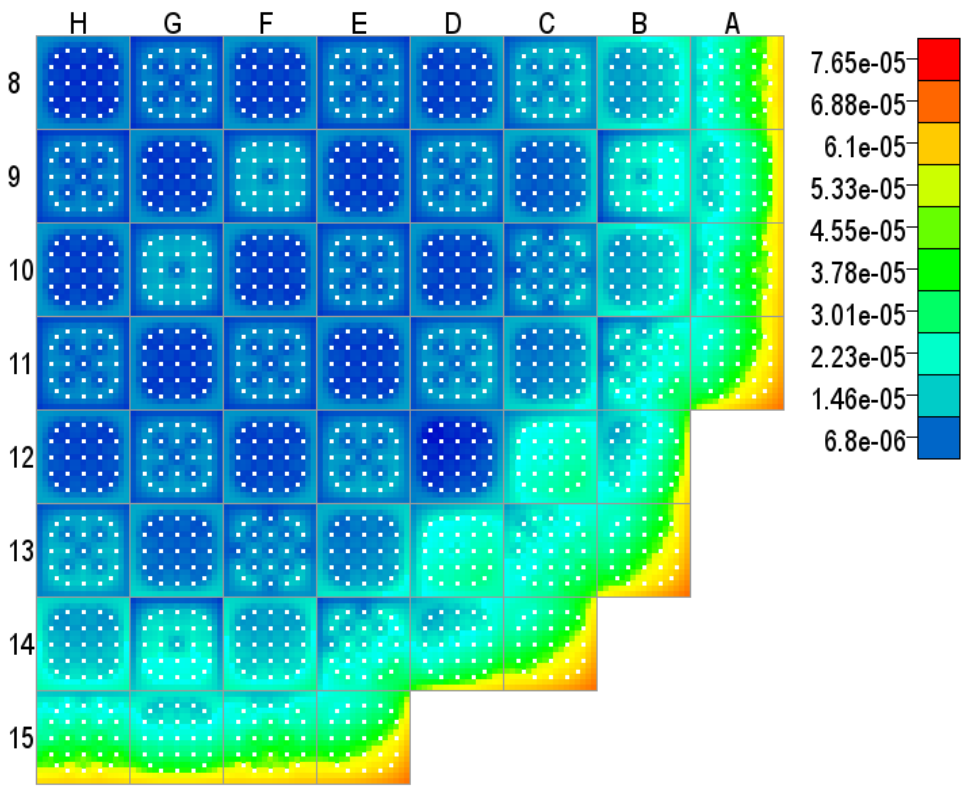

Fig. A.1.32. Cycle 1 minimum gap thickness (m) – 4.07 GWd/MT.

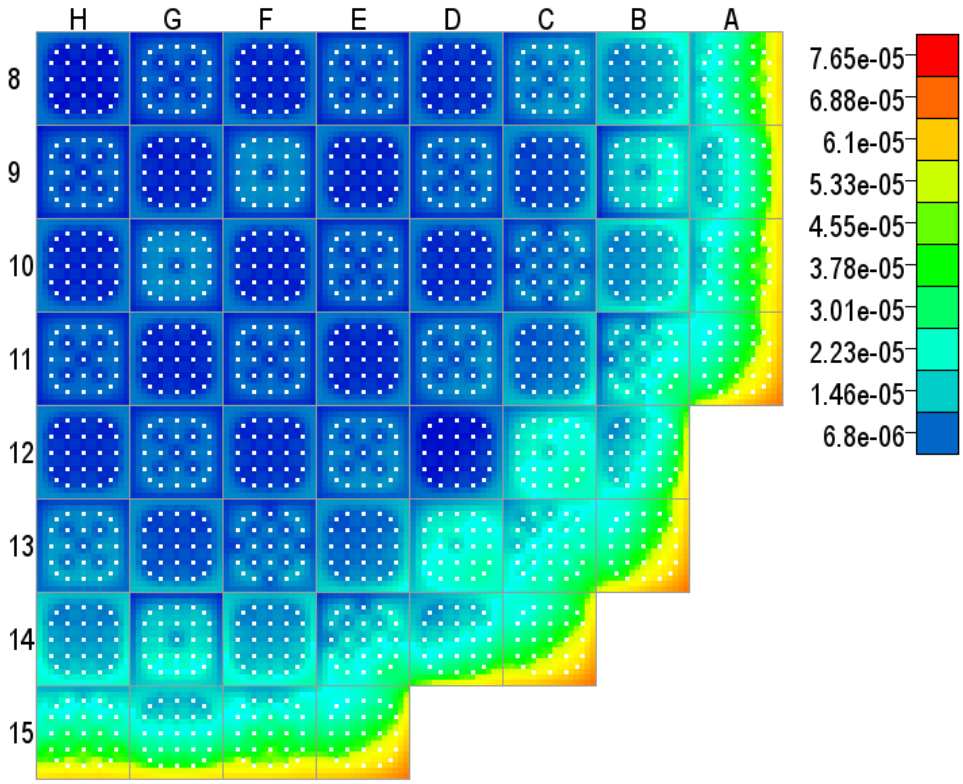

Fig. A.1.33. Cycle 1 minimum gap thickness (m) – 4.64 GWd/MT.

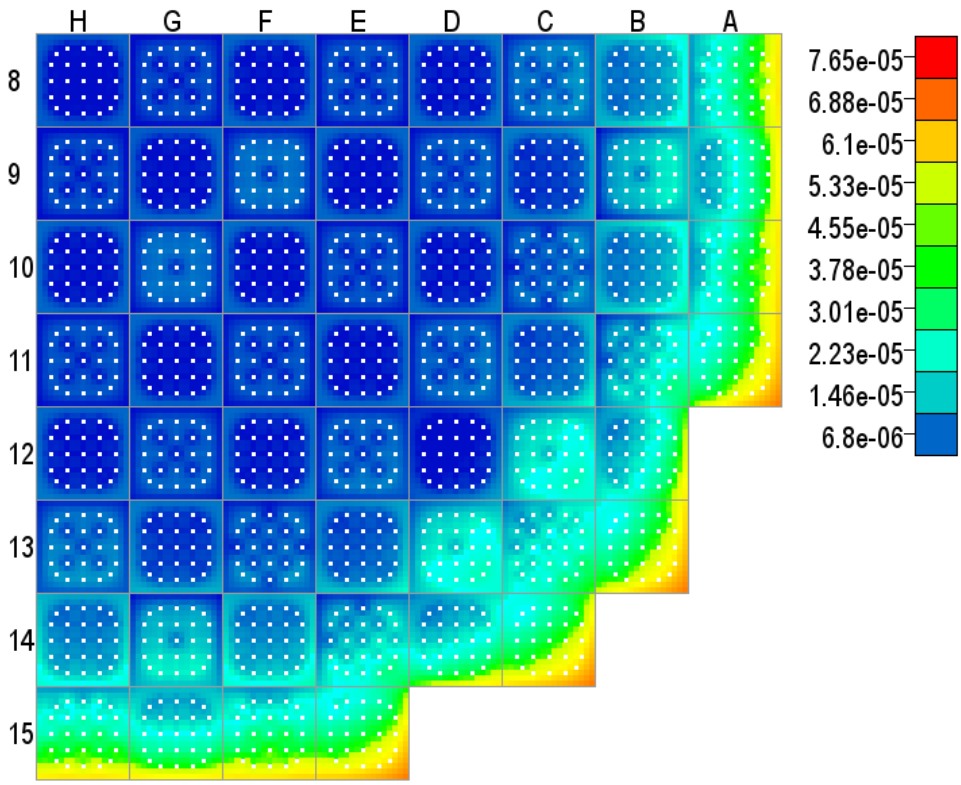

Fig. A.1.34. Cycle 1 minimum gap thickness (m) – 5.14 GWd/MT.

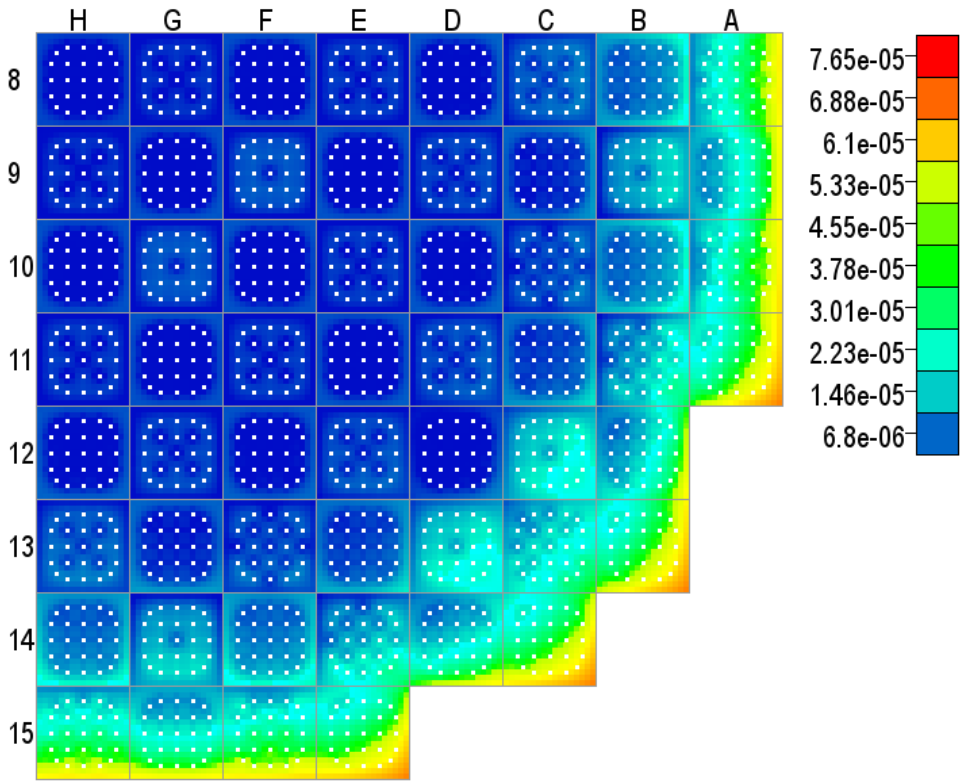

Fig. A.1.35. Cycle 1 minimum gap thickness (m) – 5.70 GWd/MT.

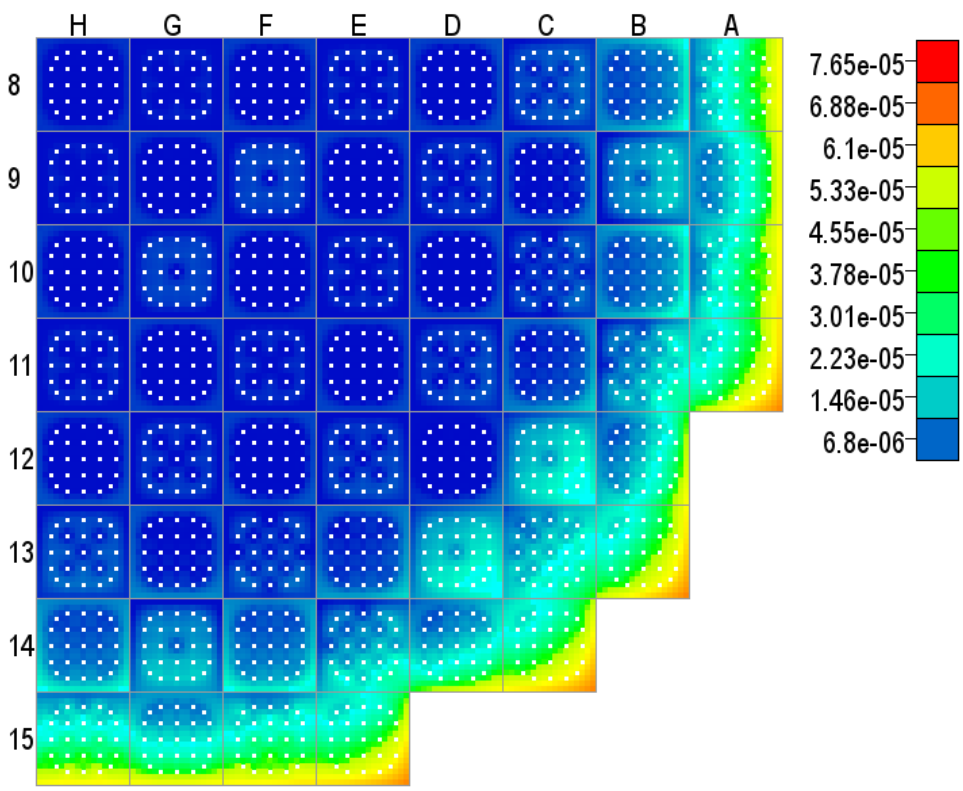

Fig. A.1.36. Cycle 1 minimum gap thickness (m) – 6.27 GWd/MT.

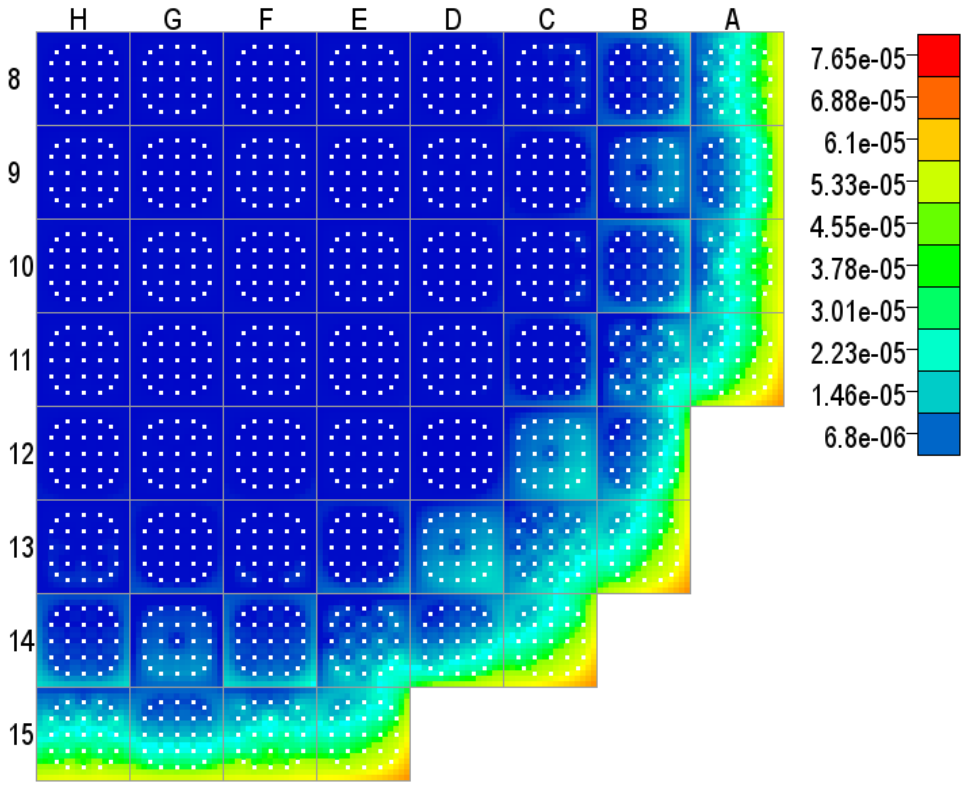

Fig. A.1.37. Cycle 1 minimum gap thickness (m) – 7.46 GWd/MT.

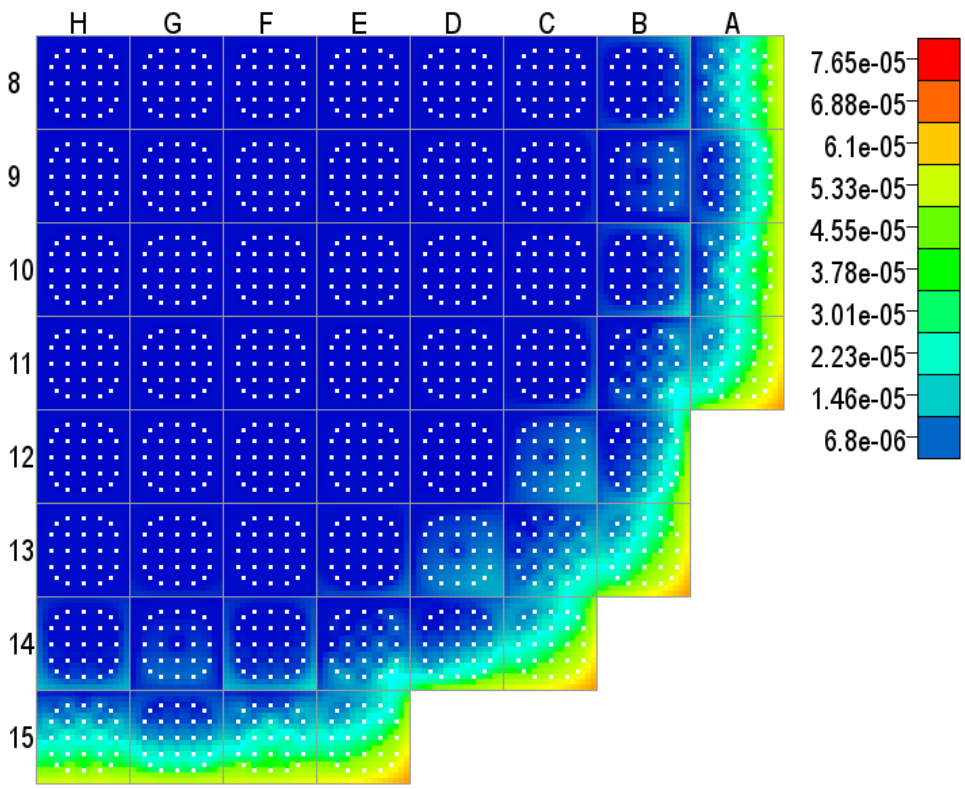

Fig. A.1.38. Cycle 1 minimum gap thickness (m) – 8.49 GWd/MT.

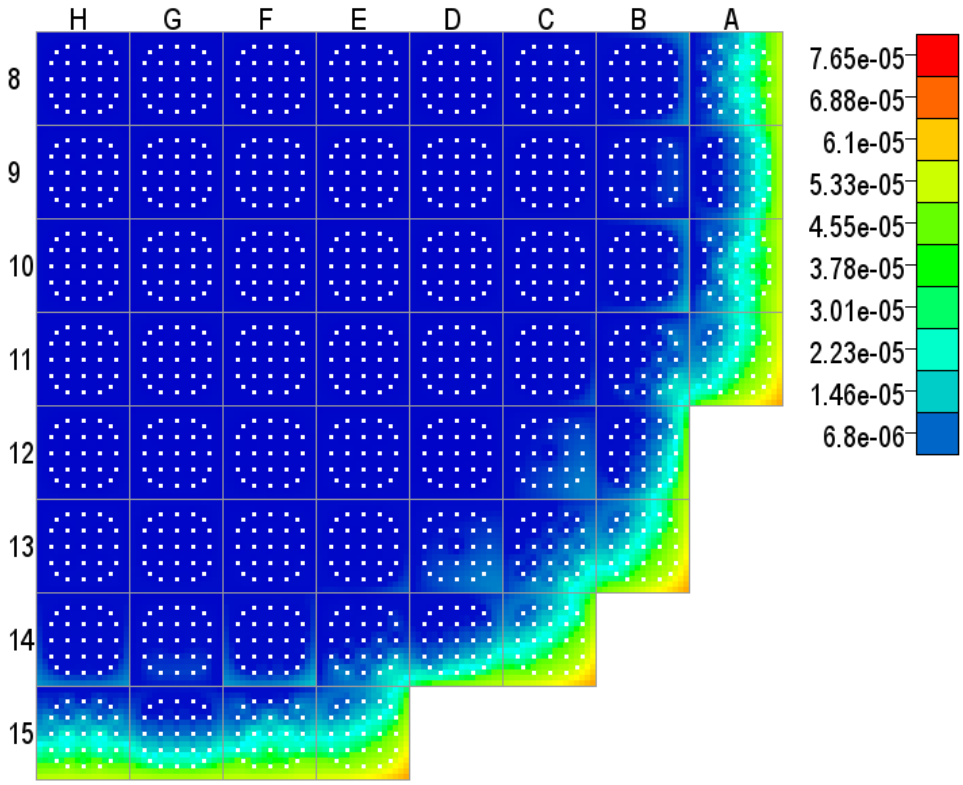

Fig. A.1.39. Cycle 1 minimum gap thickness (m) – 9.60 GWd/MT.

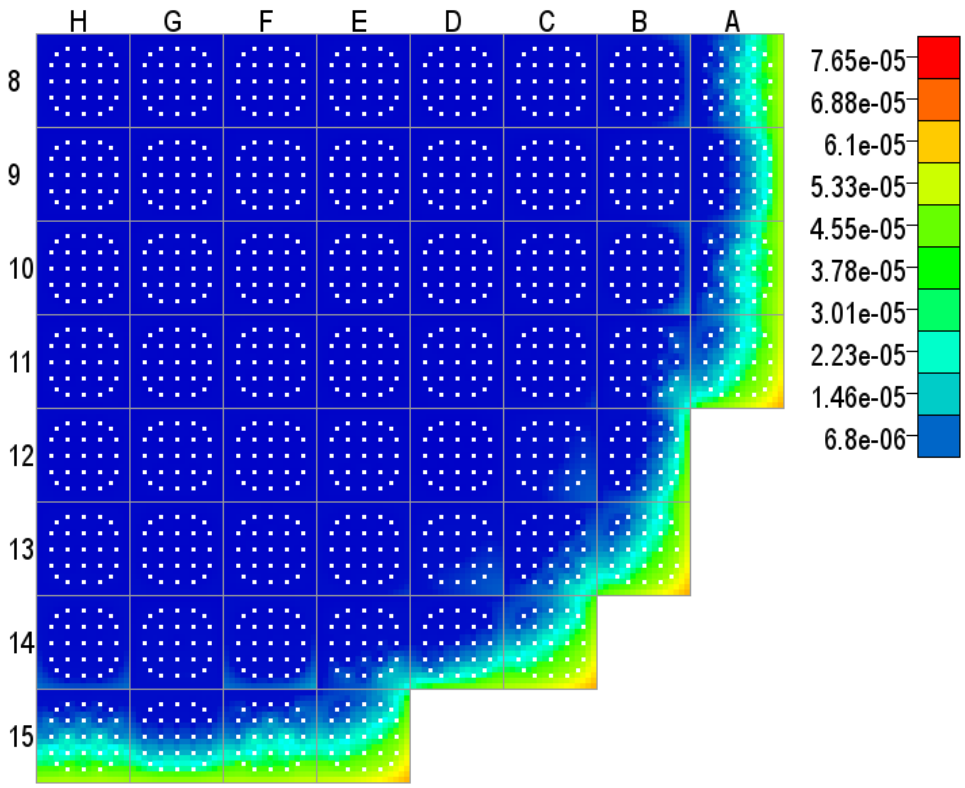

Fig. A.1.40. Cycle 1 minimum gap thickness (m) – 10.8 GWd/MT.

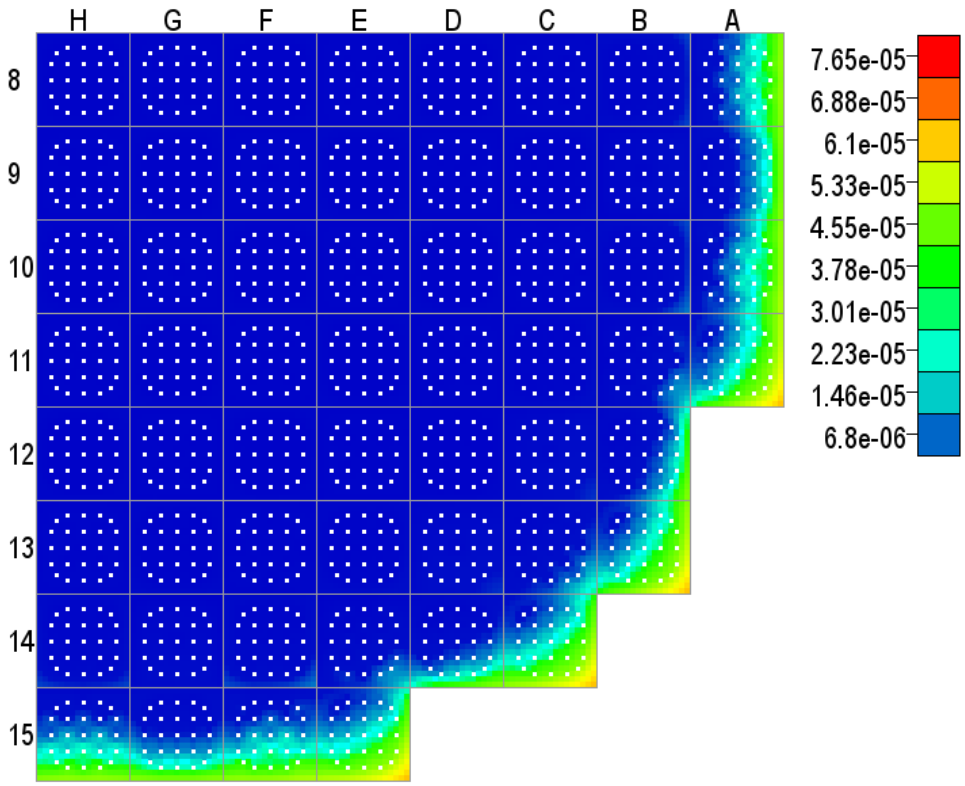

Fig. A.1.41. Cycle 1 minimum gap thickness (m) – 12.00 GWd/MT.

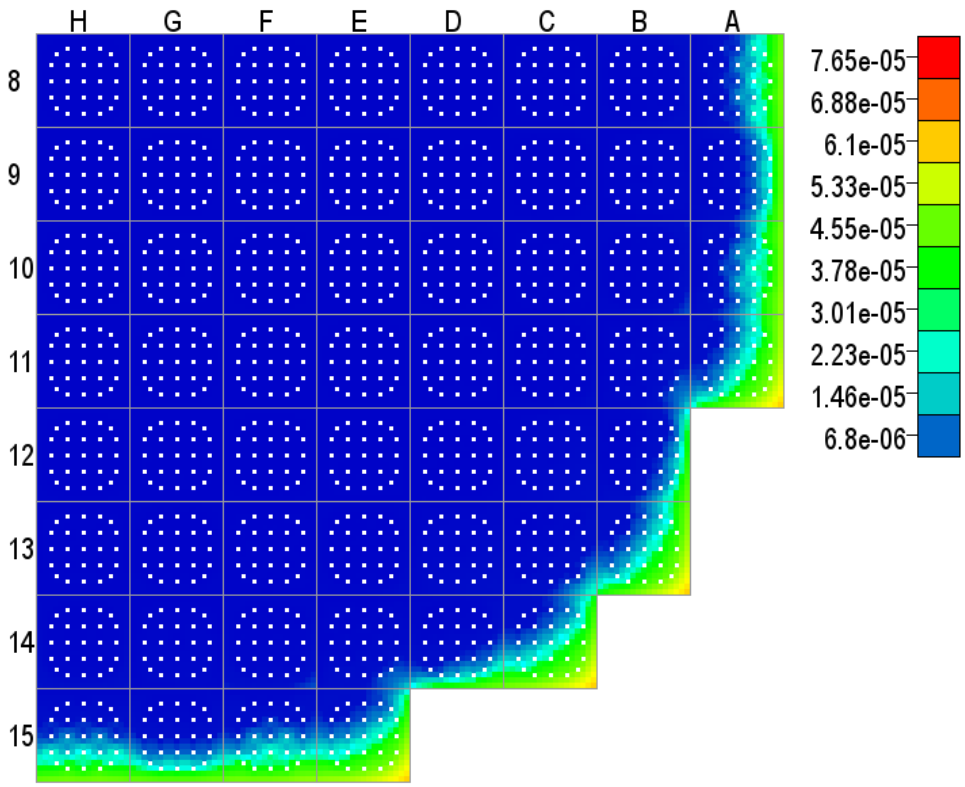

Fig. A.1.42. Cycle 1 minimum gap thickness (m) – 13.40 GWd/MT.

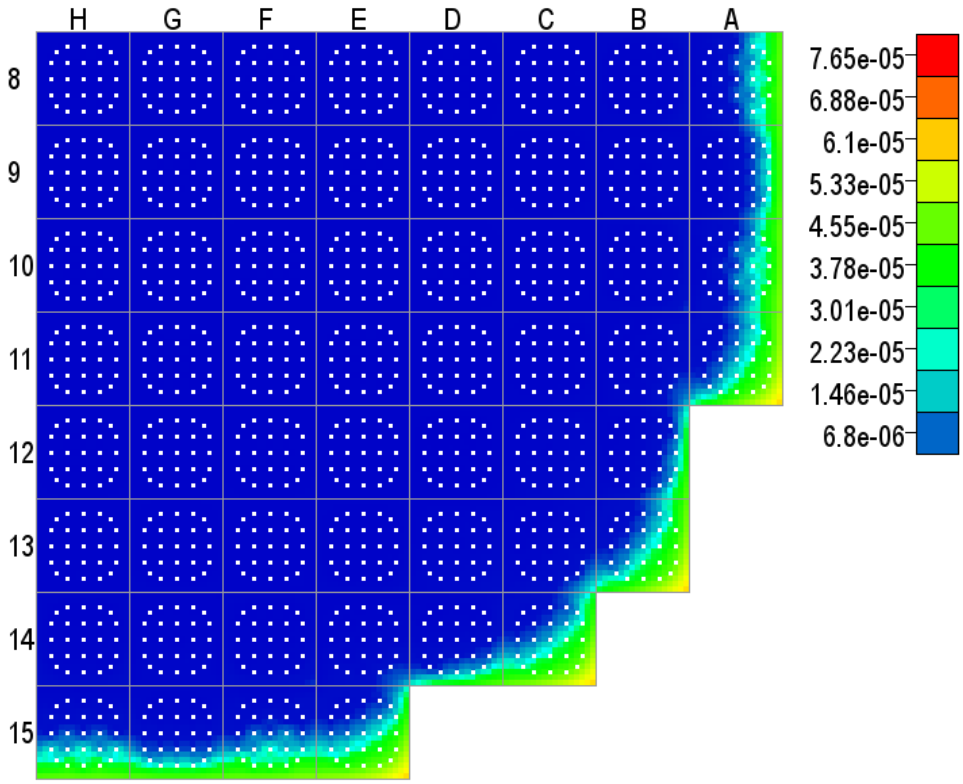

Fig. A.1.43. Cycle 1 minimum gap thickness (m) – 14.3 GWd/MT.

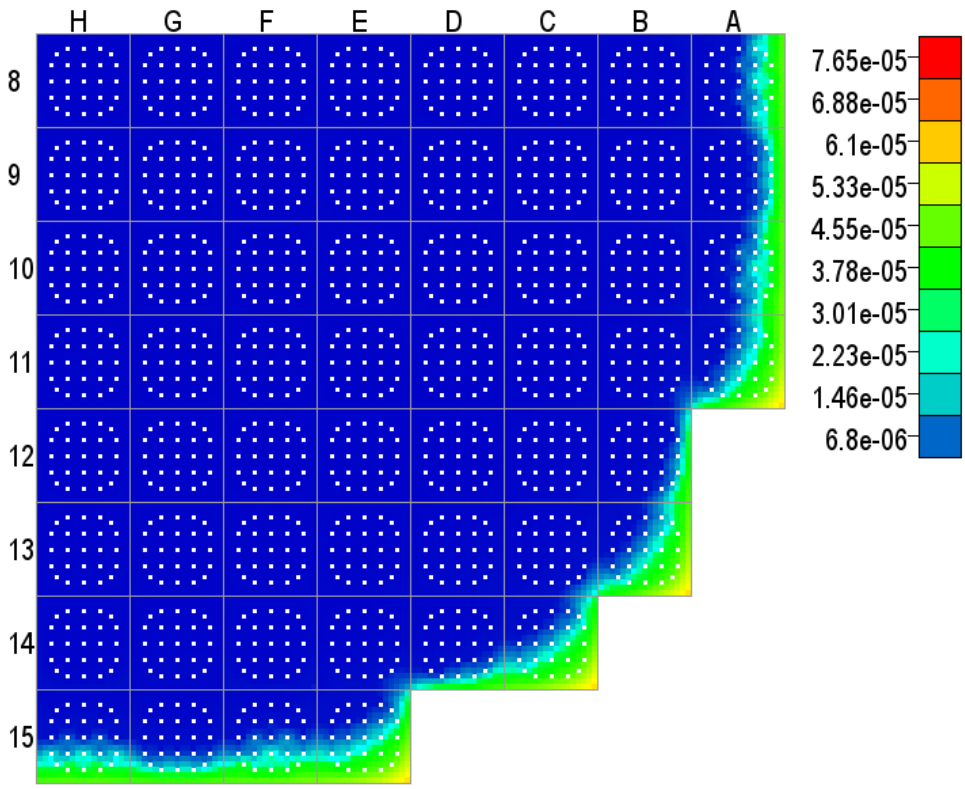

Fig. A.1.44. Cycle 1 minimum gap thickness (m) – 15.10 GWd/MT.

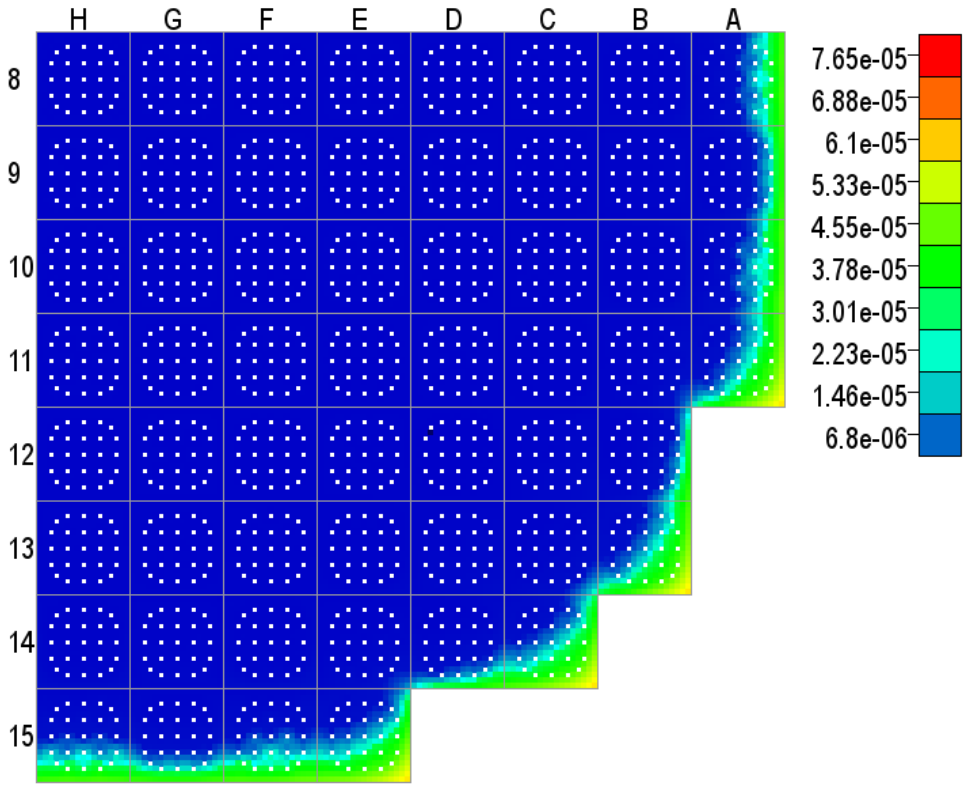

Fig. A.1.45. Cycle 1 minimum gap thickness (m) – 15.30 GWd/MT.

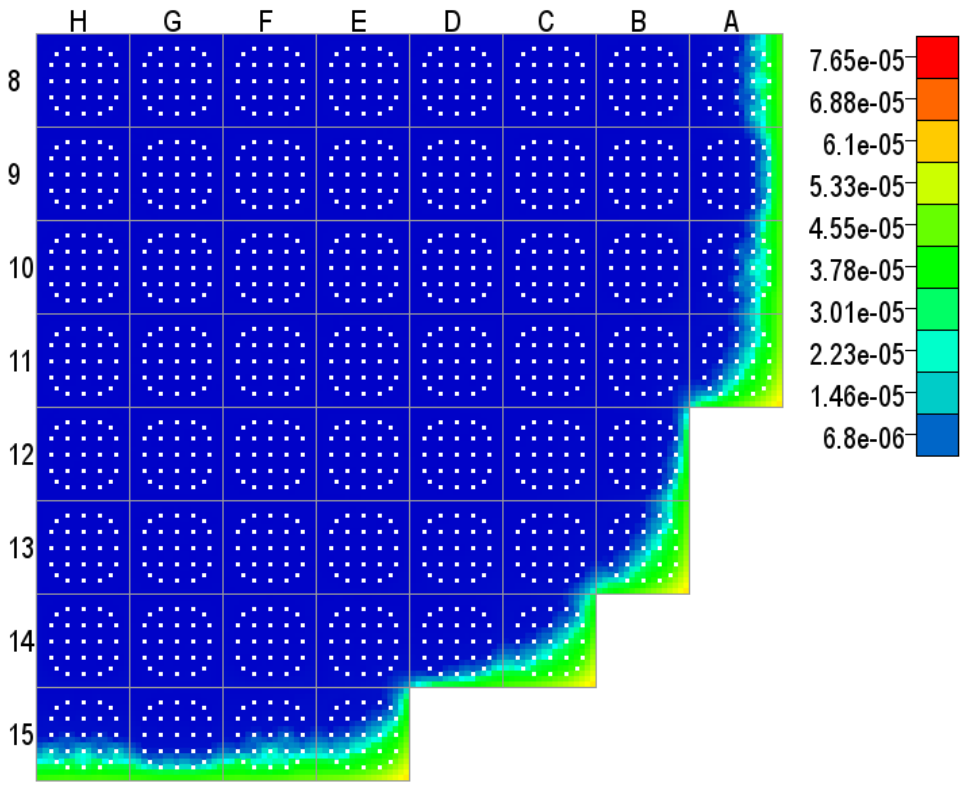

Fig. A.1.46. Cycle 1 minimum gap thickness (m) – 15.80 GWd/MT.

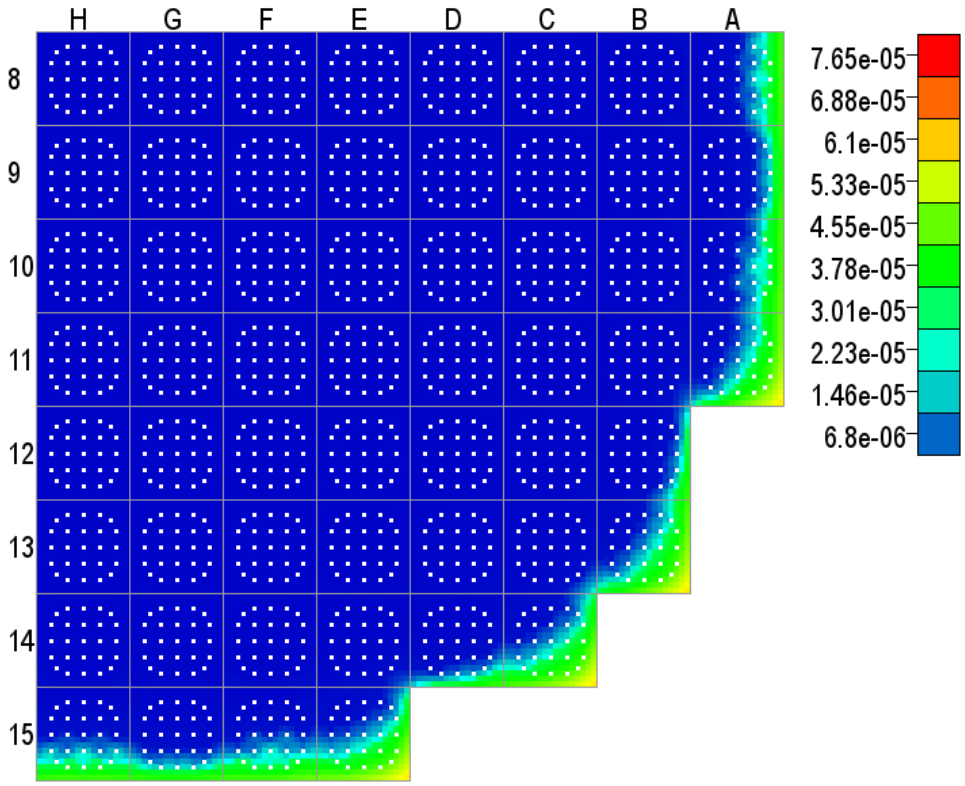

Fig. A.1.47. Cycle 1 minimum gap thickness (m) – 16.30 GWd/MT.

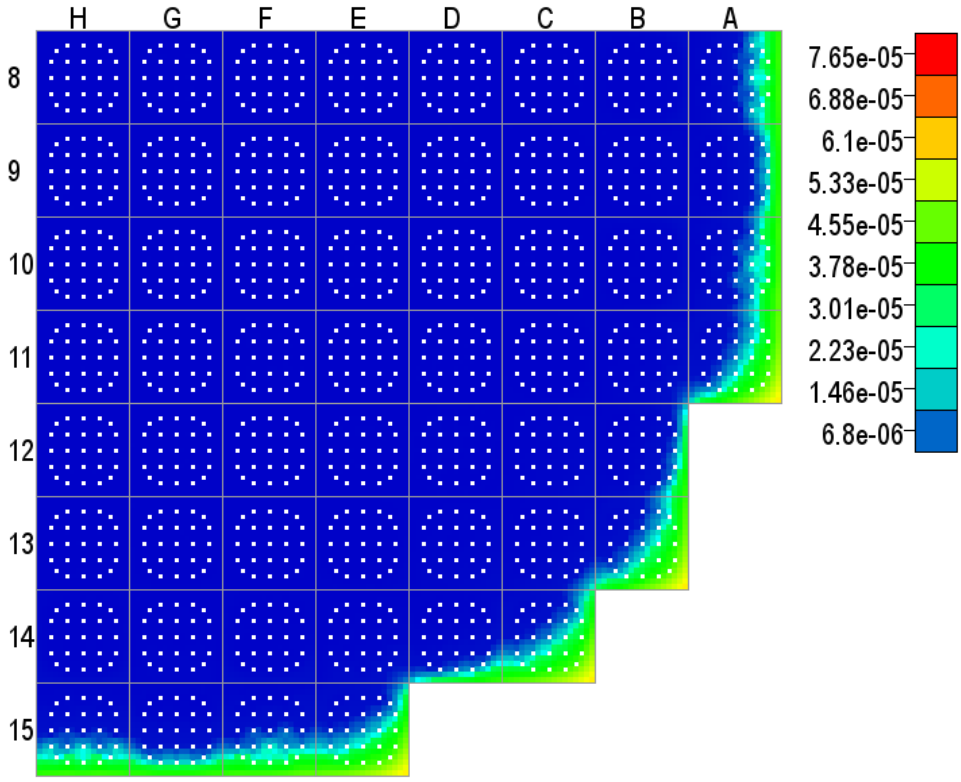

Fig. A.1.48. Cycle 1 minimum gap thickness (m) – 16.90 GWd/MT.

A.2. Cycle 2

A.2.1. Maximum Centerline Fuel Temperature

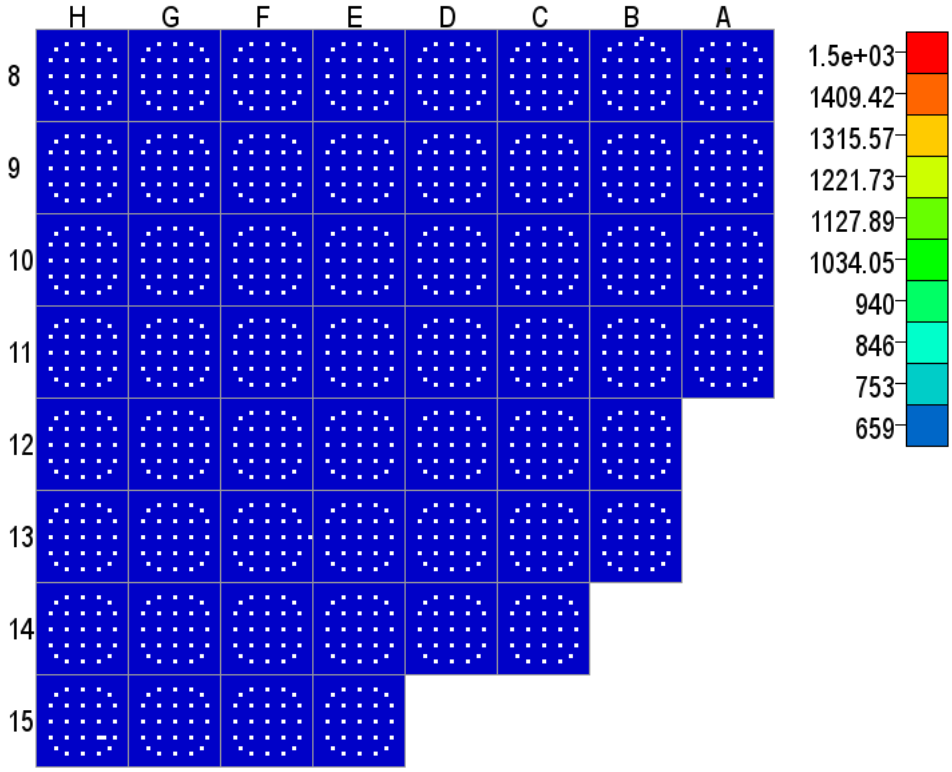

Fig. A.2.1. Cycle 2 maximum centerline fuel temperature (K) – 0.00 GWd/MT.

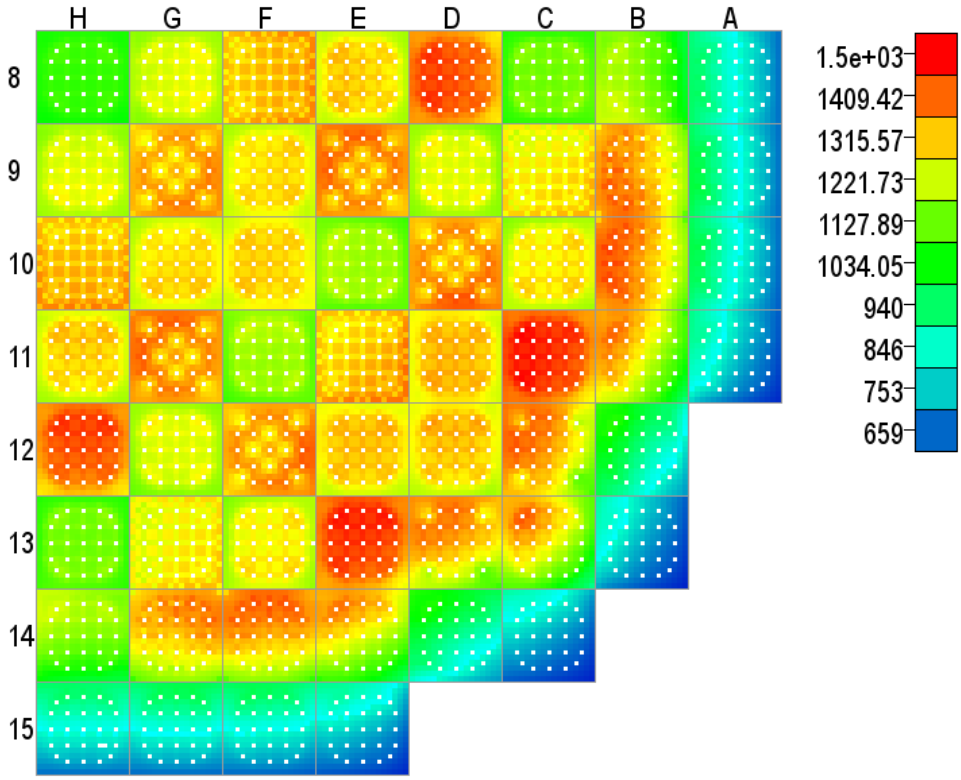

Fig. A.2.2. Cycle 2 maximum centerline fuel temperature (K) – 0.14 GWd/MT.

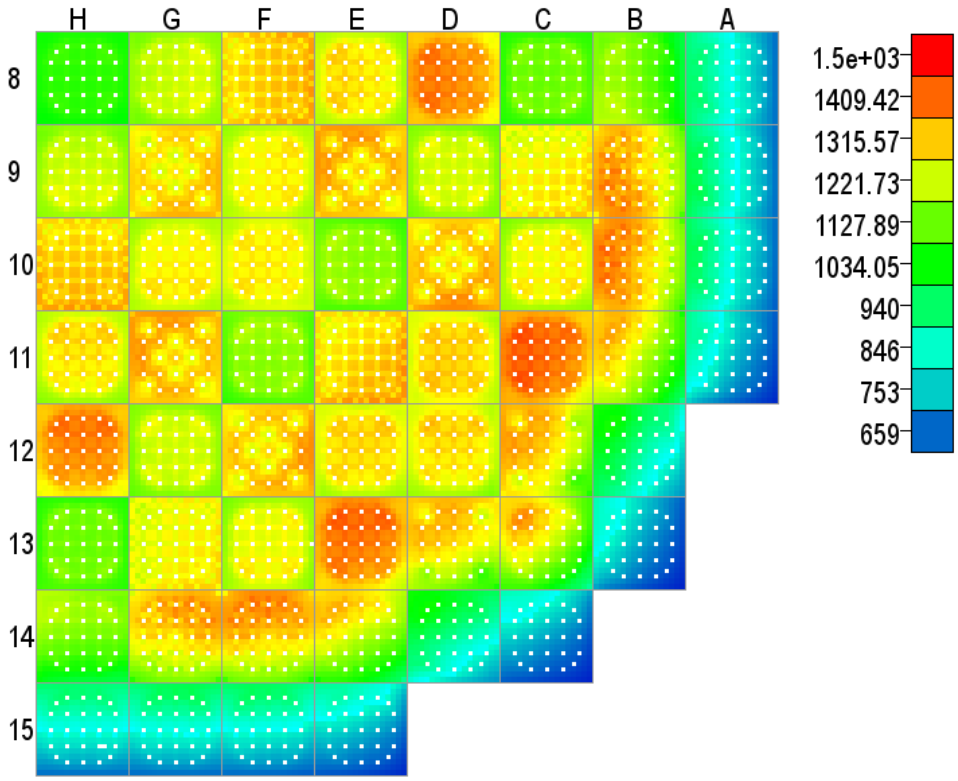

Fig. A.2.3. Cycle 2 maximum centerline fuel temperature (K) – 0.52 GWd/MT.

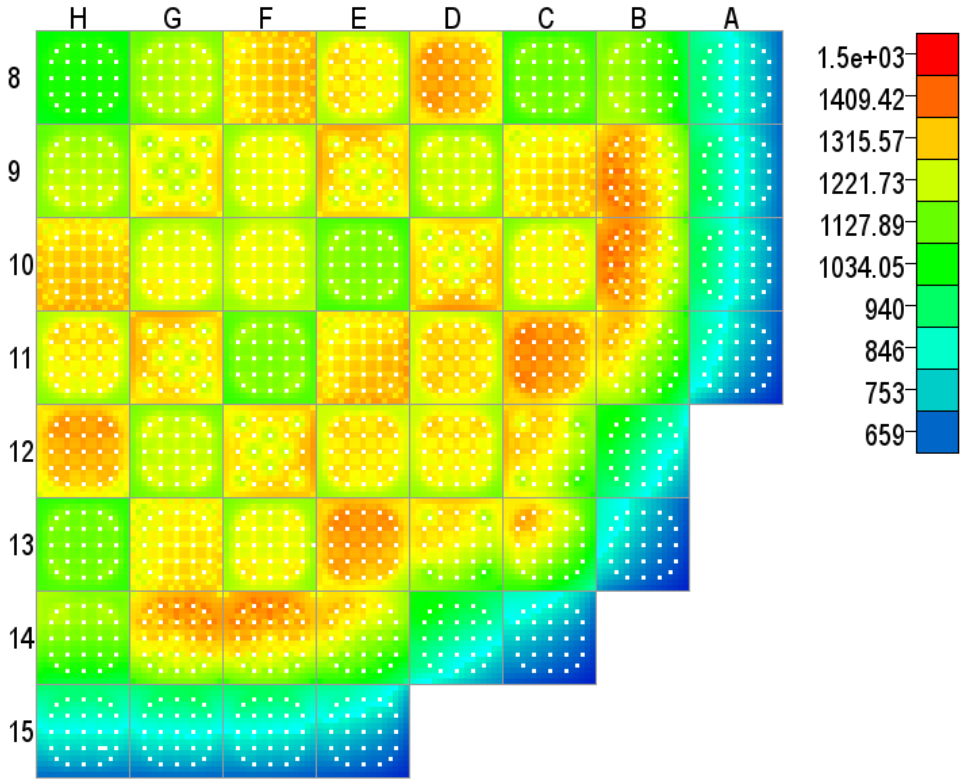

Fig. A.2.4. Cycle 2 maximum centerline fuel temperature (K) – 1.00 GWd/MT.

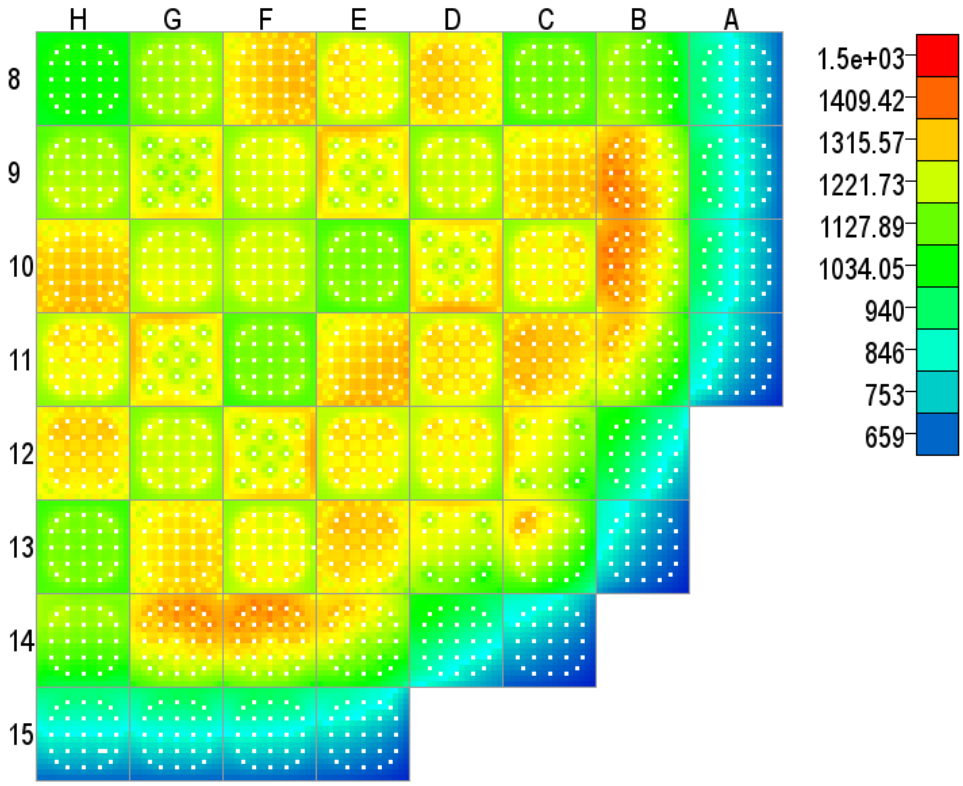

Fig. A.2.5. Cycle 2 maximum centerline fuel temperature (K) – 1.48 GWd/MT.

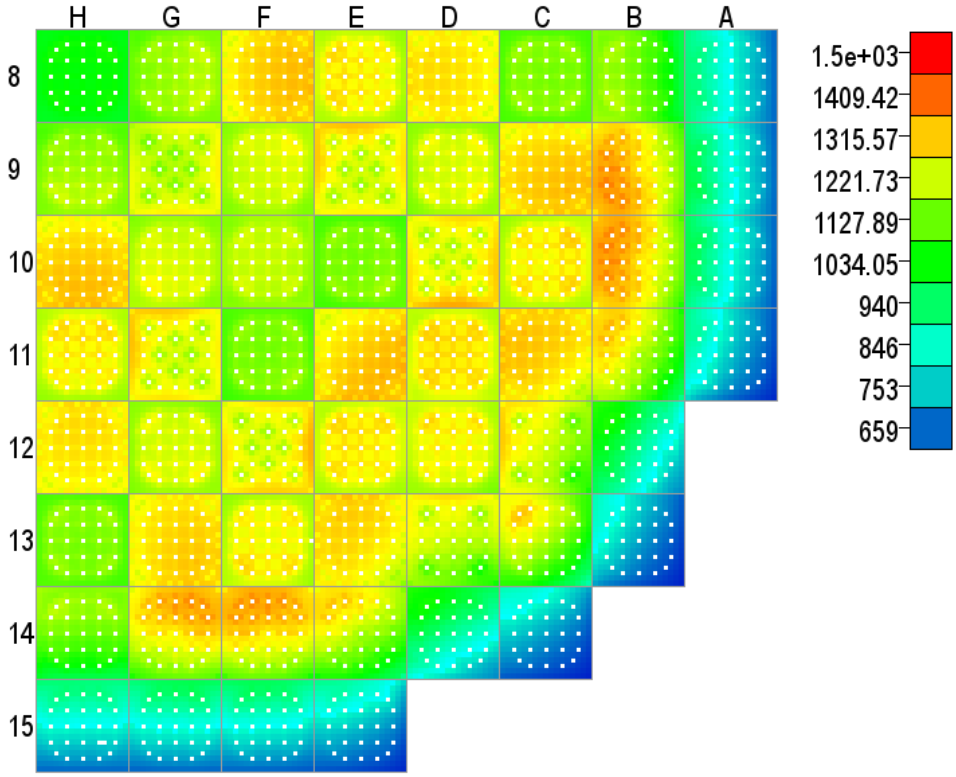

Fig. A.2.6. Cycle 2 maximum centerline fuel temperature (K) – 2.07 GWd/MT.

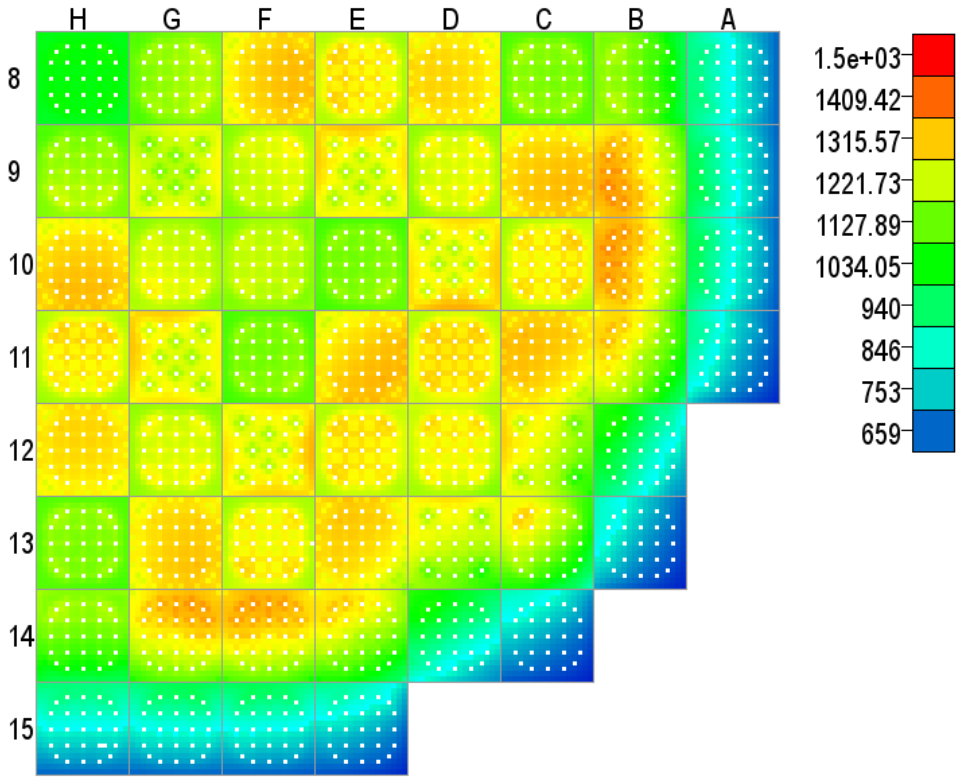

Fig. A.2.7. Cycle 2 maximum centerline fuel temperature (K) – 2.48 GWd/MT.

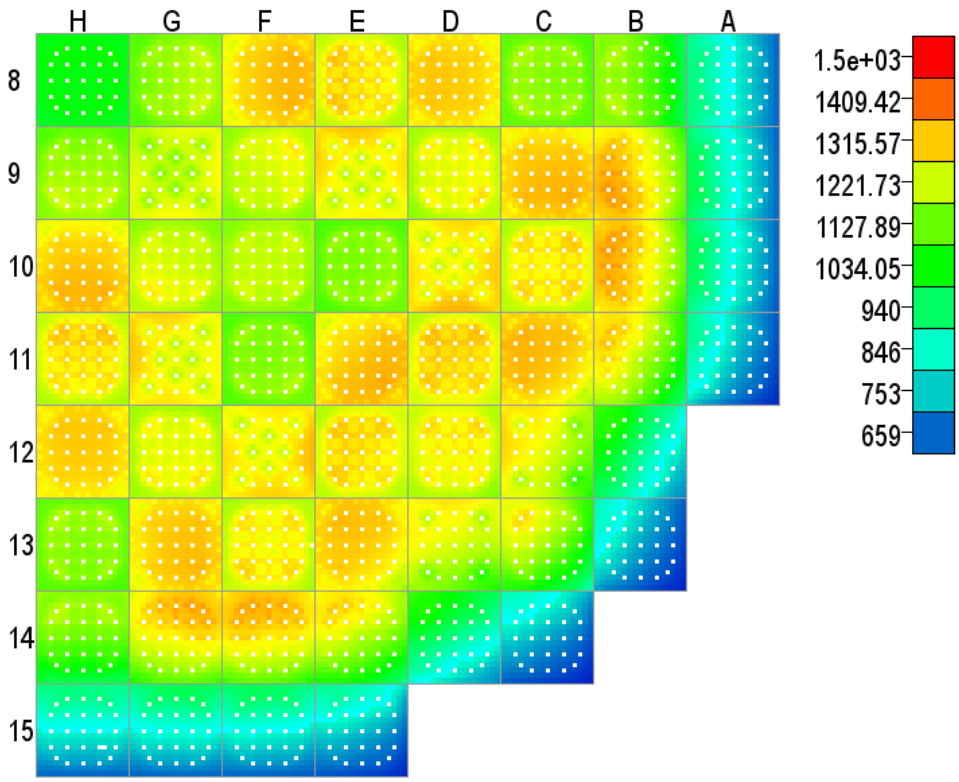

Fig. A.2.8. Cycle 2 maximum centerline fuel temperature (K) – 3.13 GWd/MT.

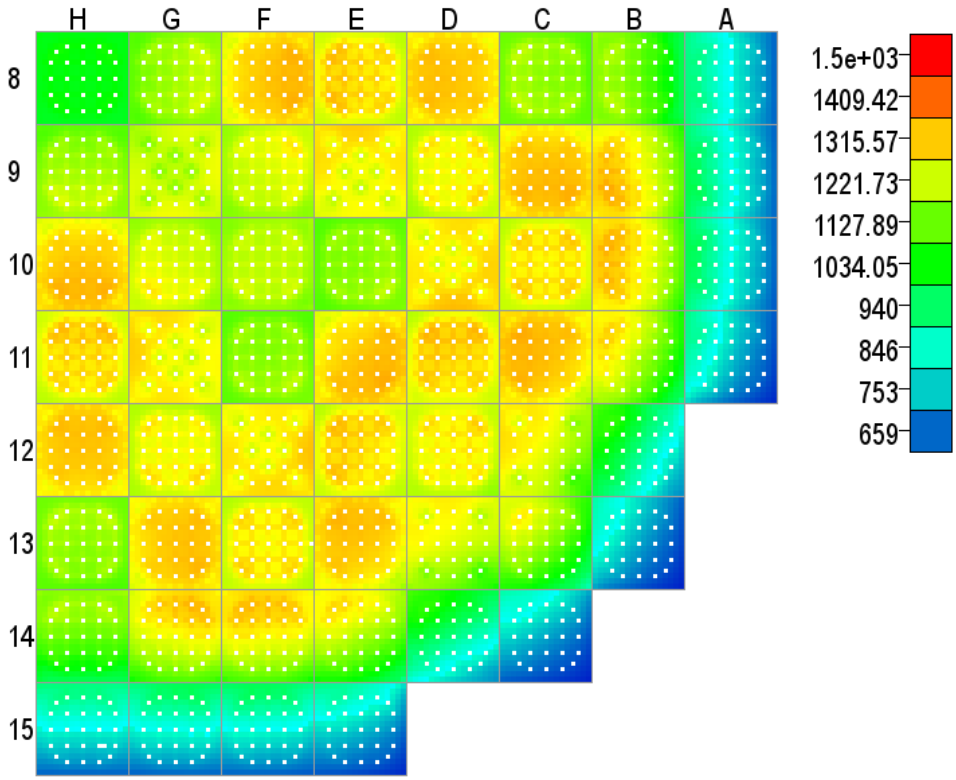

Fig. A.2.9. Cycle 2 maximum centerline fuel temperature (K) – 4.02 GWd/MT.

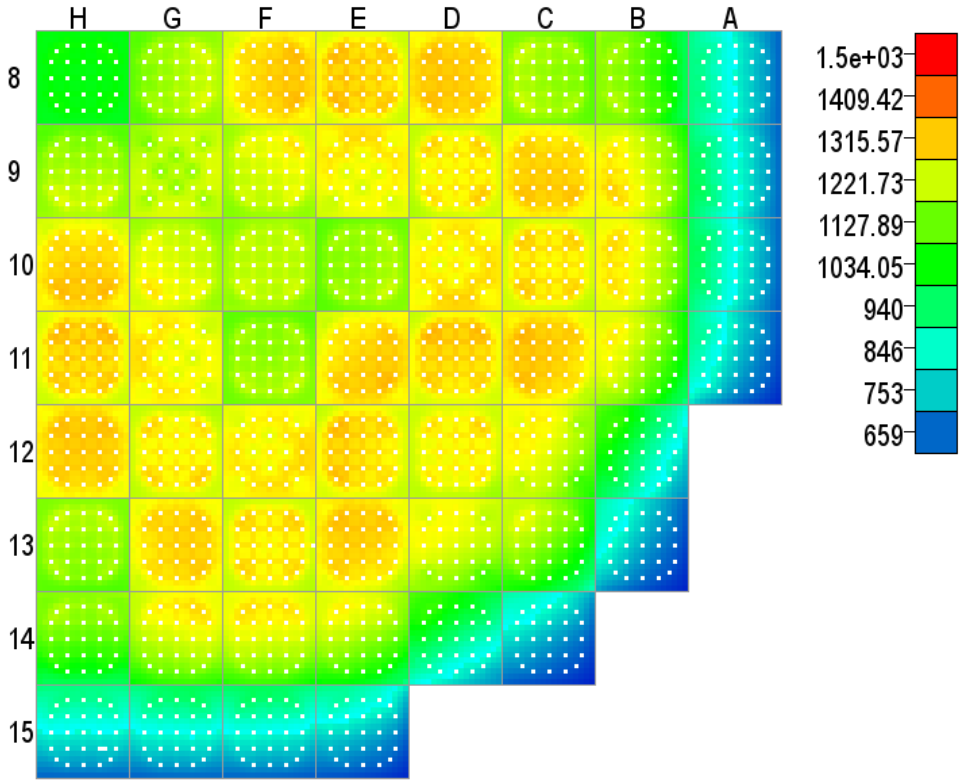

Fig. A.2.10. Cycle 2 maximum centerline fuel temperature (K) – 5.53 GWd/MT.

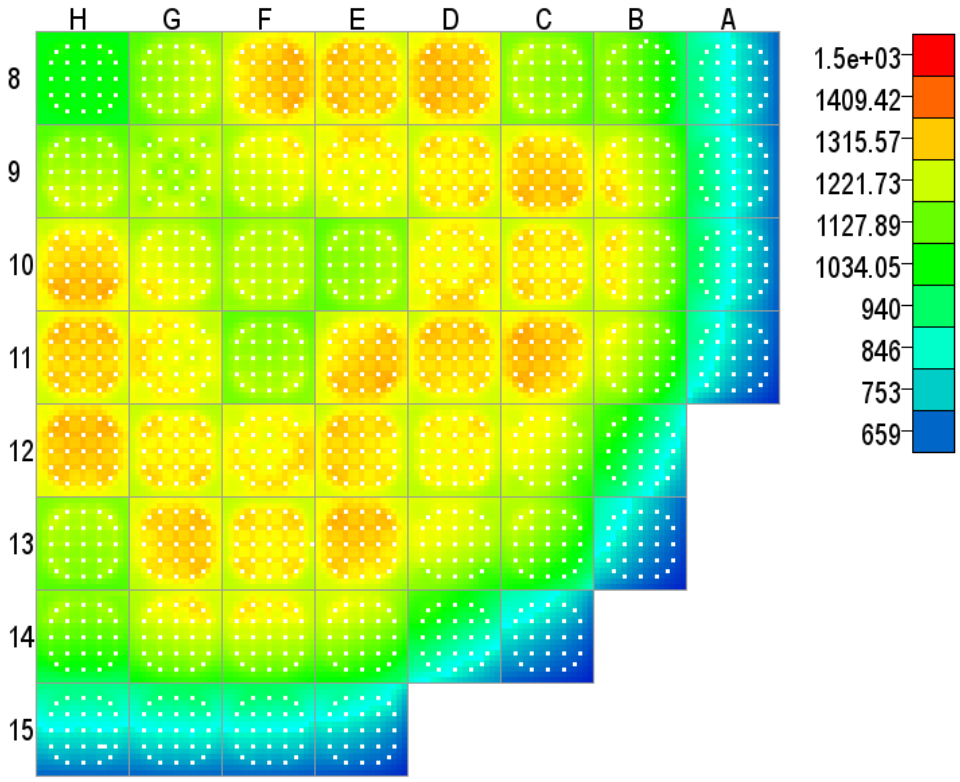

Fig. A.2.11. Cycle 2 maximum centerline fuel temperature (K) – 6.53 GWd/MT.

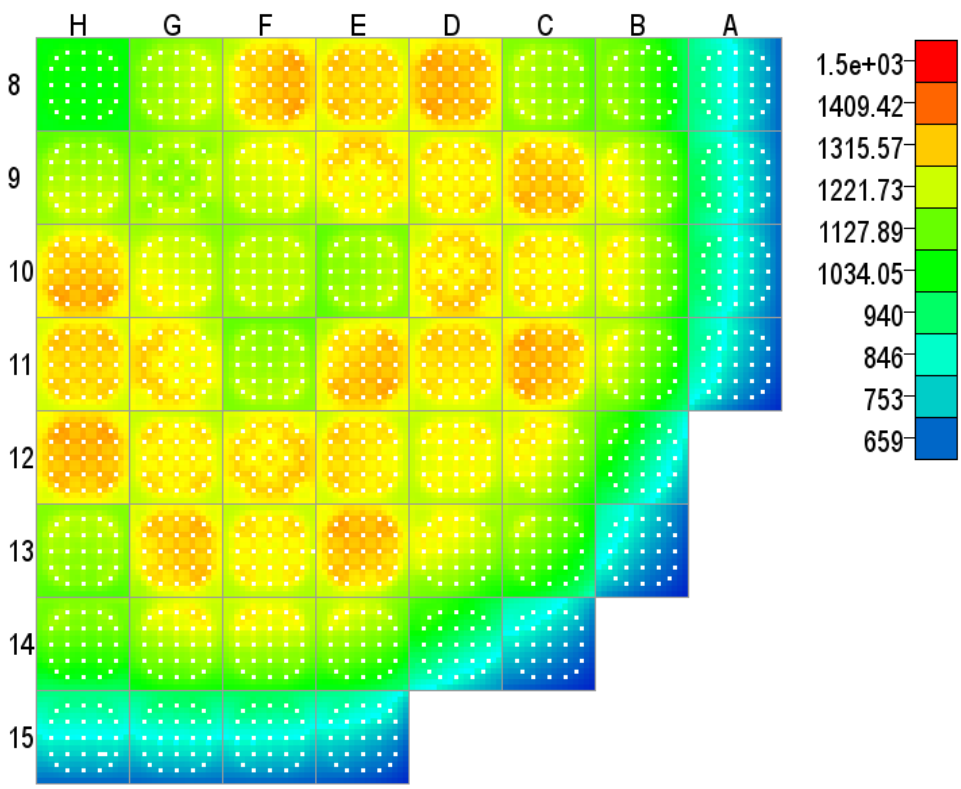

Fig. A.2.12. Cycle 2 maximum centerline fuel temperature (K) – 8.22 GWd/MT.

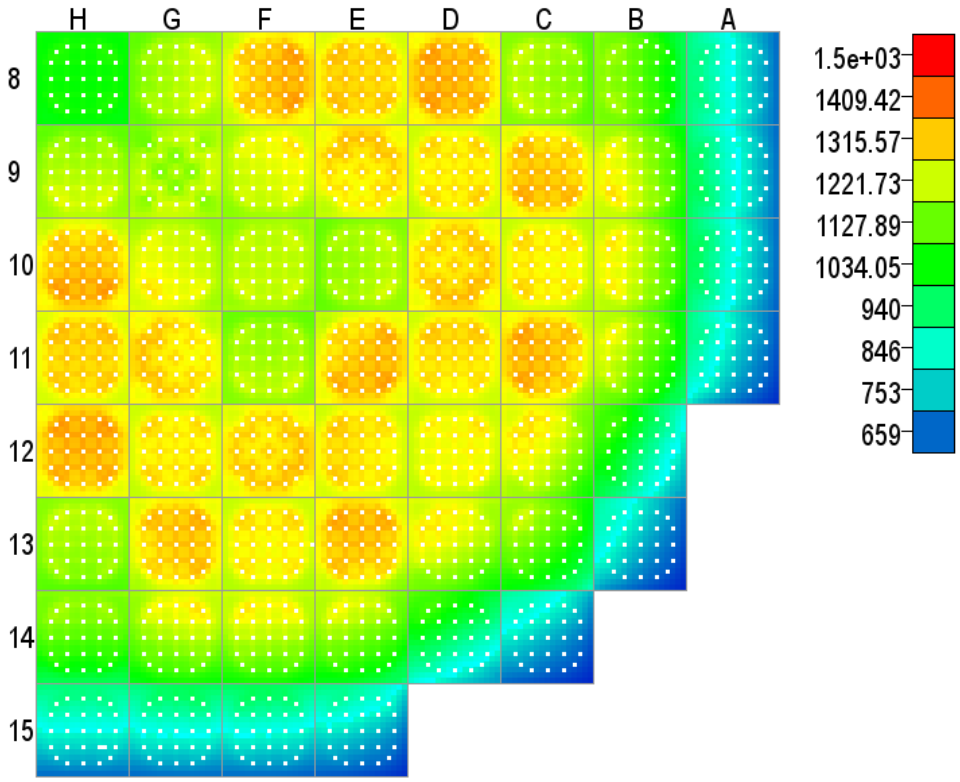

Fig. A.2.13. Cycle 2 maximum centerline fuel temperature (K) – 9.29 GWd/MT.

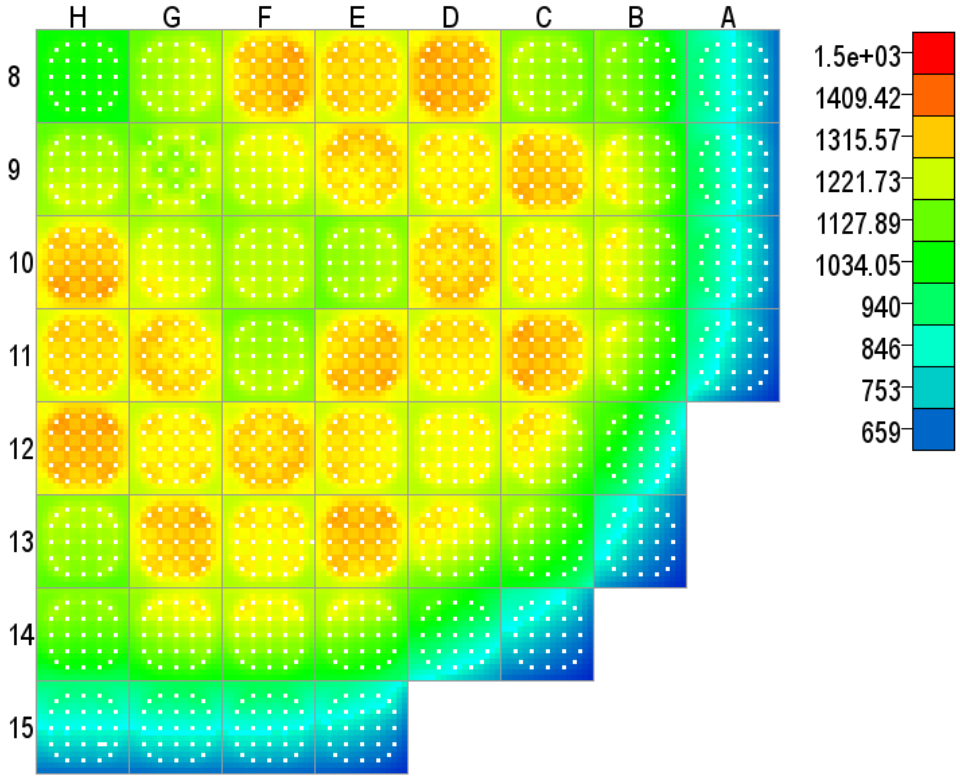

Fig. A.2.14. Cycle 2 maximum centerline fuel temperature (K) – 10.36 GWd/MT.

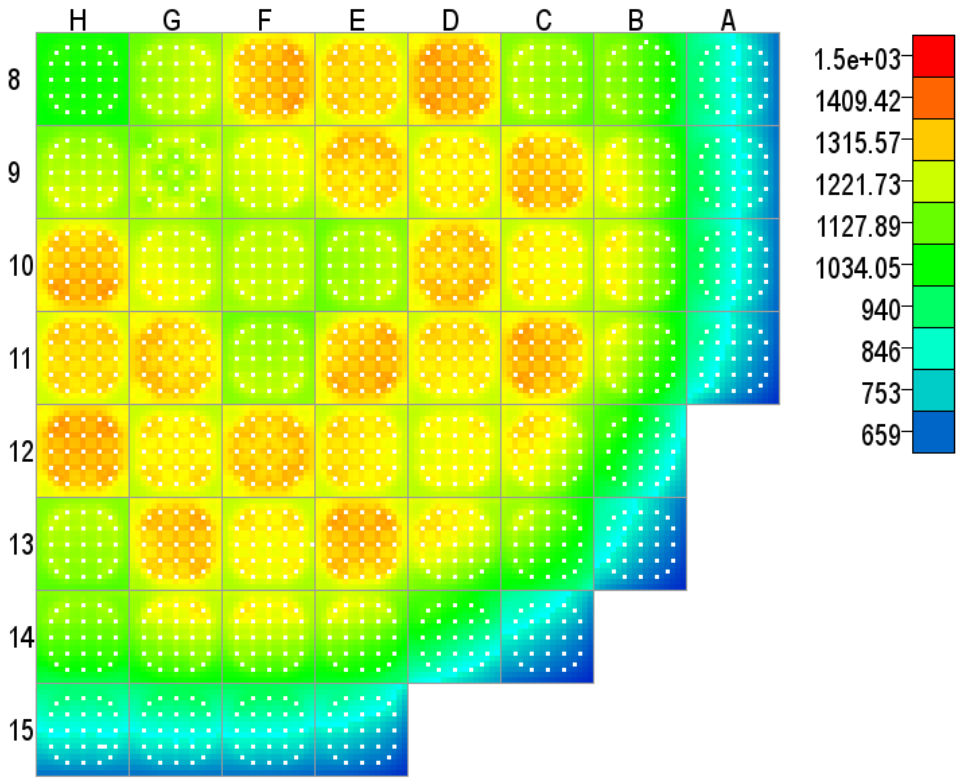

Fig. A.2.15. Cycle 2 maximum centerline fuel temperature (K) – 11.43 GWd/MT.

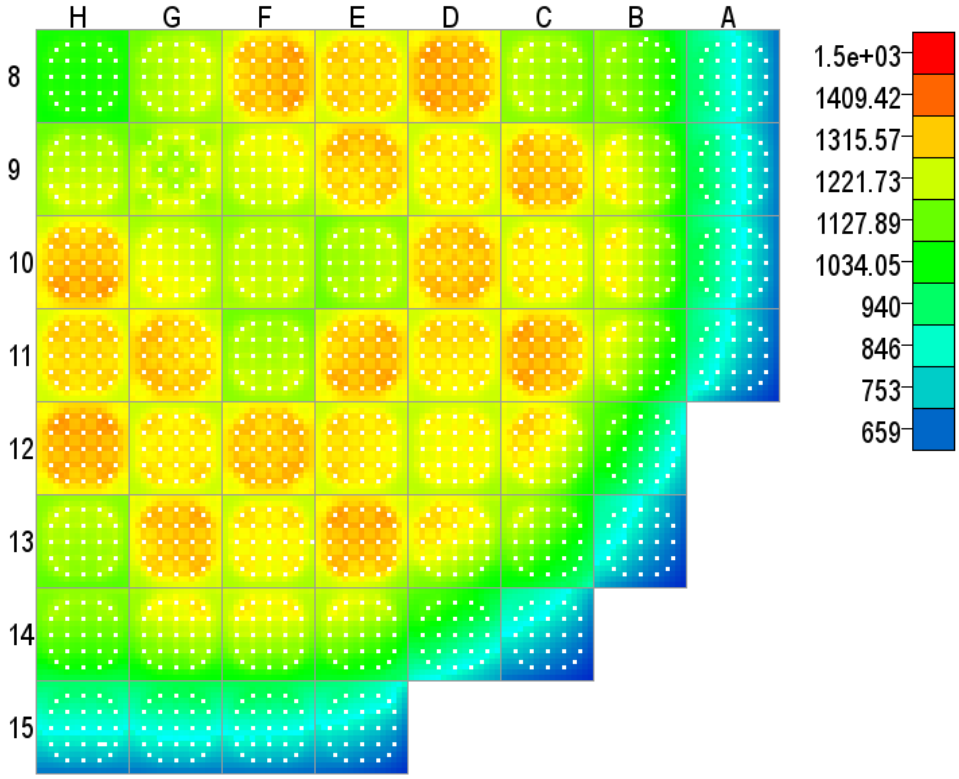

Fig. A.2.16. Cycle 2 maximum centerline fuel temperature (K) – 12.54 GWd/MT.

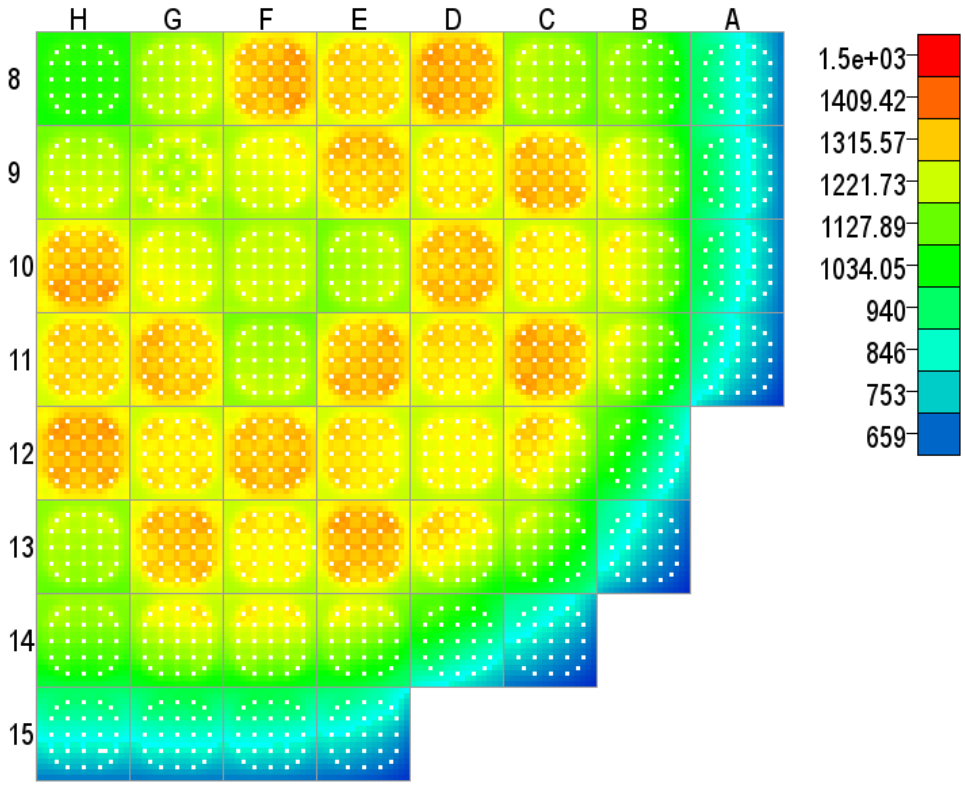

Fig. A.2.17. Cycle 2 maximum centerline fuel temperature (K) – 13.54 GWd/MT.

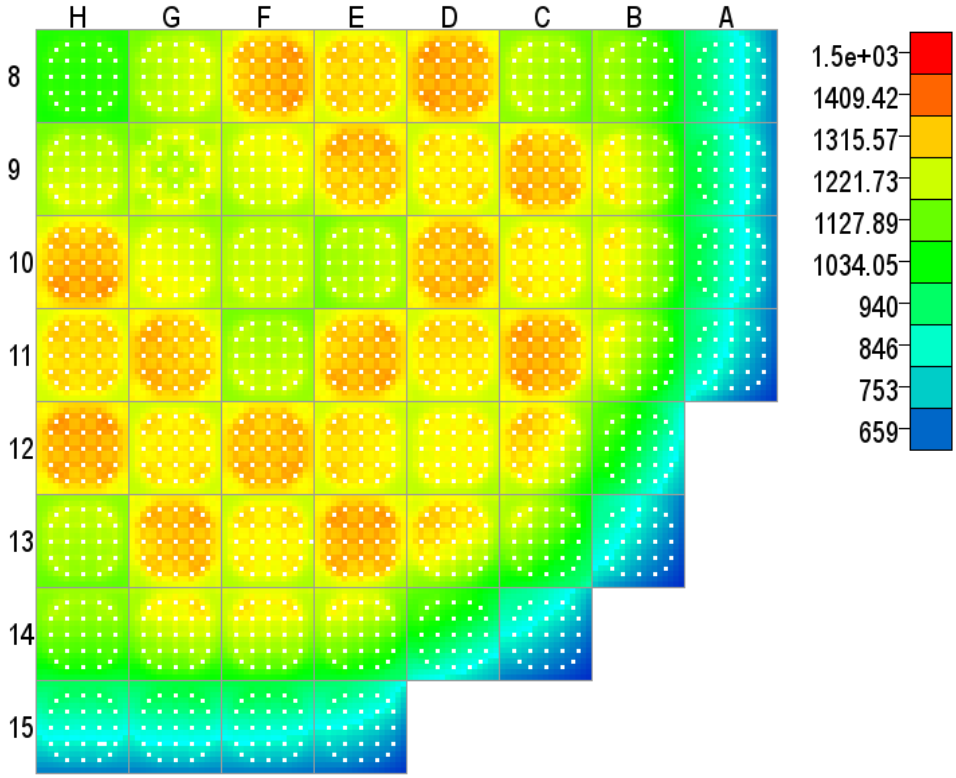

Fig. A.2.18. Cycle 2 maximum centerline fuel temperature (K) – 14.62 GWd/MT.

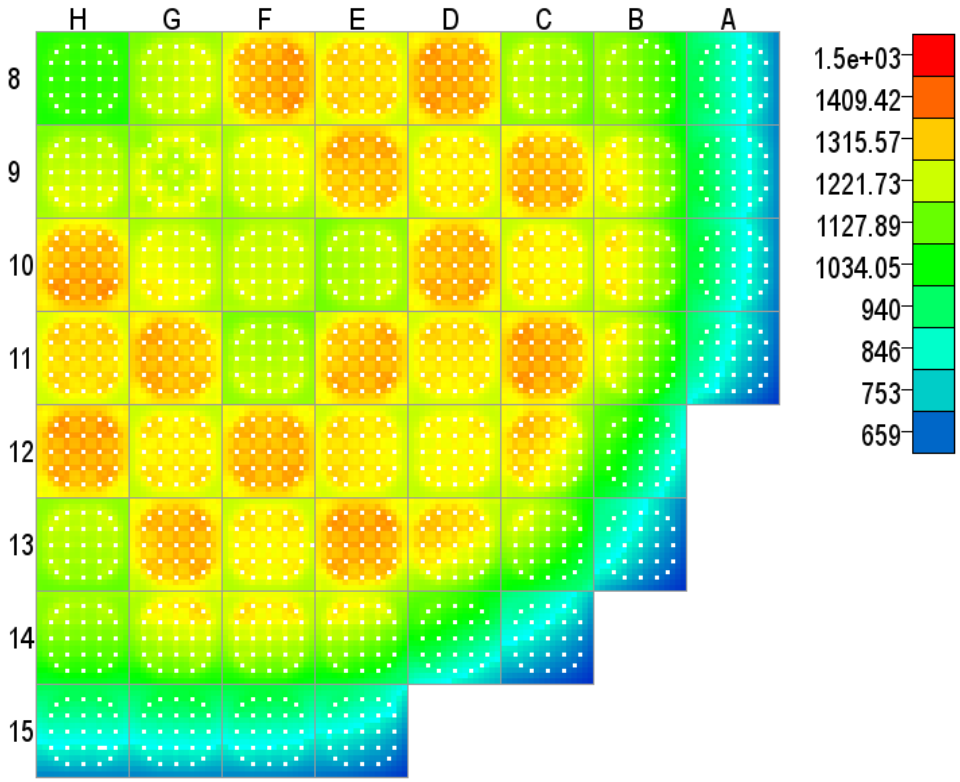

Fig. A.2.19. Cycle 2 maximum centerline fuel temperature (K) – 15.76 GWd/MT.

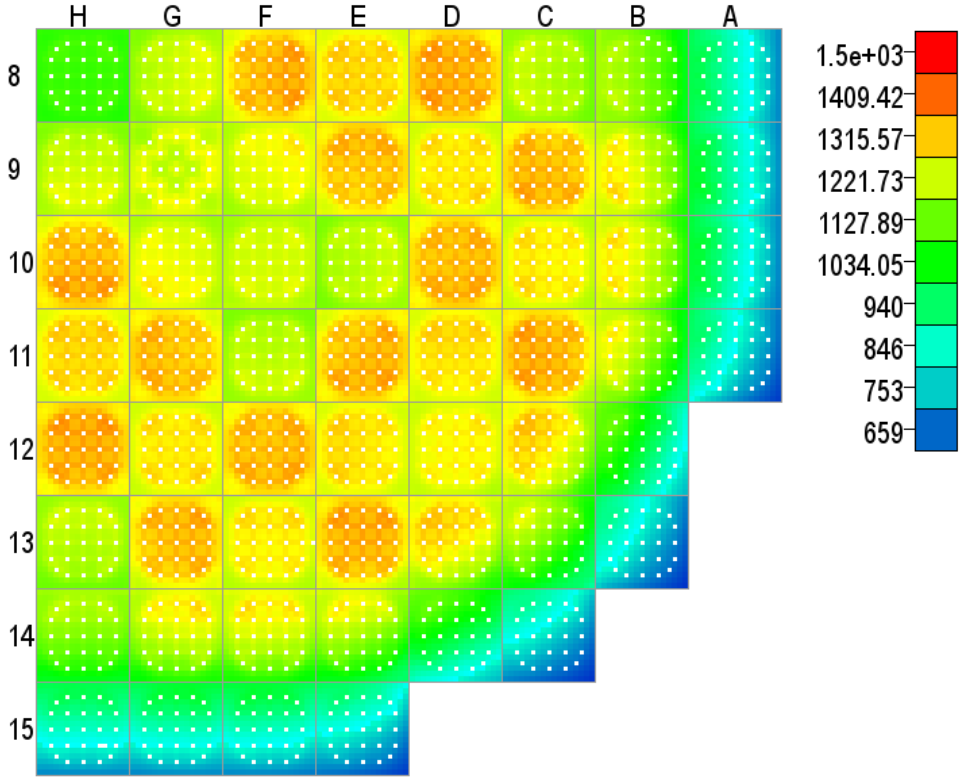

Fig. A.2.20. Cycle 2 maximum centerline fuel temperature (K) – 16.32 GWd/MT.

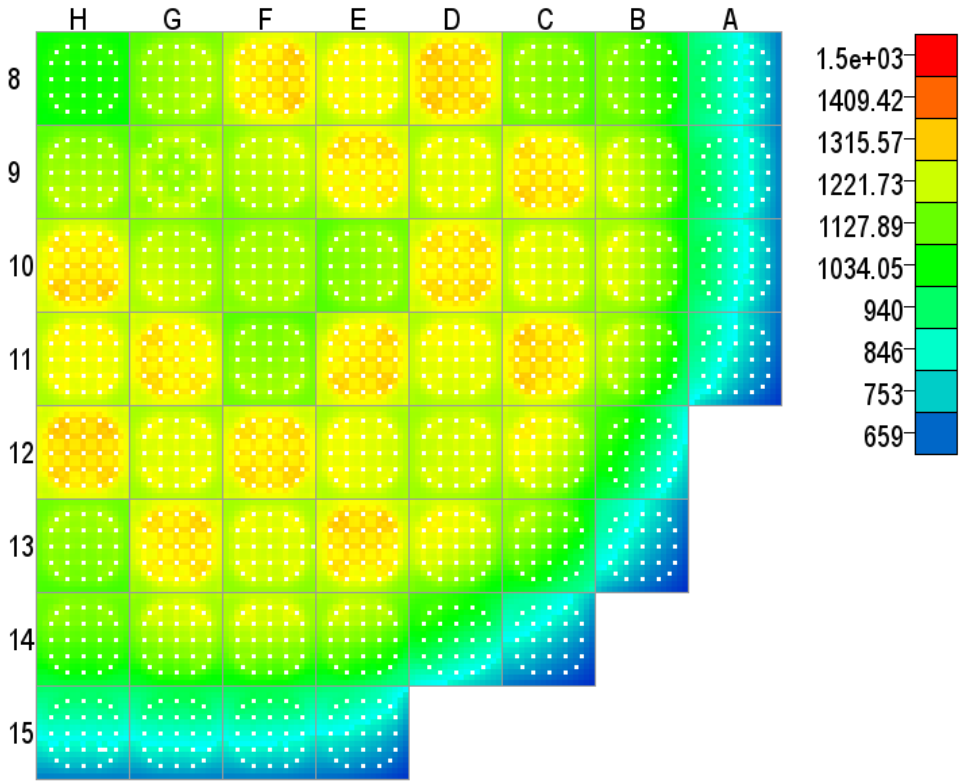

Fig. A.2.21. Cycle 2 maximum centerline fuel temperature (K) – 16.90 GWd/MT.

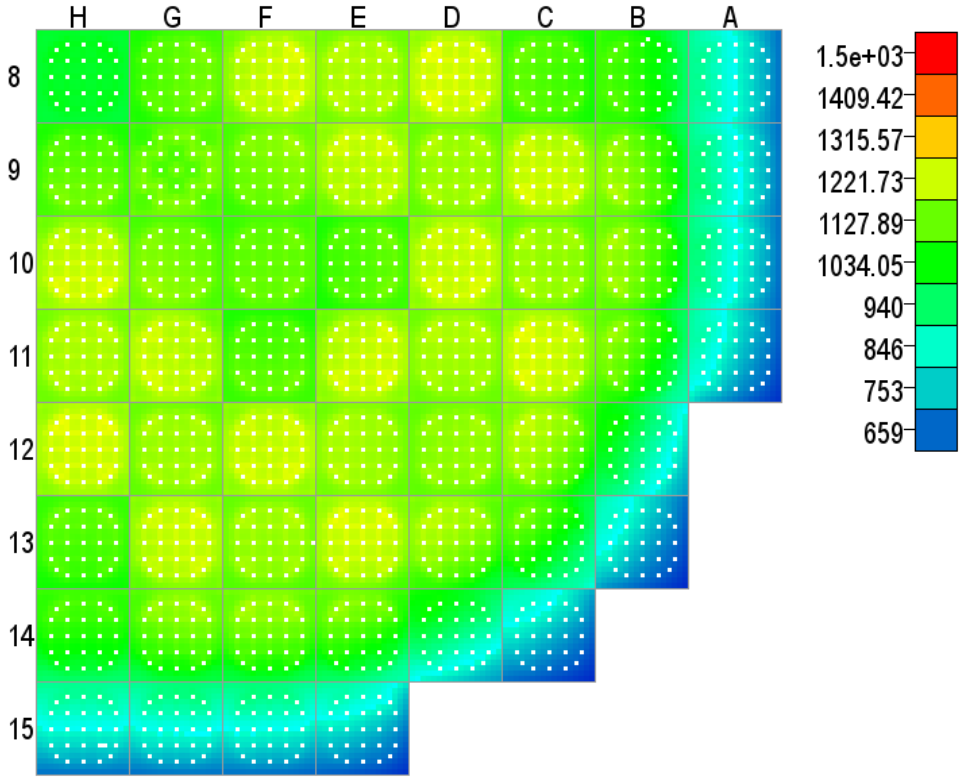

Fig. A.2.22. Cycle 2 maximum centerline fuel temperature (K) – 17.48 GWd/MT.

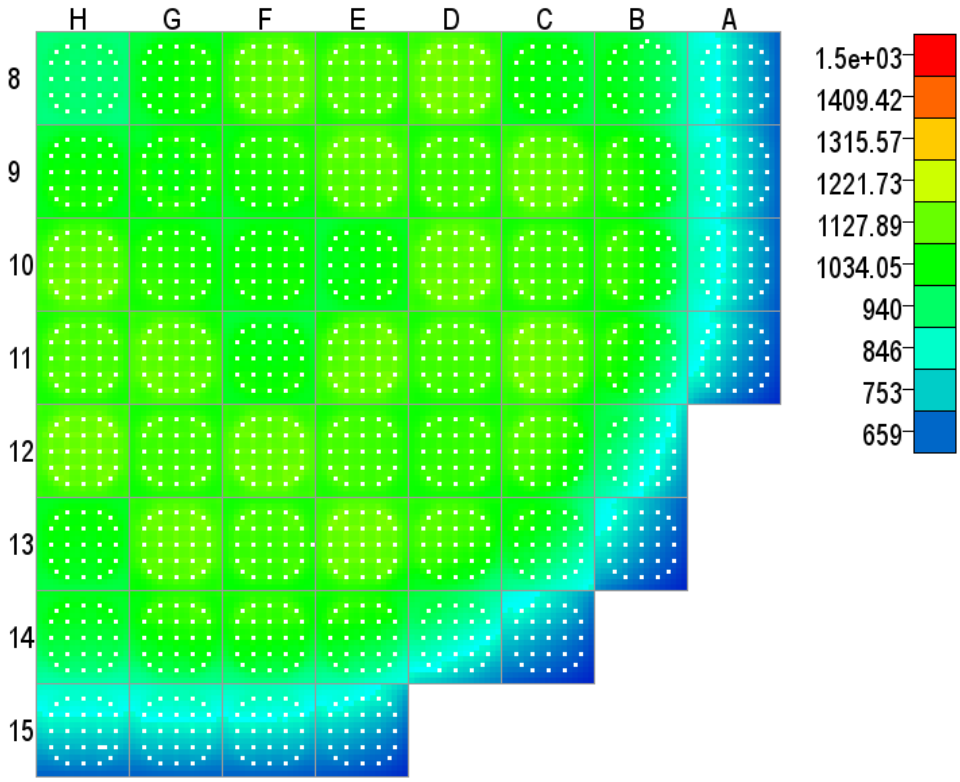

Fig. A.2.23. Cycle 2 maximum centerline fuel temperature (K) – 18.06 GWd/MT.

A.2.2. Minimum Gap Thickness

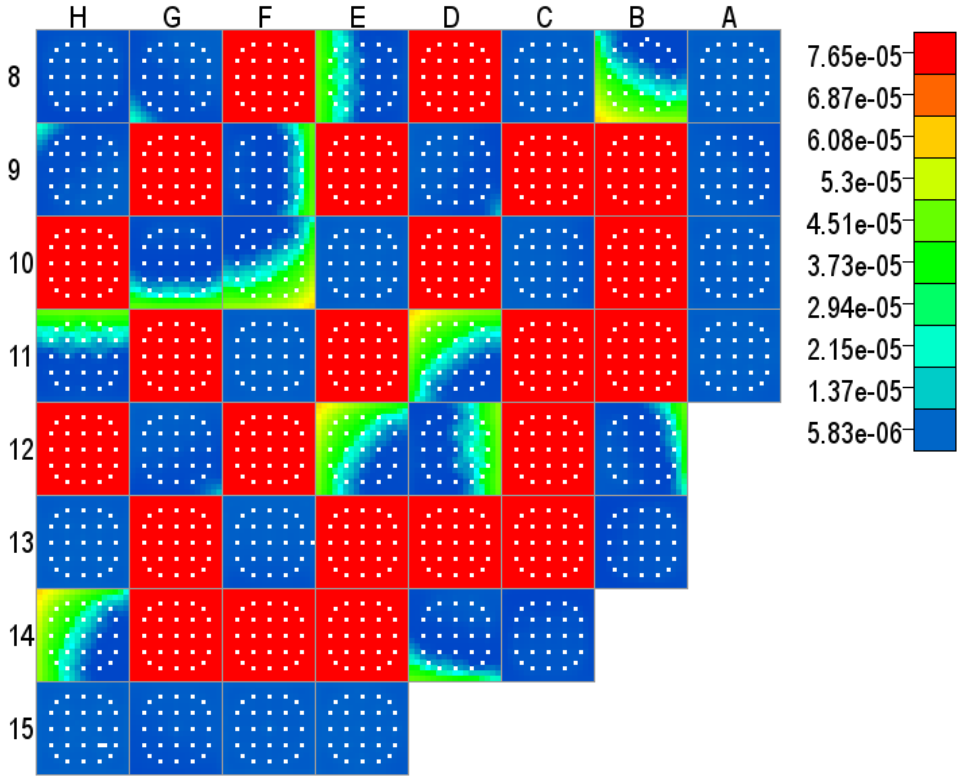

Fig. A.2.24. Cycle 2 minimum gap thickness (m) – 0.00 GWd/MT.

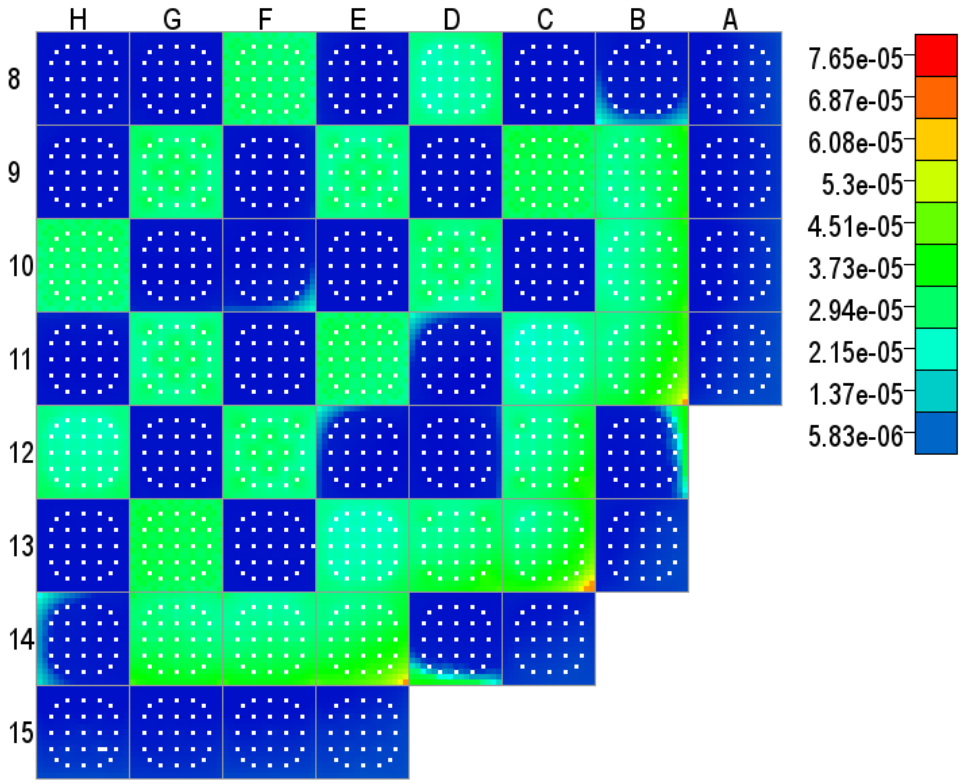

Fig. A.2.25. Cycle 2 minimum gap thickness (m) – 0.14 GWd/MT.

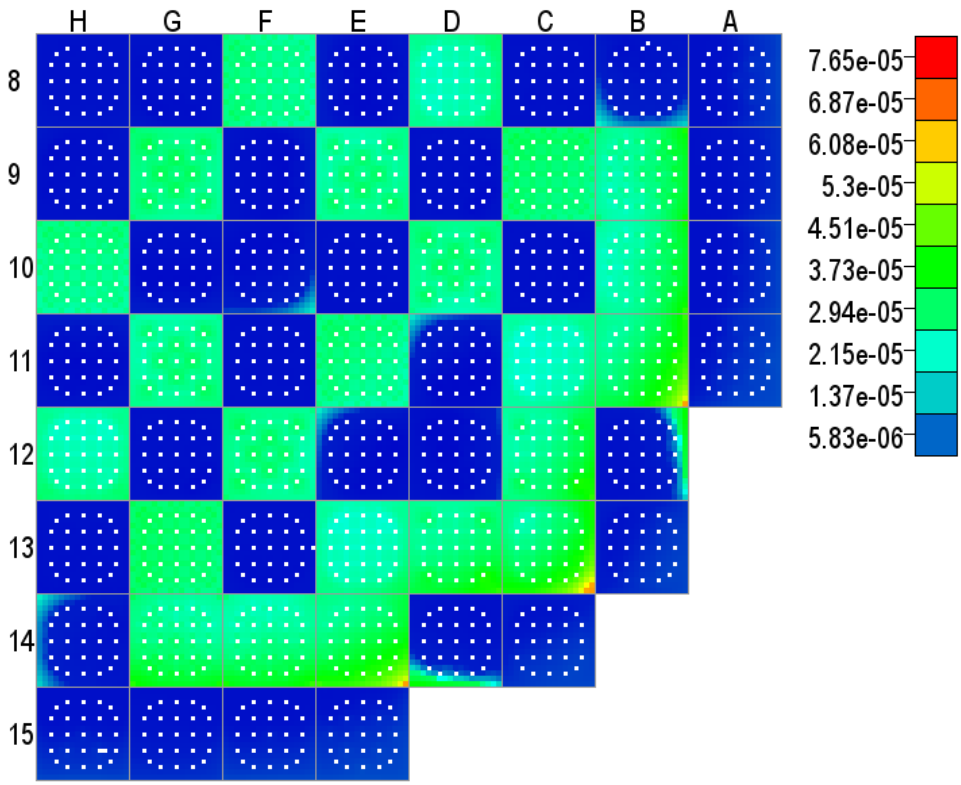

Fig. A.2.26. Cycle 2 minimum gap thickness (m) – 0.52 GWd/MT.

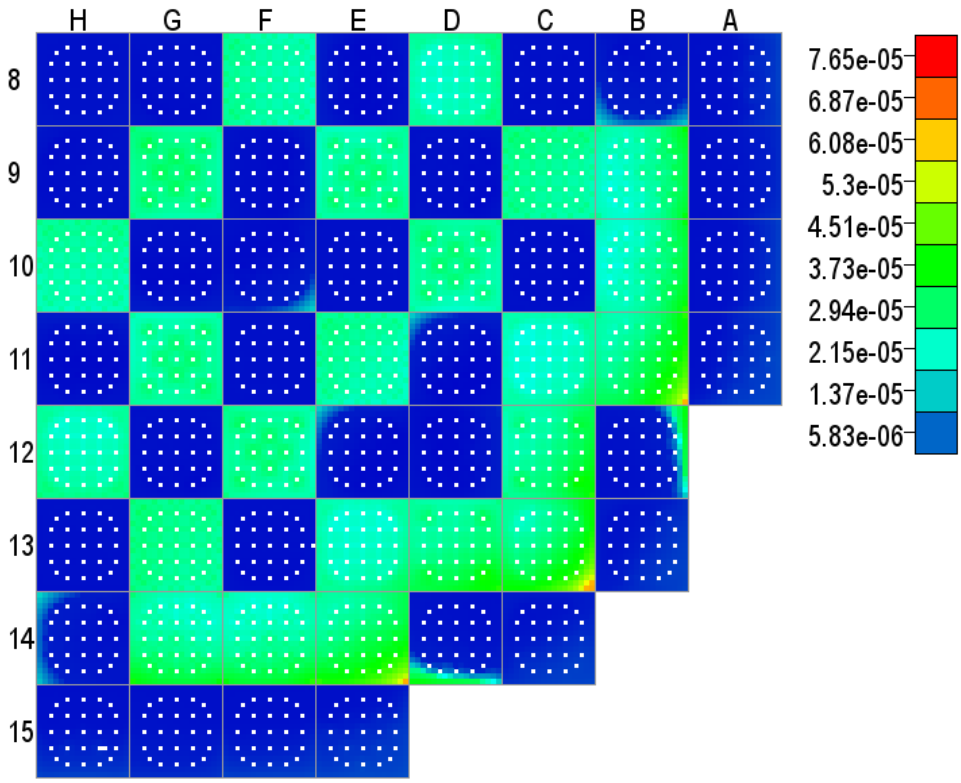

Fig. A.2.27. Cycle 2 minimum gap thickness (m) – 1.00 GWd/MT.

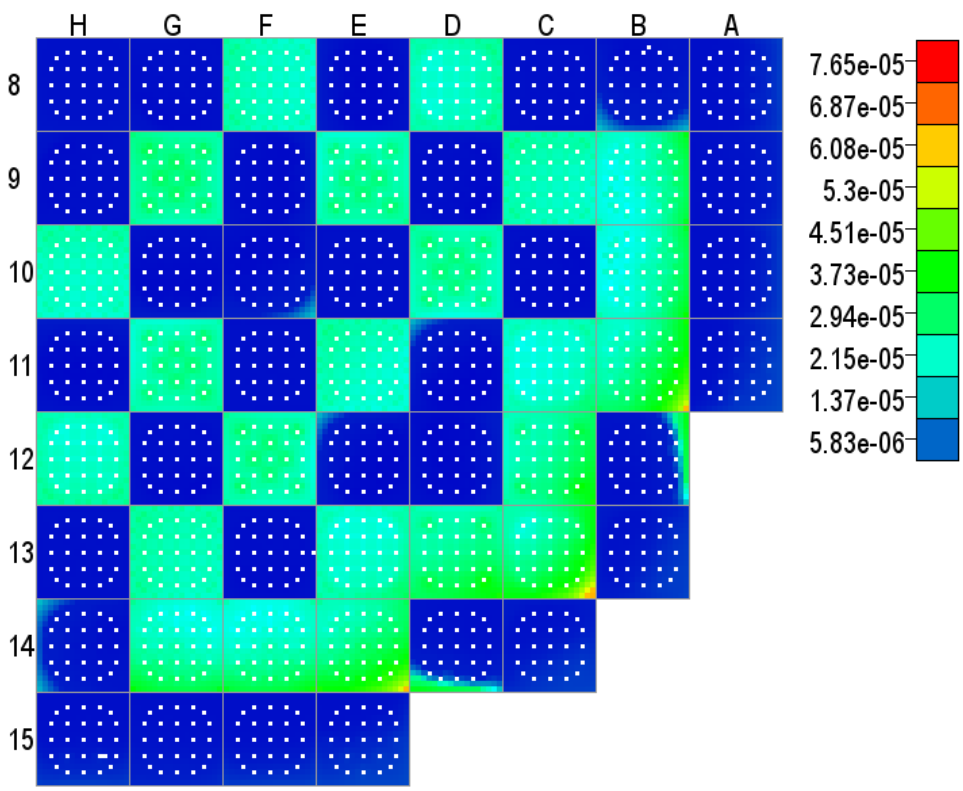

Fig. A.2.28. Cycle 2 minimum gap thickness (m) – 1.48 GWd/MT.

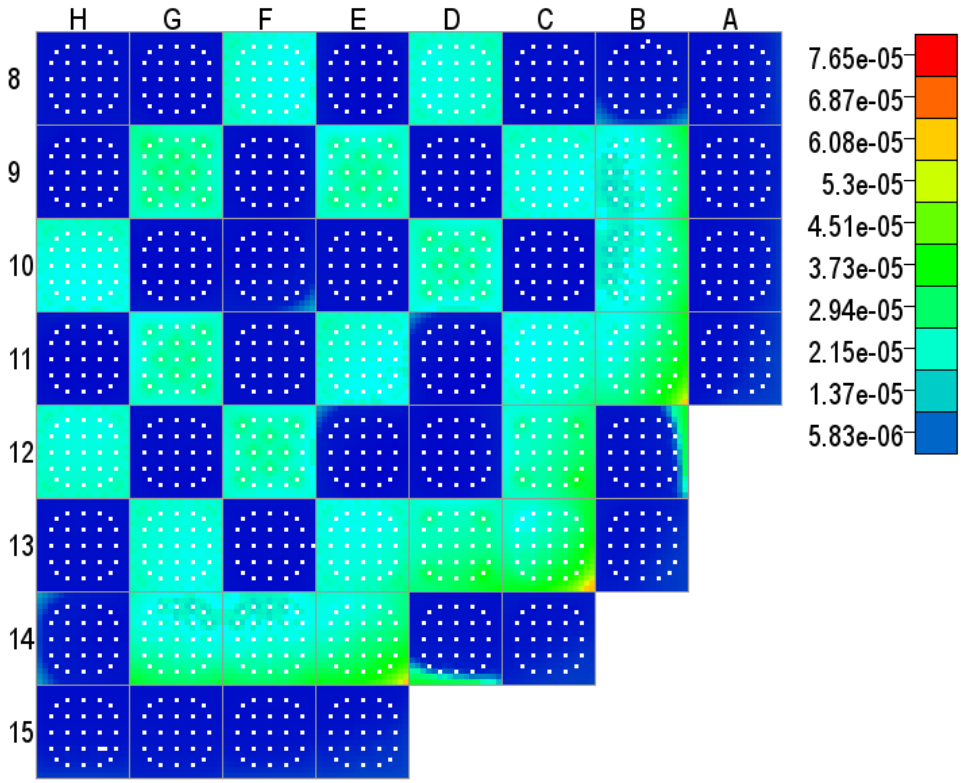

Fig. A.2.29. Cycle 2 minimum gap thickness (m) – 2.07 GWd/MT.

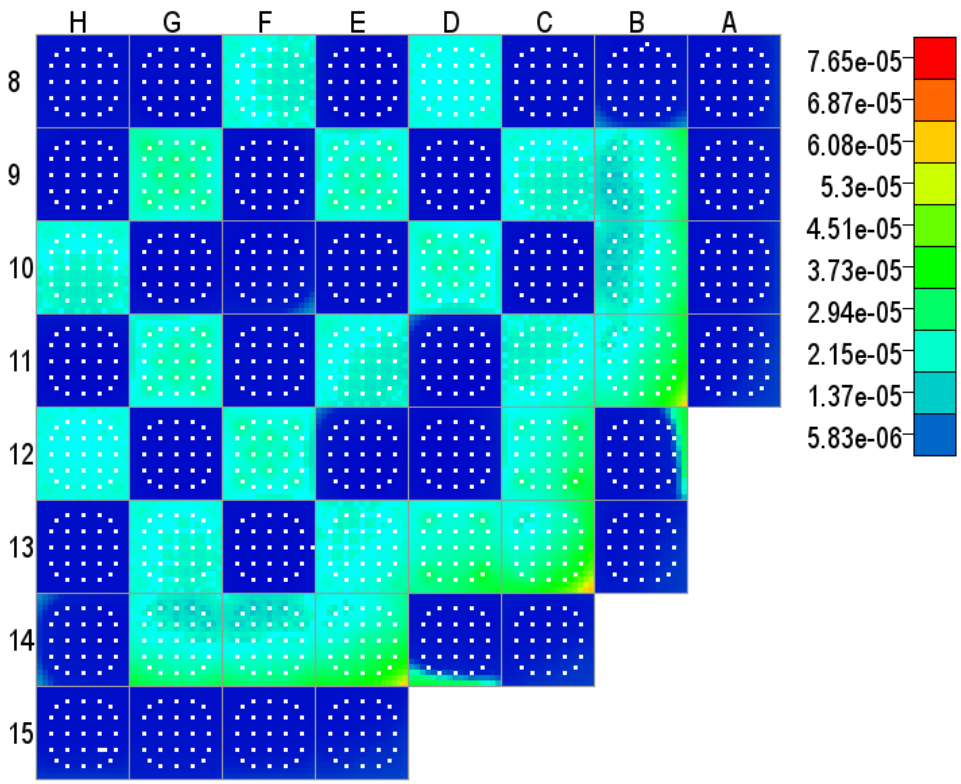

Fig. A.2.30. Cycle 2 minimum gap thickness (m) – 2.48 GWd/MT.

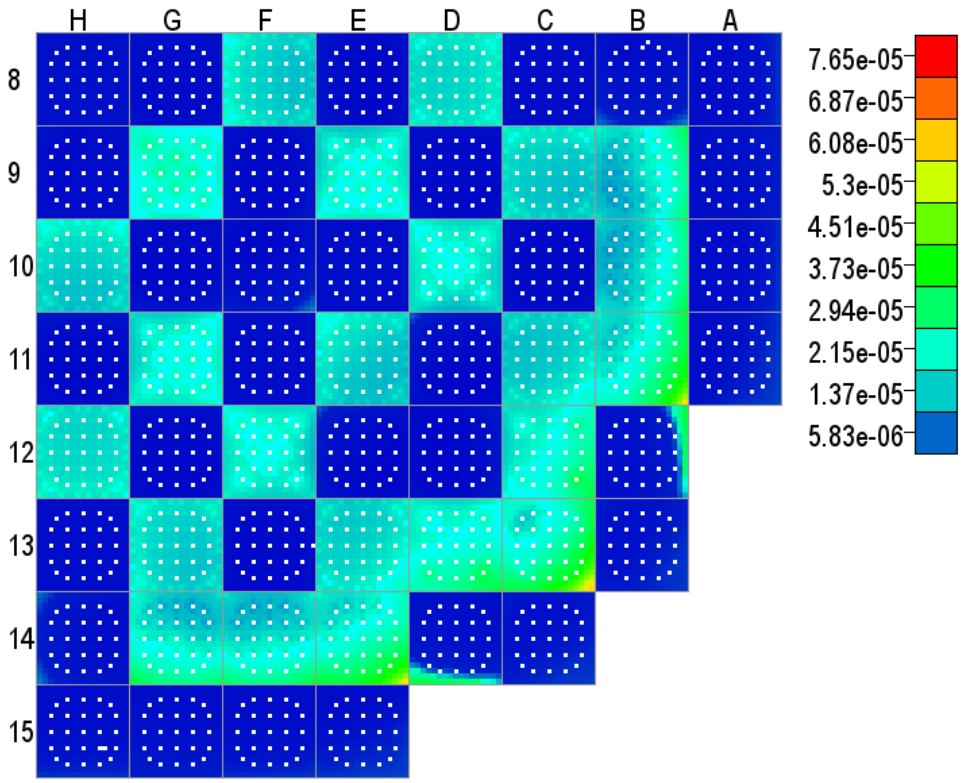

Fig. A.2.31. Cycle 2 minimum gap thickness (m) – 3.13 GWd/MT.

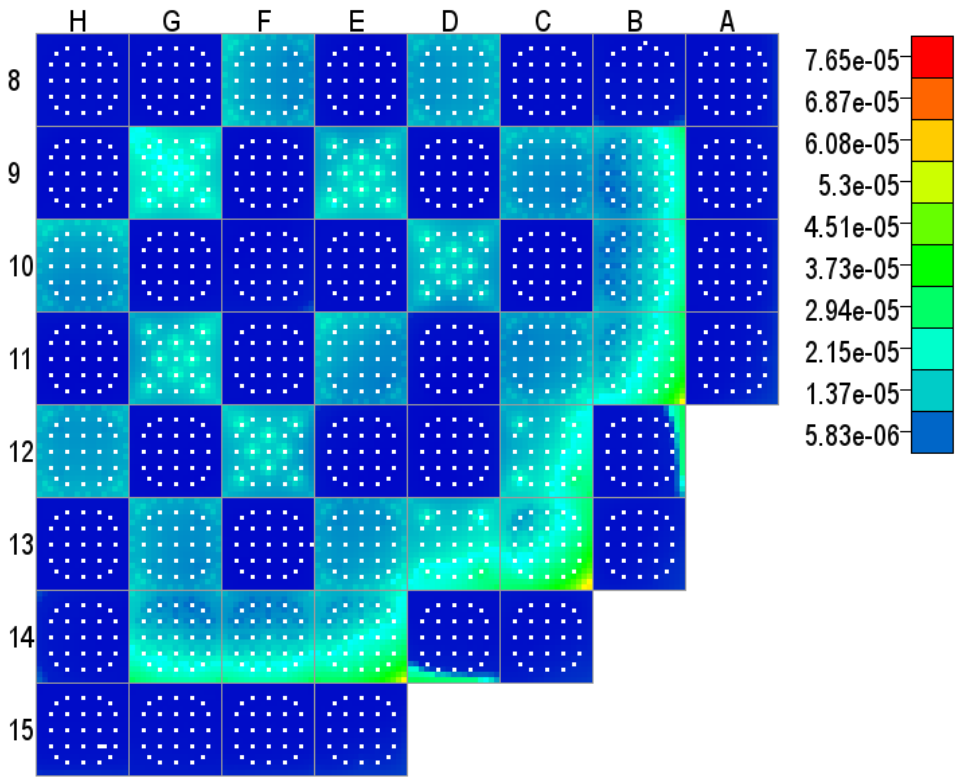

Fig. A.2.32. Cycle 2 minimum gap thickness (m) – 4.02 GWd/MT.

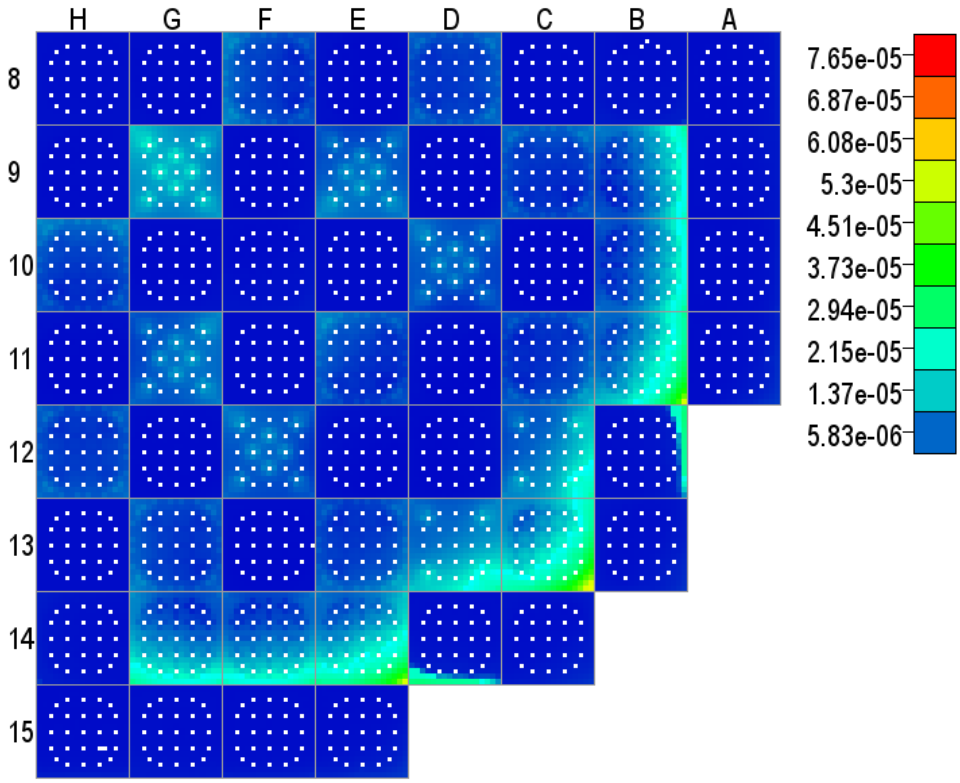

Fig. A.2.33. Cycle 2 minimum gap thickness (m) – 5.53 GWd/MT.

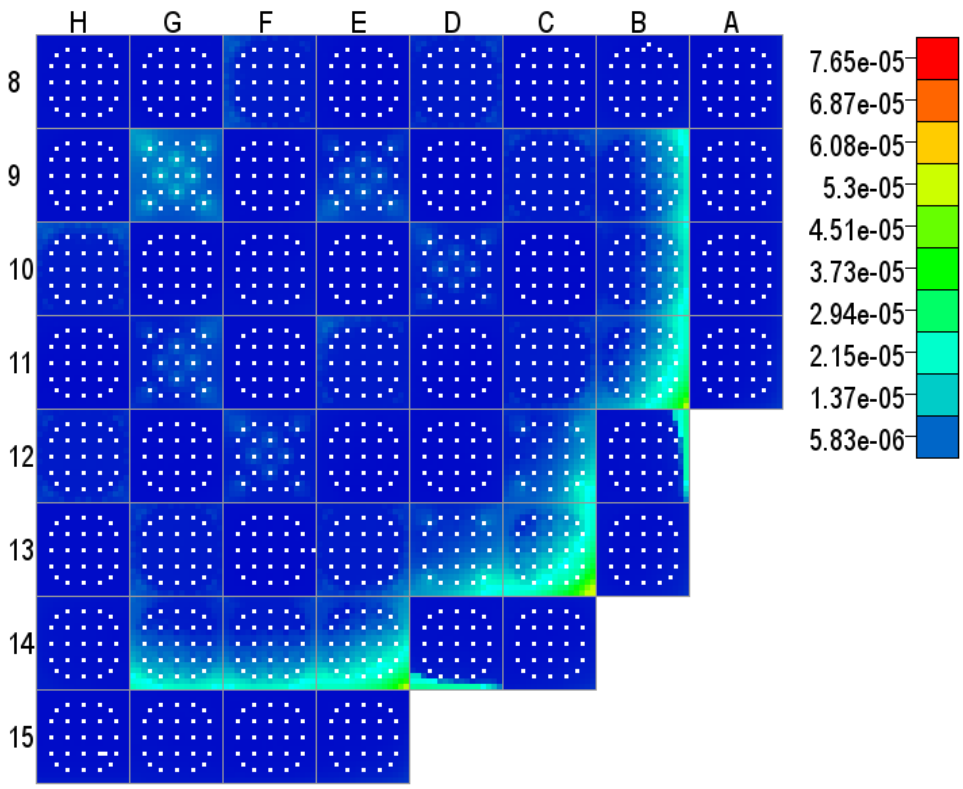

Fig. A.2.34. Cycle 2 minimum gap thickness (m) – 6.53 GWd/MT.

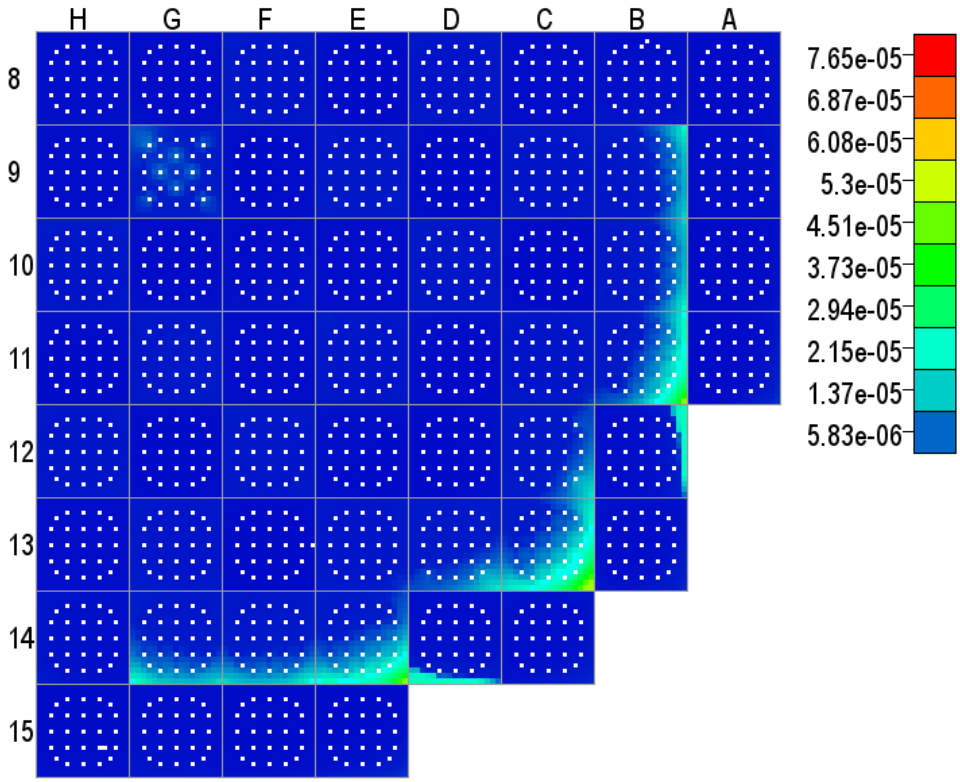

Fig. A.2.35. Cycle 2 minimum gap thickness (m) – 8.22 GWd/MT.

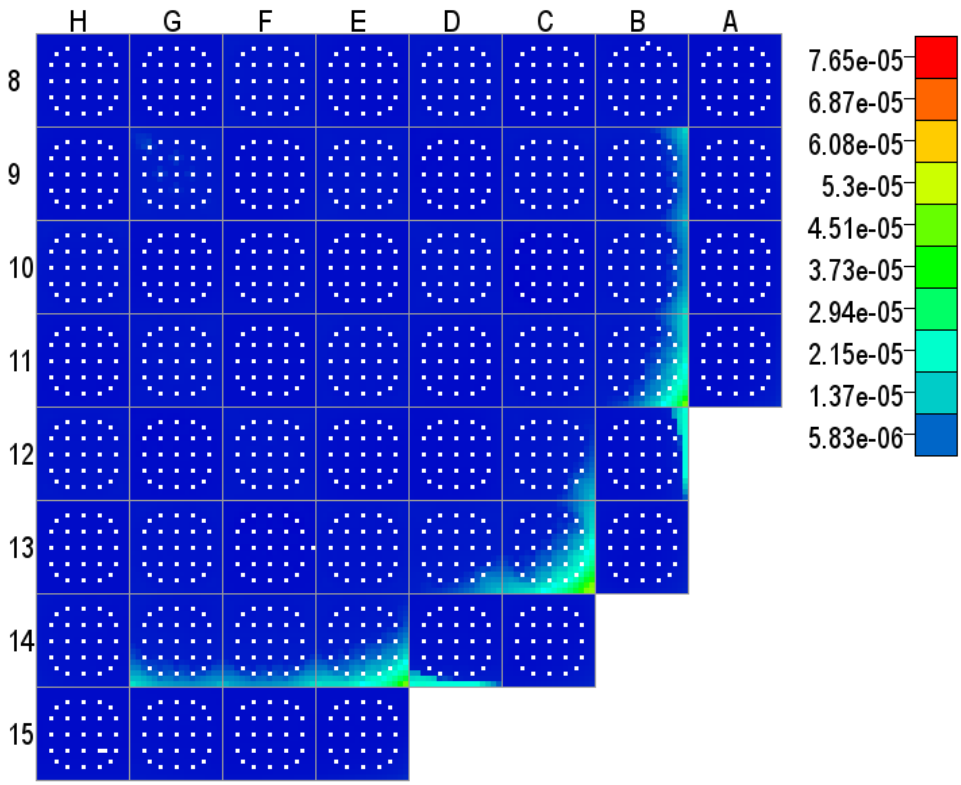

Fig. A.2.36. Cycle 2 minimum gap thickness (m) – 9.29 GWd/MT.

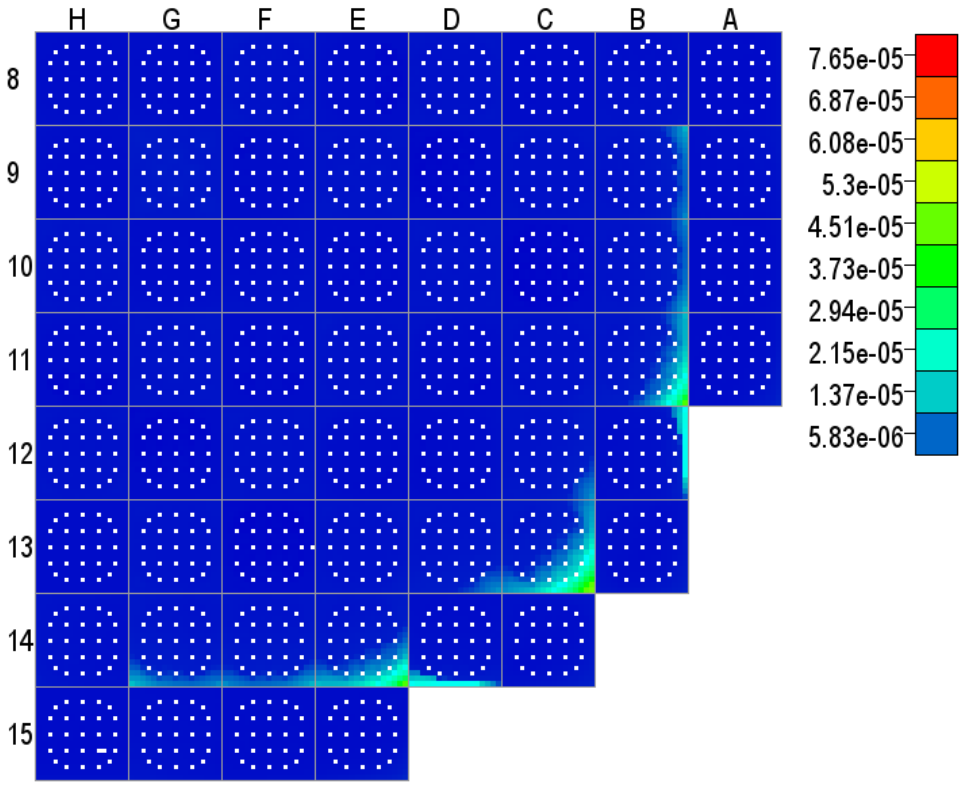

Fig. A.2.37. Cycle 2 minimum gap thickness (m) – 10.36 GWd/MT.

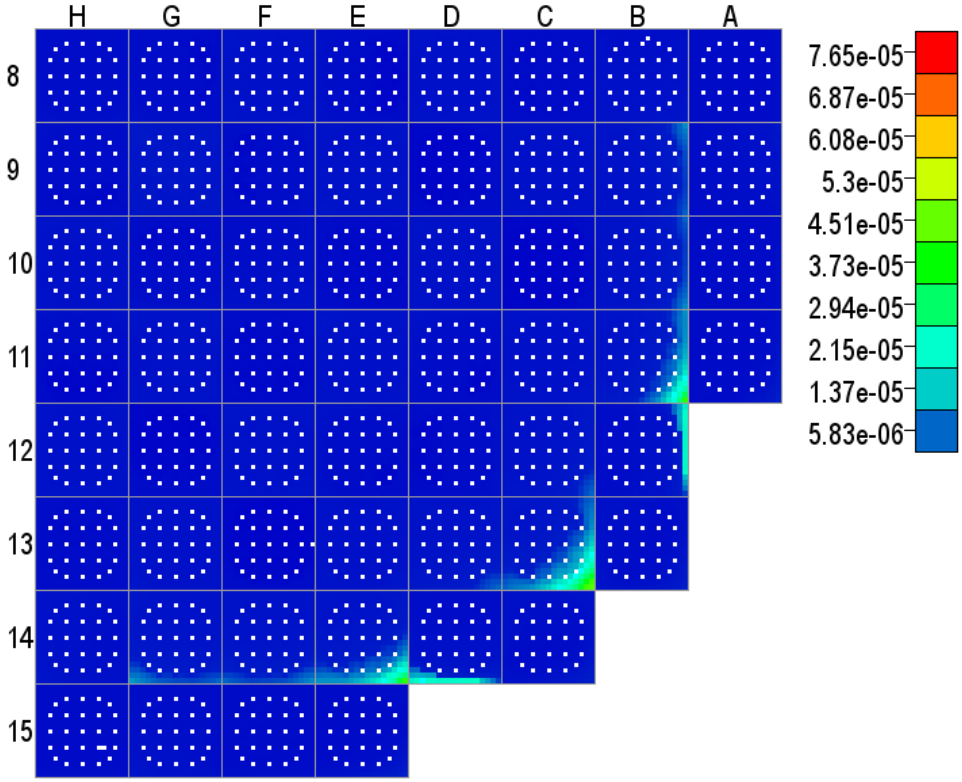

Fig. A.2.38. Cycle 2 minimum gap thickness (m) – 11.43 GWd/MT.

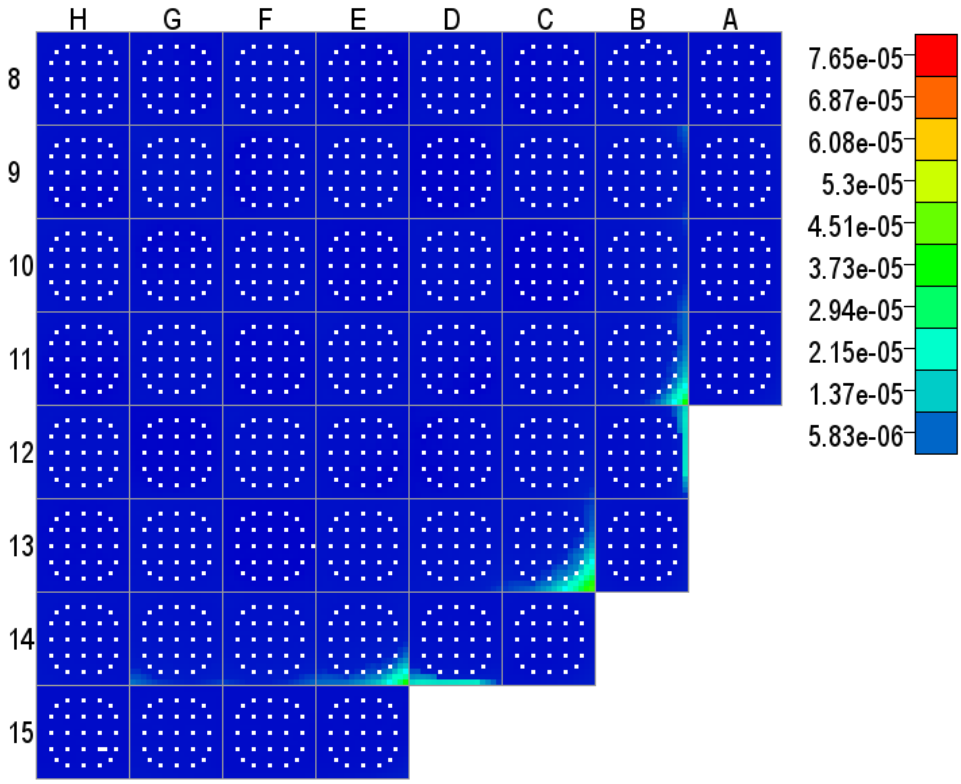

Fig. A.2.39. Cycle 2 minimum gap thickness (m) – 12.54 GWd/MT.

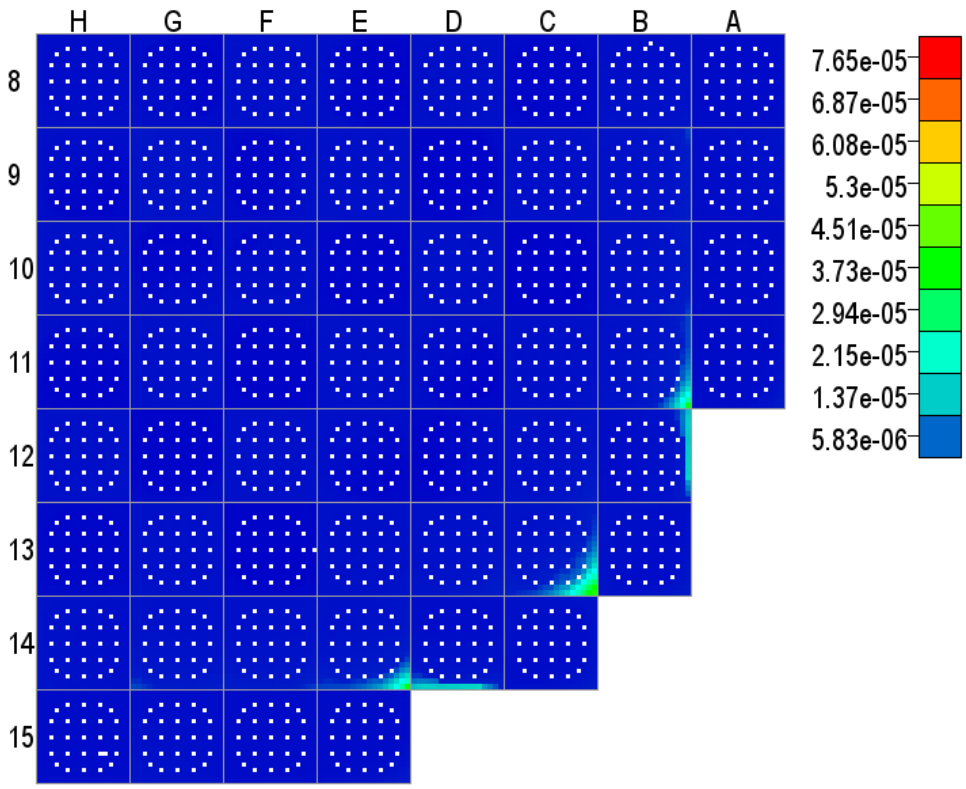

Fig. A.2.40. Cycle 2 minimum gap thickness (m) – 13.54 GWd/MT.

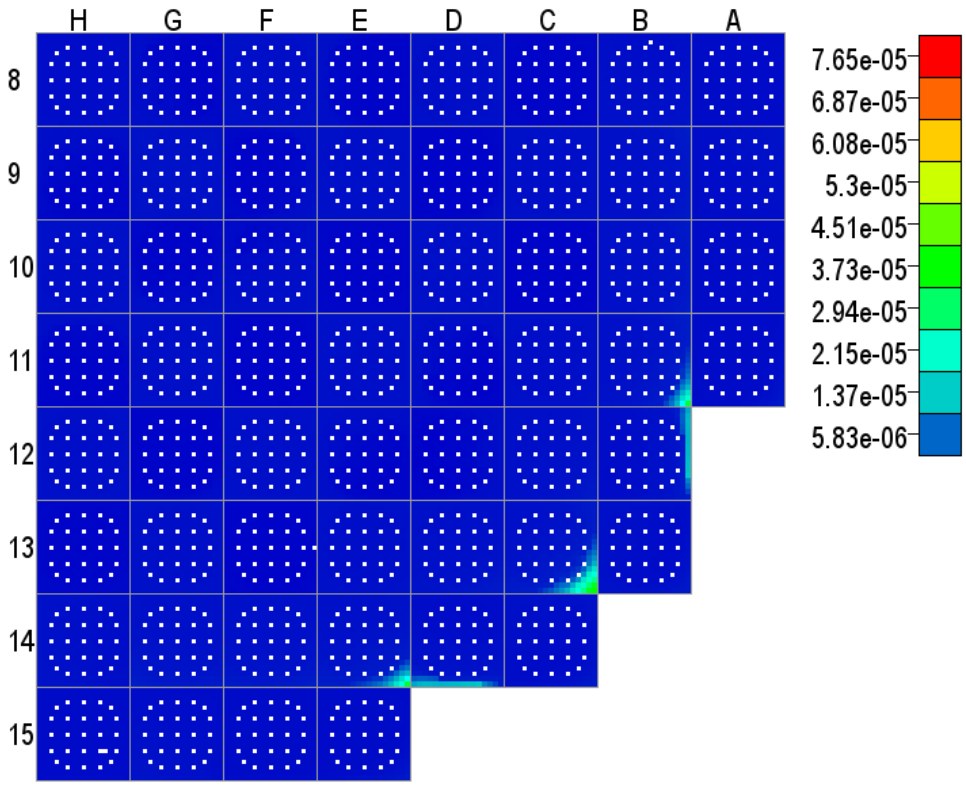

Fig. A.2.41. Cycle 2 minimum gap thickness (m) – 14.62 GWd/MT.

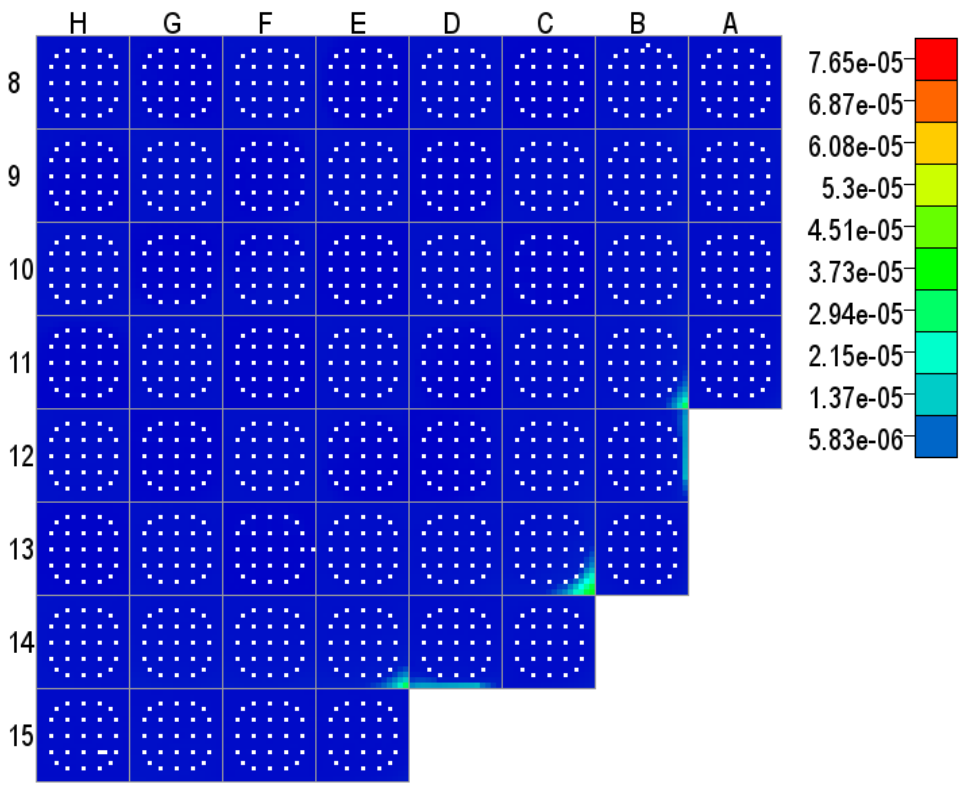

Fig. A.2.42. Cycle 2 minimum gap thickness (m) – 15.76 GWd/MT.

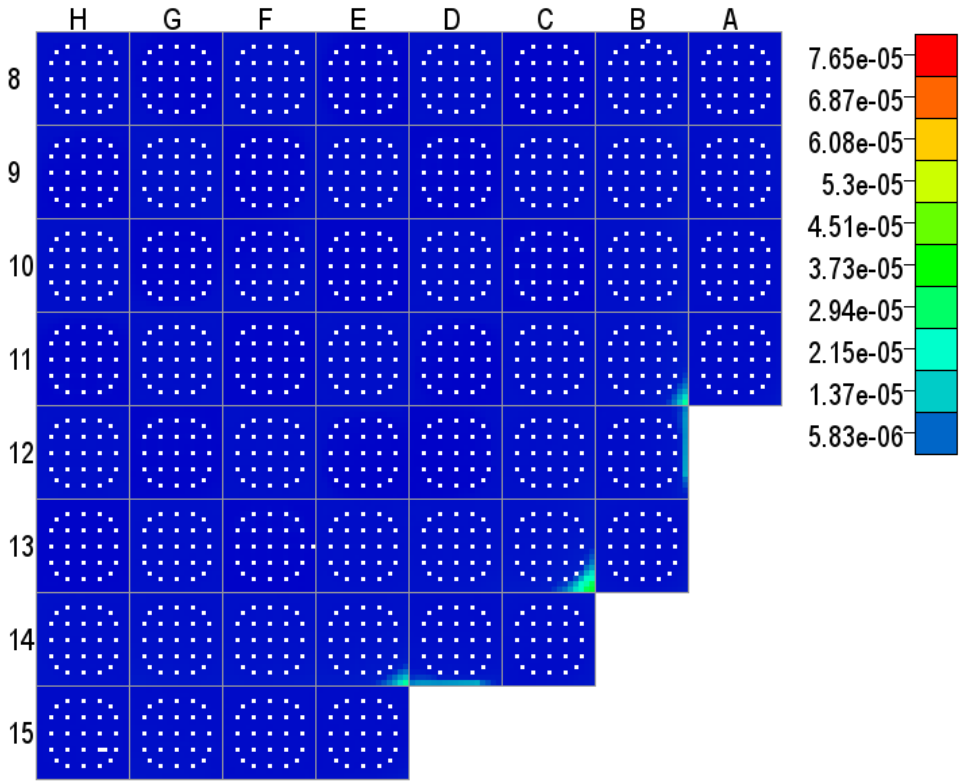

Fig. A.2.43. Cycle 2 minimum gap thickness (m) – 16.32 GWd/MT.

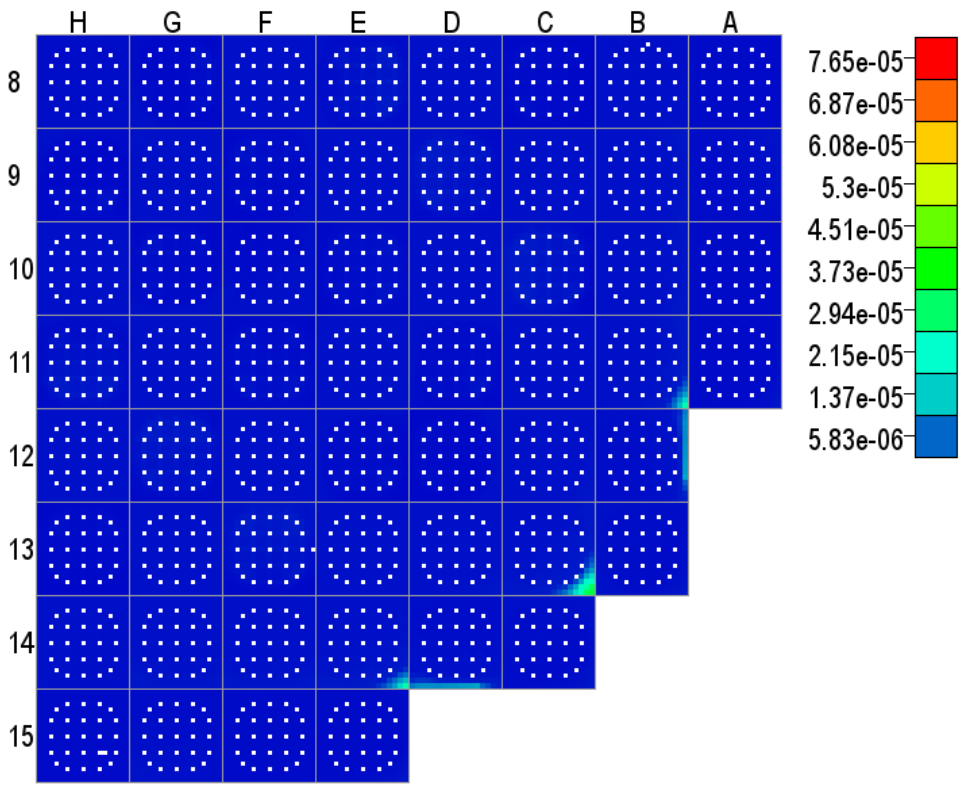

Fig. A.2.44. Cycle 2 minimum gap thickness (m) – 16.90 GWd/MT.

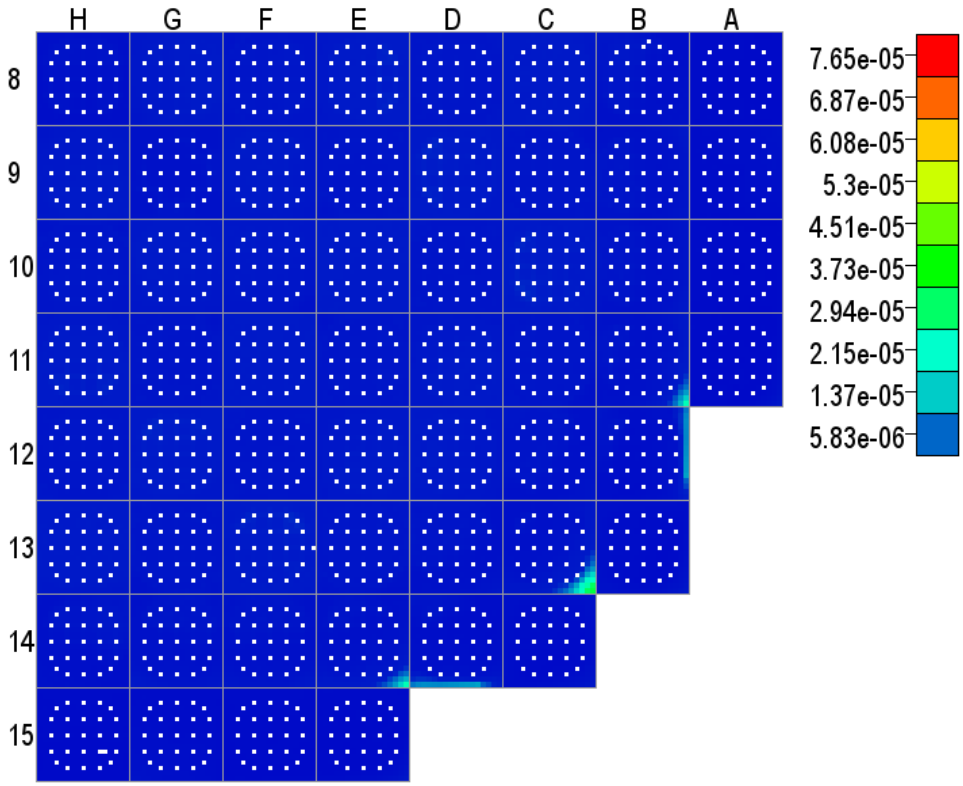

Fig. A.2.45. Cycle 2 minimum gap thickness (m) – 17.48 GWd/MT.

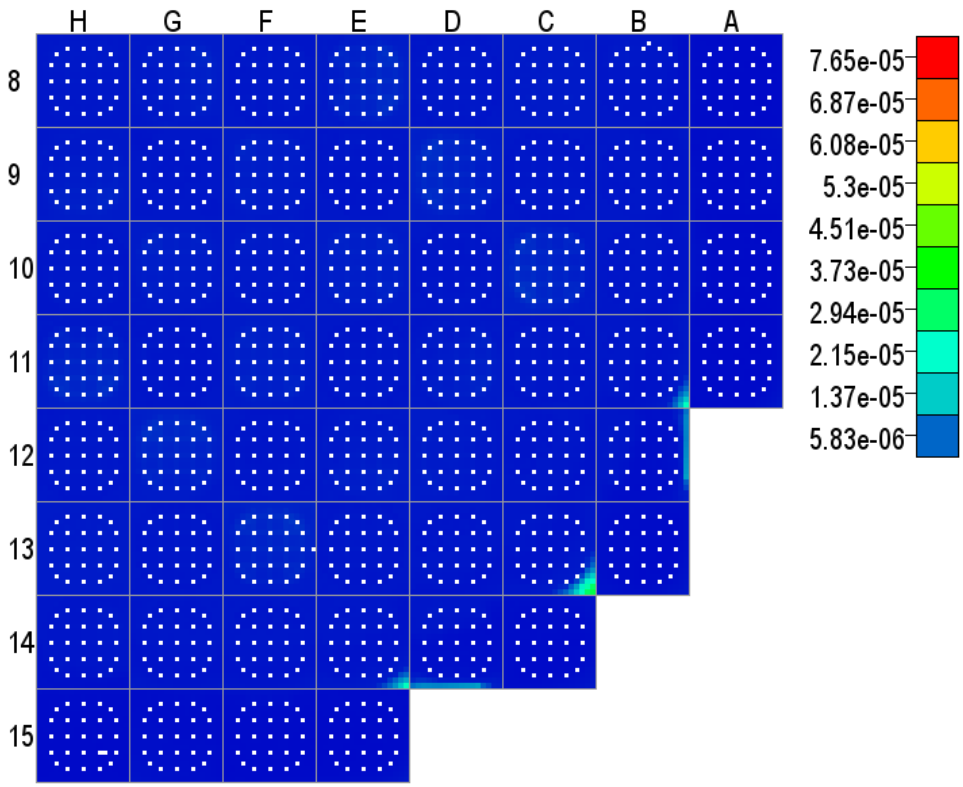

Fig. A.2.46. Cycle 2 minimum gap thickness (m) – 18.06 GWd/MT.

A.3. Cycle 3

A.3.1. Maximum Centerline Fuel Temperature

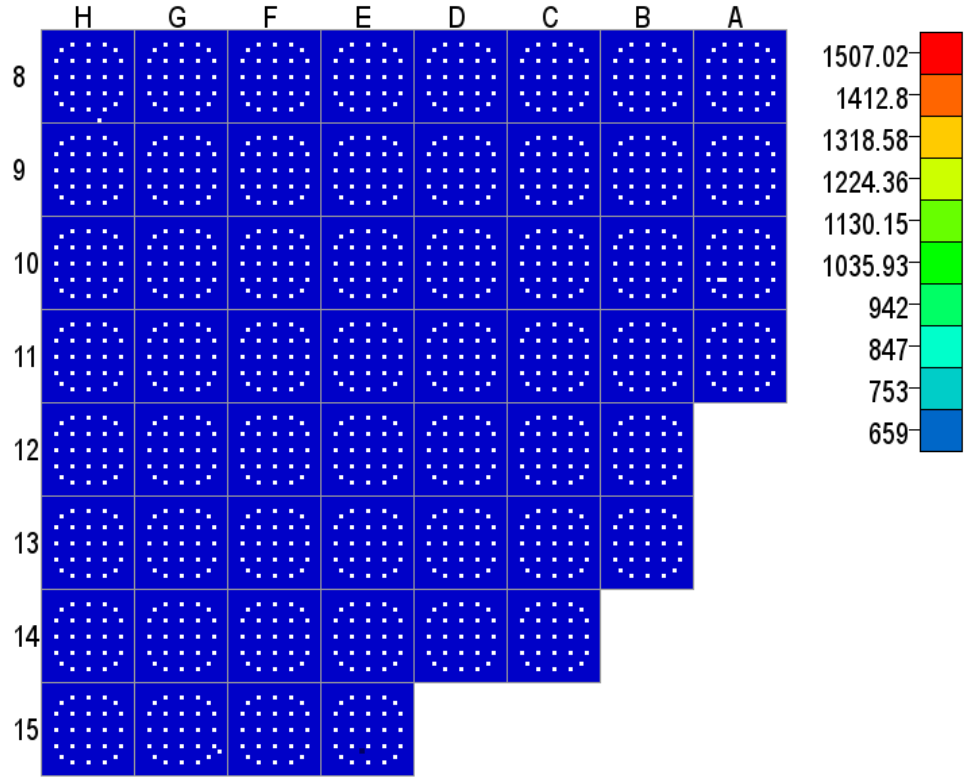

Fig. A.3.1. Cycle 3 maximum centerline fuel temperature (K) – 0.00 GWd/MT.

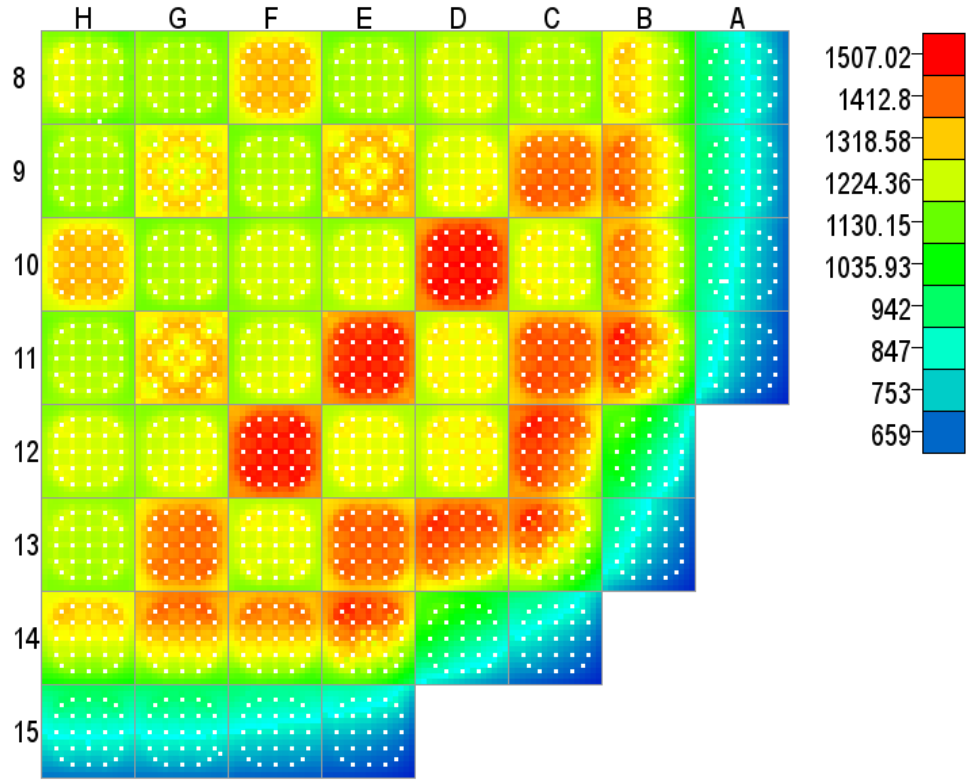

Fig. A.3.2. Cycle 3 maximum centerline fuel temperature (K) – 0.20 GWd/MT.

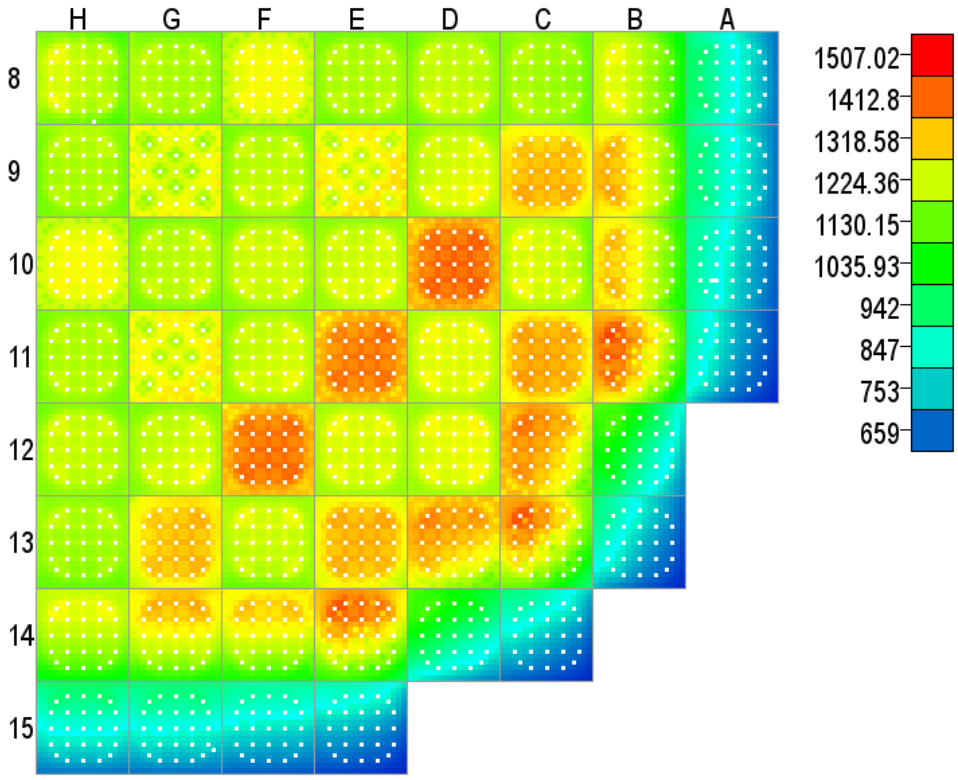

Fig. A.3.3. Cycle 3 maximum centerline fuel temperature (K) – 0.69 GWd/MT.

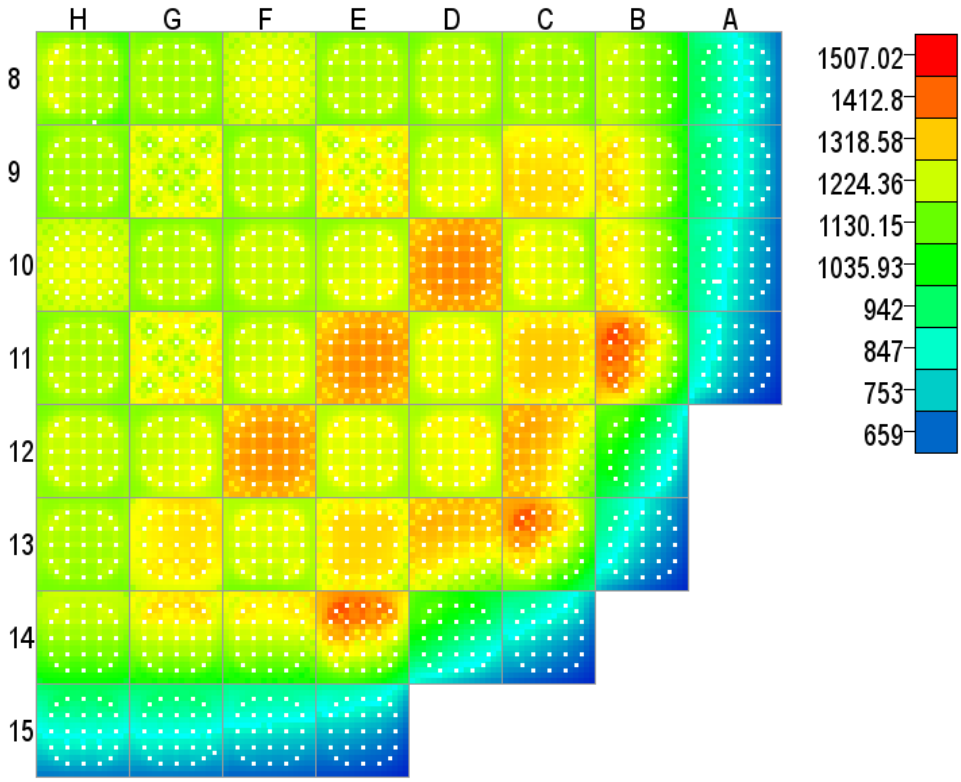

Fig. A.3.4. Cycle 3 maximum centerline fuel temperature (K) – 1.17 GWd/MT.

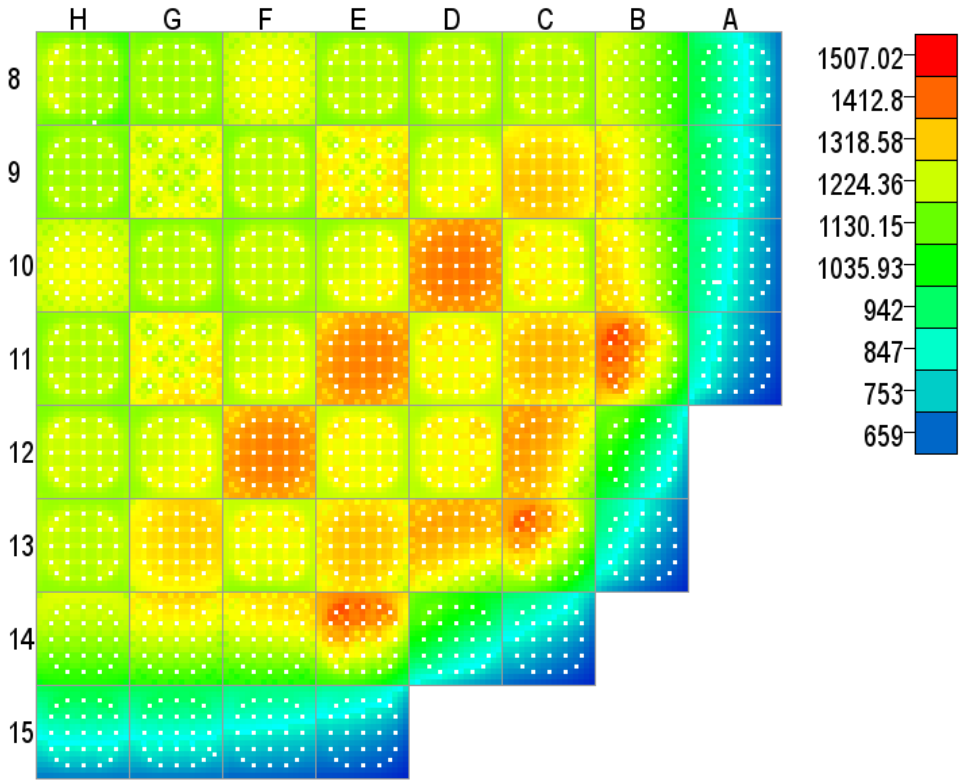

Fig. A.3.5. Cycle 3 maximum centerline fuel temperature (K) – 1.70 GWd/MT.

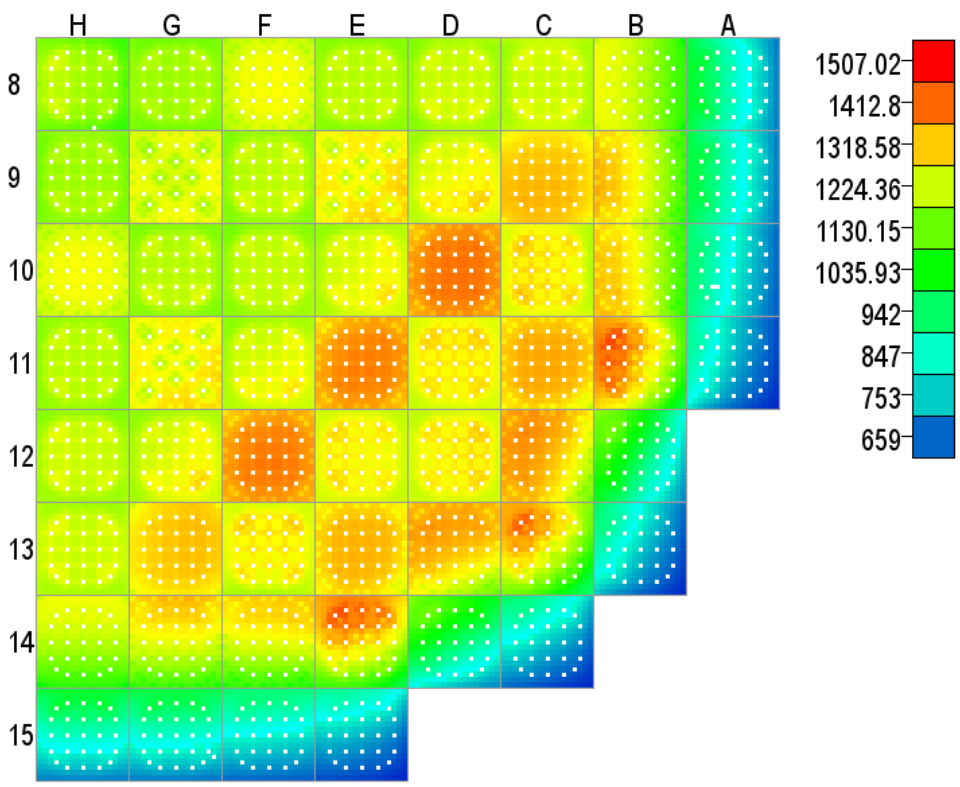

Fig. A.3.6. Cycle 3 maximum centerline fuel temperature (K) – 2.24 GWd/MT.

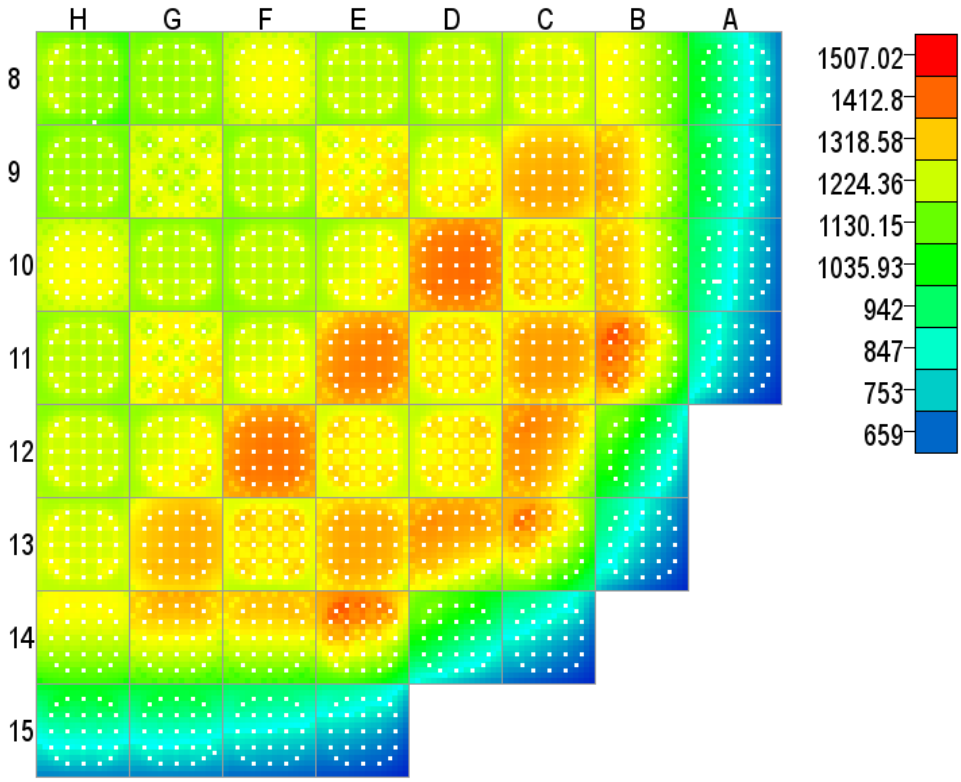

Fig. A.3.7. Cycle 3 maximum centerline fuel temperature (K) – 2.77 GWd/MT.

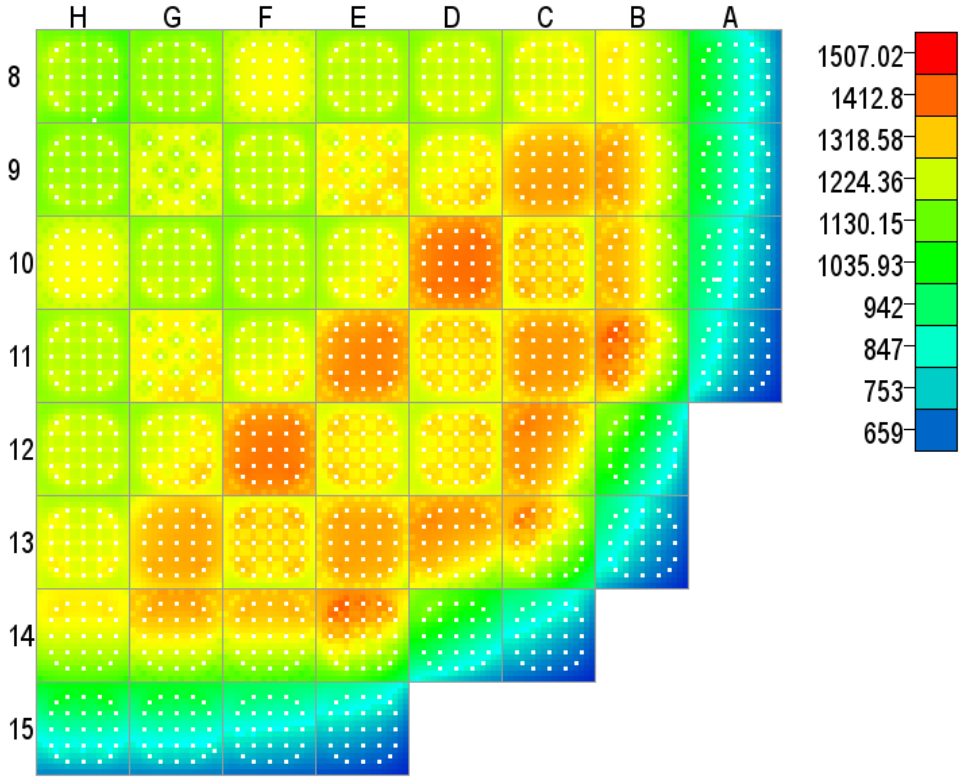

Fig. A.3.8. Cycle 3 maximum centerline fuel temperature (K) – 3.30 GWd/MT.

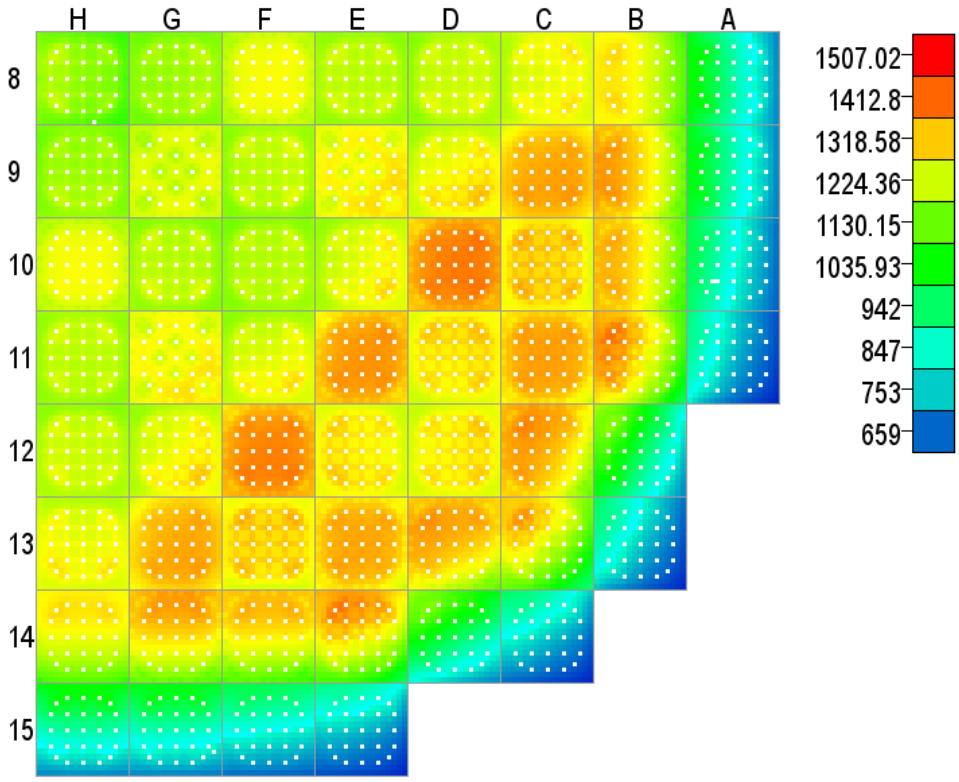

Fig. A.3.9. Cycle 3 maximum centerline fuel temperature (K) – 3.96 GWd/MT.

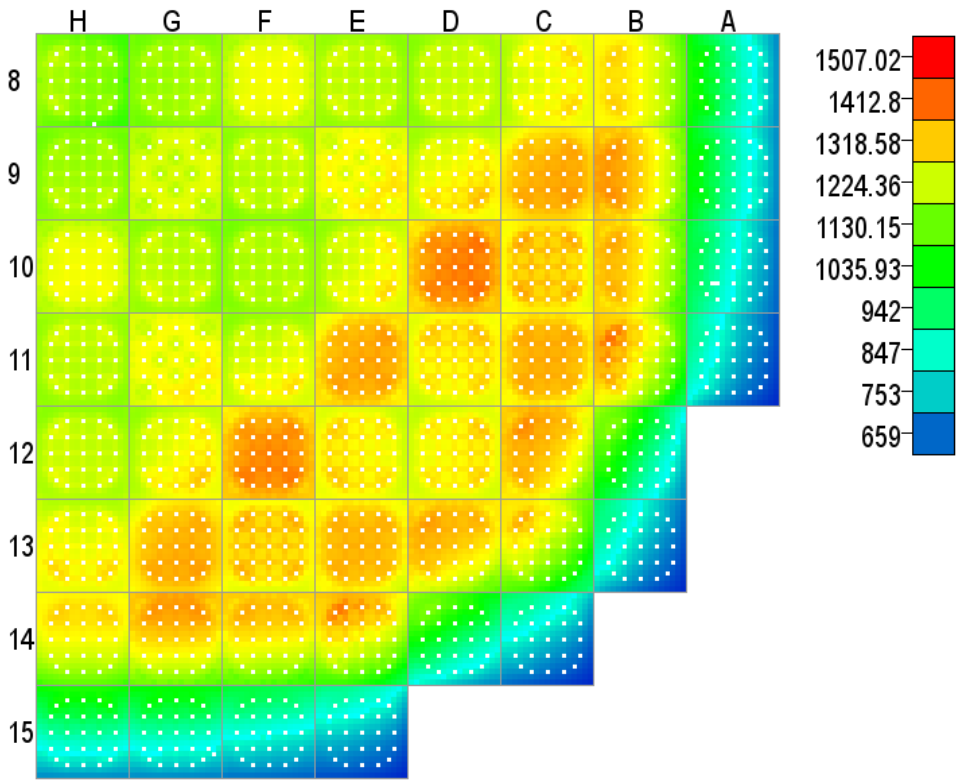

Fig. A.3.10. Cycle 3 maximum centerline fuel temperature (K) – 4.91 GWd/MT.

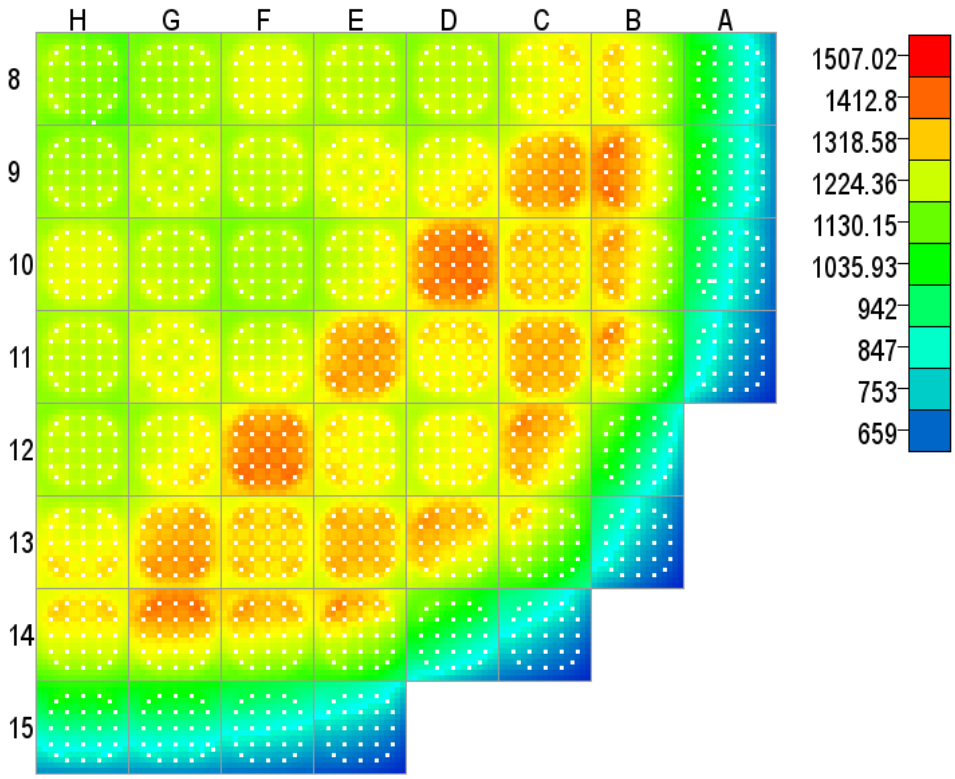

Fig. A.3.11. Cycle 3 maximum centerline fuel temperature (K) – 6.44 GWd/MT.

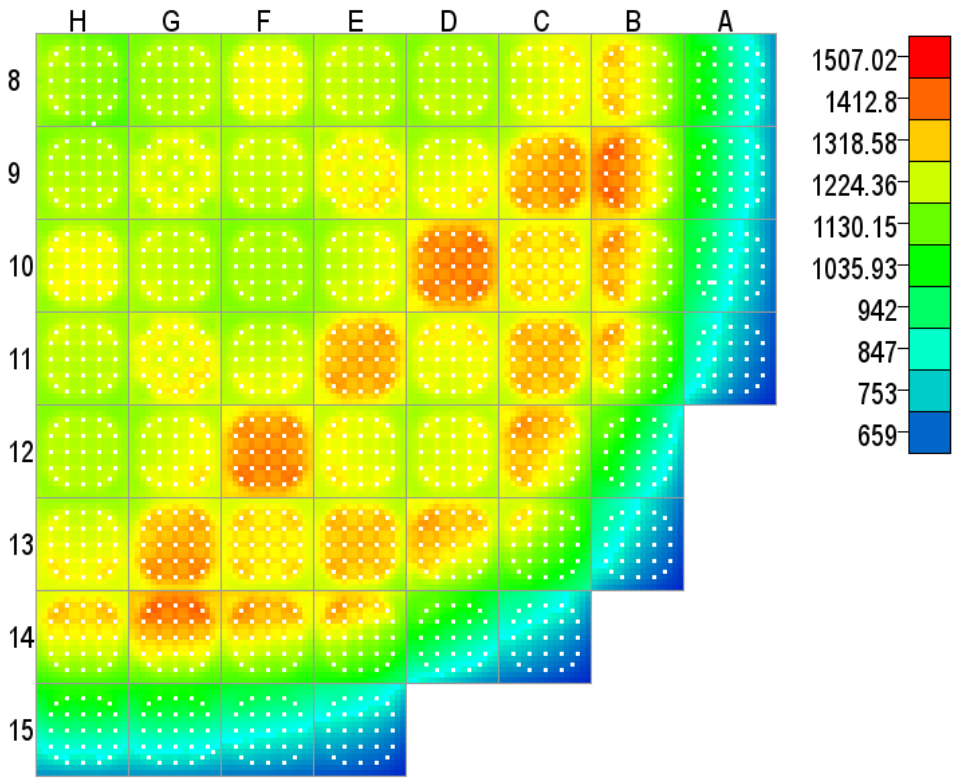

Fig. A.3.12. Cycle 3 maximum centerline fuel temperature (K) – 8.13 GWd/MT.

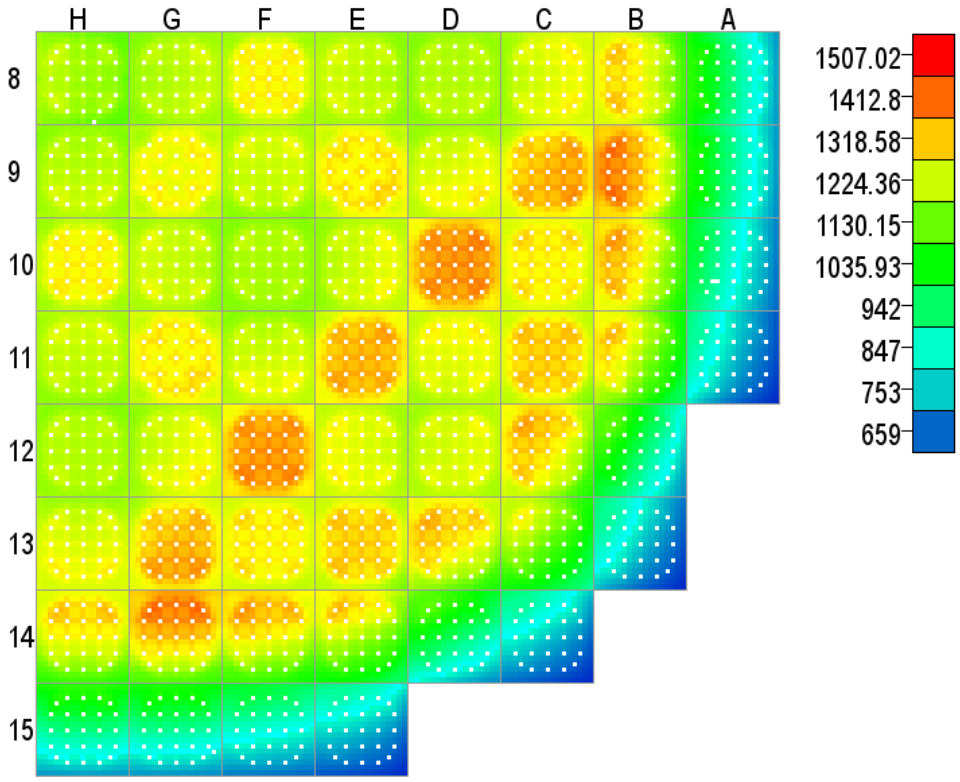

Fig. A.3.13. Cycle 3 maximum centerline fuel temperature (K) – 9.72 GWd/MT.

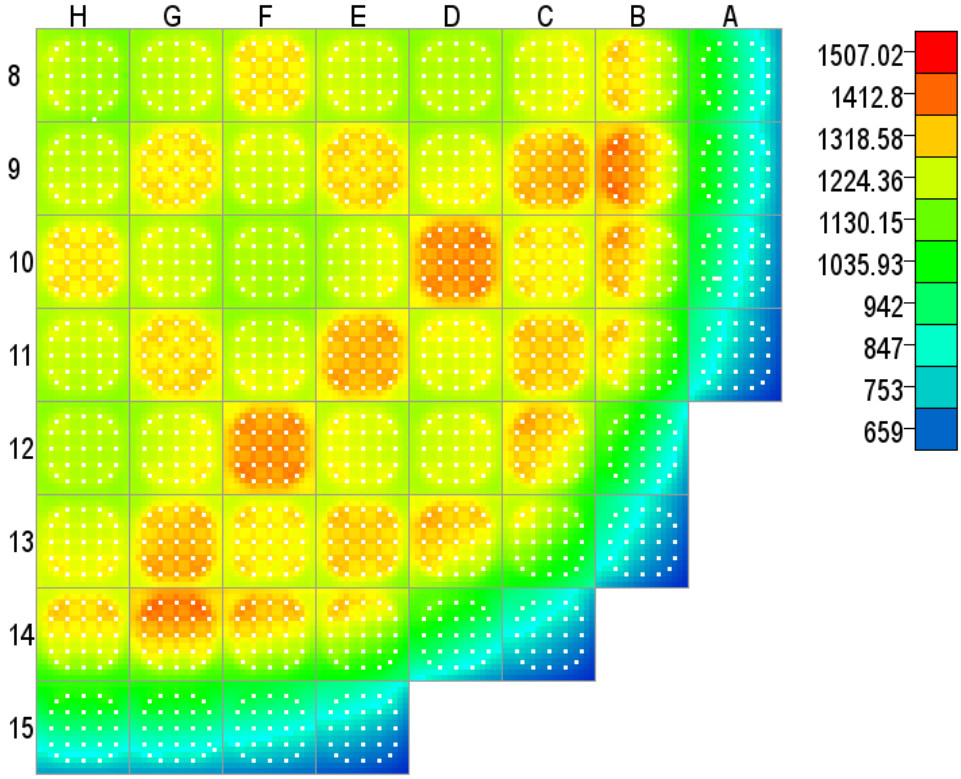

Fig. A.3.14. Cycle 3 maximum centerline fuel temperature (K) – 11.35 GWd/MT.

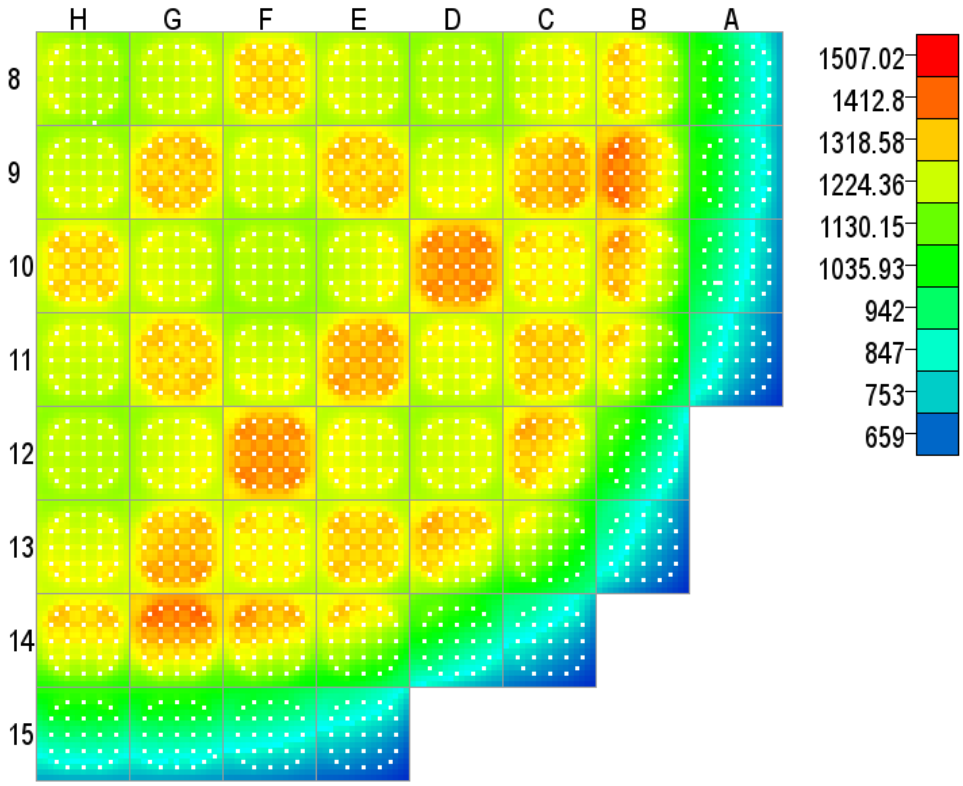

Fig. A.3.15. Cycle 3 maximum centerline fuel temperature (K) – 12.94 GWd/MT.

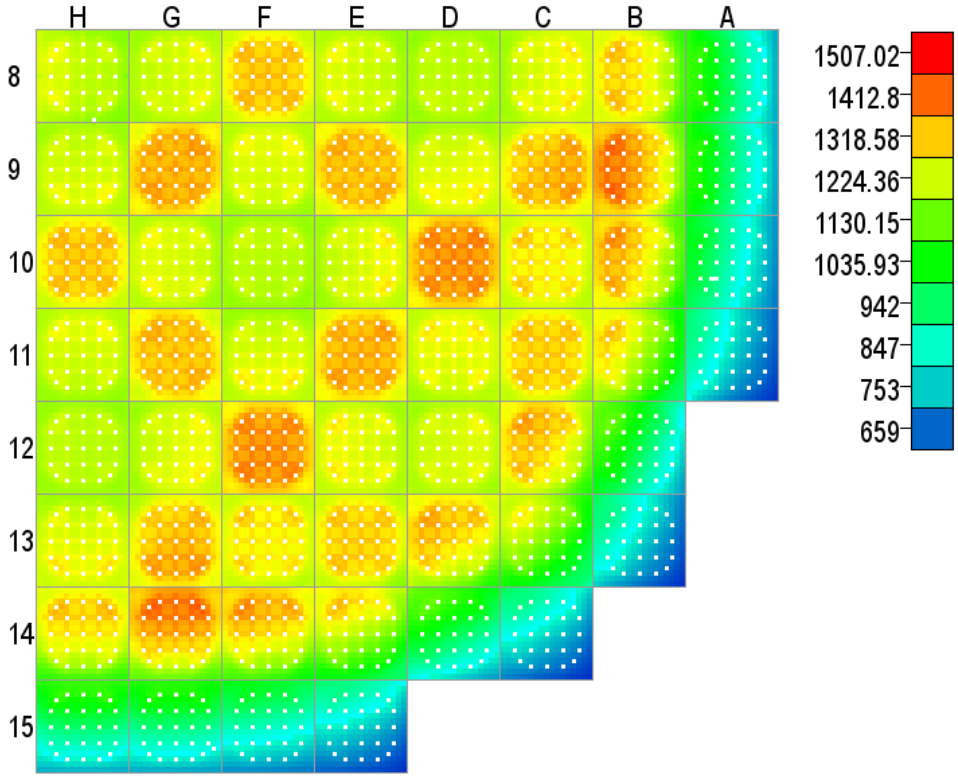

Fig. A.3.16. Cycle 3 maximum centerline fuel temperature (K) – 14.56 GWd/MT.

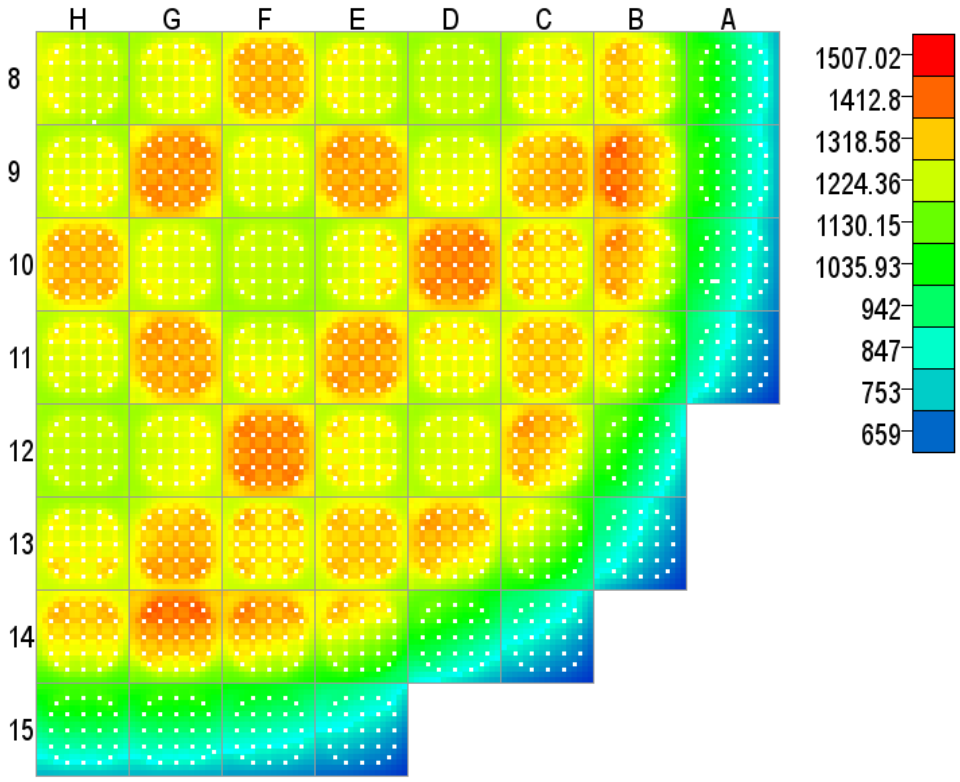

Fig. A.3.17. Cycle 3 maximum centerline fuel temperature (K) – 16.70 GWd/MT.

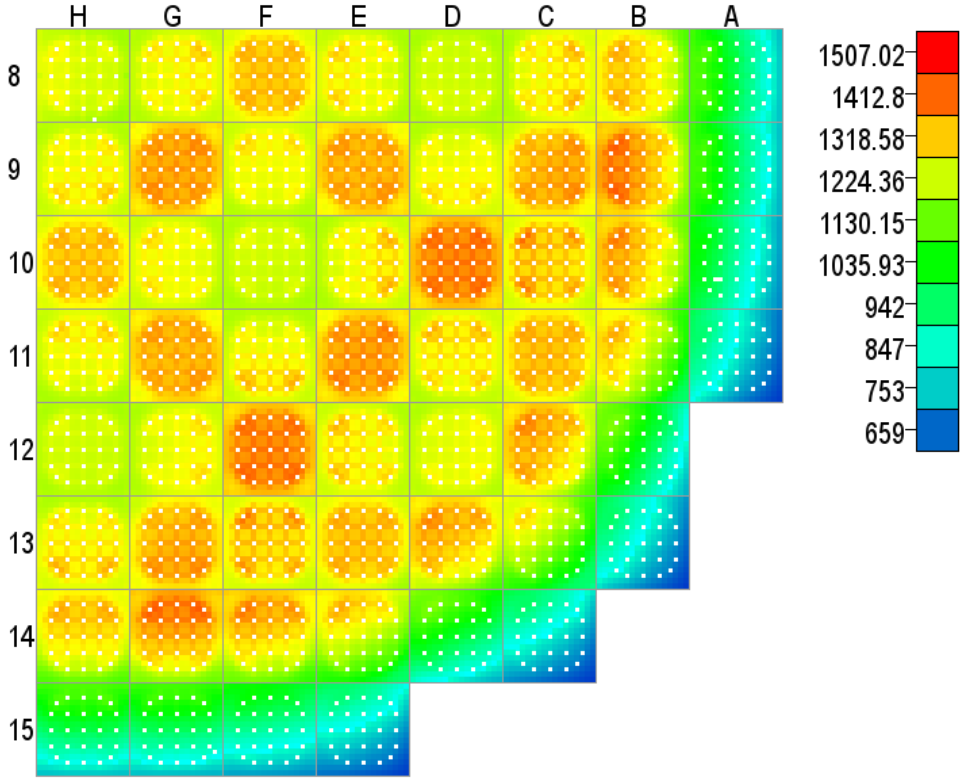

Fig. A.3.18. Cycle 3 maximum centerline fuel temperature (K) – 18.14 GWd/MT.

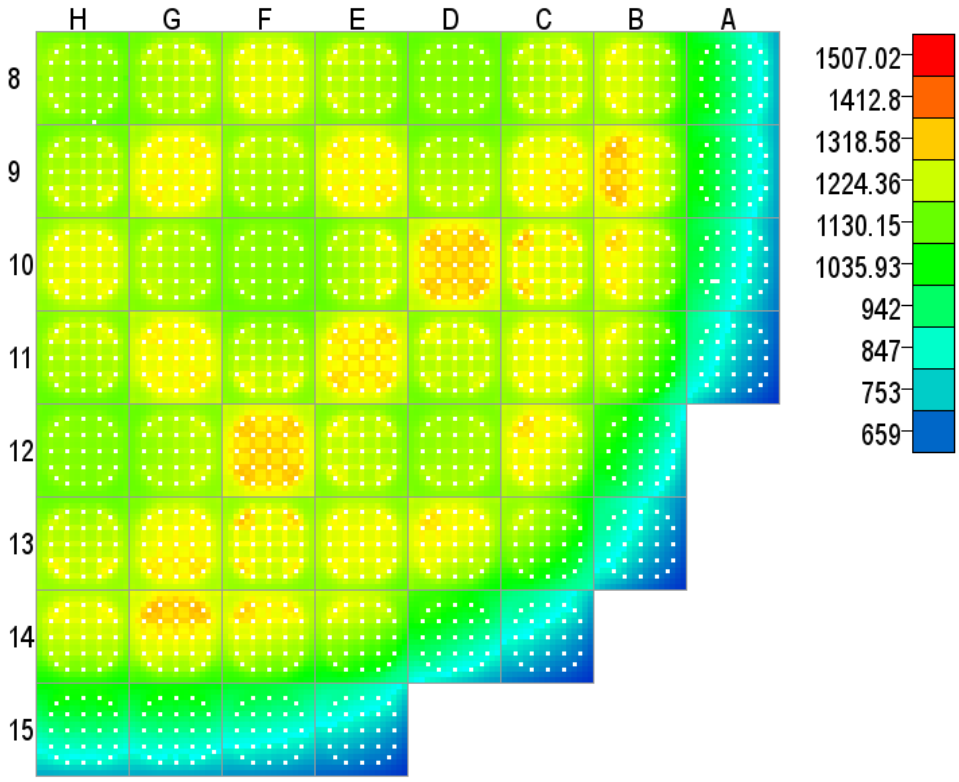

Fig. A.3.19. Cycle 3 maximum centerline fuel temperature (K) – 18.79 GWd/MT.

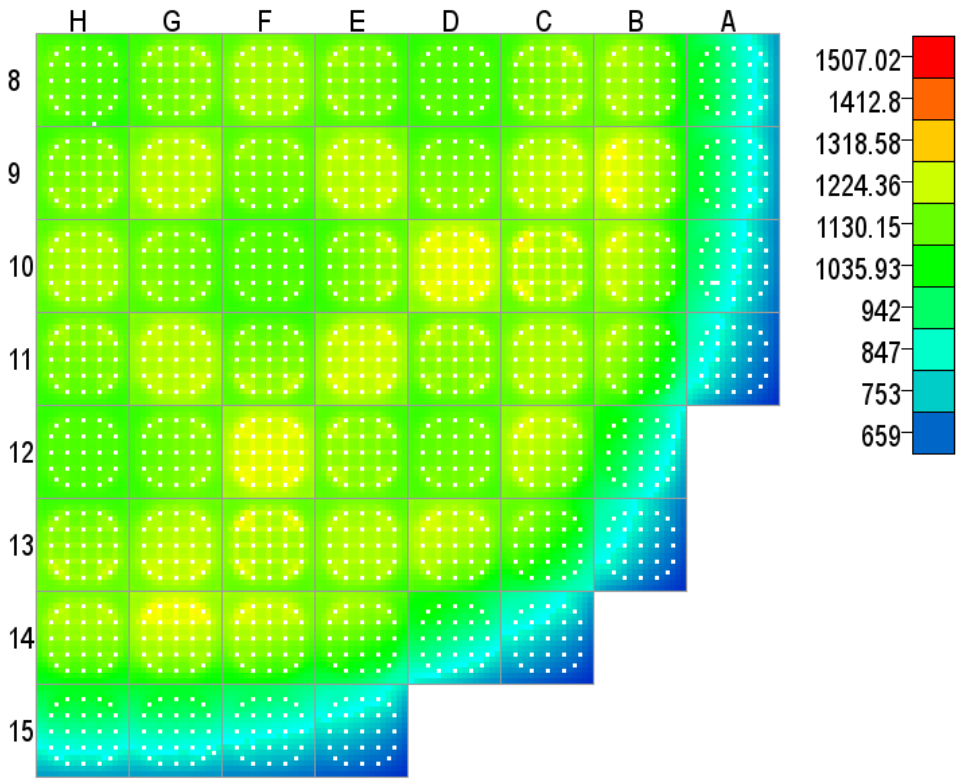

Fig. A.3.20. Cycle 3 maximum centerline fuel temperature (K) – 19.32 GWd/MT.

A.3.2. Minimum Gap Thickness

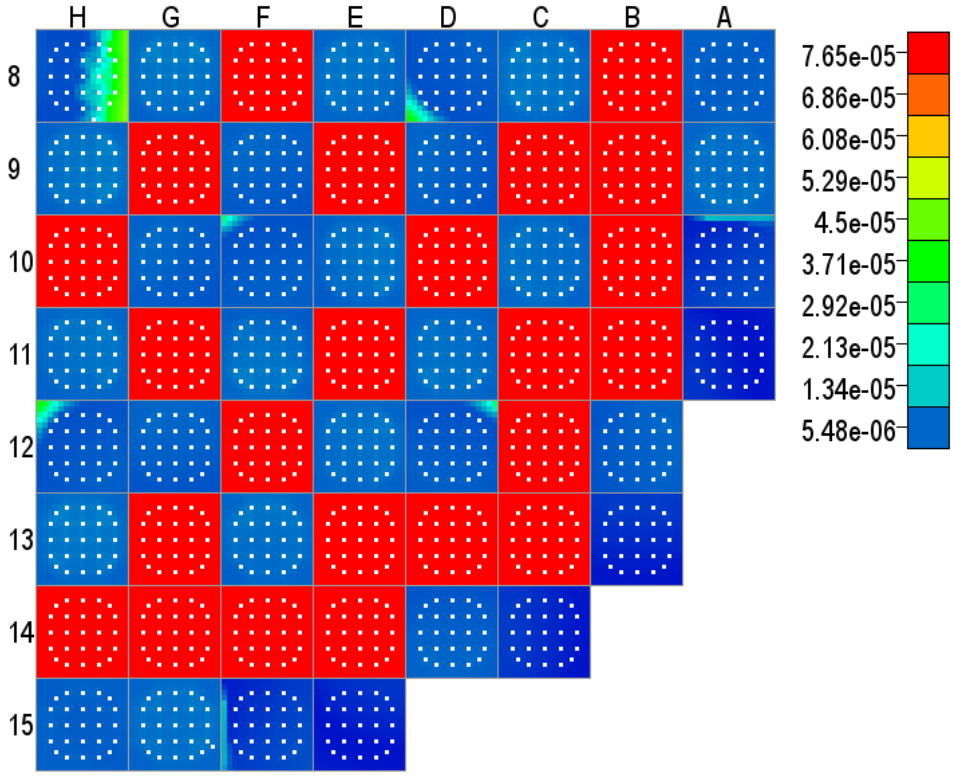

Fig. A.3.21. Cycle 3 minimum gap thickness (m) – 0.00 GWd/MT.

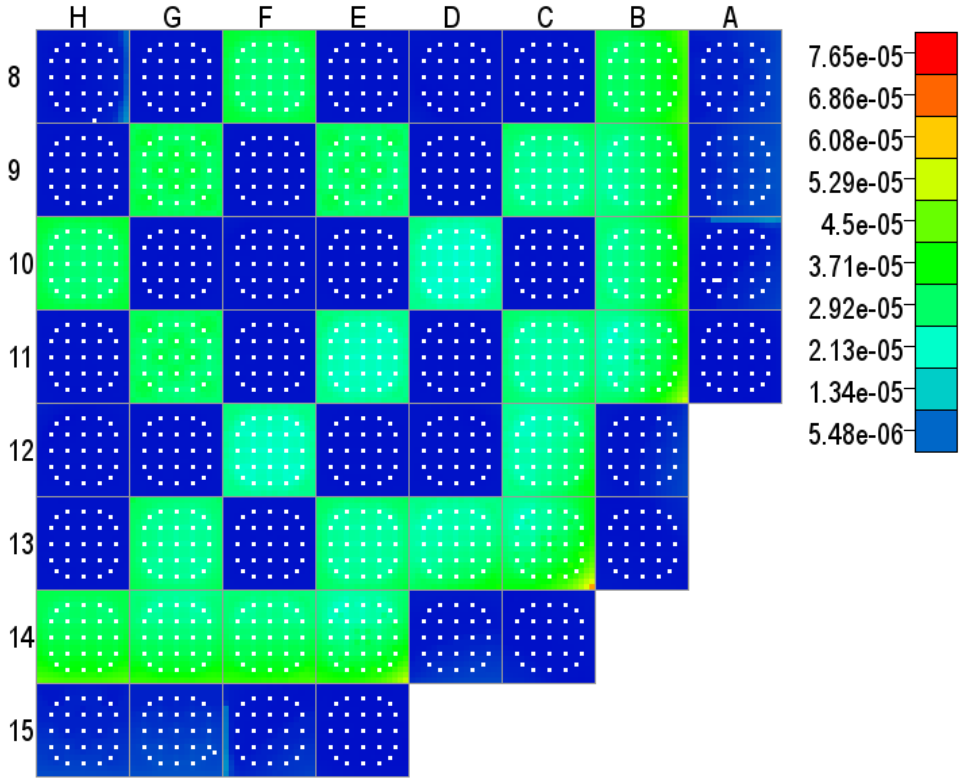

Fig. A.3.22. Cycle 3 minimum gap thickness (m) – 0.20 GWd/MT.

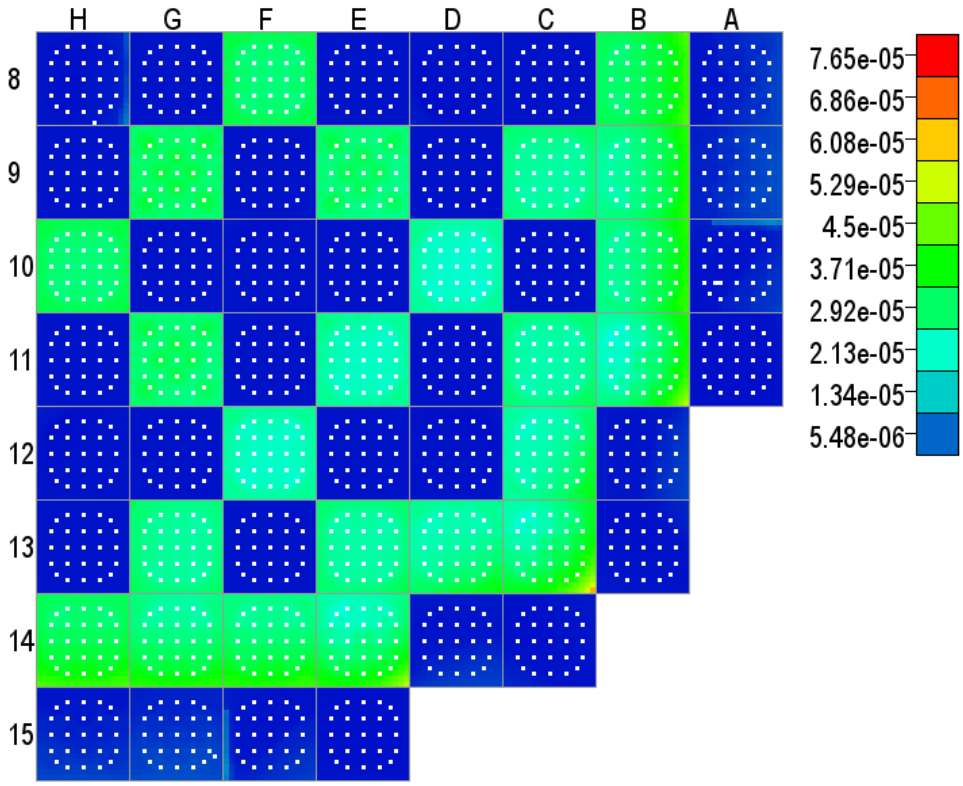

Fig. A.3.23. Cycle 3 minimum gap thickness (m) – 0.69 GWd/MT.

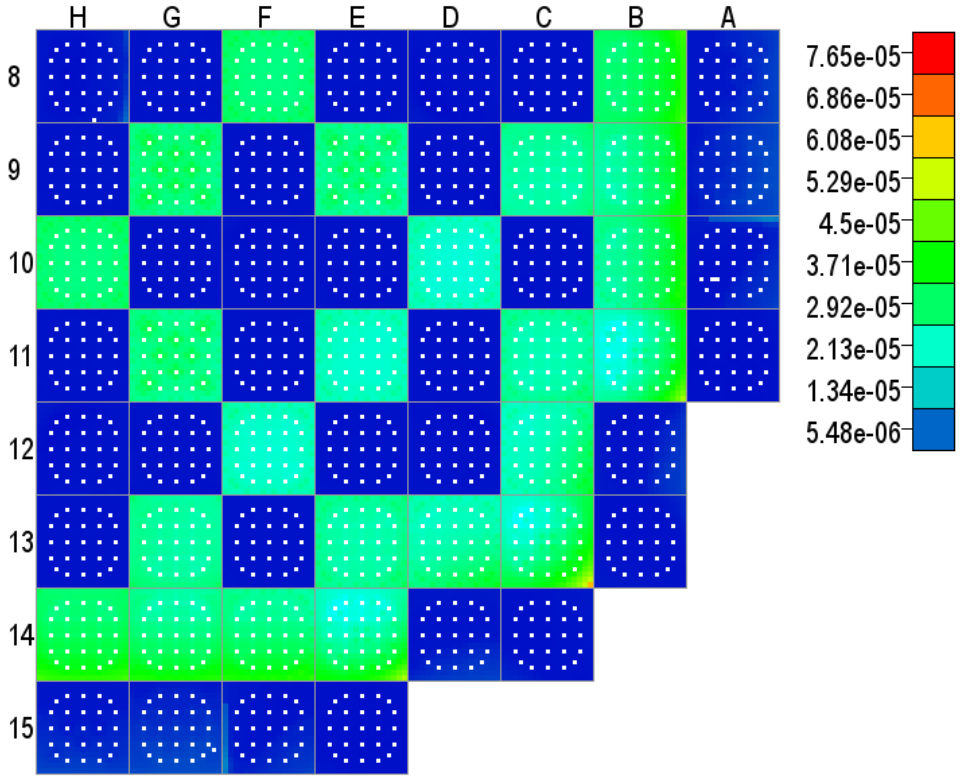

Fig. A.3.24. Cycle 3 minimum gap thickness (m) – 1.17 GWd/MT.

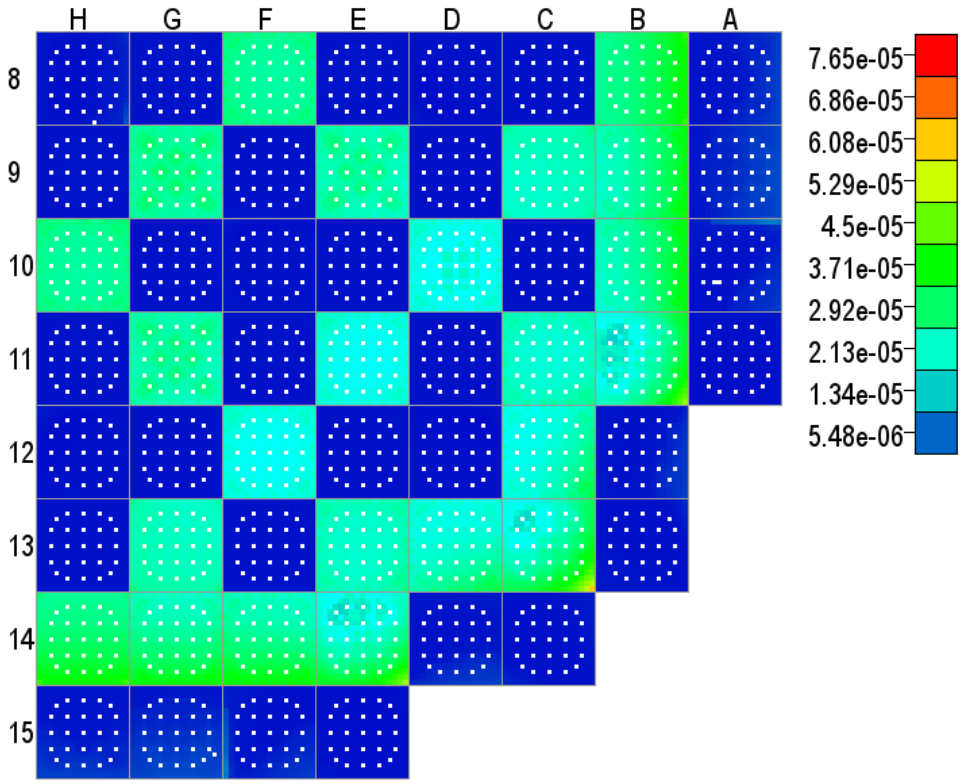

Fig. A.3.25. Cycle 3 minimum gap thickness (m) – 1.70 GWd/MT.

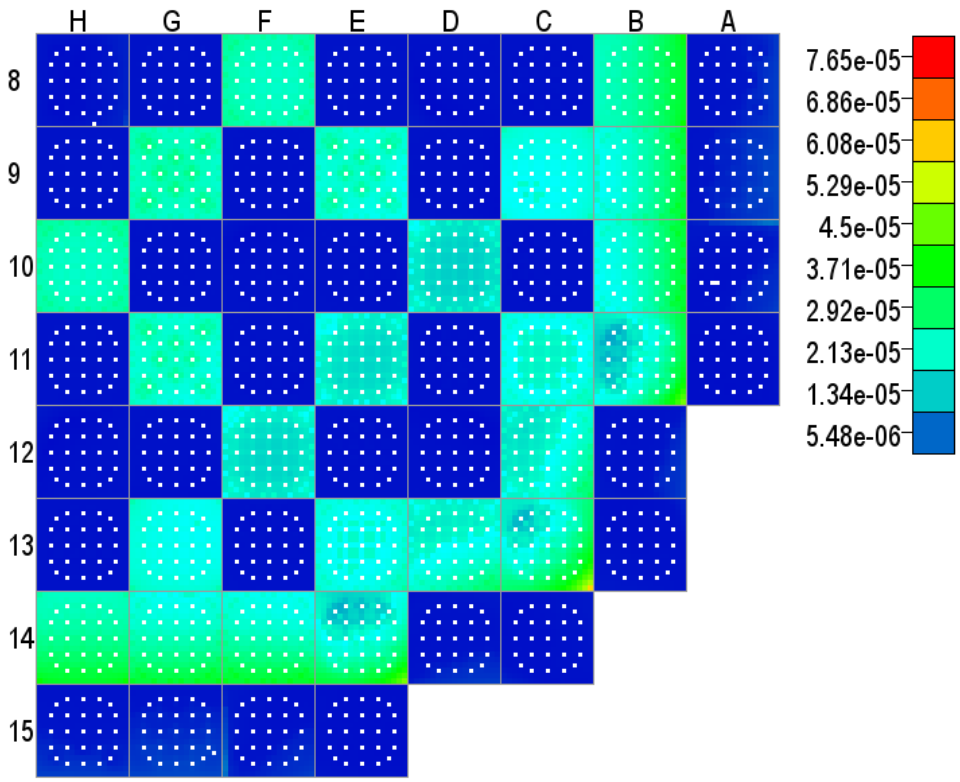

Fig. A.3.26. Cycle 3 minimum gap thickness (m) – 2.24 GWd/MT.

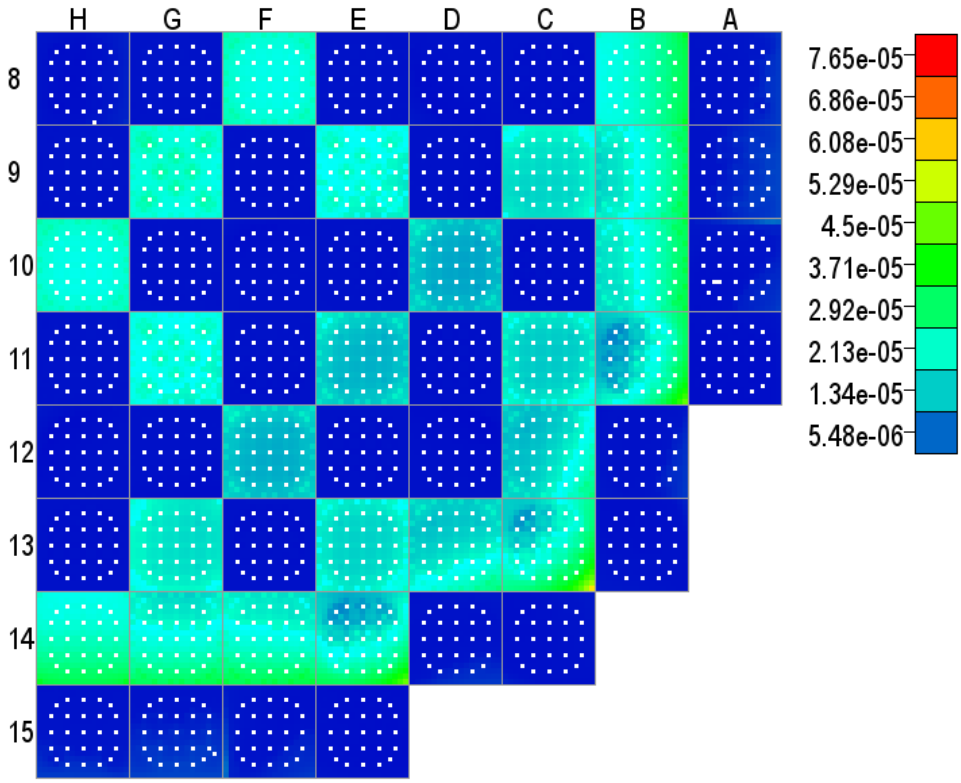

Fig. A.3.27. Cycle 3 minimum gap thickness (m) – 2.77 GWd/MT.

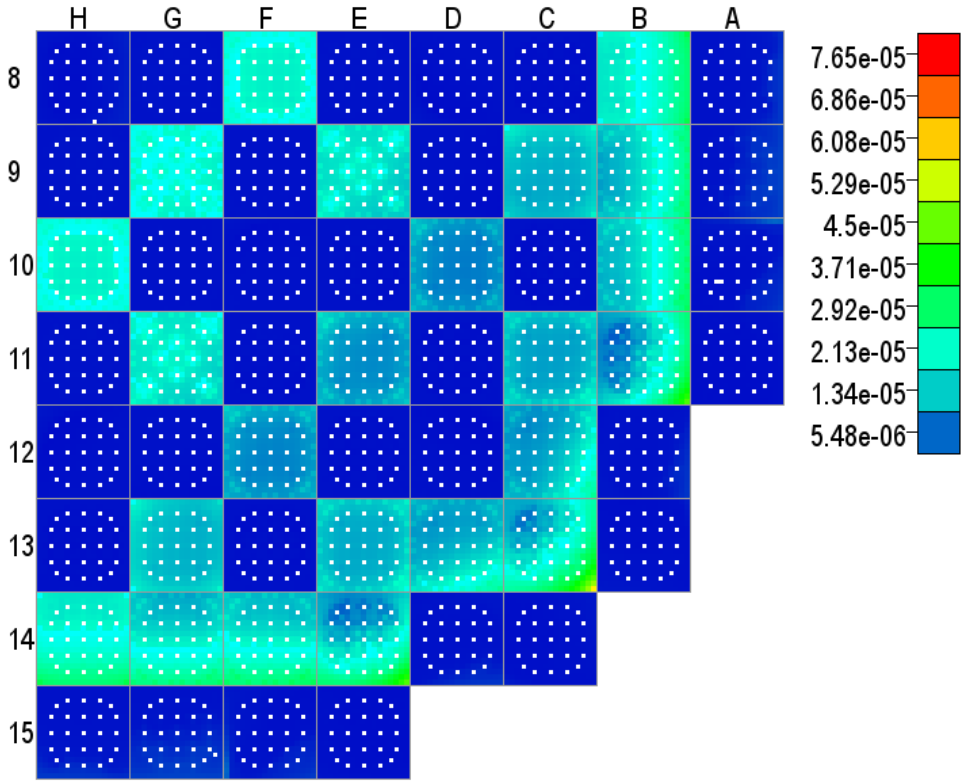

Fig. A.3.28. Cycle 3 minimum gap thickness (m) – 3.30 GWd/MT.

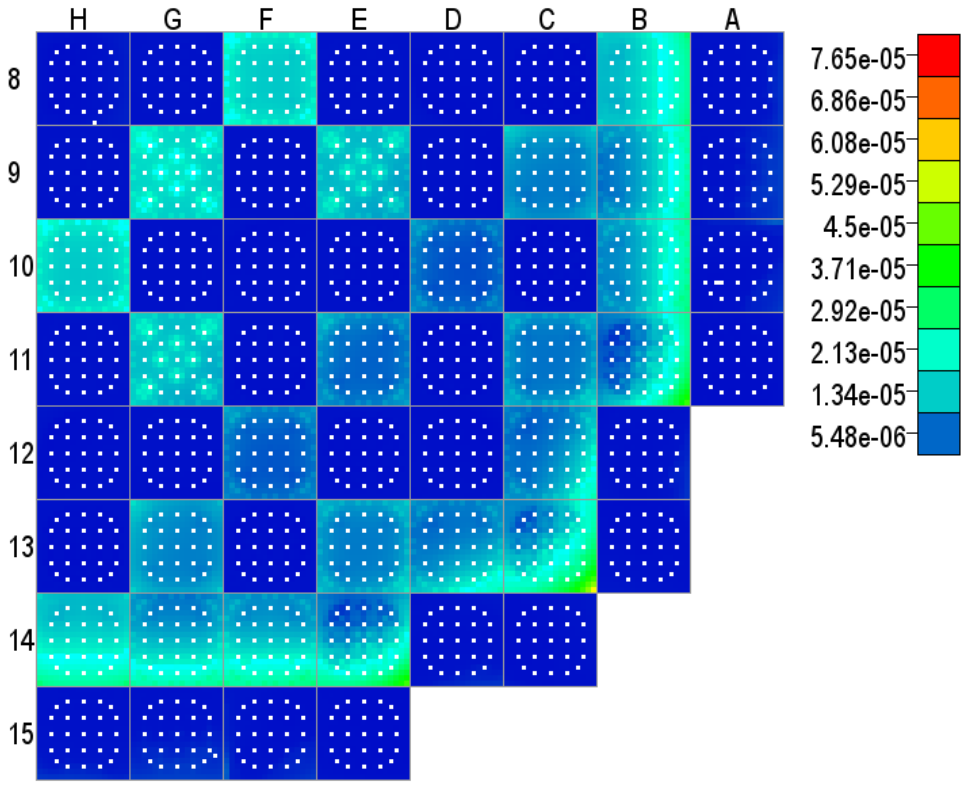

Fig. A.3.29. Cycle 3 minimum gap thickness (m) – 3.96 GWd/MT.

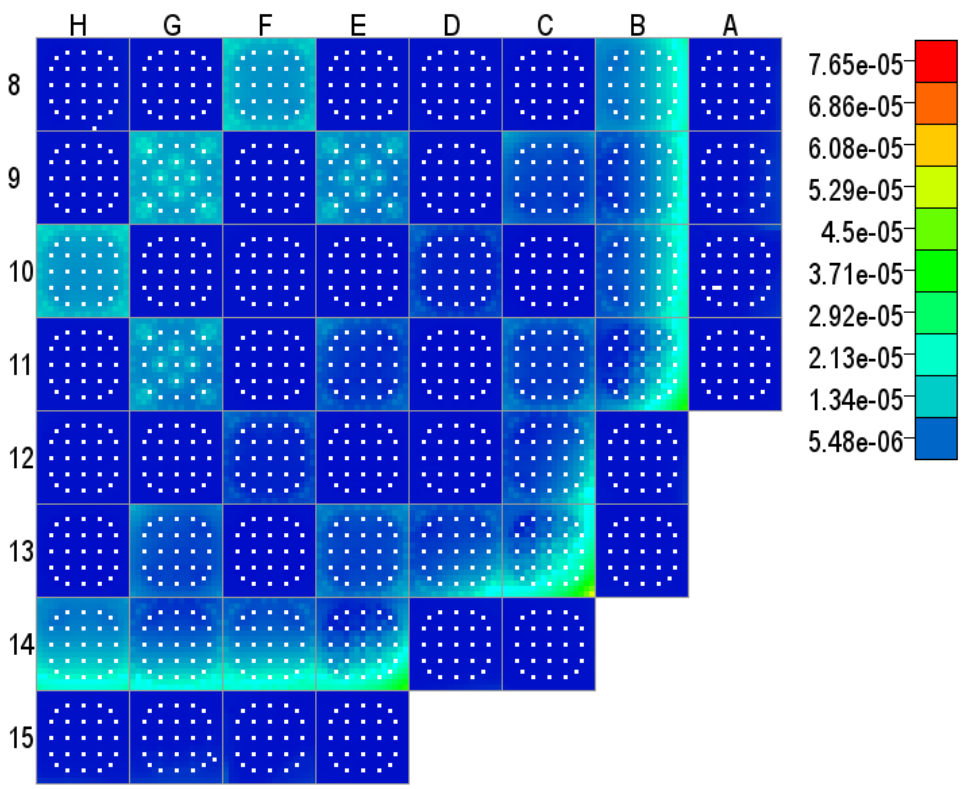

Fig. A.3.30. Cycle 3 minimum gap thickness (m) – 4.91 GWd/MT.

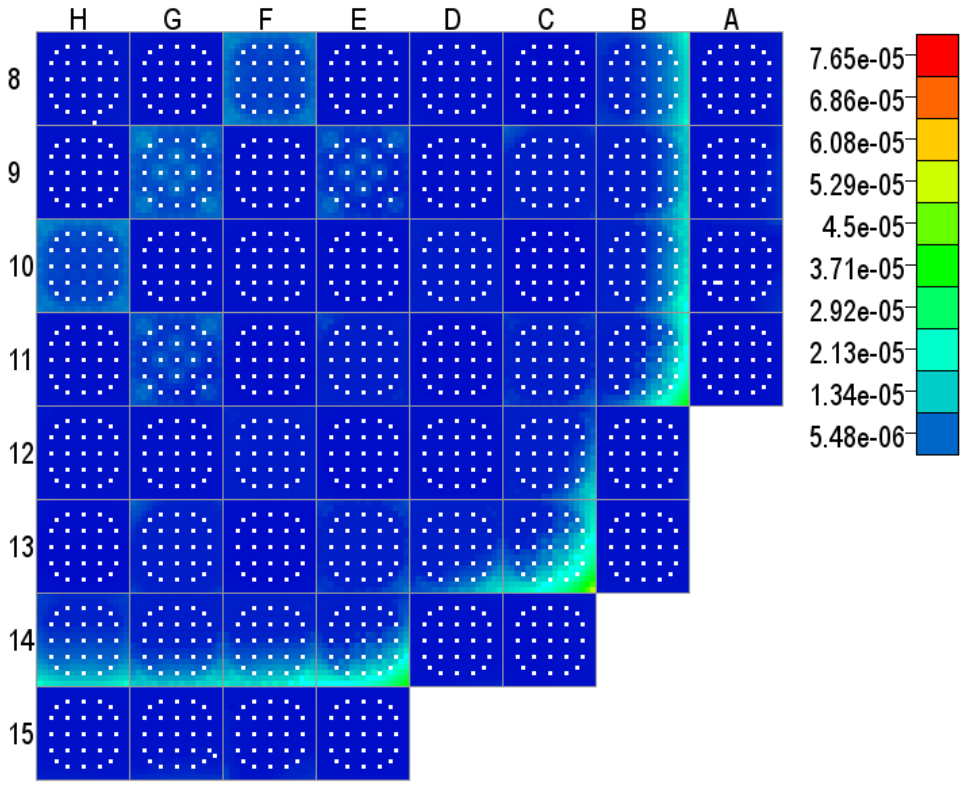

Fig. A.3.31. Cycle 3 minimum gap thickness (m) – 6.44 GWd/MT.

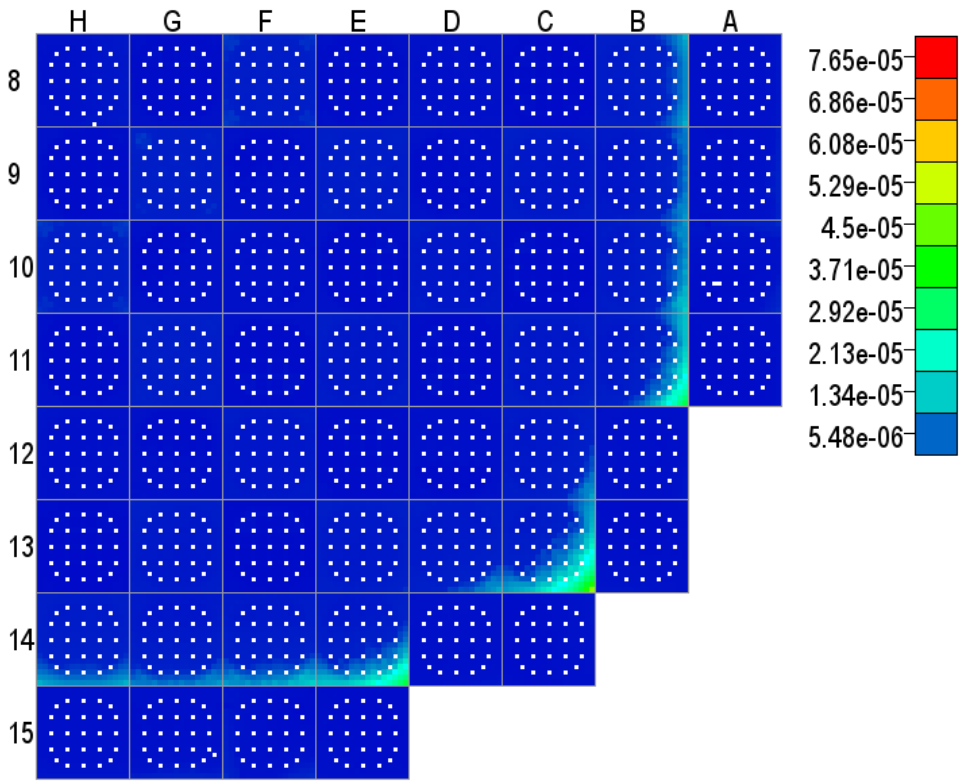

Fig. A.3.32. Cycle 3 minimum gap thickness (m) – 8.13 GWd/MT.

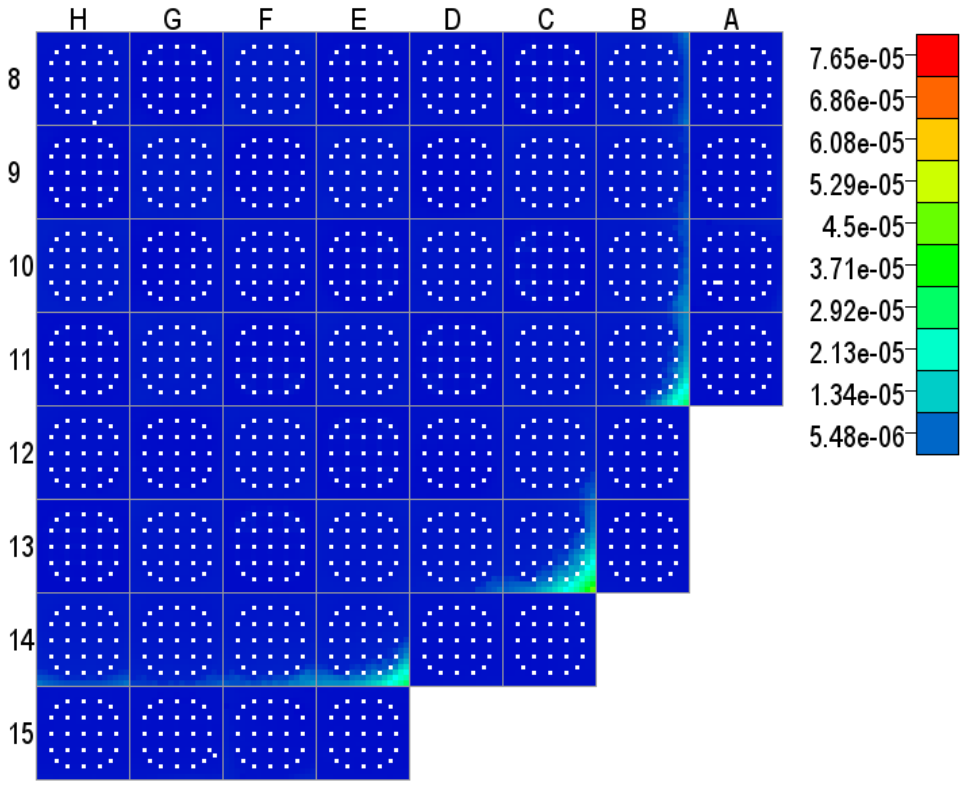

Fig. A.3.33. Cycle 3 minimum gap thickness (m) – 9.72 GWd/MT.

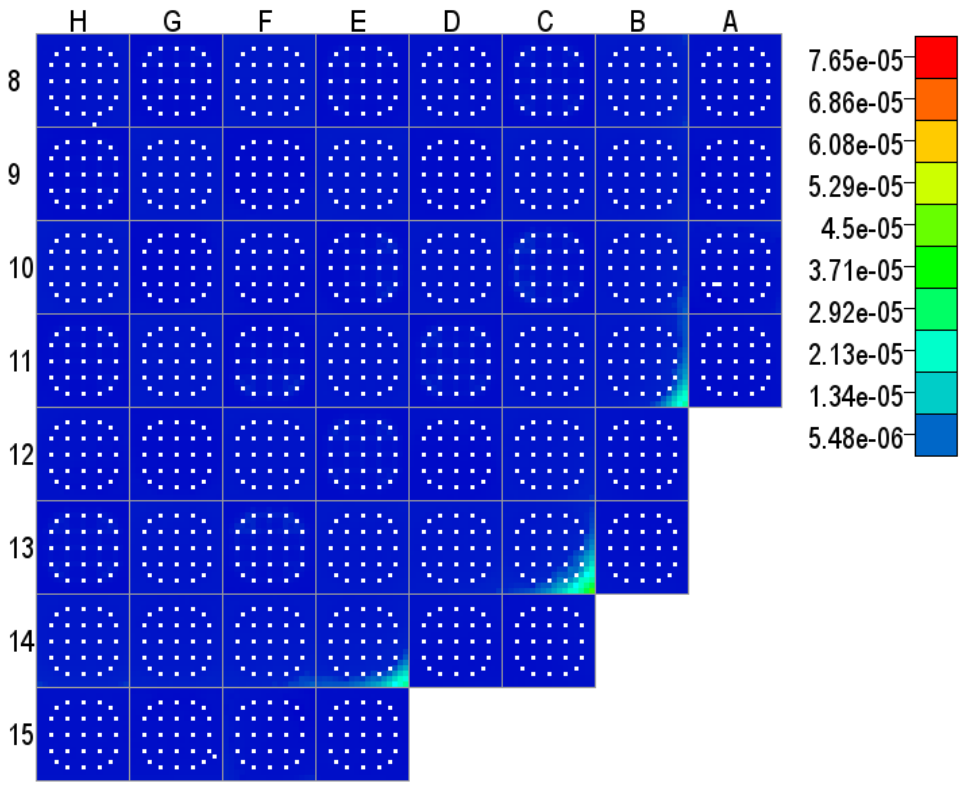

Fig. A.3.34. Cycle 3 minimum gap thickness (m) – 11.35 GWd/MT.

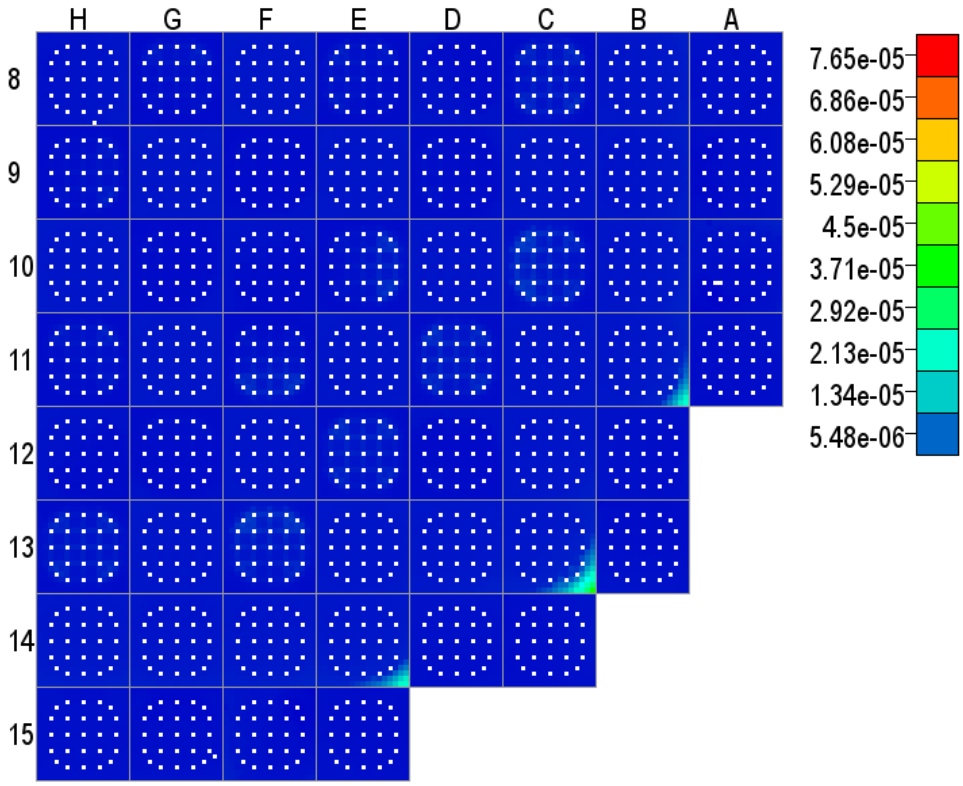

Fig. A.3.35. Cycle 3 minimum gap thickness (m) – 12.94 GWd/MT.

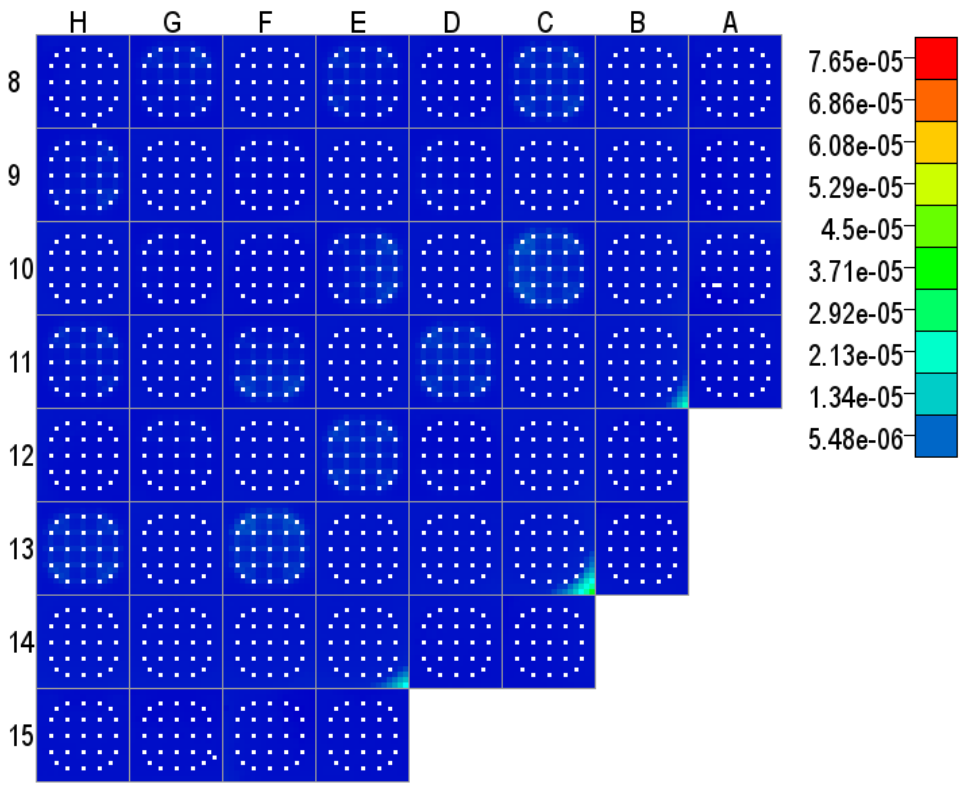

Fig. A.3.36. Cycle 3 minimum gap thickness (m) – 14.56 GWd/MT.

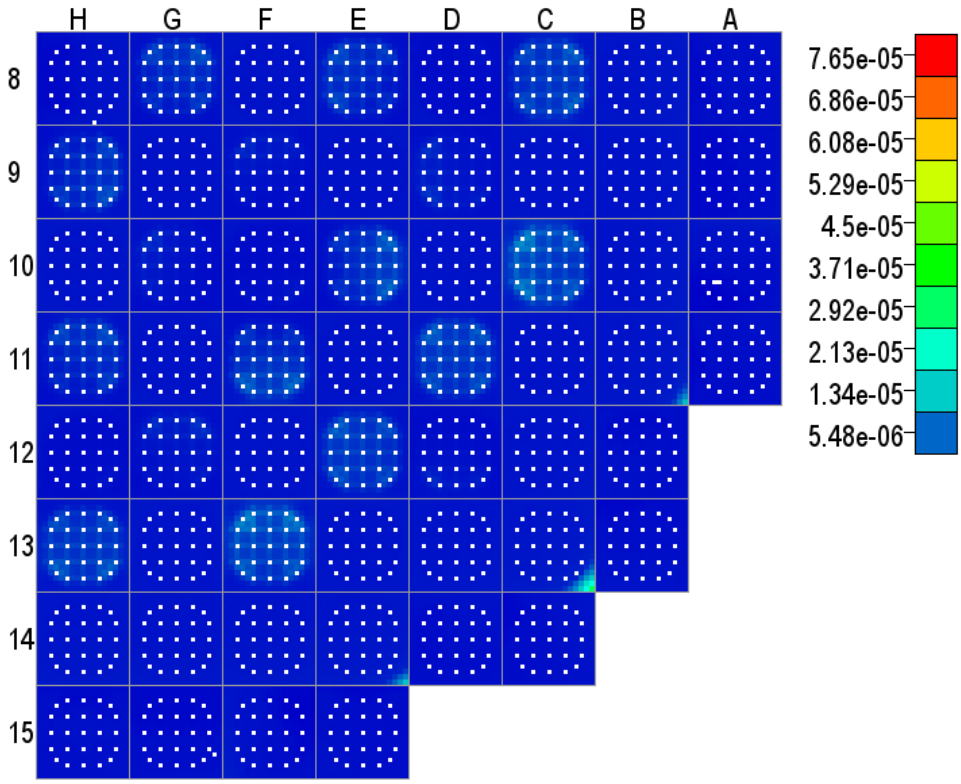

Fig. A.3.37. Cycle 3 minimum gap thickness (m) – 16.70 GWd/MT.

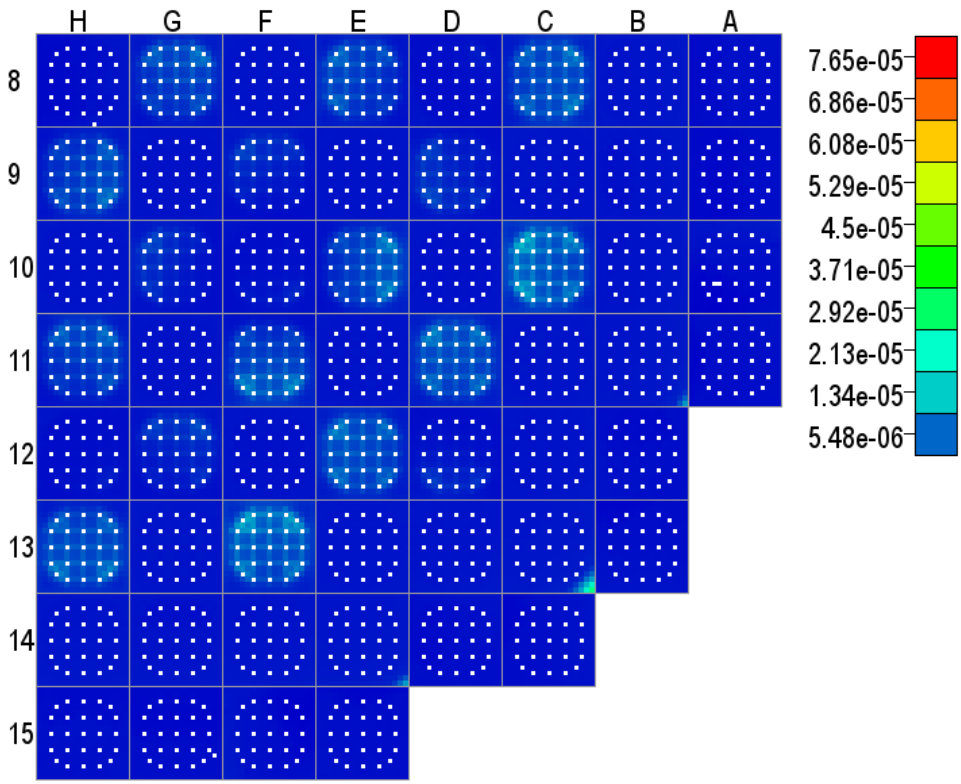

Fig. A.3.38. Cycle 3 minimum gap thickness (m) – 18.14 GWd/MT.

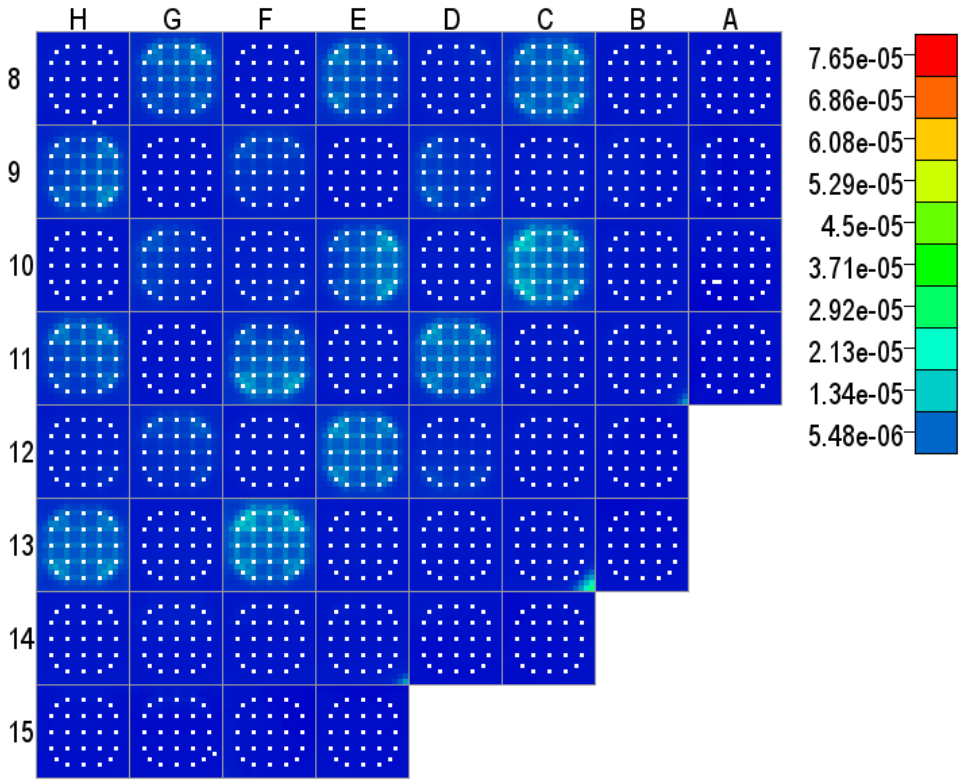

Fig. A.3.39. Cycle 3 minimum gap thickness (m) – 18.79 GWd/MT.

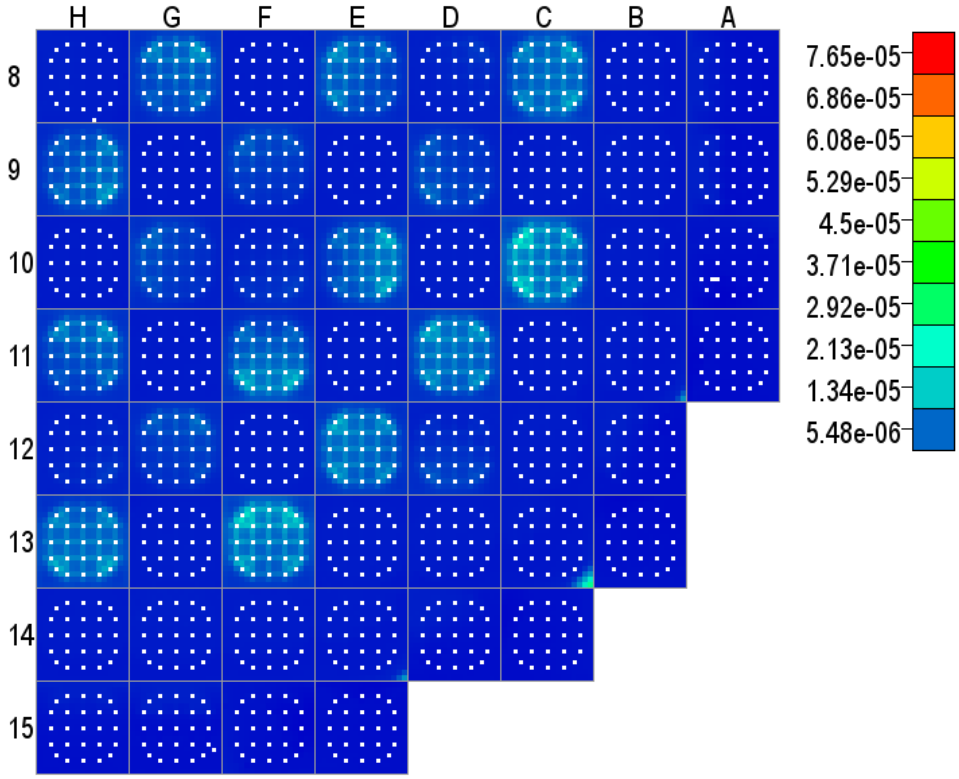

Fig. A.3.40. Cycle 3 minimum gap thickness (m) – 19.32 GWd/MT.

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.
# ================================================== #
# ================================================== #
# Global Parameters used throughout the input file
# ================================================== #
[GlobalParams]
  density =                                                    #VERA_DEFINED
  disp_x = disp_x
  disp_y = disp_y
  disp_r = disp_x
  disp_z = disp_y
  order = SECOND                                               #VERA_MODIFIABLE as globalparams_order
  family = LAGRANGE
  energy_per_fission = 3.2e-11    # J/fission                  #VERA_MODIFIABLE as globalparams_energy_per_fission
  a_lower =                                                    #VERA_DEFINED
  a_upper =                                                    #VERA_DEFINED
  initial_porosity =                                           #VERA_DEFINED (used in ./fuel_thermal and ./fission_gas_release)
[]
# ================================================== #
# Mesh (and Geometry, if internally-meshed)
# ================================================== #
[Mesh]
  displacements = 'disp_x disp_y'
  file =                                                       #BISON_CASL (conditionally included if mesh_file is specified)
  partitioner = centroid
  centroid_partitioner_direction = y
  patch_size = 10                                              #VERA_MODIFIABLE as mesh_patch_size
  patch_update_strategy = auto
  type = SmearedPelletMesh                                     # (omitted if file is specified)
  clad_mesh_density = customize                                # (omitted if file is specified)
  pellet_mesh_density = customize                              # (omitted if file is specified)
  clad_thickness =                                             #VERA_DEFINED (omitted if file is specified)
  pellet_outer_radius =                                        #VERA_DEFINED (omitted if file is specified)
  clad_bot_gap_height =                                        #VERA_DEFINED (omitted if file is specified)
  clad_top_gap_height =                                        #VERA_DEFINED (omitted if file is specified)
  pellet_quantity =                                            #VERA_DEFINED (omitted if file is specified)
  pellet_height =                                              #VERA_DEFINED (omitted if file is specified)
  clad_gap_width =                                             #VERA_DEFINED (omitted if file is specified)
  top_bot_clad_height =                                        #VERA_DEFINED (omitted if file is specified)
  nx_p =   6  # number of radial elements in the fuel          #VERA_MODIFIABLE as mesh_nx_p  (omitted if file is specified)
  ny_p = 100  # number of axial elements in the fuel           #VERA_MODIFIABLE as mesh_ny_p  (omitted if file is specified)
  nx_c =   3  # number of elements in the clad thickness       #VERA_MODIFIABLE as mesh_nx_c  (omitted if file is specified)
  ny_c = 100  # number of elements in the axially in the clad  #VERA_MODIFIABLE as mesh_ny_c  (omitted if file is specified)
  ny_cu = 1                                                    #VERA_MODIFIABLE as mesh_ny_cu (omitted if file is specified)
  ny_cl = 1                                                    #VERA_MODIFIABLE as mesh_ny_cl (omitted if file is specified)
  intervals =                                                  #VERA_DEFINED (omitted if file is specified)
  elem_type = QUAD8                                            #VERA_MODIFIABLE as mesh_elem_type (omitted if file is specified)
[]
# ================================================== #
# Dimensions and Primary Variables
# ================================================== #
[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                                  #VERA_MODIFIABLE as variables_temp_initial_condition
  [../]
[]
[SolidMechanics]
  [./solid]
    temp = temp
    save_in_disp_r = saved_x
    save_in_disp_z = saved_y
  [../]
[]
# ================================================== #
# Auxiliary Variables
# ================================================== #
[AuxVariables]
  [./saved_x]
  [../]
  [./saved_y]
  [../]
  [./saved_t]
  [../]
  # ================================================== #
  # Nodal Quantities
```

```
# ================================================ #

[./htcl]
  initial_condition = 500.0                                  #VERA_MODIFIABLE as auxvariables_htcl_initial_condition
[../]

[./htcv]
  initial_condition = 0.0                                    #VERA_MODIFIABLE as auxvariables_htcv_initial_condition
[../]
[./Tl]
  initial_condition = 565.0                                  #VERA_MODIFIABLE as auxvariables_Tl_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
  block = 1
[../]
```

```
  # ================================================== #
  # 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
    family = MONOMIAL
    initial_condition =                                          #VERA_DEFINED
  [../]
  [./gap_distance]
    order = CONSTANT
    family = MONOMIAL
    initial_condition =                                          #VERA_DEFINED
  [../]
[]
# ================================================== #
# Time- and Space-Dependent Source and BCs
# ================================================== #
[Functions]
  [./linear_heat_rate_profile]  #>> replaced power_history and power_profile
    type = PiecewiseLinear
    x = '-100 0 5000'                                            #VERA_MODIFIABLE as functions_linear_heat_rate_profile_x
    y = '0 0 25000'                                              #VERA_MODIFIABLE as functions_linear_heat_rate_profile_y
    data_file =                                                  #BISON_CASL as functions_linear_heat_rate_profile_data_file
    format = columns                                             #BISON_CASL as functions_linear_heat_rate_profile_format
    scale_factor = 1                                             #VERA_MODIFIABLE as functions_linear_heat_rate_profile_scale_factor
  [../]
  [./axial_peaking_factors]
    type =                                                       #TIAMAT/BISON_CASL as functions_axial_peaking_factors_type (defaults
to ParsedFunction if TIAMAT, PiecewiseBilinear if BISON_CASL (data_file necessary))
    value = 1                                                    #VERA_MODIFIABLE as functions_axial_peaking_factors_value for TIAMAT
    data_file =                                                  #VERA_MODIFIABLE as functions_axial_peaking_factors_data_file for
BISON_CASL
    axis = 1                                                     #BISON_CASL
    scale_factor = 1                                             #BISON_CASL
  [../]
  [./coolant_temperature]
    type = PiecewiseLinear                                       #VERA_MODIFIABLE as functions_coolant_temperature_type (defaults to
PiecewiseBilinear if BISON_CASL (data_file necessary))
    data_file = user_coolant_temp.csv                            #VERA_MODIFIABLE as functions_coolant_temperature_data_file (omitted
otherwise)
    x = '-100 0'                                                 #VERA_MODIFIABLE as functions_coolant_temperature_x (omitted if
data_file included)
    y = '293 565'                                                #VERA_MODIFIABLE as functions_coolant_temperature_y (omitted if
data_file included)
    axis = 1
  [../]
  [./coolant_pressure_ramp]                                      #>> CHECK: Should start at atmospheric, not Zero pressure
    # used in coolantPressure BC
    type = PiecewiseLinear
    scale_factor = 1
    x = '-100 0'                                                 #VERA_MODIFIABLE as functions_coolant_pressure_ramp_x
    y = '0 1.0'                                                  #VERA_MODIFIABLE as functions_coolant_pressure_ramp_y
  [../]
  [./q]
    type = CompositeFunction
    functions = 'linear_heat_rate_profile axial_peaking_factors' #VERA_MODIFIABLE as functions_q_functions
  [../]
[]
# ================================================== #
# Burnup Equation Set
# ================================================== #
[Burnup]
  [./burnup]
    block = 3
    rod_ave_lin_pow = linear_heat_rate_profile                  #VERA_MODIFIABLE as burnup_burnup_rod_ave_lin_pow
    axial_power_profile = axial_peaking_factors                 #VERA_MODIFIABLE as burnup_burnup_axial_power_profile
    num_radial = 80                                             #VERA_MODIFIABLE as burnup_burnup_num_radial
    num_axial = 100                                             #VERA_MODIFIABLE as burnup_burnup_num_axial
    fuel_inner_radius = 0.0                                     #VERA_MODIFIABLE as burnup_burnup_fuel_inner_radius
    fuel_outer_radius =                                         #VERA_DEFINED
    fuel_volume_ratio = 1.0                                     #VERA_MODIFIABLE as burnup_burnup_fuel_fuel_volume_ratio
    i_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
    RPF = RPF
  [../]
```

```
[]
# ==================================================== #
# Coolant Channel Equation Set (#COOLANT_FLOW)
# ==================================================== #
#[CoolantChannel]
#
#  [./convective_clad_surface]
#    boundary = '1 2 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            #VERA_MODIFIABLE as
coolantchannel_convective_clad_surface_linear_heat_rate_profile
#    axial_power_profile = axial_peaking_factors            #VERA_MODIFIABLE as
coolantchannel_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                               #CASL_MOOSE_MK_Source if TIAMAT, NeutronHeatSource if BISON_CASL
    fission_rate = fission_rate                            #BISON_CASL
    aux_var =                                              #TIAMAT sets to casl_fission_rate
    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                #VERA_MODIFIABLE as auxkernels_fast_neutron_flux_rod_ave_lin_pow
    axial_power_profile = axial_peaking_factors               #VERA_MODIFIABLE as
auxkernels_fast_neutron_flux_axial_power_profile
    factor = 4.29768x13 # (n/m2-s per W/m)                    #VERA_MODIFIABLE as auxkernels_fast_neutron_flux_factor
    execute_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                                       #VERA_MODIFIABLE as auxkernels_fuel_porosity_execute_on
  [../]

  [./grain_radius]
    type = GrainRadiusAux
    block = 3
    variable = grain_radius
    temp = temp
    execute_on = linear                                       #VERA_MODIFIABLE as auxkernels_grain_radius_execute_on
  [../]

  [./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
  variable = creep_strain_mag
  quantity = plasticstrainmag
  execute_on = timestep_begin                                   #VERA_MODIFIABLE as auxkernels_creep_strain_mag_execute_on
  # block = 1
[../]

[./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
  new_power_name = casl_new_fission_rate
  casl_time_values = casl_time_values
  multiplier = 1.0
  print_debug = false
  variable = casl_fission_rate
  execute_on = timestep_begin
[../]
[./casl_interpolated_clad_temp]
  type = CASL_MOOSE_AK_TimeInterpolatedCladTemperature
  old_clad_temp_name = casl_old_clad_temperature
  new_clad_temp_name = casl_new_clad_temperature
  casl_time_values = casl_time_values
  multiplier = 1.0
  print_debug = false
  variable = casl_clad_surface_temperature
  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                                                  # clad
    slave = 10                                                  # fuel
    penalty = 1e14                                              #VERA_MODIFIABLE as pellet_clad_mechanical_penalty
    normalize_penalty = true
    normal_smoothing_distance = 0.1                             #VERA_MODIFIABLE as pellet_clad_mechanical_normal_smoothing_distance
    model = frictionless                                        #VERA_MODIFIABLE as pellet_clad_mechanical_model
    formulation = kinematic                                     #VERA_MODIFIABLE as pellet_clad_mechanical_formulation
    system = Constraint                                         #VERA_MODIFIABLE as pellet_clad_mechanical_system (omitted otherwise)
 [../]
[]
[ThermalContact]
  [./thermal_contact]
    type = GapHeatTransferLWR
    variable = temp
    master = 5                                                  # clad
    slave = 10                                                  # fuel
    roughness_coef = 3.2                                        #VERA_MODIFIABLE as thermalcontact_roughness_coef
    roughness_fuel = 1.8e-06                                    #VERA_MODIFIABLE as thermalcontact_roughness_fuel
    roughness_clad = 8.0e-07                                    #VERA_MODIFIABLE as thermalcontact_roughness_clad
    jump_distance_model = KENNARD
    plenum_pressure = plenum_pressure
    contact_pressure = contact_pressure
    initial_moles = initial_moles
    initial_gas_fractions = '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-4                               #VERA_MODIFIABLE as thermalcontact_tangential_tolerance
    normal_smoothing_distance = 0.1
    quadrature = true                                           #VERA_MODIFIABLE as thermalcontact_quadrature
    order = SECOND                                              #VERA_MODIFIABLE as thermalcontact_order
  [../]
[]
[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                                             #VERA_MODIFIABLE as bcs_no_y_fuel_bottom_boundary
    value = 0.0
  [../]
  [./no_y_clad_bottom]
    type = DirichletBC
    variable = disp_y
    boundary = 1
    value = 0.0
  [../]
  [./clad_coolant_surface]
    type = ConvectiveFluxFunction                               #CASL_MOOSE_MK_AuxVarDirichletBC for TIAMAT and
ConvectiveFluxFunction for BISON_CASL
    coefficient = 1e5                                           #BISON_CASL
    coefficient_function = 1.0e6                                #BISON_CASL
    T_infinity = coolant_temperature                            #BISON_CASL
    aux_var = 'casl_clad_surface_temperature'                   #TIAMAT
    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                                        #VERA_DEFINED
      function = coolant_pressure_ramp                          #VERA_MODIFIABLE as bcs_pressure_coolantpressue_function
    [../]
  [../]
  [./PlenumPressure]
    # apply plenum pressure on clad inner walls and pellet surfaces
    [./plenumPressure]
      boundary = '9'                                            #VERA_MODIFIABLE as bcs_plenumpressure_plenumpressure_boundary
      initial_pressure = <!whited_out!>                        #VERA_MODIFIABLE as bcs_plenumpressure_plenumpressure_initial_pressure
      startup_time = 0                                          #VERA_MODIFIABLE as bcs_plenumpressure_plenumpressure_startup_time
      R = 8.314462
      output_initial_moles = initial_moles   # coupling to post processor to get initial fill gas mass
      temperature = ave_temp_interior        # coupling to post processor to get temperature for plenum gas
      volume = gas_volume                    # coupling to post processor to get gas volume
      material_input = fis_gas_released      # coupling to post processor to get fission gas added
      output = plenum_pressure               # coupling to post processor to output plenum/gap pressure
    [../]

  [../]
```

```
  #>> 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
# ================================================== #
[Materials]
  [./fuel_thermal]
    type = UO2Therm
    block = 3
    temp = temp
    burnup = burnup
  [../]

  [./fuel_swelling]
    type = VSwellingUO2
    block = 3
    temp = temp
    burnup = burnup
    total_densification = 0.005                                 #VERA_MODIFIABLE as materials_fuel_swelling_total_densification
  [../]

  [./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                                     #VERA_MODIFIABLE as materials_fuel_mech_grain_radius
    oxy_to_metal_ratio = 2.0
    max_its =                                                   #VERA_MODIFIABLE as materials_fuel_mech_max_its (omitted otherwise)
    output_iteration_info = false                               #VERA_MODIFIABLE as materials_fuel_mech_output_iteration_info
    model_thermal_expansion = true
    model_swelling = true                                       #VERA_MODIFIABLE as materials_fuel_mech_model_swelling
    name_swelling_model = fuel_swelling                         #VERA_MODIFIABLE as materials_fuel_mech_name_swelling_model (omitted
otherwise)
    model_relocation = true
    name_relocation_model = fuel_relocation
    model_creep = false                                         #VERA_MODIFIABLE as materials_fuel_mech_model_creep
    matpro_youngs_modulus = true                                #VERA_MODIFIABLE as materials_fuel_mech_matpro_youngs_modulus
    matpro_poissons_ratio = true
    dep_matl_props = deltav_v0_bd
  [../]

  [./fuel_relocation]
    type = RelocationUO2
    model = ESCORE
    block = 3
    burnup = burnup
    q = q                                                       #VERA_MODIFIABLE as materials_fuel_relocation_q
    diameter = 0.008192                                         #VERA_DEFINED
    gap = 0.000168                                              #VERA_DEFINED
    relocation_activation1 = 16404                              #VERA_MODIFIABLE as materials_fuel_relocation_relocation_activation1
    burnup_relocation_stop = 0.03                               #VERA_MODIFIABLE as materials_fuel_relocation_burnup_relocation_stop
  [../]

  [./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                                  #VERA_MODIFIABLE as materials_clad_solid_mechanics_absolute_tolerance
    relative_tolerance = 1e-5                                   #VERA_MODIFIABLE as materials_clad_solid_mechanics_relative_tolerance
(omitted if BISON_CASL)
    stress_free_temperature = 523                               #VERA_MODIFIABLE as
materials_clad_solid_mechanics_stress_free_temperature (omitted if BISON_CASL)
    model_primary_creep = true                                  #VERA_MODIFIABLE as
materials_clad_solid_mechanics_model_primary_creep (omitted otherwise)
    model_thermal_creep = true                                  #VERA_MODIFIABLE as
materials_clad_solid_mechanics_model_thermal_creep (omitted otherwise)
    model_irradiation_creep = true                              #VERA_MODIFIABLE as
materials_clad_solid_mechanics_model_irradiation_creep (omitted otherwise)
    model_irradiation_growth = true                             #VERA_MODIFIABLE as
materials_clad_solid_mechanics_model_irradiation_growth
    model_thermal_expansion = true                              #VERA_MODIFIABLE as
materials_clad_solid_mechanics_model_thermal_expansion
    output_iteration_info = false
    model_elastic_modulus = true                                #VERA_MODIFIABLE as
materials_clad_solid_mechanics_model_elastic_modulus
```

```
    cold_work_factor = 4.812700e-02                              #VERA_MODIFIABLE as materials_clad_solid_mechanics_cold_work_factor
(omitted otherwise)
    oxygen_concentration = 0.0                                   #VERA_MODIFIABLE as
materials_clad_solid_mechanics_oxygen_concentration (omitted otherwise)
  [../]

  [./fission_gas_release]
    type = Sifgrs
    axial_power_profile = axial_peaking_factors                  #VERA_MODIFIABLE as materials_fission_gas_release_axial_power_profile
(omitted otherwise)
    block = 3
    burnup = burnup
    fission_rate = casl_fission_rate                             #casl_fission_rate with TIAMAT, fission rate with BISON_CASL
    grain_radius = grain_radius                                  #VERA_MODIFIABLE as materials_fission_gas_release_grain_radius
    hydrostatic_stress =                                         #VERA_MODIFIABLE as materials_fission_gas_release_hydrostatic_stress
(omitted otherwise)
    pellet_brittle_zone =                                        #VERA_MODIFIABLE as materials_fission_gas_release_pellet_brittle_zone
(omitted otherwise)
    pellet_id =                                                  #VERA_MODIFIABLE as materials_fission_gas_release_pellet_id (omitted
otherwise)
    rod_ave_lin_pow =                                            #VERA_MODIFIABLE as materials_fission_gas_release_rod_ave_lin_pow
(omitted otherwise)
    temp = temp
  [../]

  [./clad_density]
    type = Density
    block = 1
    density = 6551.0                                             #VERA_DEFINED or VERA_MODIFIABLE as materials_clad_density_density
  [../]
  [./fuel_density]
    type = Density
    block = 3
  [../]
[]
# ===================================================== #
# 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 =                                              #VERA_DEFINED
    number_pellets = 1
    execute_on = linear                                          #VERA_MODIFIABLE as userobjects_pbz_execute_on
  [../]
  [./casl_average_fission_rate]
    variable = casl_fission_rate                                 #casl_fission_rate with TIAMAT, fission rate with BISON_CASL
    type = LayeredAverage
    block = 3
    direction = y
    bounds =                                                     #VERA_DEFINED
  [../]

  [./surface_temp]
    type = LayeredSideAverage
    boundary = 2
    variable = temp
    direction = y
    bounds =                                                     #VERA_DEFINED
    use_displaced_mesh = 0
  [../]

  [./axial_fission_rate]
    type = LayeredAverage
    block = 3
    variable = fission_rate
    direction = y
    bounds =                                                     #VERA_DEFINED
  [../]
  [./axial_temperature]
    type = LayeredAverage
    block = 3
    variable = temp
    direction = y
    bounds =                                                     #VERA_DEFINED
  [../]
  [./axial_burnup]
    type = LayeredAverage
    block = 3
    variable = burnup
    direction = y
    bounds =                                                     #VERA_DEFINED
  [../]
  [./axial_surface_temperature]
    type = LayeredSideAverage
    boundary = 2
    variable = temp
    direction = y
    bounds =                                                     #VERA_DEFINED
    use_displaced_mesh = 0
  [../]
```

```
  [./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 =                                                    #VERA_DEFINED
    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                                        #VERA_MODIFIABLE as dampers_limitt_max_increment
    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 -ksp_gmres_restart'  #VERA_MODIFIABLE as
executioner_petsc_options_iname #RECOMMENDED BY DANIELLE
  petsc_options_value = 'lu       superlu_dist                 51'                  #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                                               #VERA_MODIFIABLE as executioner_l_max_its
  l_tol = 8e-3                                                  #VERA_MODIFIABLE as executioner_l_tol
  # controls for nonlinear iterations
  nl_max_its = 15                                               #VERA_MODIFIABLE as executioner_nl_max_its
  nl_rel_tol = 0.0001                                           #VERA_MODIFIABLE as executioner_nl_rel_tol
  nl_abs_tol = 1e-10                                            #VERA_MODIFIABLE as executioner_nl_abs_tol

  # ================================================== #
  # Time Step Control
  # ================================================== #
  start_time = -100                                             #VERA_MODIFIABLE as executioner_start_time
  end_time   = 6e+07                                            #VERA_PREPARED as executioner_end_time
  num_steps  = 1                                                #VERA_PREPARED as executioner_num_steps (omitted if BISON_CASL)
  dtmax      =                                                  #VERA_MODIFIABLE as executioner_dtmax (omitted otherwise)
  dtmin      =                                                  #VERA_MODIFIABLE as executioner_dtmin (omitted otherwise)
  [./TimeStepper]
    type = IterationAdaptiveDT                                  #IterationAdaptiveDT with TIAMAT, FunctionDT with BISON_CASL
    dt = 100.0                                                  #TIAMAT or as executioner_timestepper_dt
    optimal_iterations = 1000                                   #TIAMAT or as executioner_optimal_iterations
    linear_iteration_ratio = 100                                #TIAMAT or as executioner_timestepper_linear_iteration_ratio
    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. QUAD8 in 2D-RZ)
  [./Quadrature]
    order = FIFTH                                               #VERA_MODIFIABLE as executioner_quadrature_order
    side_order = SEVENTH
  [../]

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

```
[./fis_gas_released]
  type = ElementIntegralFisGasReleasedSifgrs
  variable = temp
  block = 3
  outputs = 'exodus'
[../]
[./gas_volume]
  type = InternalVolume
  boundary = 9
  execute_on = linear
  outputs = 'exodus'
[../]

[./fis_gas_grain]
  type = ElementIntegralFisGasGrainSifgrs
  variable = temp
  block = 3
  outputs = exodus
[../]

[./fis_gas_boundary]
  type = ElementIntegralFisGasBoundarySifgrs
  variable = temp
  block = 3
  outputs = exodus
[../]
# ================================================== #
# Output-Only: Fission Gas Release Data
# ================================================== #
[./average_grain_radius]
  type = ElementAverageValue
  block = 3
  outputs = 'exodus'
  variable = grain_radius
[../]
[./clad_inner_vol]
  type = InternalVolume
  boundary = 7
  outputs = 'exodus'
[../]
[./pellet_volume]
  type = InternalVolume
  boundary = 8
  outputs = 'exodus'
[../]
[./avg_clad_temp]
  type = SideAverageValue
  boundary = 7
  variable = temp
  outputs = 'exodus'
[../]
[./fis_gas_produced]
  type = ElementIntegralFisGasGeneratedSifgrs
  variable = temp
  block = 3
  outputs = 'exodus'
[../]
# ================================================== #
# Output-Only: Gap-Conductance Related
# ================================================== #
[./flux_from_clad]
  type = SideFluxIntegral
  variable = temp
  boundary = 5
  diffusivity = thermal_conductivity
  outputs = 'exodus'
[../]
[./flux_from_fuel]
  type = SideFluxIntegral
  variable = temp
  boundary = 10
  diffusivity = thermal_conductivity
  outputs = 'exodus'
[../]
# ================================================== #
# Output-Only: Solver Related
# ================================================== #
[./_dt]
  type = TimestepSize
  outputs = 'exodus'
[../]
[./nonlinear_its]
  type = NumNonlinearIterations
  outputs = 'exodus'
[../]
[./linear_its] # number of nonlinear iterations at each timestep
  type = NumLinearIterations
[../]
# ================================================== #
# Output-Only: Power
# ================================================== #

[./rod_average_fuel_temp]
   type =  ElementAverageValue
   block = 3
   variable = temp
[../]
[./rod_total_power]
  type = ElementIntegralPower
  variable = temp
```

```
    fission_rate = casl_fission_rate                          #casl_fission_rate with TIAMAT, fission_rate with BISON_CASL
    block = 3
  [../]
  [./rod_input_power]
    # Watts
    type = FunctionValuePostprocessor
    function = linear_heat_rate_profile
    scale_factor = 3.6576 # rod height                        #VERA_DEFINED
  [../]
  [./average_fission_rate]
    type = AverageFissionRate
    rod_ave_lin_pow = linear_heat_rate_profile
    outputs = 'exodus'
  [../]
  # ================================================== #
  # Tiamat: Conservation of Energy (#TIAMAT)
  # ================================================== #

  [./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
  [../]
  # ================================================== #
  # PCI Indicators
  # ================================================== #
  [./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
    block = 1
    variable = temp
  [../]

  [./min_clad_temp]
    type = ElementExtremeValue
    value_type = MIN
    block = 1
    variable = temp
  [../]
  [./CDI]
    type = ElementAverageValue
    variable = cumulative_damage_index
    outputs = 'csv'
  [../]
  [./burnup]
    type = ElementAverageValue
    variable = burnup
  [../]

[]
# ================================================== #
# Location and format of output
# ================================================== #
[Outputs]
  output_initial = true
  csv = true
  exodus = true
  file_base =                                                 #BISON_CASL as outputs_file_base (omitted otherwise)
  interval = 1
  [./console]
```

```
    type = Console
    perf_log = true
    max_rows = 25
    output_linear = false
    output_nonlinear = false
  [../]
[]
# ================================================== #
# Debug Output
# ================================================== #
[Debug]
#  show_var_residual_norms = true
#  show_var_residual = 'disp_x disp_y temp'
[]
# ================================================== #
# Use of this input template
# ================================================== #
#
# This is a VERA input template for Bison-CASL.
#
# A VERA input file (input.vera) can be used to produce
# a VERA xml input file (input.xml) using the VERAIn
# script:
#
# > VERA/VERAIn/verain/scripts/react2xml.pl input.vera input.xml
#
# The xml2moose preprocessors can be used to produce
# Bison-CASL input files using the xml input (input.xml)
# and a template (defined in input.vera):
#
# > BUILD/MOOSE/xml2moose -c input
#
# Currently, xml2moose generates an input for use with
# Tiamat, which assumes that power-history comes from
# the Neutronics code, clad surface temperature comes
# from Cobra-TF, the average fuel temperature on the
# axial_edit_bounds computed for passing to the
# Neutronics code, and the average heat flux on the
# clad outer surface at the axial_edit_bounds must be
# computed for passing to Cobra-TF.
#
# In the near future, xml2moose will have additional
# options to modify this input to support:
#
# - 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 bulk-coolant 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:
#   -- Zircalloy
#   -- 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.
#
# ================================================== #
```