Assessment of Pellet-Clad Interaction Indicators in Watts Bar Unit 1, Cycles 1-3 Using VERA

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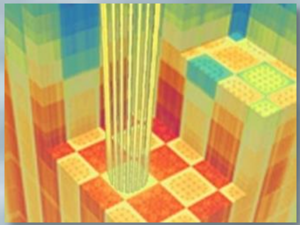
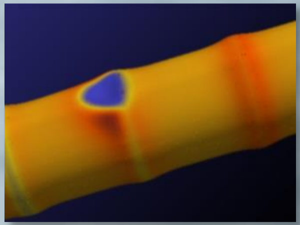
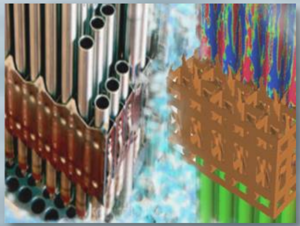




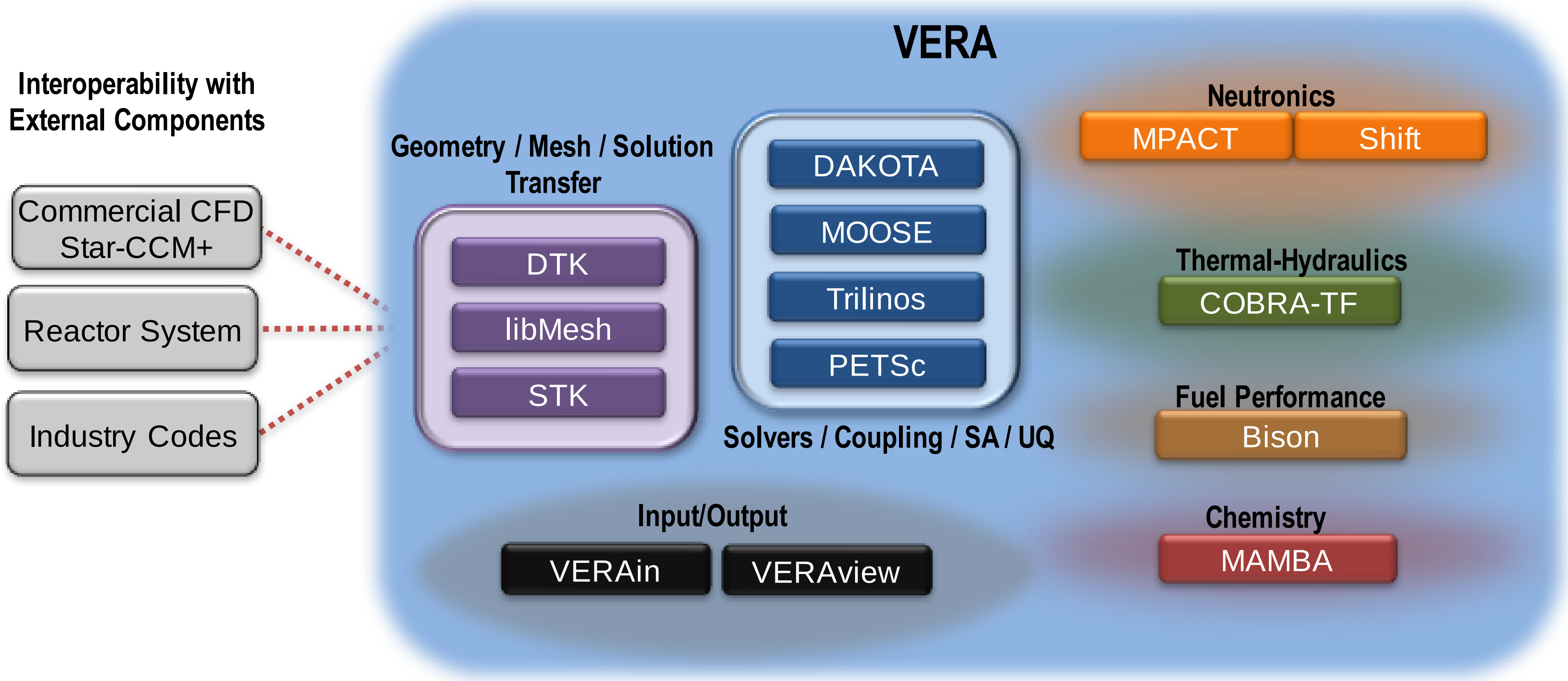
CASL The Consortium for Advanced Simulation of LWRs
A DOE Energy Innovation Hub

U.S. DEPARTMENT OF ENERGY

Outline

- Motivation
  – What is VERA?
  – Why do we want to use BISON?
- Generating BISON Input Files
  – BISON Template File
  – XML2MOOSE Preprocessor
  – Input Data from VERA-CS
  – Output Data Available from BISON
- Watts Bar Unit 1
- Results
- Conclusions and Future Work

What is VERA?



Interoperability with External Components
Commercial CFD Star-CCM+
Reactor System
Industry Codes
VERA
Geometry / Mesh / Solution Transfer
DTK
libMesh
STK
DAKOTA
MOOSE
Trilinos
PETSc
Solvers / Coupling / SA / UQ
Neutronics
MPACT
Shift
Thermal-Hydraulics
COBRA-TF
Fuel Performance
Bison
Chemistry
MAMBA
Input/Output
VERAin
VERAview

Motivation

- Why are we using BISON (INL)?
  - More attention to additional physics with MPACT/CTF becoming more mature
  - Provides high-fidelity, finite element-based fuel performance simulations built on the MOOSE framework [1,2]
    - Swelling, densification, relocation, gap closure, etc.
    - Provides insights into fuel behavior that VERA-CS does not directly take into account
  - Already being used in several applications within CASL:
    - Tiamat provides fully coupled simulations with MPACT/CTF/BISON [3,4]
    - Is being used to generate more accurate fuel temperatures for VERA-CS
    - Ongoing work to tackle the pellet-clad interaction (PCI) challenge problem
- The work covered here pertains to streamlining standalone BISON usability
  - Generate individual BISON cases for each rod using VERA-CS neutronics/TH output
  - Potentially as a screening tool for further analysis
  - This is not considered BISON V&V
    - Merely showing one of the directions being pursued in CASL

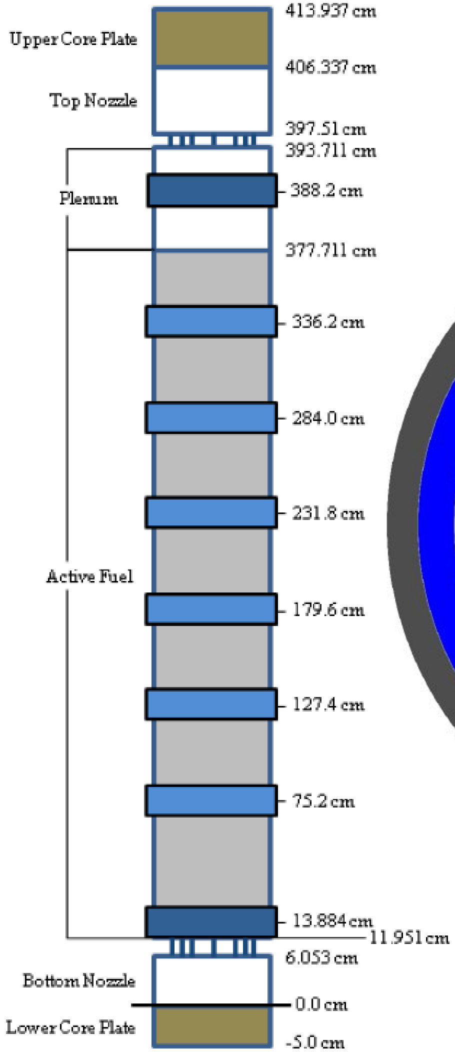
Generating BISON Inputs

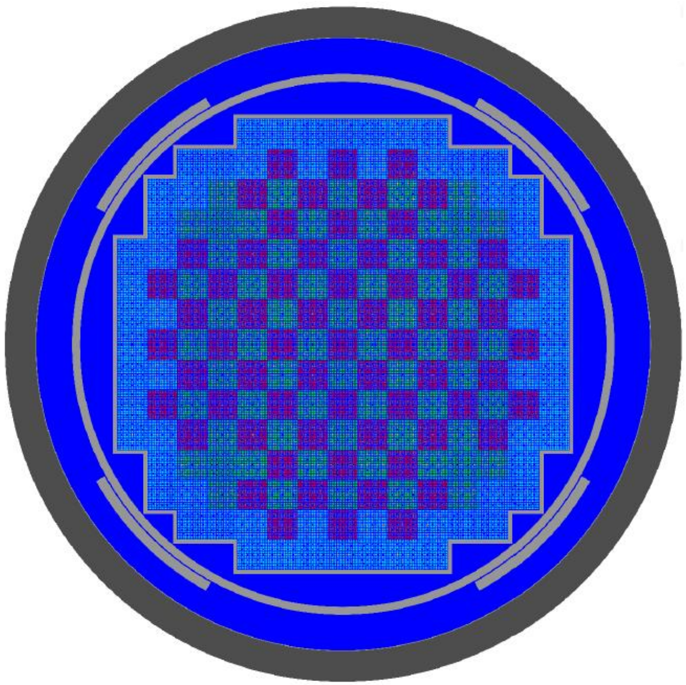
- VERA simulations start of an ASCII input file, which is converted to XML
- The XML2MOOSE preprocessor creates an input for each rod
  - Uses a BISON template as the starting point
  - Updates the values in the template based on the parameters in the extended markup language (XML) file
  - Reads the VERA-CS output hierarchical data format (HDF5) file and populates input files that BISON can process
    - Normalized Axial Power Distribution
    - Rod Power History
    - Moderator Temperature Distribution
  - Shuffles fuel as appropriate by linking up data

Output Data

- BISON outputs a CSV and an EXODUS file
- CSV
  - typically Max/Min/Avg quantities of interest
    - Max/Min/Avg Fuel/Clad Temperature
    - Max/Min Clad Hoop Stress
    - Min. Gap Thickness
    - Rod Power, Burnup, Internal Pressure
- EXODUS
  - more finely resolved data (such as axial distributions)
  - more complicated to access (currently in progress)
- A postprocessor has been developed that reads appropriate data from the CSV file and consolidates that data onto the HDF5 file produced by VERA-CS
- This can then be visualized with VERAView

Watts Bar Unit 1 [5]





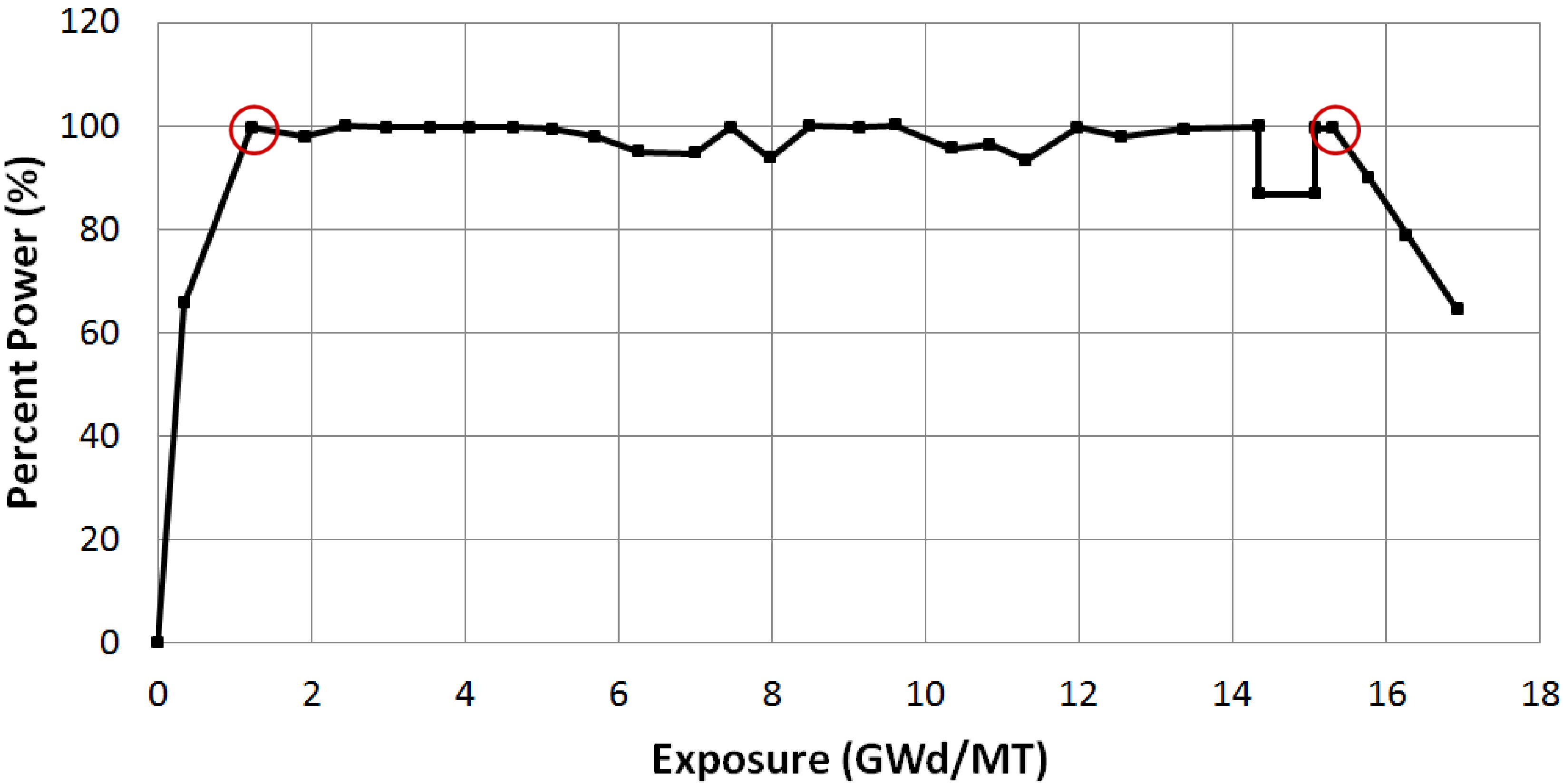
- Began operating in 1996
- Operating 14th cycle now
- 3,411 MWth with 1.4% uprate in 2001
- 193 Westinghouse fuel assemblies
  - 17x17
    - 264 fuel rods
    - 25 guide/instrumentation
  - 12' tall
- 8 spacer grids
  - 2 Inconel
  - 6 Zircaloy
- Cycles 1-12 have been simulated with VERA-CS
  - Tomorrow Morning 8 am

Cycle 1 Core Layout and Rod Banks

	H	G	F	E	D	C	B	A
8	2.1	2.6 20	2.1	2.6 20	2.1	2.6 20	2.1	3.1 12
9	2.6 20	2.1	2.6 24	2.1	2.6 20	2.1	3.1 24	3.1
10	2.1	2.6 24	2.1	2.6 20	2.1	2.6 16	2.1	3.1 8
11	2.6 20	2.1	2.6 20	2.1	2.6 20	2.1	3.1 16	3.1
12	2.1	2.6 20	2.1	2.6 20	2.6	2.6 24	3.1	
13	2.6 20	2.1	2.6 16	2.1	2.6 24	3.1 12	3.1	
14	2.1	3.1 24	2.1	3.1 16	3.1	3.1		
15	3.1 12	3.1	3.1 8	3.1	Enrichment Number of Pyrex Rods			

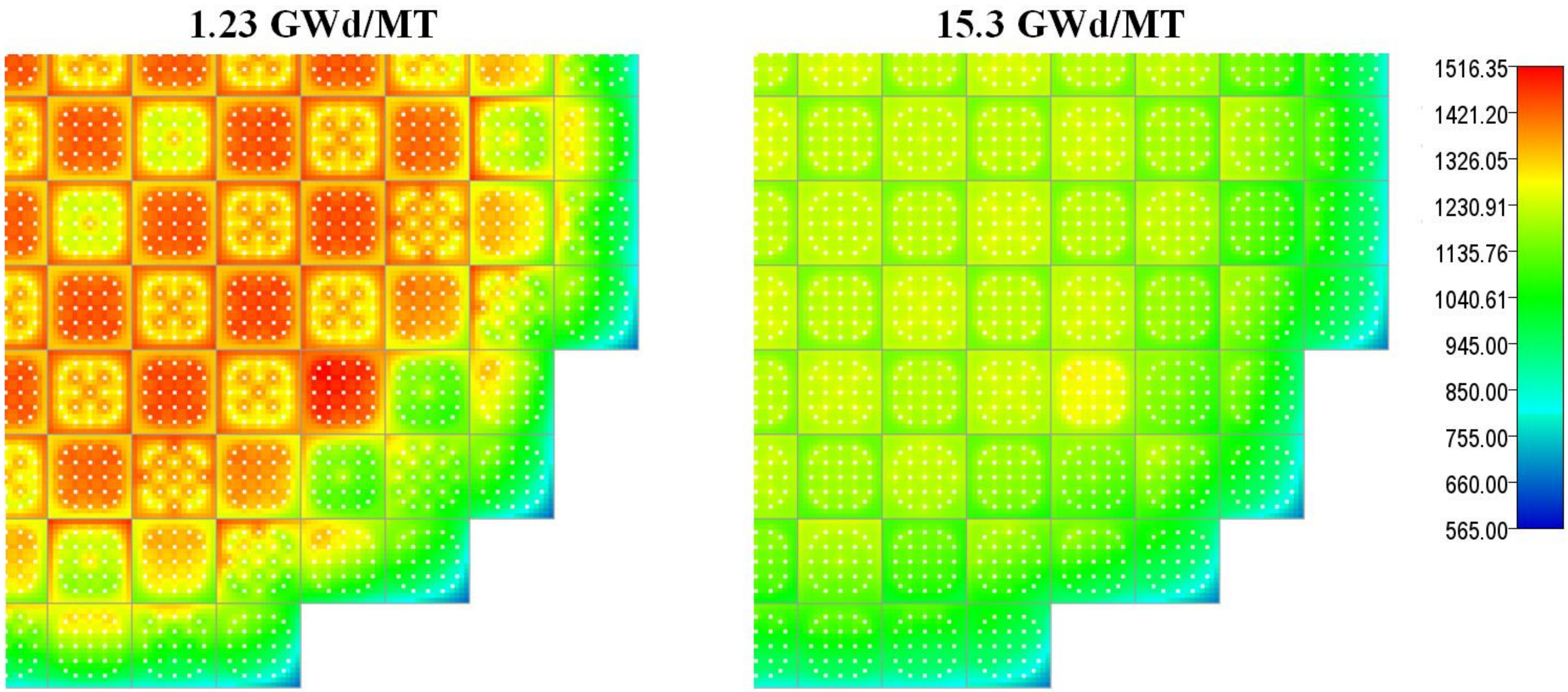
	H	G	F	E	D	C	B	A
8	D		A		D		C	
9						SB		
10	A		C				B	
11				A		SC		
12	D				D		SA	
13		SB		SD				
14	C		B		SA			
15								

Cycle 1 Power History



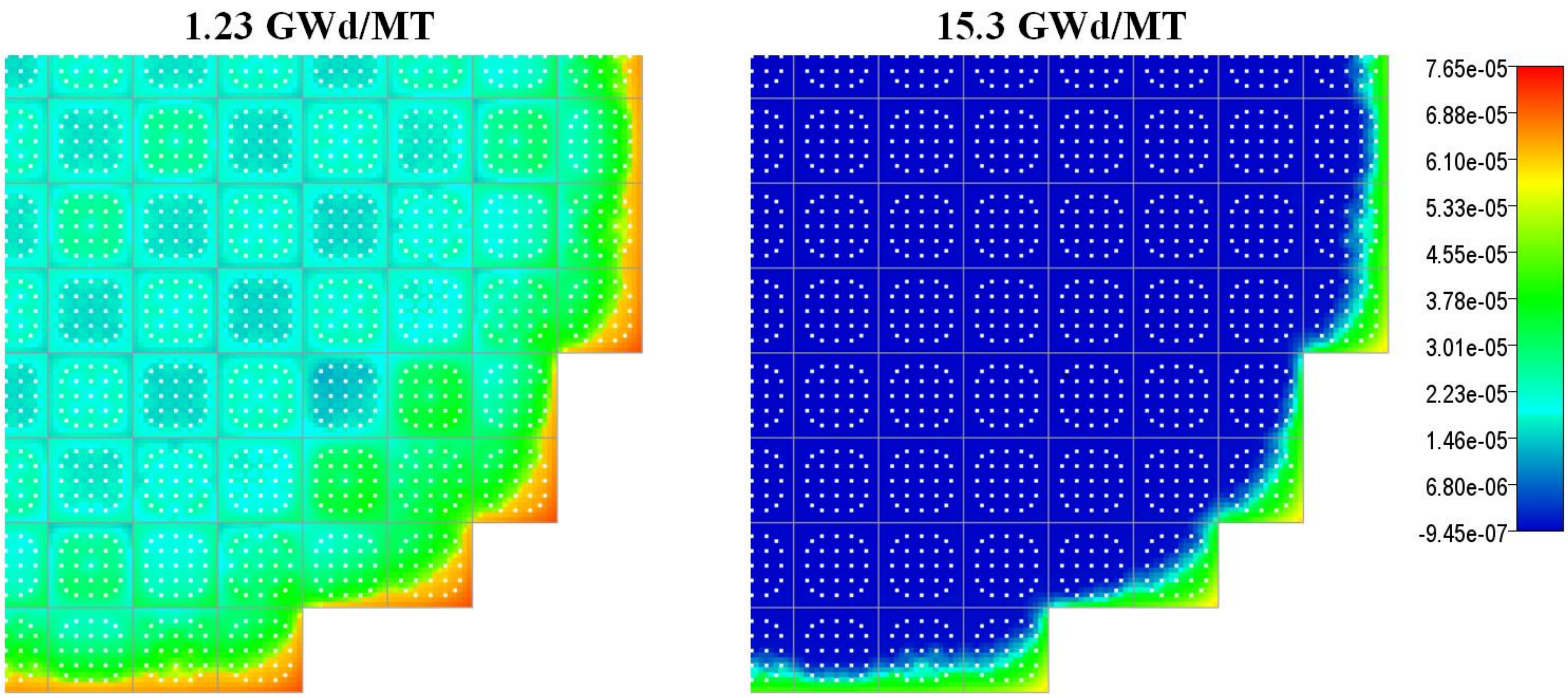
Results – Cycle 1

Maximum Centerline Fuel Temperature (K)



Results – Cycle 1

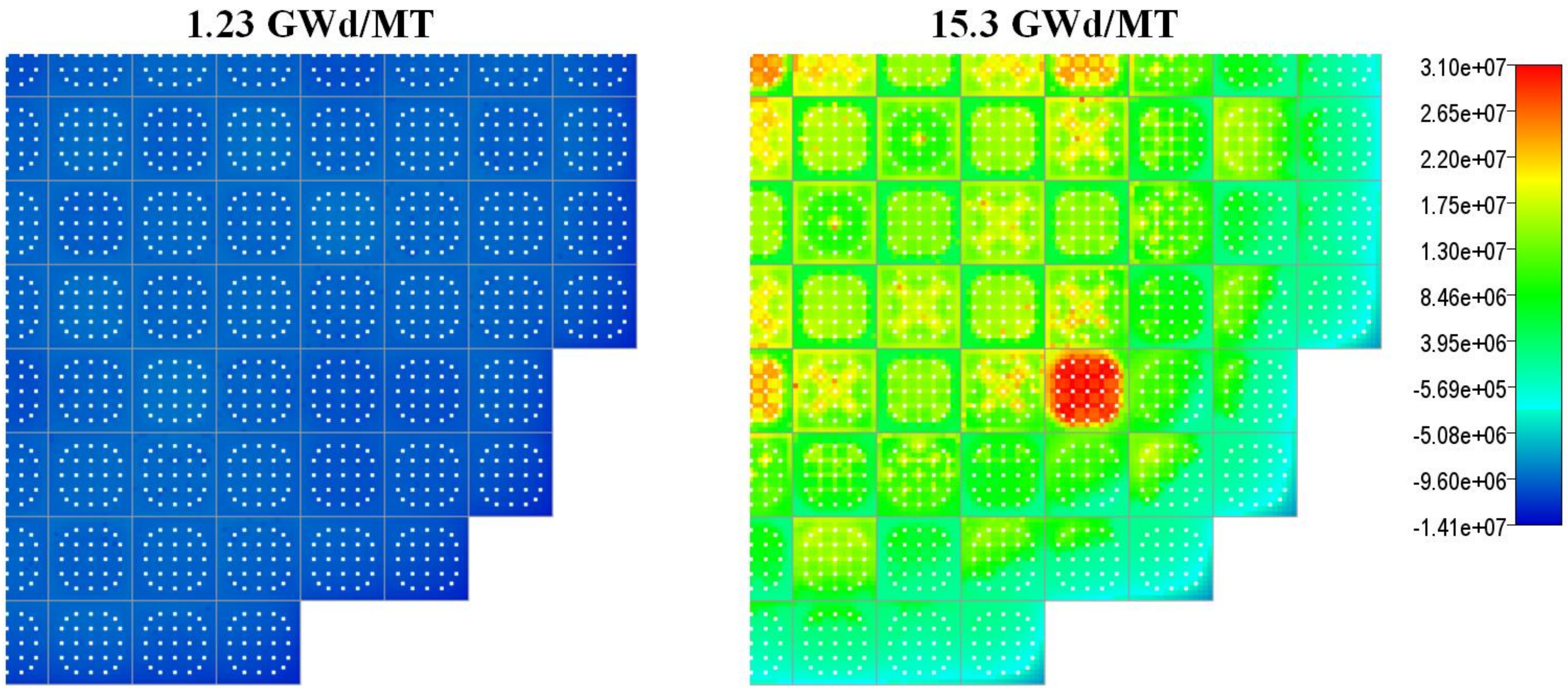
Minimum Gap Thickness (m)



Negative gap thickness indicate mesh overlap in BISON

Results – Cycle 1

Maximum Clad Hoop Stress (Pa)



Stress spiking after coming back to full power, though values are still low

Cycle 2 Core Layout

<table>
<tr><th></th><th>H</th><th>G</th><th>F</th><th>E</th><th>D</th><th>C</th><th>B</th><th>A</th></tr>
<tr><td>8</td><td>H-14</td><td>N-13</td><td>128*</td><td>R-8</td><td>128</td><td>N-8</td><td>L-15</td><td>F-11</td></tr>
<tr><td>9</td><td>N-3</td><td>104</td><td>A-9</td><td>104 | 8</td><td>B-11</td><td>128*</td><td>48</td><td>C-4</td></tr>
<tr><td>10</td><td>128*</td><td>G-15</td><td>E-15</td><td>D-7</td><td>104 | 8</td><td>B-7</td><td>48</td><td>G-10</td></tr>
<tr><td>11</td><td>H-1</td><td>104 | 8</td><td>J-12</td><td>128*</td><td>N-2</td><td>128</td><td>48</td><td>F-13</td></tr>
<tr><td>12</td><td>128</td><td>E-14</td><td>104 | 8</td><td>P-3</td><td>A-6</td><td>104 | 4</td><td>B-4</td><td></td></tr>
<tr><td>13</td><td>H-3</td><td>128*</td><td>J-14</td><td>128</td><td>104 | 4</td><td></td><td>P-6</td><td></td></tr>
<tr><td>14</td><td>R-5</td><td>48</td><td>48</td><td>48</td><td>M-14</td><td>K-2</td><td></td><td></td></tr>
<tr><td>15</td><td>L-10</td><td>M-13</td><td>F-9</td><td>C-10</td><td colspan="4">IFBA | WABA or
Previous Cycle 1 Location</td></tr>
</table>

* 132 inch IFBA (All others 120 inch)

Batch 1 - 2.11%

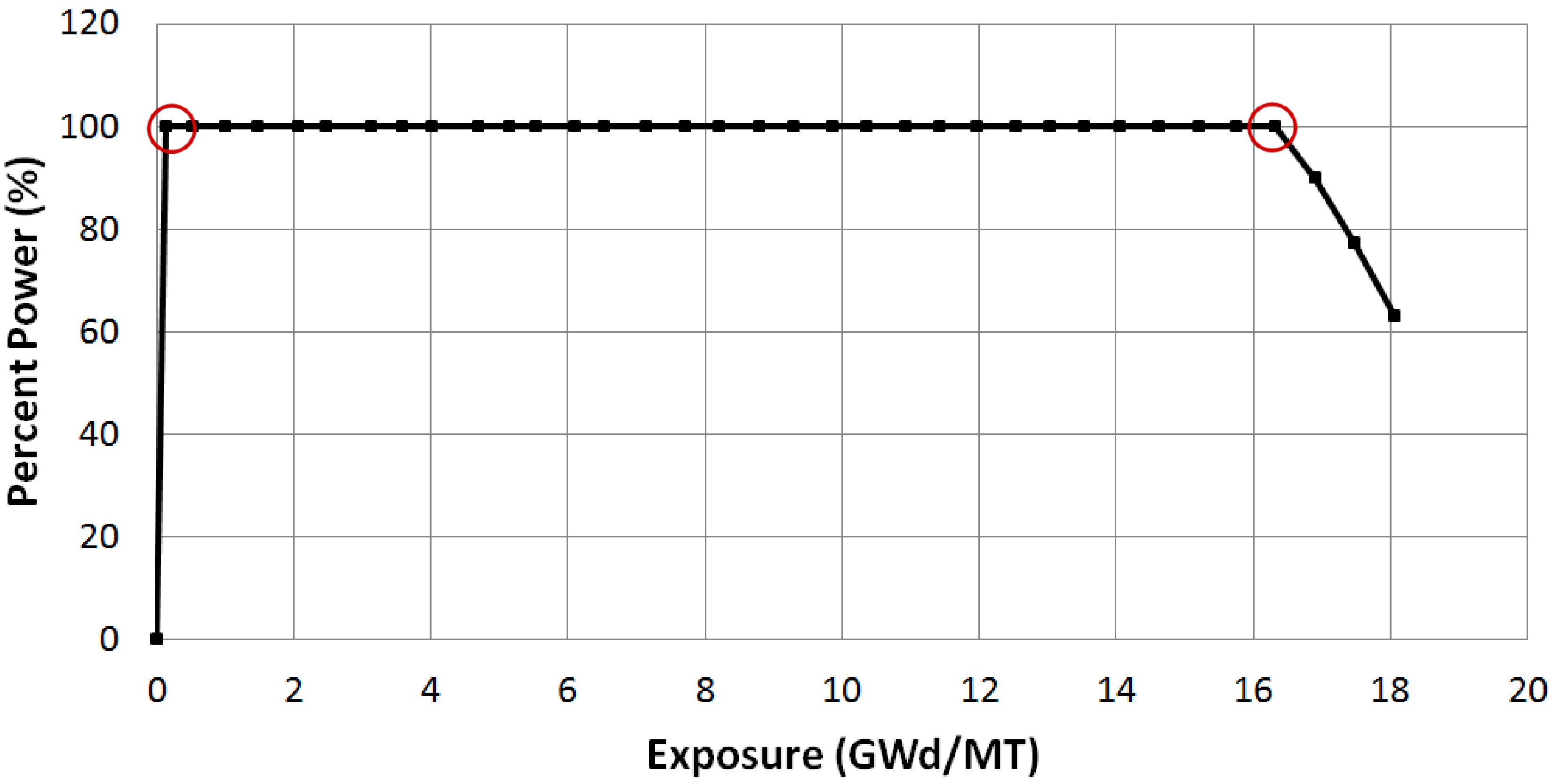
Batch 2 - 2.619%

Batch 3 - 3.1%

Batch 4 - 3.709%

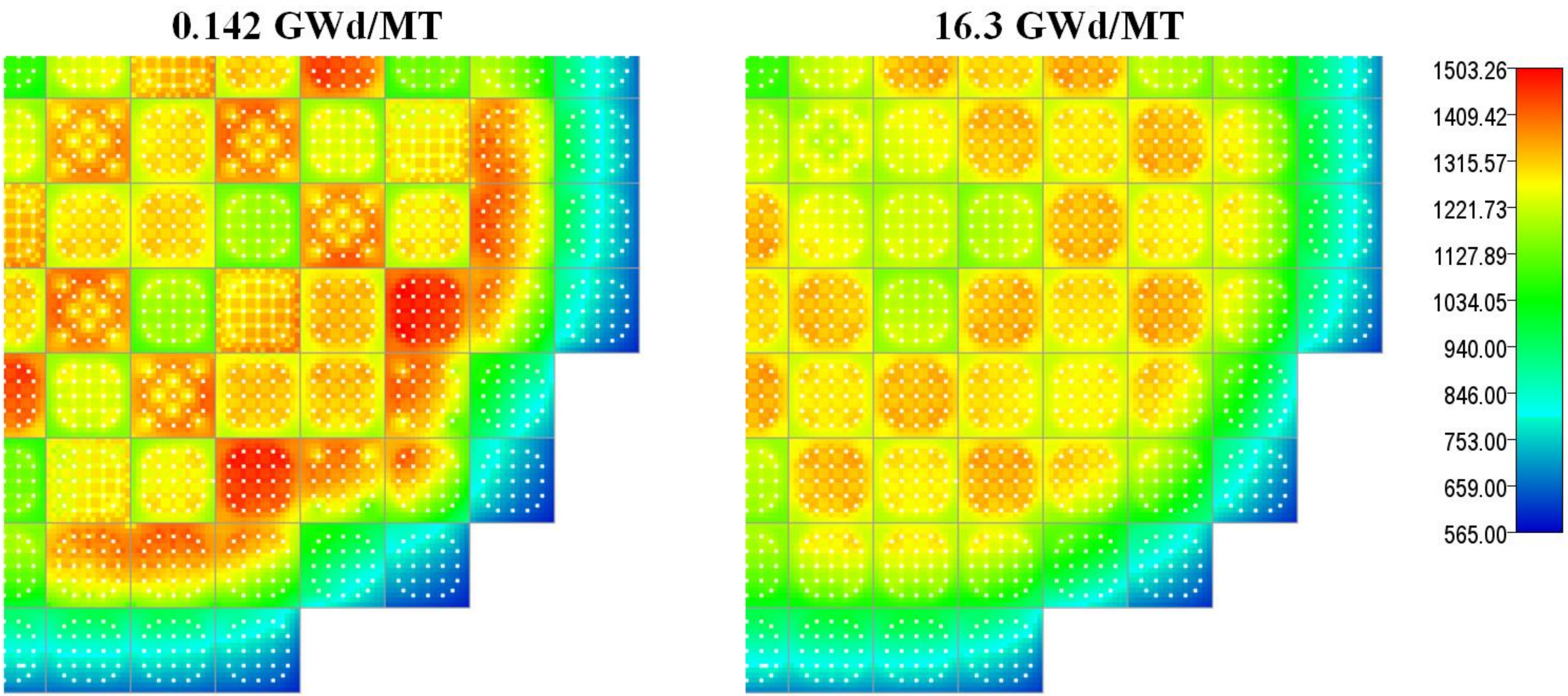
NOTE: These results were obtained before IFBA capability (He production) was available in BISON (as of March 2016). Ongoing and future analysis includes IFBA.

Cycle 2 Power History



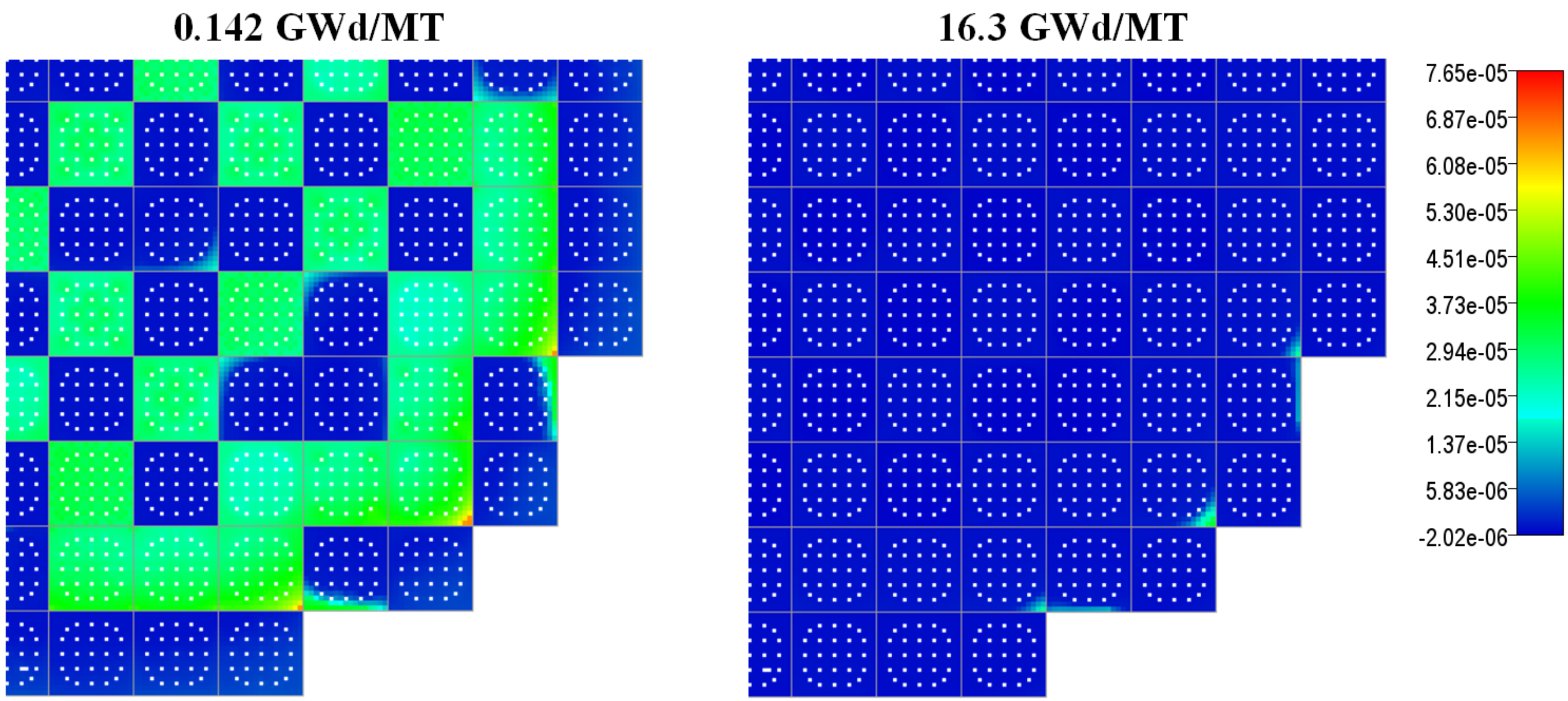
Results – Cycle 2

Maximum Centerline Fuel Temperature (K)



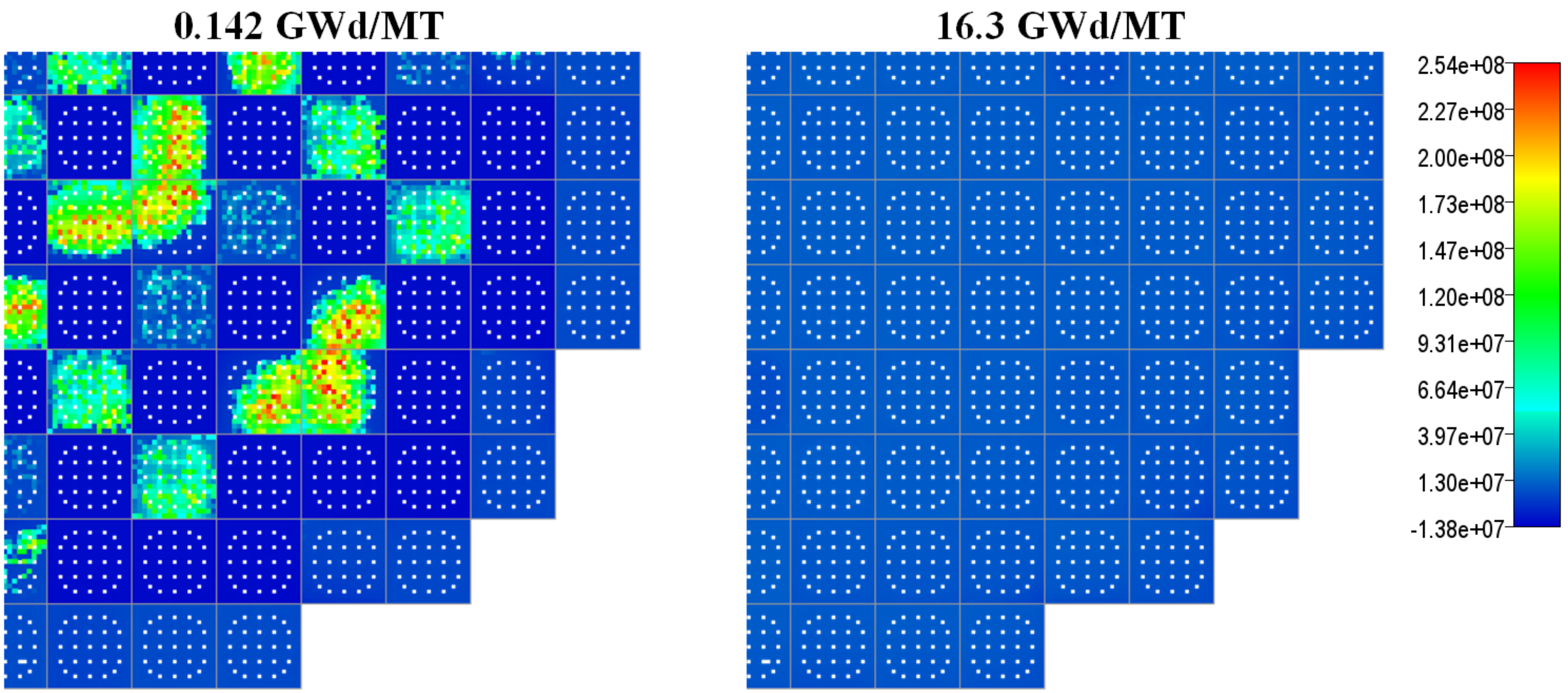
Results – Cycle 2

Minimum Gap Thickness (m)



Results – Cycle 2

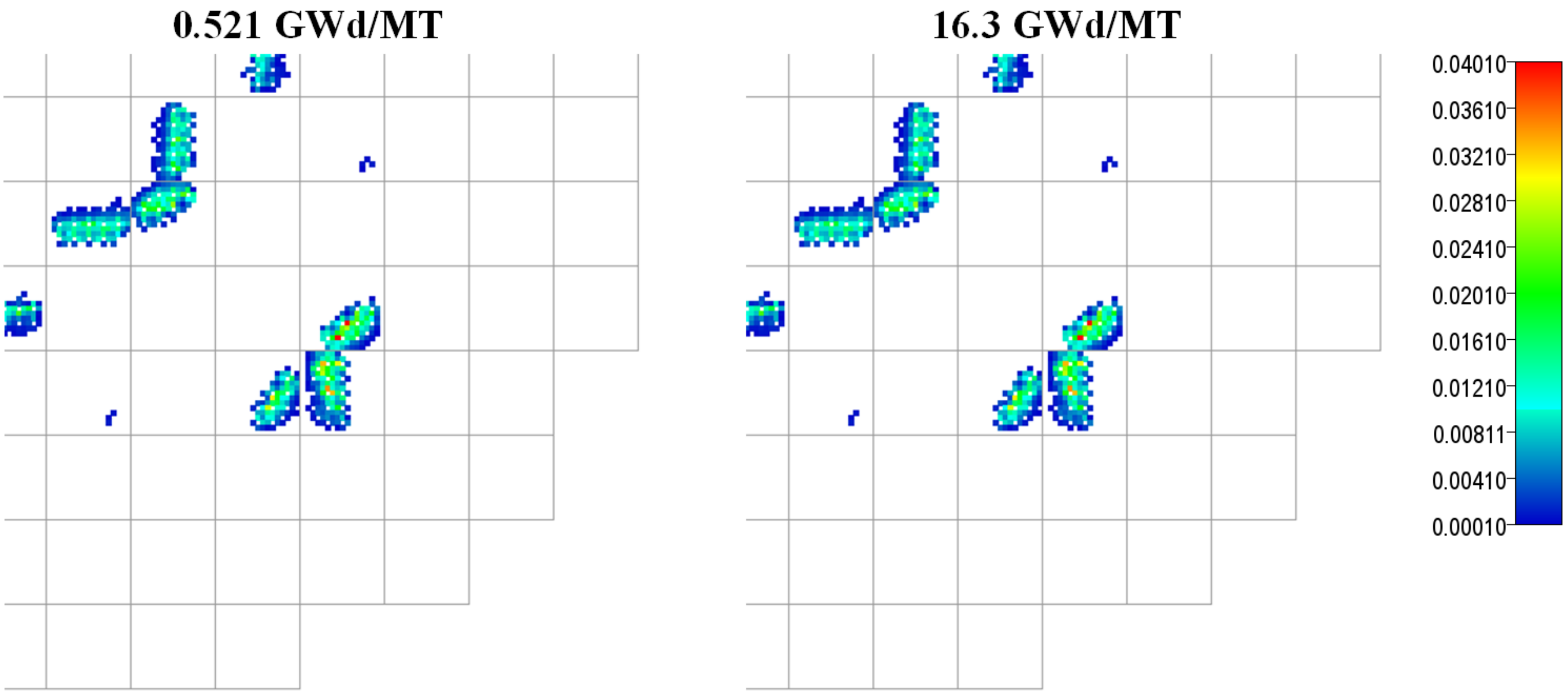
Maximum Clad Hoop Stress (Pa)



Stresses spike after startup and relax by end of cycle

Results – Cycle 2

Cumulative Damage Index (%)



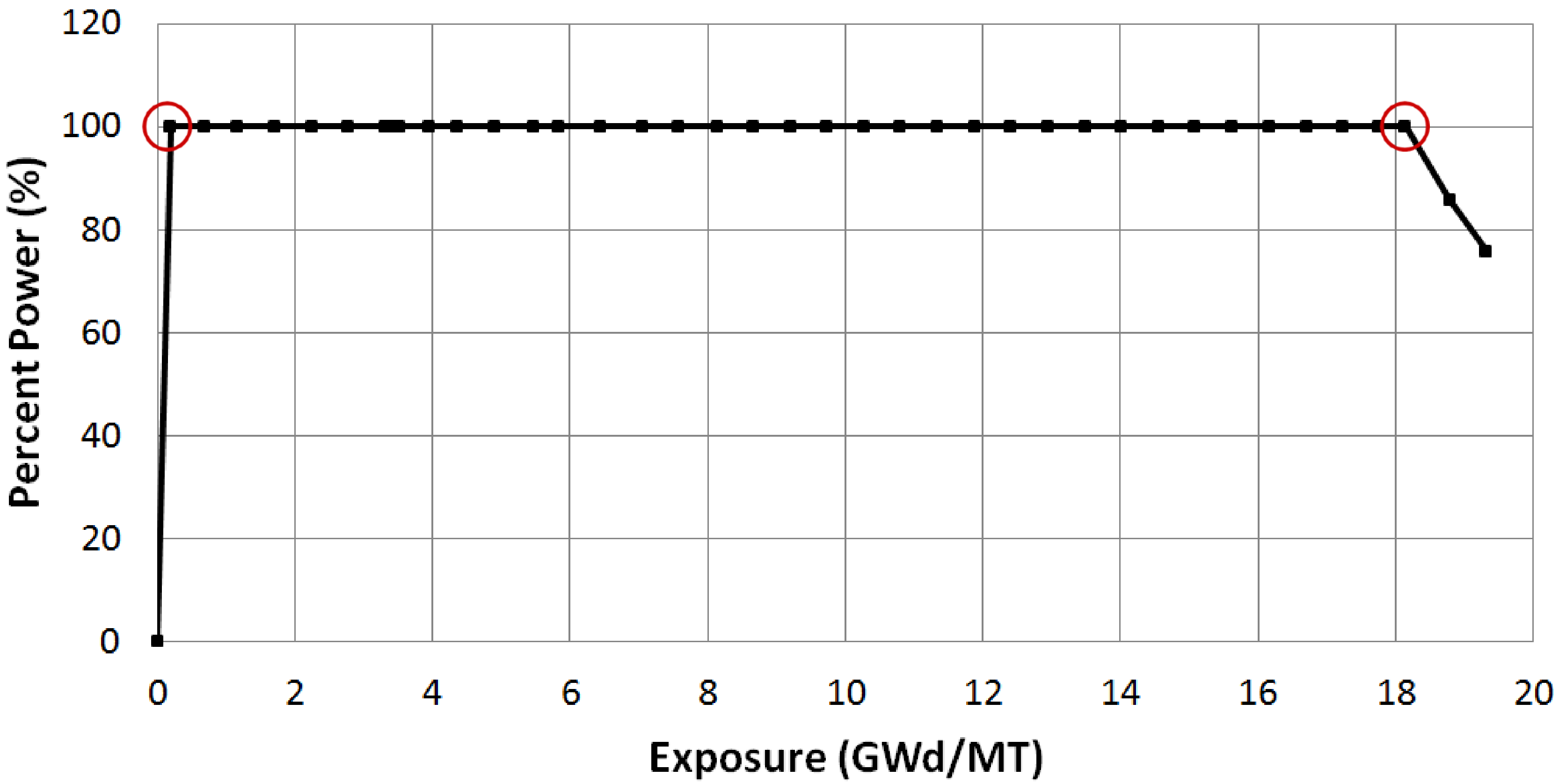
Cycle 3 Core Layout

<table>
<tr><th></th><th>H</th><th>G</th><th>F</th><th>E</th><th>D</th><th>C</th><th>B</th><th>A</th></tr>
<tr><td>8</td><td>1A-10</td><td>H-6</td><td>128</td><td>L-5</td><td>N-13</td><td>D-8</td><td>104</td><td>J-9</td></tr>
<tr><td>9</td><td>F-8</td><td>128 | 8</td><td>D-13</td><td>128 | 8</td><td>B-7</td><td>104</td><td>128</td><td>M-10</td></tr>
<tr><td>10</td><td>128</td><td>C-12</td><td>L-2</td><td>N-11</td><td>128</td><td>G-11</td><td>128</td><td>M-2</td></tr>
<tr><td>11</td><td>E-5</td><td>128 | 8</td><td>E-3</td><td>128</td><td>J-3</td><td>128</td><td>16</td><td>A-5</td></tr>
<tr><td>12</td><td>N-3</td><td>J-14</td><td>128</td><td>N-7</td><td>E-2</td><td>128</td><td>P-10</td><td></td></tr>
<tr><td>13</td><td>H-12</td><td>104</td><td>E-9</td><td>128</td><td>128</td><td>16</td><td>G-15</td><td></td></tr>
<tr><td>14</td><td>104</td><td>128</td><td>128</td><td>16</td><td>F-2</td><td>A-9</td><td></td><td></td></tr>
<tr><td>15</td><td>J-7</td><td>F-4</td><td>P-4</td><td>L-15</td><td></td><td></td><td></td><td></td></tr>
</table>

IFBA | WABA or
Previous Cycle 1 Location

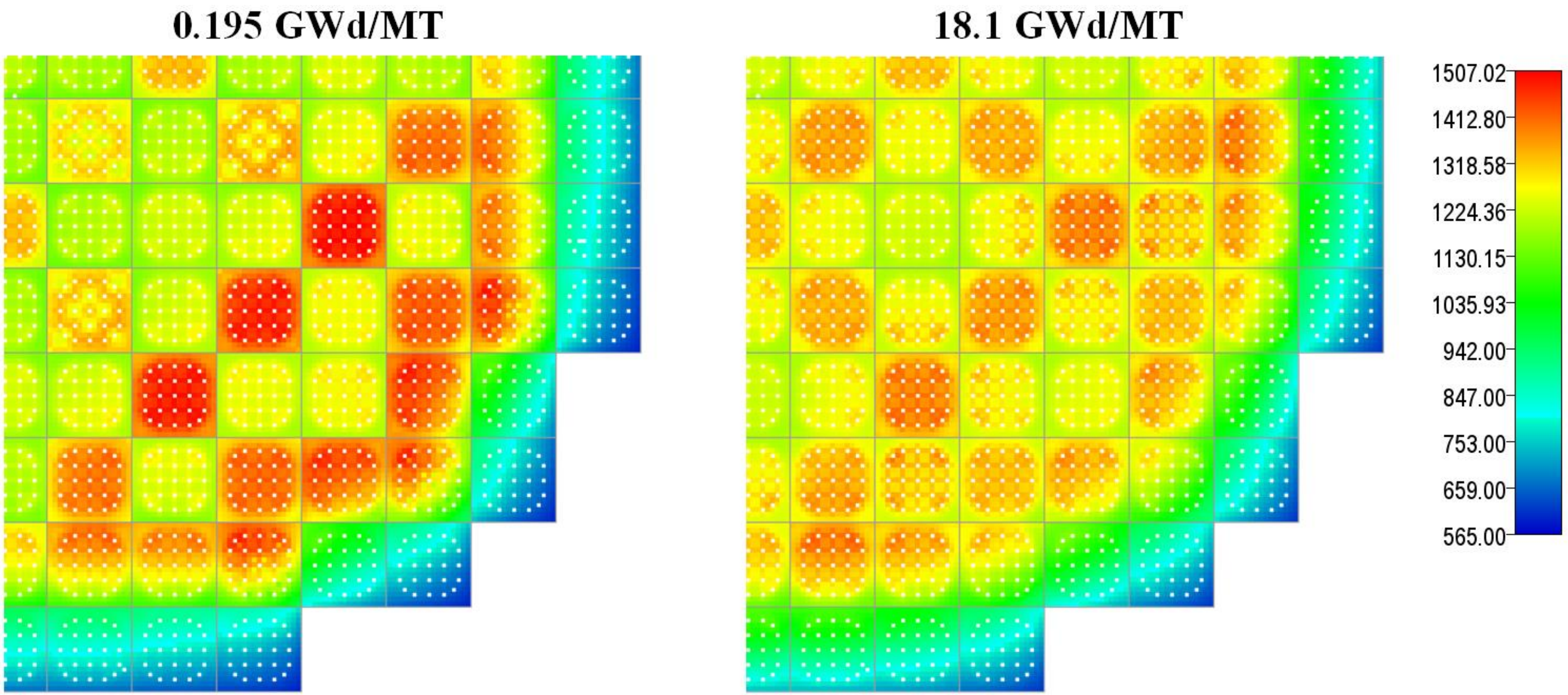
- Batch 1 - 2.11%
- Batch 2 - 2.619%
- Batch 3 - 3.1%
- Batch 4 - 3.709%
- Batch 5A - 3.807%
- Batch 5B - 4.401%

Cycle 3 Power History



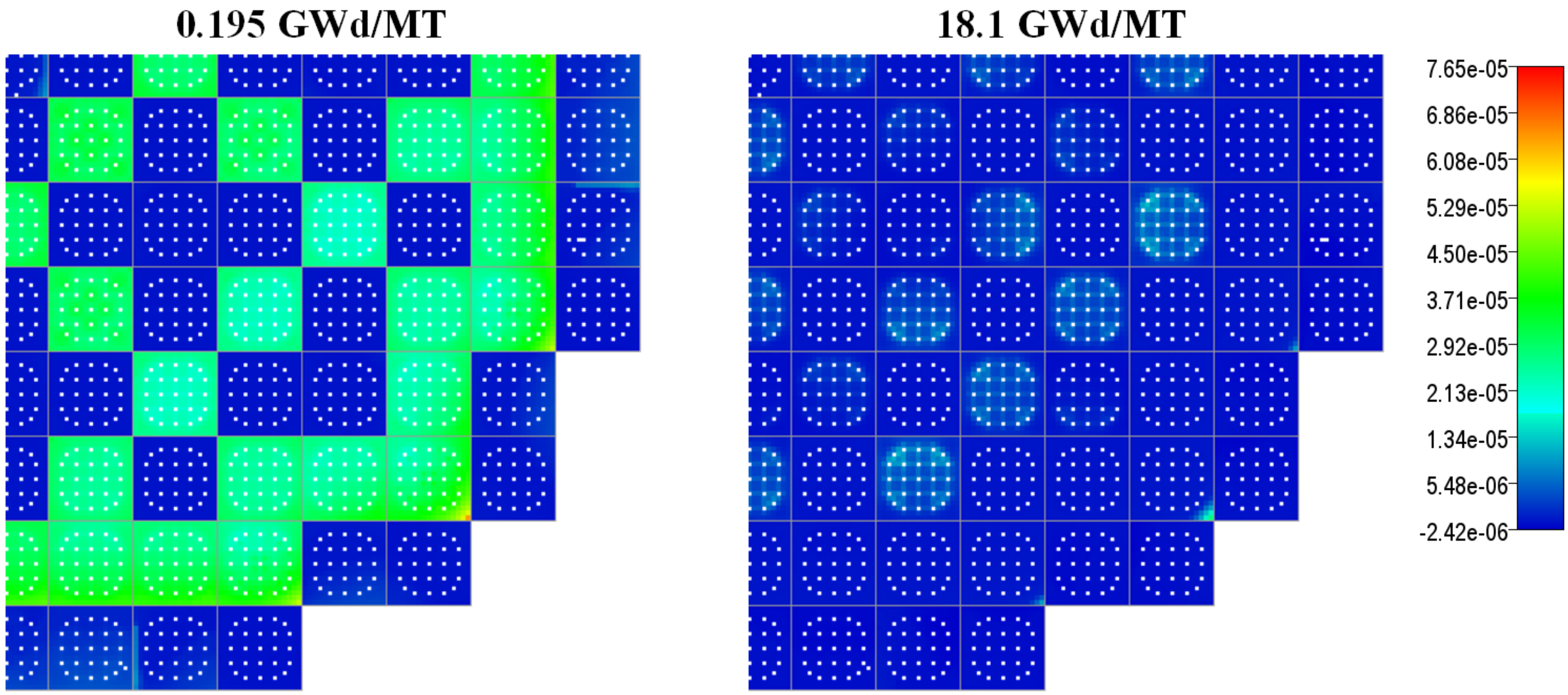
Results – Cycle 3

Maximum Centerline Fuel Temperature (K)



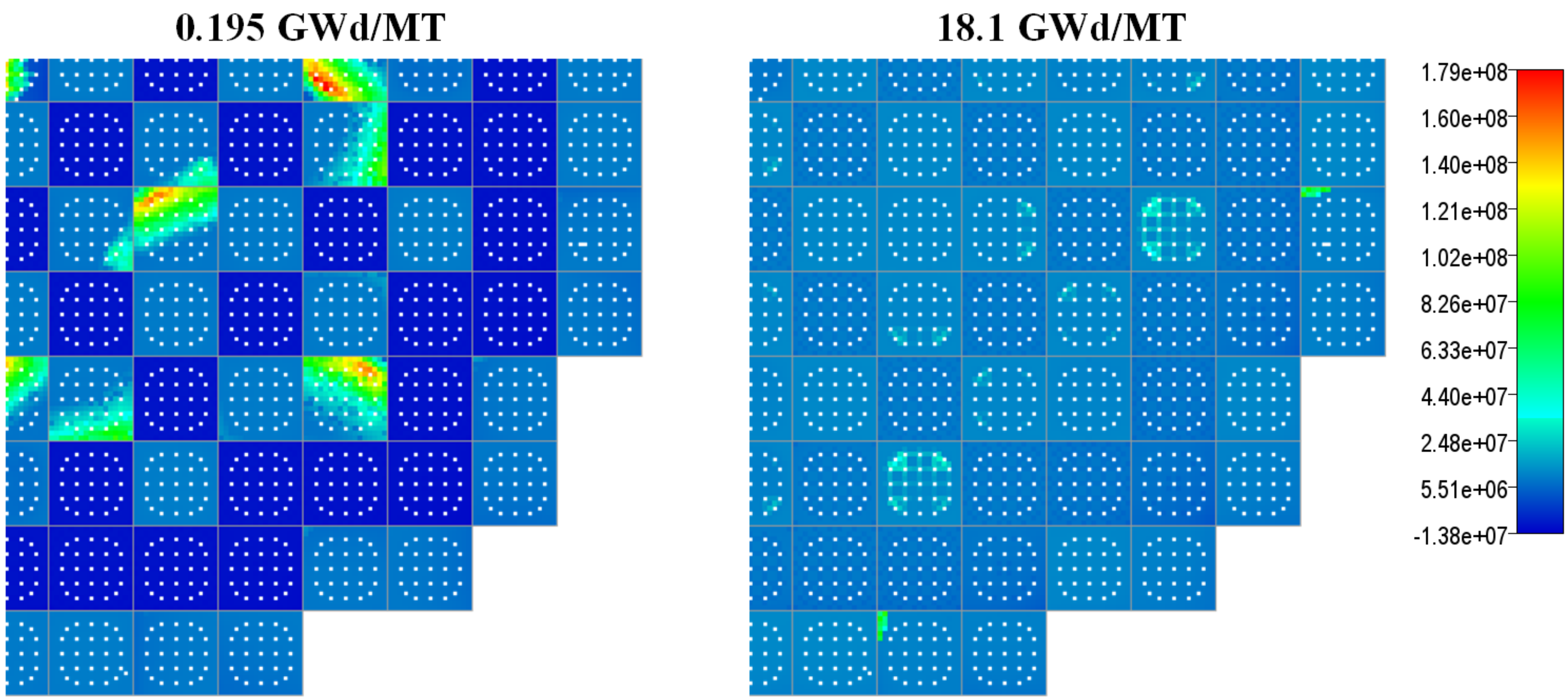
Results – Cycle 3

Minimum Gap Thickness (m)



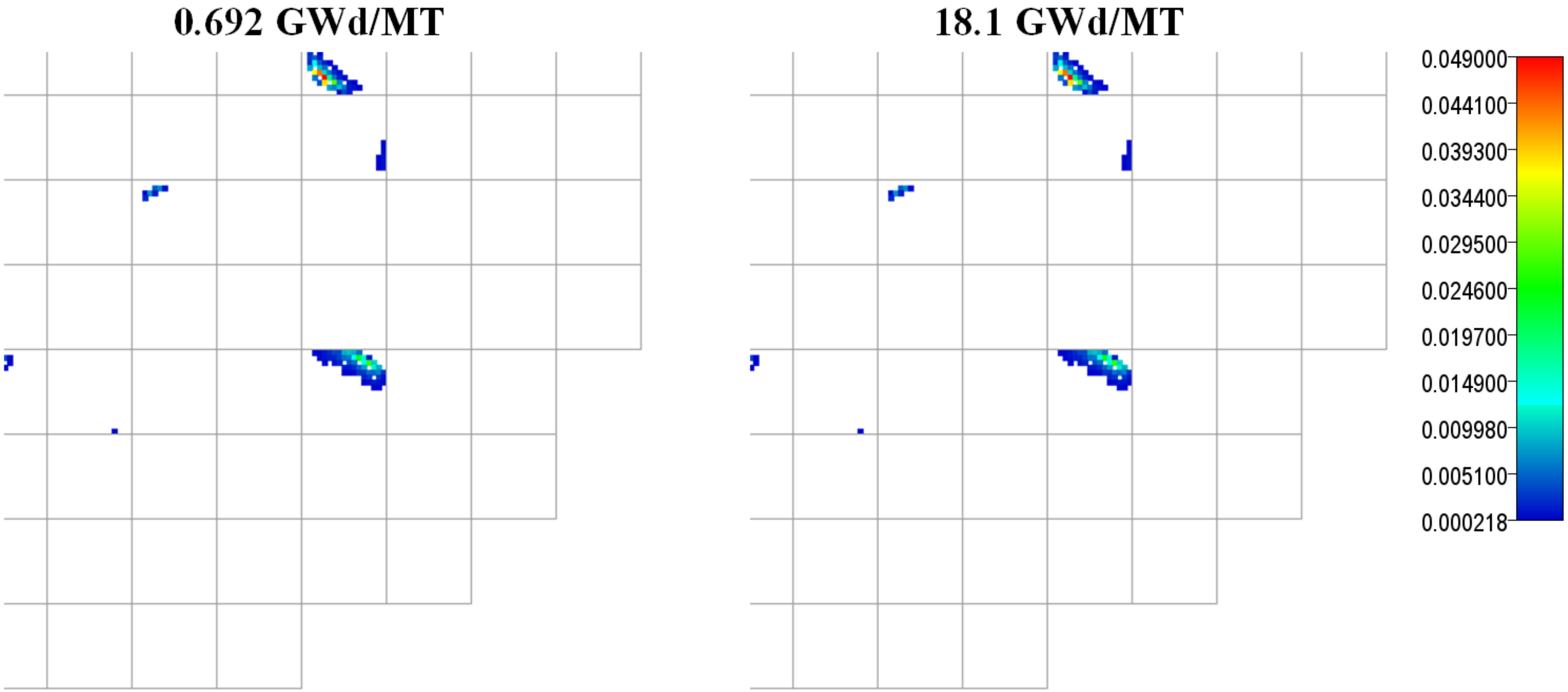
Results – Cycle 3

Maximum Clad Hoop Stress (Pa)



Results – Cycle 3

Cumulative Damage Index (%)



Conclusions

- Standalone Capability demonstrated for WBN1, Cycles 1-3
  - Better estimation of PCI indicators
    - Which rods are in contact?
    - How high are the clad stresses?
    - Which may need more detailed analysis?
  - Observed trends resulting from various fuel performance phenomena
    - Swelling, densification, clad creep
  - No rods were particularly concerning with respect to failure
    - No reported failures, so this is expected

Future Work and Application

- Developing Capability
  - Need IFBA modelling capability (already complete)
  - Processing more detailed results with EXODUS files
- Perform fuel temperature comparisons to existing simulations
- Future Application
  - Start-up simulation
    - Assess ramping speed and impact on hoop stress and damage
  - Assessing PCI in Watts Bar Cycles 6-7

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- This research made use of the resources of the High Performance Computing Center at Idaho National Laboratory (INL), which is supported by the Office of Nuclear Energy of the U.S. Department of Energy under Contract No. DE-AC07-05ID14517.

References

[1] D. Gaston *et al.* “Moose: A parallel computational framework for coupled systems of nonlinear equations.” *Nuclear Engineering Design*, **239**: pp. 1768–1778 (2009).

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[4] K. T. Clarno *et al.* “High fidelity modeling of pellet-clad interaction using the CASL virtual environment for reactor applications.” *Proc. M&C 2015*. Nashville, TN, USA (2015).

[5] A. Godfrey *et al. VERA Benchmarking Results for Watts Bar Nuclear Plant Unit 1 Cycles 1-12*. *Technical Report CASL-U-2015-0206-000*, Oak Ridge National Laboratory (2015).

Questions?