CASL-U-2016-1257-001

Demonstration of Load-Follow Simulation with VERA-CS and Standalone BISON

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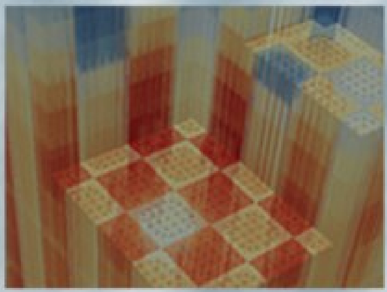

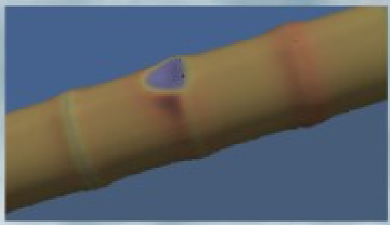

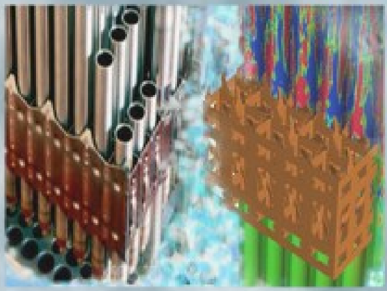

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EXECUTIVE SUMMARY

In the past year, CASL has partnered with Exelon and the University of Illinois at Urbana Champaign (UIUC) to begin simulating some of Exelon's plants, particularly focusing on load-follow operations. In such operations, the power output from the plant will vary based on the demand or anticipated demand at the time. For example, late at night, the demand is much lower than during the day when people are awake, so it would be potentially advantageous to operate the plant at lower power. Historically, nuclear power generation has been among the cheapest sources of energy, so most plants in the United States have been operated with core-follow operations basically at full power with the exception of outages and various small scale events. But in the current economic climate, priorities have changed.

There are a number of questions that arise when considering load-follow operations, particularly with respect to VERA's tools and capabilities. Will the coupled neutronics and thermal hydraulics simulations with MPACT and CTF be able to perform well without substantial convergence issues? Will BISON be able to handle the somewhat rapid power changes that are present with load-follow? Will the clad hoop stresses be alarmingly high as a result of these power changes? This milestone (L3:PHI.CMD.P14.02) has been intended to answer these questions and demonstrate such operations to assess feasibility and robustness before Exelon and UIUC proceed with their simulations using VERA.

In this report, load-follow simulations using VERA-CS with one-way coupling to standalone BISON has been demonstrated including both a single rod with a full cycle of load-follow operations and a quarter-core model with a single month of load-follow. From the single rod case, we observed no convergence issues in any of the ~1800 statepoints it simulated. This provided sufficient confidence to proceed with the quarter-core model with a single month of load follow operations. This simulation also completed successfully with only minor issues encountered along the way, though adequate workarounds were typically found. However, 16 rods that failed to converge in BISON are part of ongoing discussions with INL that will hopefully have a meaningful impact on the robustness of future cases.

The results obtained made qualitative sense, and the impact of the power cycling is understandable. We would be able to identify a number of rods for further analysis, but nothing from these results was particularly alarming. There is some question as to how many rods should experience fuel-clad separation as the power is dropped and by how much they should separate, but this is something that can be addressed in future analysis. There may also be questions as to whether or not additional statepoints would be needed to accurately predict the transient xenon behavior during the load-follow operations. However, the goal of this milestone was to demonstrate that the VERA tools were able to simulate these operations, which it has accomplished with only minor source code modifications. Exelon and UIUC should be able to proceed with their simulations with more confidence now that this analysis has been performed.

CONTENTS

FIGURES

ACRONYMS

BOC	beginning of cycle
BOL	beginning of life
CASL	Consortium for Advanced Simulation of Light Water Reactors
CSV	comma separated value
EFPD	effective full power days
EOC	end of cycle
IFBA	integral fuel burnable absorber
INF	CASL Infrastructure focus area
INL	Idaho National Laboratory
LHR	linear heat rate
ORNL	Oak Ridge National Laboratory
UIUC	University of Illinois at Urbana Champaign
UTK	University of Tennessee at Knoxville
VERA	Virtual Environment for Reactor Analysis
VERA-CS	VERA Core Simulator
WBN1	Watts Bar Nuclear Unit 1

1. INTRODUCTION

To set the stage for this report, a brief description of VERA-CS is provided as well as some background information on why load-follow operations are of importance to CASL, particularly to the Exelon and UIUC collaboration. Additionally, the objectives of this milestone will be outlined.

1.1 VERA-CS Description

The Virtual Environment for Reactor Analysis (VERA) is a simulation environment being developed by CASL, which is comprised of codes collectively used for nuclear reactor modeling and simulation. VERA-CS is considered to be the subset of VERA for core simulation, which is typically neutronics and thermal hydraulics. The primary deterministic neutron transport solver is MPACT, and CTF is the subchannel thermal hydraulics solver. Much of the work in this report relates to the BISON fuel performance code. Figure 1.1.1 shows the components of VERA.

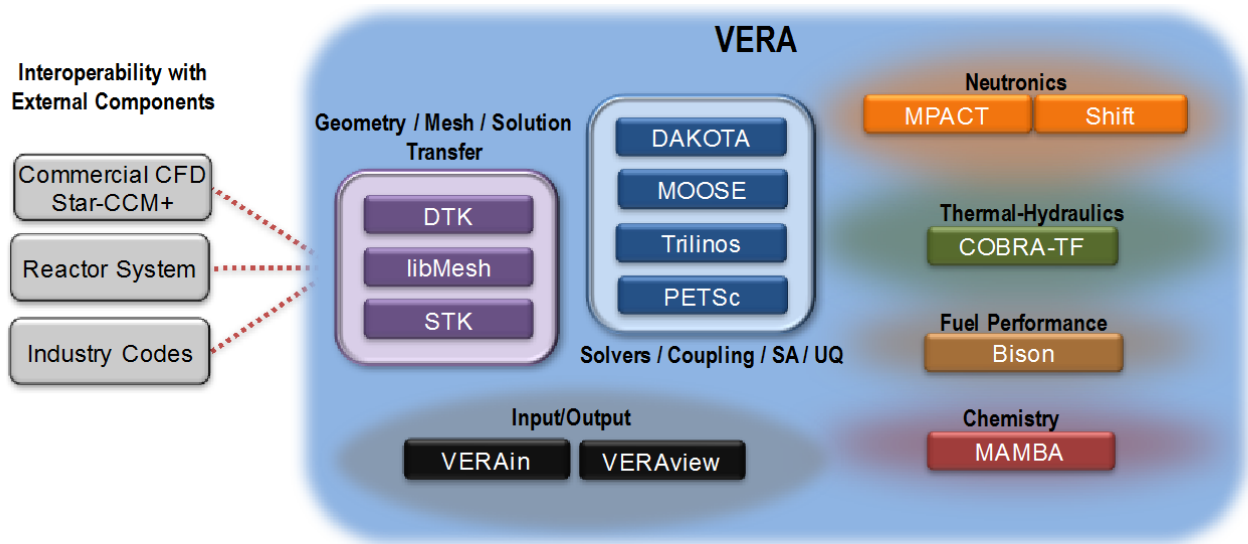

Figure 1.1.1. VERA Components

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 [1]. 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 [2]. 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 [3]. 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).

CTF

CTF is a subchannel TH code being developed by ORNL and North Carolina State University (NCSU) specifically for light water reactor (LWR) analysis [4]. 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 and physics detail than the internal thermal hydraulics solver (Simplified TH) in MPACT, thus longer execution times.

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) [5,6]. 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 [7,8] which use the finite element method for geometric representation and a Jacobian Free Newton-Krylov (JFNK) scheme to solve systems of partial differential equations [8]. For this work, BISON uses a 2D azimuthally symmetric (R-Z), smeared-pellet thermomechanical fuel pin model with boundary and heat source data from VERA-CS, which generates the time-dependent power shape/history and moderator temperature inputs needed for BISON.

1.2 Collaboration with Exelon and UIUC

In the past year, CASL has partnered with Exelon and the University of Illinois at Urbana Champaign (UIUC) to begin simulating some of Exelon's plants, particularly focusing on load-follow operations. In such operations, the power output from the plant will vary based on the demand or anticipated demand at the time. For example, late at night, the demand is much lower than during the day when people are awake, so it would be potentially advantageous to operate the plant at lower power. Historically, nuclear power generation has been among the cheapest sources of energy, so most plants in the United States have been operated at full power with the exception of outages and various small scale events. But in the current economic climate, priorities have changed.

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1.3 Milestone Objectives

The primary objectives to this milestone (L3:PHI.CMD.P14.02) are fairly straight-forward:

1. Demonstrate MPACT/CTF (VERA-CS) load-follow simulation on a later cycle in WBN1 operation.
2. Use VERA-CS output data to generate and execute standalone BISON cases, assessing stresses encountered during power ramps.

By going to a later cycle in Watts Bar Unit 1 operation, you can see more important effects that fuel-clad contact can have on the hoop stress predicted by BISON. In this work, a single month of load follow history was placed in the middle of Cycle 3. This allows fresh, twice-, and thrice-burned assemblies to be incorporated into the analysis.

There were additionally two stretch goals specified:

3. If computation burden is reasonable, perform load-follow for a full cycle.
4. If Tiamat-Inline capability is stable, test simulation for either single month or full cycle of MPACT/CTF/BISON inline.

Unfortunately, simulating a full cycle of load-follow operations was deemed impractical, particularly for VERA-CS due to the long runtime from the case with just a single month. Projecting from the results presented in this report, one might expect a full cycle of VERA-CS operations to take roughly 3 months of continuous runtime on 1,000 cpu cores. However, there is additional research being done to speed up VERA-CS calculations in general and to load-follow operations specifically. So in the coming months, it might be anticipated that this number could be reduced considerably. Additionally, issues were identified in Tiamat-Inline that deemed a comparable simulation to that shown here to be unattainable, especially in conjunction with the failed BISON rods discussed in Section 5.4.

2. WATTS BAR UNIT 1, CYCLE 3 DESCRIPTION

The Watts Bar Nuclear Plant is a Westinghouse four-loop PWR operated by the Tennessee Valley Authority (TVA) and has been online since 1996. It began with a 3,411 MWth power rating, but it had a 1.4% power uprate in 2001. It is currently operating in its fourteenth cycle, logging over 6,000 effective full power days (EFPD) of operation [9].

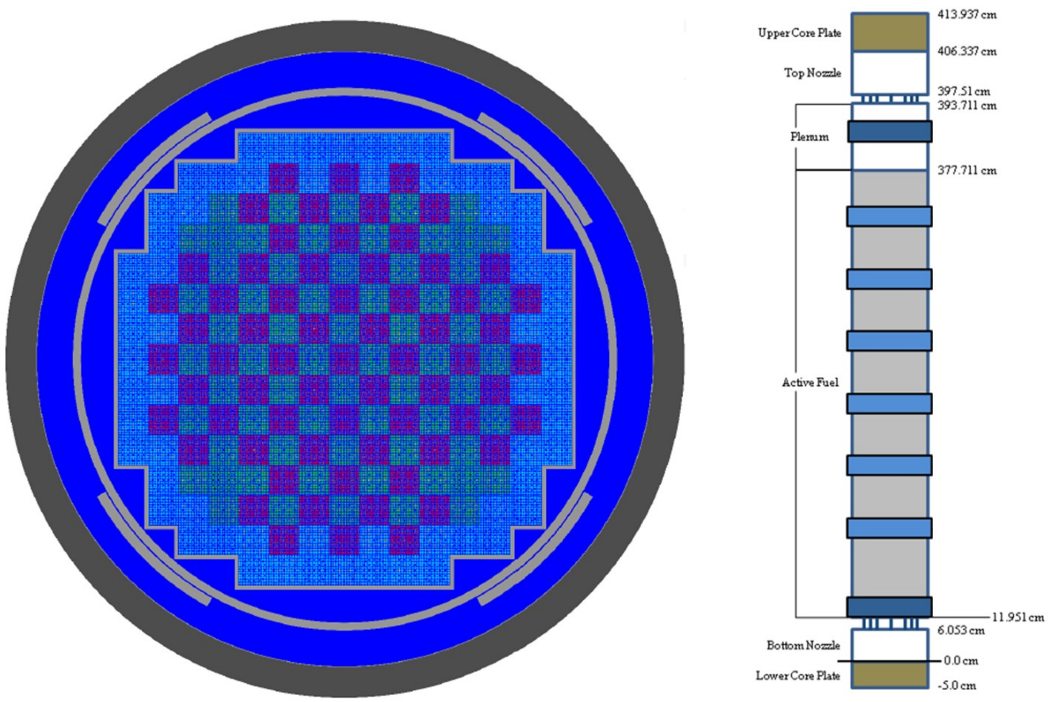

Figure 2.1. Watts Bar Unit 1 – Core Geometry

The left component of Figure 2.1 shows a 2D slice of the WBN1 Cycle 1 full core layout. It is important to note that VERA currently does not model the core barrel, pads, or vessel, as are shown in the diagram. The unit has 193 Westinghouse 17×17 fuel assemblies which are 12 feet tall 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.

Figure 2.2 shows the core layout in Cycle 3, which is the basis for the quarter-core demonstration. Each assembly is color-coded based on enrichment. Fresh assemblies include data on the number of integral fuel burnable absorber (IFBA) and wet annular burnable absorber (WABA) rods, whereas others contain the corresponding location from previous cycles. It is worth noting that the center assembly (H-8) comes directly from Cycle 1, skipping Cycle 2 operations.

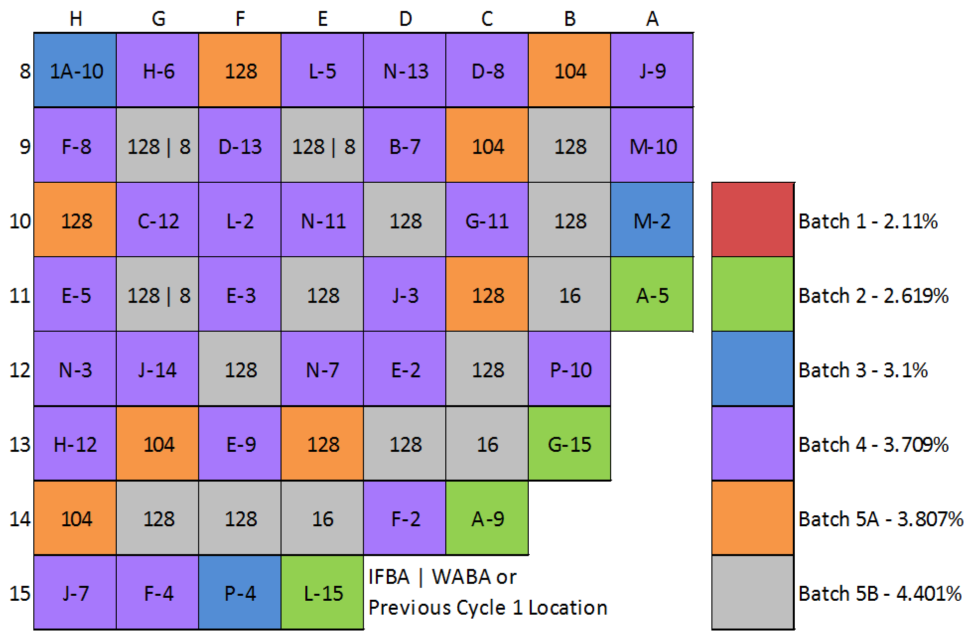

Figure 2.2. Watts Bar Unit 1 – Cycle 3 Core Layout

Figure 2.3 shows the idealized power history for Cycles 1-3 that was used in the VERA-CS simulation. Cycle 1 has a more gradual ramp to power than is seen in subsequent cycles. There is also slightly more variation during the cycle than in Cycles 2-3, which are primarily at 100% throughout the entire cycle. Shortly after 14 gigawatt-days per metric ton (GWd/MT) in Cycle 1, VERA-CS imposes a step change to 86.9% power. This was reflected in the BISON inputs, allowing a one-day transition to and from 86.9% power (an instantaneous power change would be problematic for BISON and most other codes). At all other statepoints, BISON uses a linear interpolation of the power.

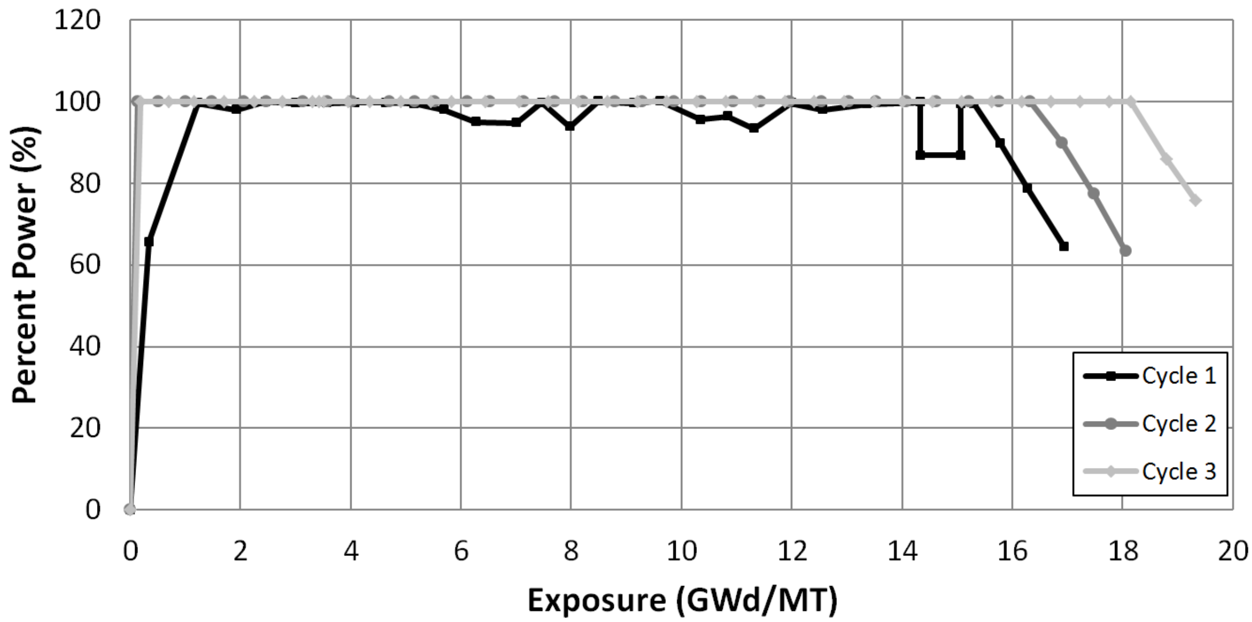

Figure 2.3. Watts Bar Unit 1 – Cycles 1-3 VERA-CS Power History

The changes to the Cycle 3 power history to represent load-follow operation will be outlined in a later section.

3. MONTH OF REPRESENTATIVE POWER HISTORY

In planning this work, it was decided that it would be advantageous to use a non-proprietary core power history to allow for an easier documentation and dissemination of the demonstration. Discussing this with Exelon engineer Christopher Demetriou, he provided a single month of hour-by-hour load-follow operations that is not based on any particular plant's operation but is representative of the power changes Exelon is expecting during this type of operation. Figure 3.1 shows the hourly data that Exelon provided (blue) as well as the condensed representation that was used in VERA (green). This condensed data uses 101 statepoints, making the calculations much more tractable than using the hourly data with 744 statepoints.

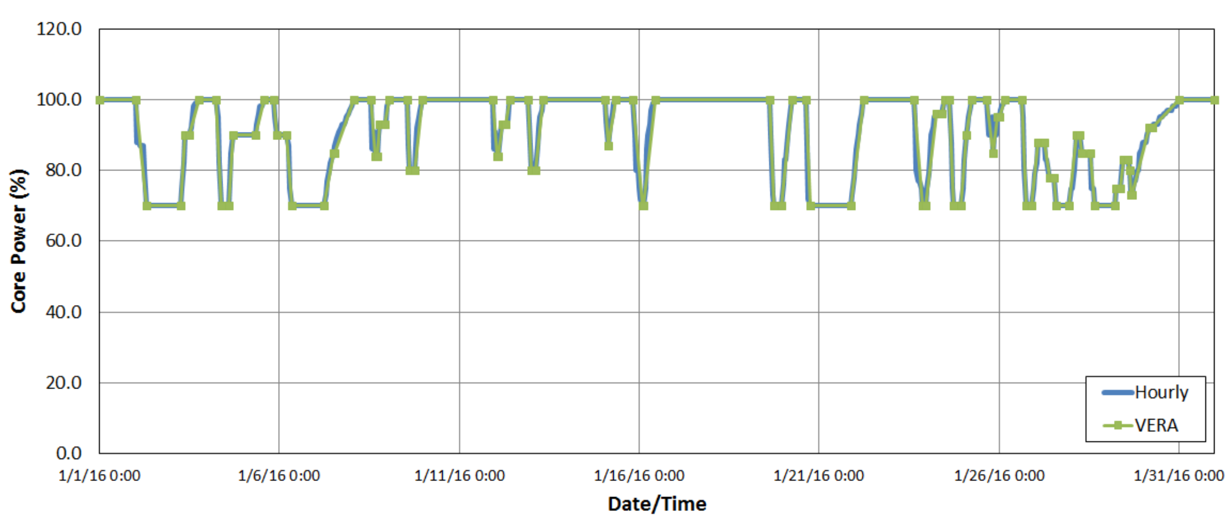

Figure 3.1. Month of Representative Load-Follow Core Power History

4. SINGLE ROD DEMONSTRATION

Before jumping into a larger case, such as a quarter-core model, there were several questions that needed to be answered about the ability of the VERA tools to handle this simulation. For example, initial concerns centered around general convergence of MPACT/CTF calculations, as well as the standalone BISON cases. To see if there were any warning signs or convergence issues, a single rod demonstration was performed with a full cycle of load-follow operation. This was accomplished by appending 18 months of the representative load-follow power history to make up Cycle 2 of the rod's life. Cycle 1 was run at a constant power (100% of a roughly average linear heat rate) for 440 EFPD. This would allow the rod to come into contact before starting Cycle 2, where we might expect to see more considerable hoop stresses. If the rod were not in contact, there likely would not be anything of interest, at least with respect to the hoop stress distributions. Once Cycle 1 is complete, there is a short, month-long outage, then Cycle 2 is performed. Figure 4.1 shows the power history for this rod, which corresponds to the behavior just described.

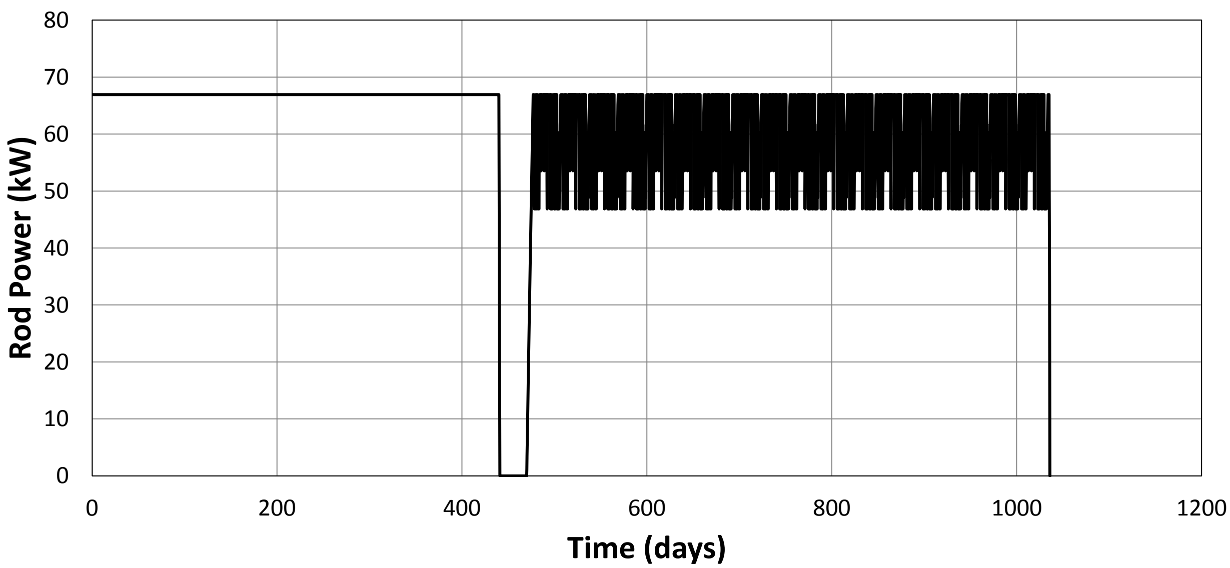

Figure 4.1. Single Rod Demonstration – Rod Power History (kW)

This single rod case was executed on a CASL development cluster at ORNL, where the VERA-CS calculation required roughly 16 hours on 60 cores. The BISON calculation required roughly 4.5 hours on 32 cores. Moving into the results, Figure 4.2 shows the maximum centerline fuel temperature for the rod. During Cycle 1, we see the centerline temperature drop as the fuel-cladding gap closes due to fuel relocation and cladding creep, leveling off near the end of the first cycle. As we go into Cycle 2 and the load-follow operations, we see notable oscillations as the power is cycled, which is expected. We also see a secondary trend where the temperature gradually increases as we move through the cycle, which is primarily driven by degradation of the fuel conductivity.

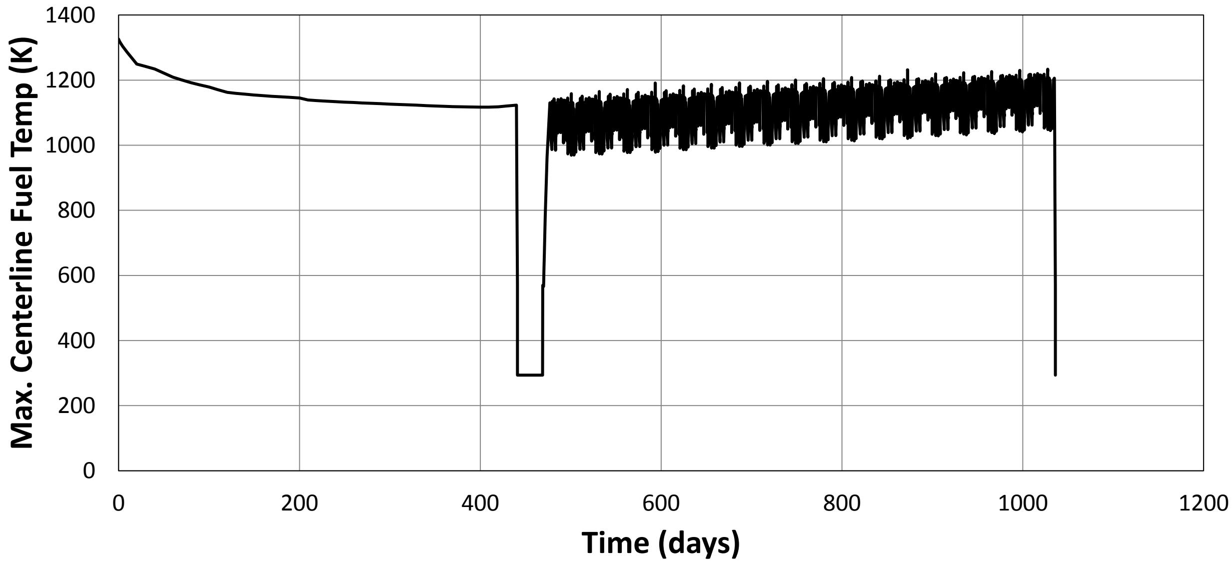

Figure 4.2. Single Rod Demonstration – Maximum Centerline Fuel Temperature (K)

Figure 4.3 shows the minimum fuel-clad gap thickness. As the simulation starts, we see a quick drop in the gap thickness, which is due to the fuel relocation that is occurring. Going through Cycle 1, the fuel eventually comes into contact at roughly 400 EFPD. During the outage, the temperature is dropped to cold conditions (293 K and atmospheric pressure), causing the fuel and clad to separate. Once the fuel is brought back up to HFP conditions at the start of Cycle 2, contact is again achieved and maintained through the cycle. There has been some discussion as to whether or not the gap thickness should vary more during the load-follow operations, particularly as the power is decreased and the fuel/clad geometrically adjust to the new thermal conditions. Gap reopening was not observed here during load-follow operations, but will be a topic of future consideration.

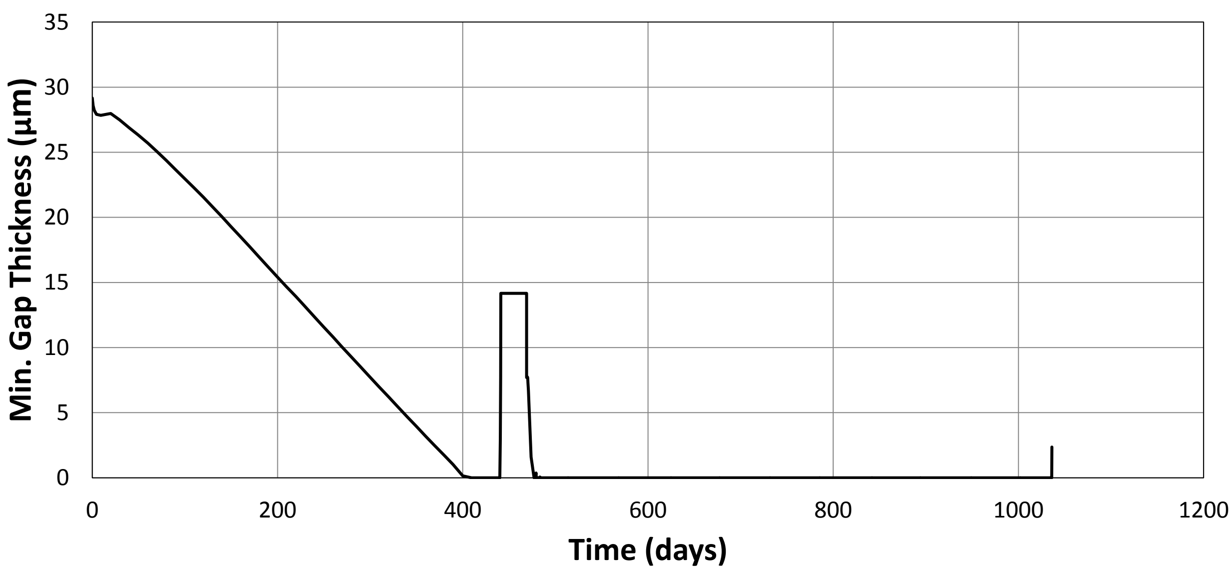

Figure 4.3. Single Rod Demonstration – Min. Fuel-Clad Gap Thickness (μm)

Figure 4.4 shows the maximum clad hoop stress experienced in the rod. During Cycle 1, particularly before contact is achieved, the hoop stress is primarily driven by the difference between the system (~15 MPa) and rod internal pressure (~2-6 MPa). As a result, the hoop stress is compressive (negative). During the cycle outage, the system pressure is dropped to atmospheric, so the hoop stress becomes tensile (positive) as the internal pressure exceeds the system pressure. This is reversed going into Cycle 2, once full system pressure is restored. Once we move into the load follow operations, we eventually see that the hoop stress becomes positive as the fuel begins to press harder on the clad. We also observe oscillations corresponding to power changes. So even though the fuel-cladding gap does not reopen, the contact stress decreases at lower power.

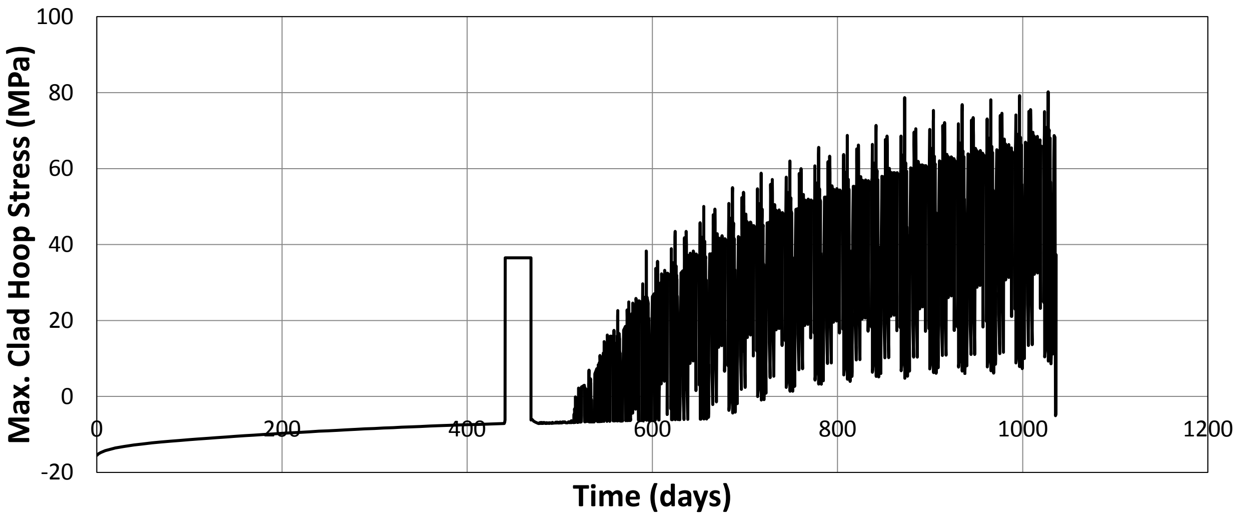

Figure 4.4. Single Rod Demonstration – Maximum Clad Hoop Stress (MPa)

From these results, we did not see any substantial convergence issues and the stresses observed seemed mostly reasonable. There are still some open questions about specific issues, particularly fuel-clad gap thickness behavior, but nothing indicates that analysis should not progress to a larger problem, such as the quarter-core case presented in the next section.

5. QUARTER CORE DEMONSTRATION

5.1 Cycle 3 Power History With Load-Follow

In Section 2, background on the Watts Bar Unit 1 core was provided, especially the details related to Cycle 3, which is the basis for this problem. Additionally, the idealized VERA-CS power histories for Cycles 1-3 were also presented. To simulate load-follow operations, the month of representative history described in Section 3 was inserted near the middle of Cycle 3 (10.27 GWd/MT, 268.7 EFPD). Figure 5.1.1 shows the new Cycle 3 core power history reflecting this modification, where the simulation ends once load-follow operations are completed. In a typical cycle of nominal operation, VERA-CS uses 20-30 statepoints. With this month of load-follow operations, there are roughly 114 statepoints in the new Cycle 3 definition (13 from initial core-follow then 101 from load-follow), substantially more than is usually used. It is worth noting that Figure 5.1.1 uses hours for the x-axis to more easily reflect the load-follow power transitions.

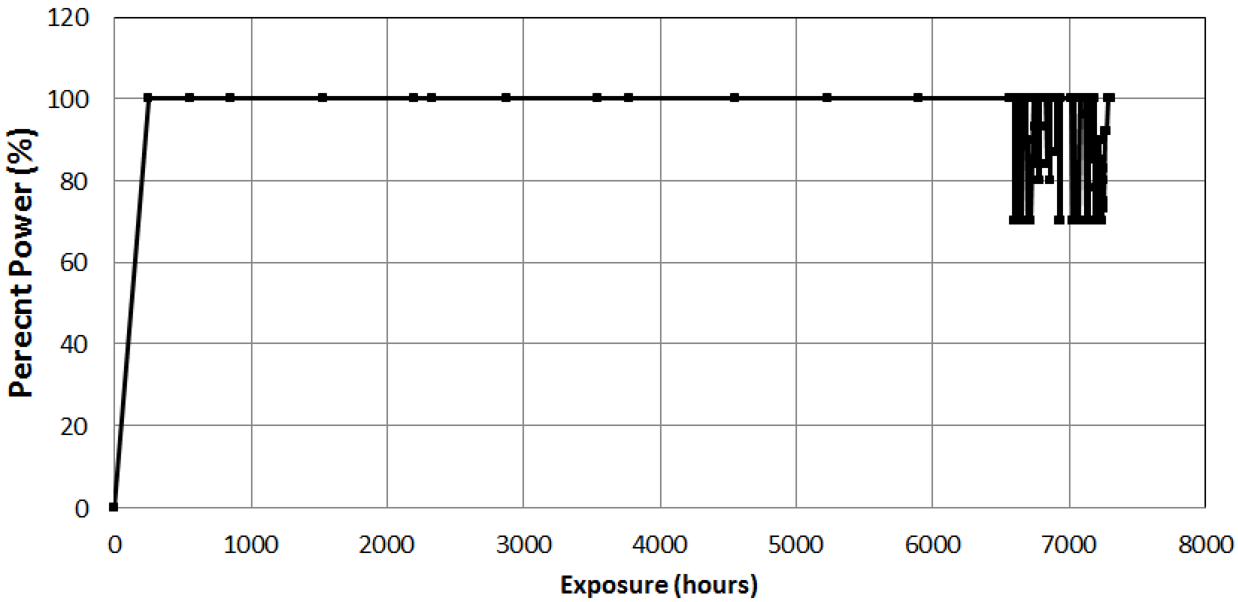

Figure 5.1.1. Quarter-core Power History With Month of Load Follow

To get an idea of what a multicycle power history looks like in BISON, Figure 5.1.2 shows the three cycle power history for a sample rod. This one, in particular, is slightly below average power in general. Comparing each cycle's power history to the core power histories previously presented, it can be seen that there is some variation as a result of the radial power changes during operation. For example, the core power in Cycles 2-3 is fairly constant, at least in the first part of Cycle 3, but in this case we see that the power increases as the cycle is depleted. This means that the radial power for this rod experiences an increase. From Figure 5.1.2, we can also see the zero power periods during the cycle outages.

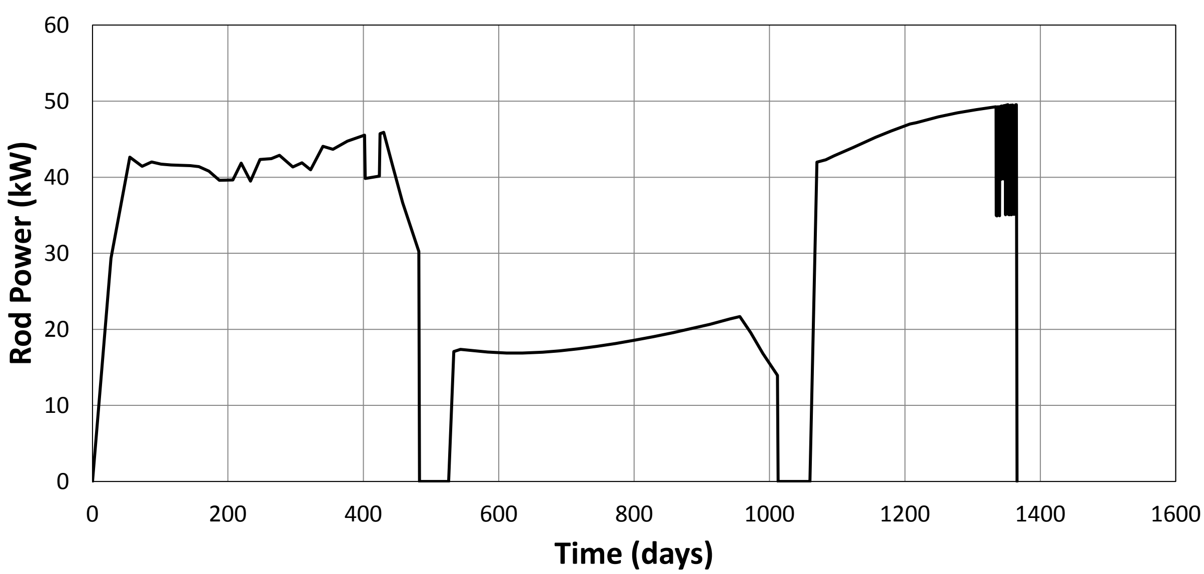

Figure 5.1.2. Sample Rod Multicycle Power History

5.2 Reactivity and Axial Power Control

In consulting with Exelon, their reactivity control during load-follow operations would actually be very similar to core-follow, leaning on critical boron concentration to control reactivity along with minor control rod bank insertions to manage the axial offset (AO). Figure 5.2.1 shows the critical boron concentration as a function of burnup for the load-follow demonstration core. Until load-follow operations start, the trend is very similar to what has been seen in other analyses. Initially the boron concentration is high when at HZP because there is no Doppler feedback to drive down reactivity. As the core is brought up to power, however, feedback allows the boron concentration to drop considerably. During the first few GWd/MT, the IFBA and WABA rods deplete, losing some of the reactivity worth, which is offset by an increase in the critical boron concentration. As the cycle progresses, fuel burnup becomes more dominant and the core is less reactive, requiring less boron to control criticality. By the time we start the load-follow operations, the critical boron concentration is lower (~700 ppm). When power decreases during load-follow operations, Doppler feedback increases reactivity and more boron is necessary to control the reactivity. Once it comes back up to full power, the boron decreases. Effectively, the boron concentration is inversely proportional to the power level.

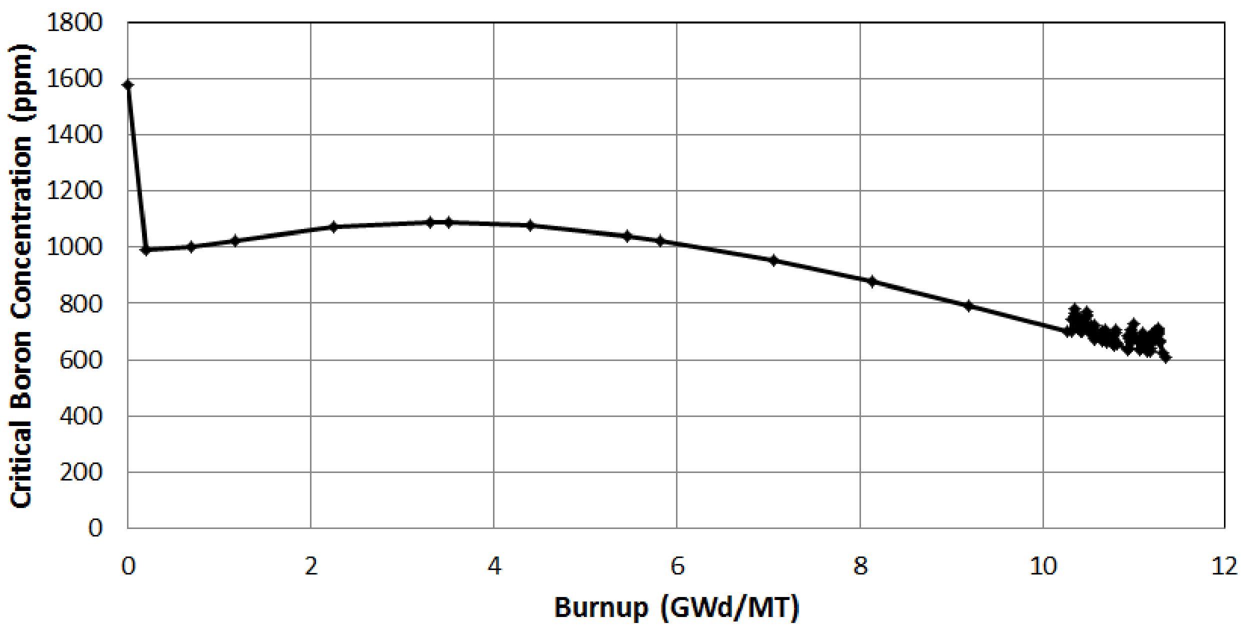

Figure 5.2.1. Quarter Core Demonstration – Boron Letdown Curve

As mentioned, there are some changes to the bank insertion to control the axial offset. While this work did not perform a full design study to assess the necessary bank insertion to maintain an acceptable AO, it did use a simplified, linear relationship between core power and Bank D insertion based on discussions with Andrew Godfrey. At 70% power, Bank D is positioned at 190 steps, and at 100% it is at 220 steps. Any power in between simply linear interpolated to yield the insertion for that state. From the results, this approach did a reasonable job of managing the AO, but in a production case the insertion would be provided from the operation data.

5.3 Performance Notes

The VERA-CS calculations for this problem were run on the Panacea cluster at ORNL, taking roughly 7 days on 1,000 cores (~168,000 core-hours). It is worth noting that the CMFD speed-ups that were recently added have been observed to have some remaining convergence characteristics that are being explored, so the previous CMFD formulation was used here. In the future, once the issues are resolved with CMFD, we would expect this case to run notably faster. However, this enabled us to get a rough estimate of the computational resources necessary to complete both this case and project the requirements for a full cycle of load-follow operations. With these numbers we might expect a full cycle to take between 2.5 and 3.0 million core-hours. With CMFD speed ups, maybe 1.0 to 2.0 million. Additionally, there is active research being performed collaboratively by ORNL and the University of Tennessee – Knoxville (UTK) to address load-follow VERA-CS performance specifically, by altering the transport algorithm being used. Hopefully, near-future cases may be able to take advantage of the improvements made there.

The BISON cases were run on the Falcon supercomputer at Idaho National Laboratory, requiring roughly 70,000 core-hours. This performance substantially improves upon the Cycle 6-7 results obtained earlier this year [12], in which the quarter-core BISON results required roughly 35,000-40,000 core-hours. By nearly quadrupling the number of statepoints in the cycle, it would not have been unreasonable to expect 120,000 to 160,000 core-hours. However, various improvements in both BISON itself and CASL's use of BISON likely played a large factor in reducing the run times.

5.4 Results

To present the results, four statepoints have been selected from the simulation to highlight the changes during the cycle:

1. HZP, State 1
2. Early in HFP Operations, State 7
3. Start of Load-Follow Operations, State 13
4. Low Power Point in Load-Follow, State 90

Figures 5.4.1 through 5.4.3 show the results for the maximum centerline temperature, fuel-clad gap thickness, and maximum clad hoop stress, respectively. Each figure contains the results for 4 statepoints and three images for each state. The top left image for each corresponds to the 2D radial layout containing either the maximum or minimum value for that rod. All of the 2D images were created with the VERAView graphical user interface (GUI) [13]. The top right image corresponds to the 3D data distribution as visualized using Visit [14]. The quarter-core orientation has been rotated such that the quarter symmetry lines are visible, providing a better view of the data distributions axially. The final, bottom image for each statepoint is the core power where the red, dashed line denotes the current timestep and power level. For clarity, the colorbar legend is enlarged and shown on the rightmost location on each figure.

It should be noted that in all of the 2D figures, assembly locations B-9 and G-14 each have 8 rods that demonstrated convergence issues, so they are missing data and are denoted with white, similar to guide tubes. The inputs for these rods have been communicated to the BISON team and are part of ongoing discussions to resolve the issues they have posed.

These figures provide useful information about what is happening in the reactor. In Figure 5.4.1, State 1 (top left), which is at HZP, reports that all of the maximum centerline fuel temperatures are at 565 K, as expected. At State 7 (top right), the reactor is at HFP with substantial centerline temperatures. By State 13 (bottom left), a lot of the major peaks in centerline temperature have decreased due to closure of the fuel-cladding gap. State 90 shows the results during load-follow at

70% power, which causes lower centerline temperatures. A full set of results for the centerline temperature are available in Appendix A.

In Figure 5.4.2, the minimum gap thickness across all axial locations is shown. State 1 (HZP) shows the fresh assemblies in red. The 69.5 micron gap is the result of thermal expansion of the rod, closing a bit from the fabricated gap thickness. We can also see the distributions on the burned assemblies which are the result of their power profiles from Cycle 2 (or Cycle 1 in the case of H-8). By State 7, the gap has closed in nearly all of the burned assemblies, and even the fresh assemblies are experiencing significant closure, if not full contact. States 13 and 90 look quite similar in that many of the rods are experiencing contact, with the exception of some rods near the periphery. The full set of results in Appendix B shows that as the power changes from high to low power, some of the rods that are in contact experience a small amount of lift-off and contact is not maintained.

In Figure 5.4.3, the maximum clad hoop stresses are shown. It should be noted that for this figure the 2D and 3D data correspond to different legends. In this case the 2D data corresponds to the numbers on the left side of the legend and the 3D data to the numbers are the right. At BOC, we see that many of the stresses are negative, though all are very small. The fresh assemblies and rods not experiencing any contact demonstrate negative stresses because of the difference between the higher system pressure and the lower rod internal pressure. The burned assemblies have some fission gas produced from previous operation as well as helium gas in IFBA rods, so their rod internal pressures are higher than the fresh assemblies. By State 7, we see that some of the burned assemblies demonstrate considerable tensile hoop stresses (~80 MPa), but likely not high enough for concern. Additionally, many of the fresh assemblies still have not experienced much contact, so the stresses are still negative. In State 13, many of the higher stress locations have relaxed some as the magnitudes are lower. However, many of the fresh assemblies have numerous rods experiencing contact, resulting in low-magnitude positive stresses. During State 90 where the power is decreased, the magnitude of the hoop stresses drops considerably, as seen in the single rod demonstration. A full set of results for the hoop stress are available in Appendix C.

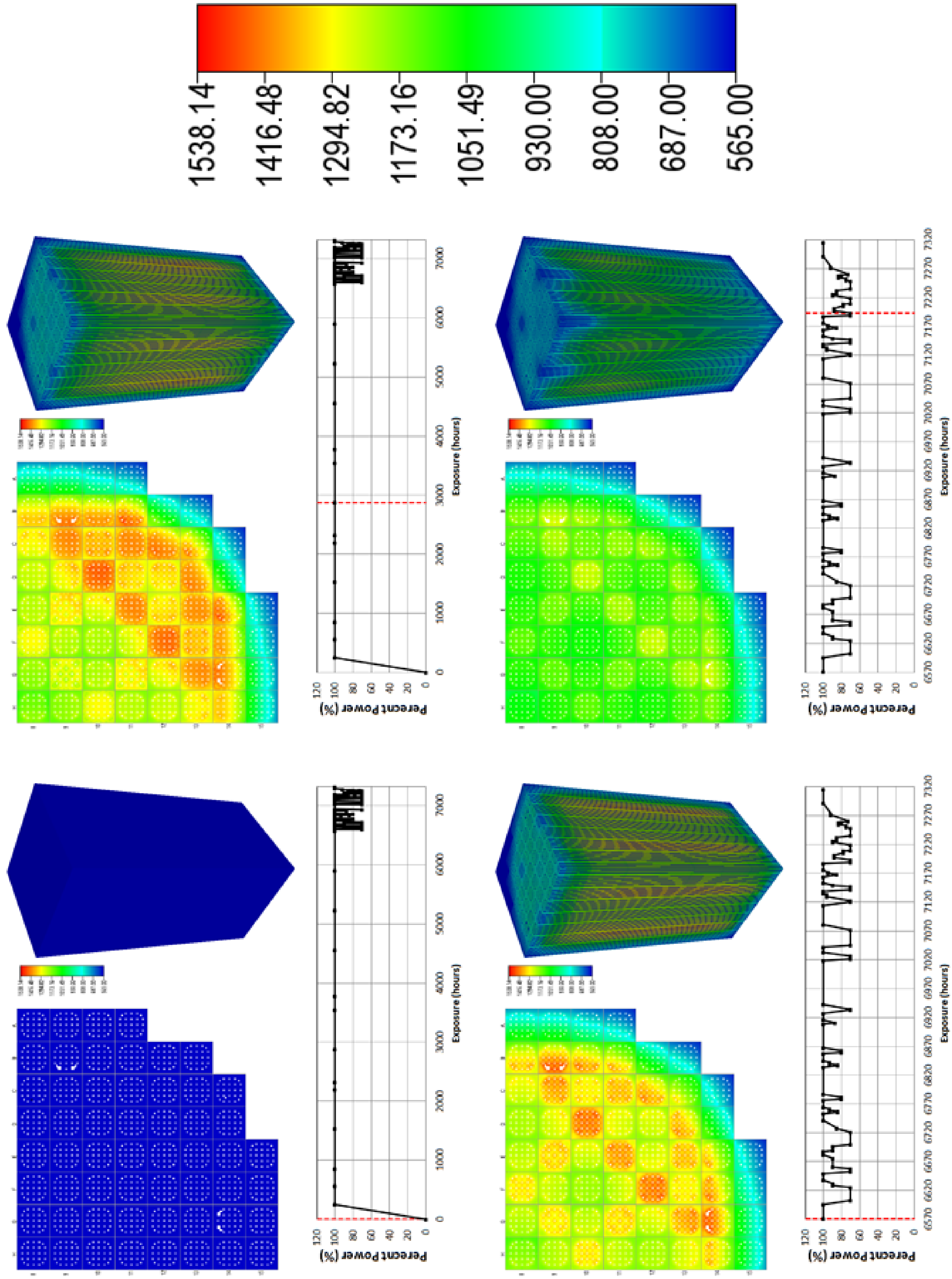

Figure 5.4.1. Quarter Core Demonstration – Maximum Centerline Fuel Temperature (K)

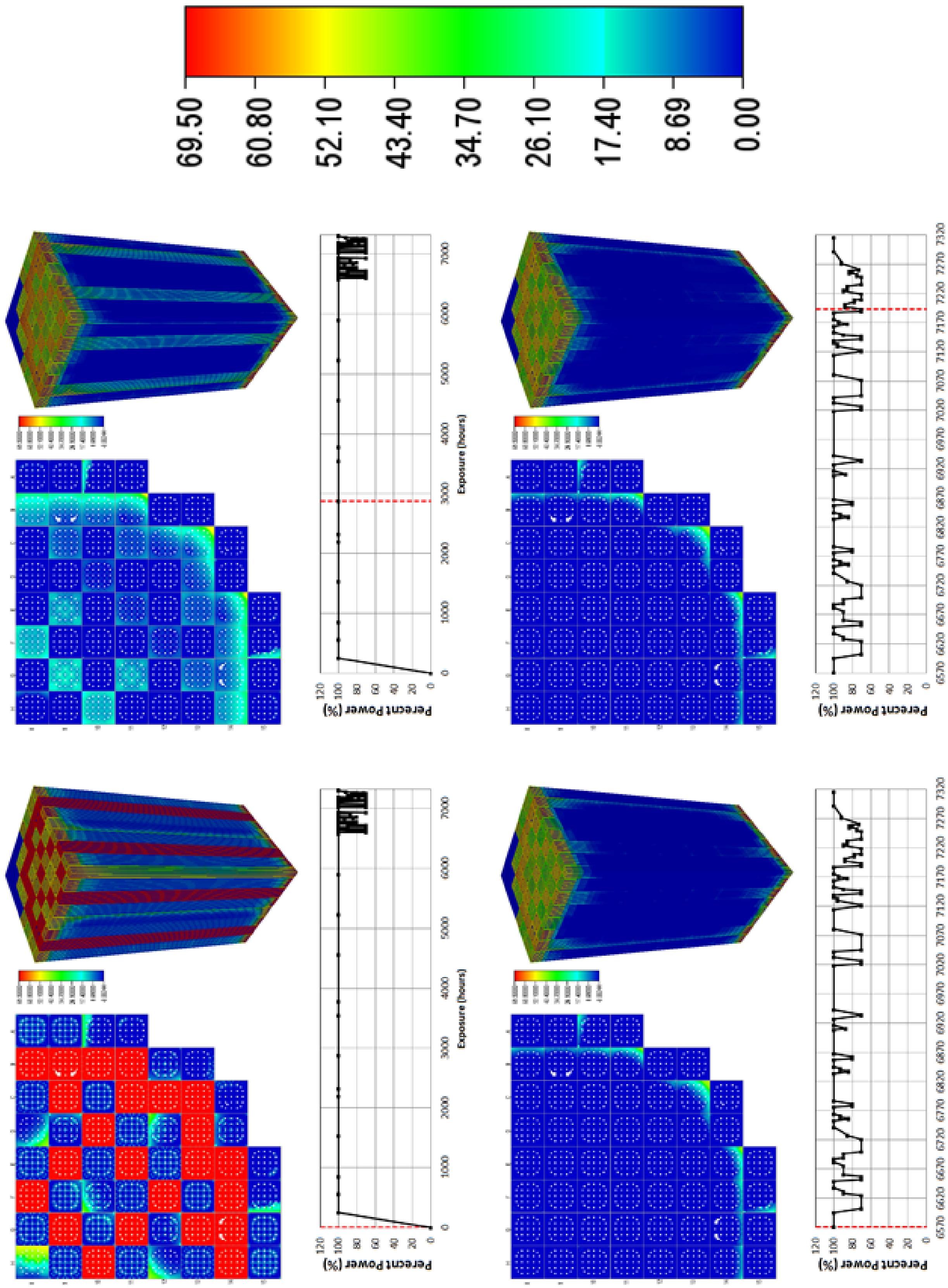

Figure 5.4.2. Quarter Core Demonstration – Fuel-Clad Gap Thickness (µm)

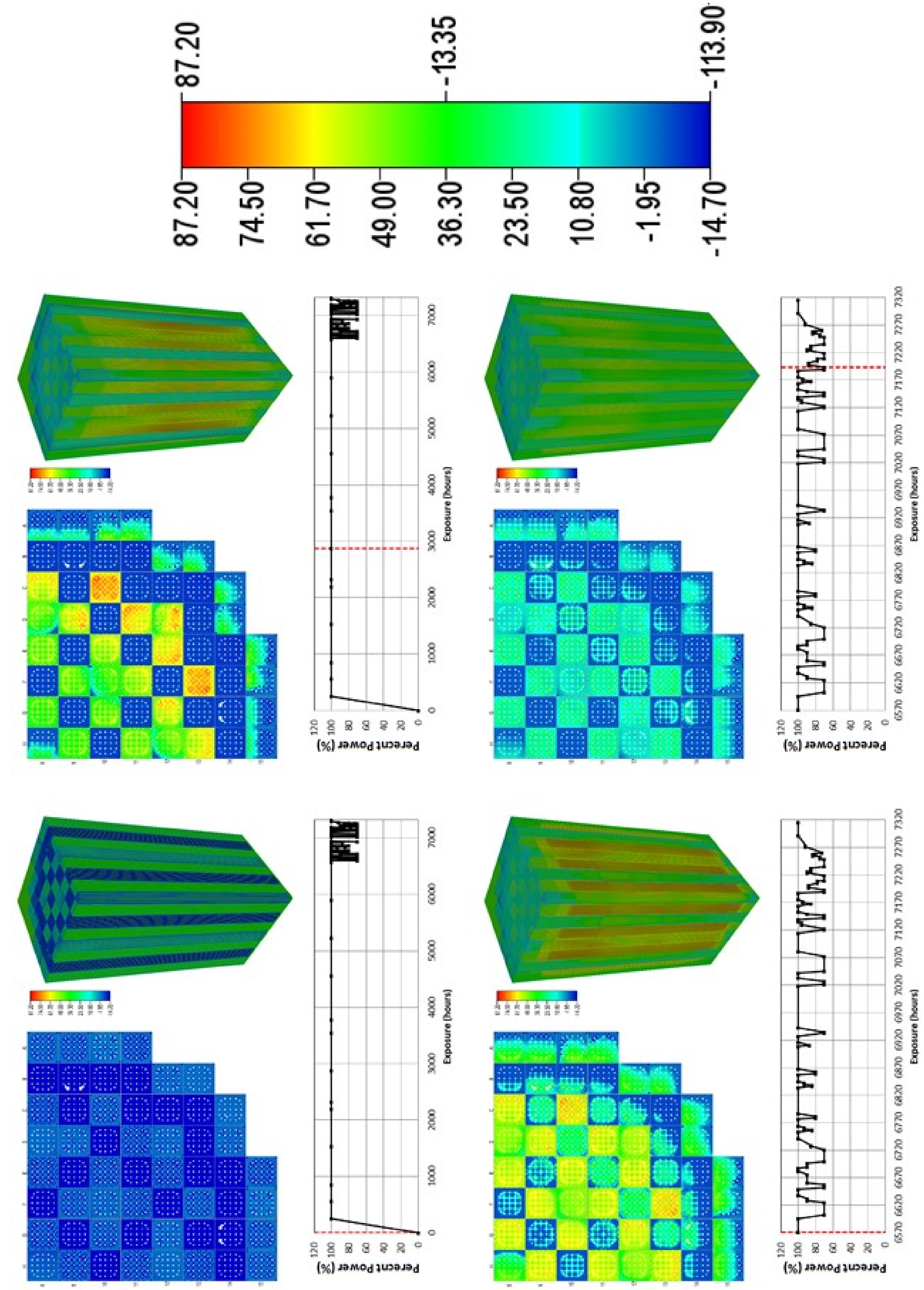

Figure 5.4.3. Quarter Core Demonstration – Maximum Clad Hoop Stress (MPa)

6. CONCLUSIONS

In this report, load-follow simulations using VERA-CS with one-way coupling to standalone BISON has been demonstrated including both a single rod with a full cycle of load-follow operations and a quarter-core model with a single month of load-follow. From the single rod case, we observed no convergence issues in any of the ~1800 statepoints it simulated. This provided sufficient confidence to proceed with the quarter-core model with a single month of load follow operations. This simulation also completed successfully with only minor issues encountered along the way, though adequate workarounds were typically found. The 16 rods that failed to converge in BISON are part of ongoing discussions with INL that will hopefully have a meaningful impact on the robustness of future cases.

The results obtained made qualitative sense, and the impact of the power cycling is understandable. We would be able to identify a number of rods for further analysis, but nothing from these results was particularly alarming. There is some question as to how many rods should experience fuel-clad separation as the power drops and by how much they should separate, but this is something that can be addressed in future analysis. There may also be questions as to whether or not additional statepoints would be needed to accurately predict the transient xenon behavior during the load-follow operations. However, the goal of this milestone was to demonstrate that the VERA tools were able to simulate these operations, which it has accomplished with only very minor source modifications. Exelon and UIUC should be able to proceed with their simulations with more confidence now that this analysis has been performed.

One major point of future work should focus on improving the performance and fully incorporating the speed ups projected in MPACT. For example, additional plans are already underway to improve the robustness of the CMFD speedups through the incorporation of a multilevel (in energy) CMFD solver. Furthermore, the work between ORNL and UTK will hopefully yield substantial improvements specific to load follow. With the current projection of ~2 million core-hours for a full load-follow cycle (compared to the 15,000-20,000 for a full cycle of nominal operations), substantial improvements will likely be needed before this is attractive beyond a research exercise.

7. ACKNOWLEDGMENTS

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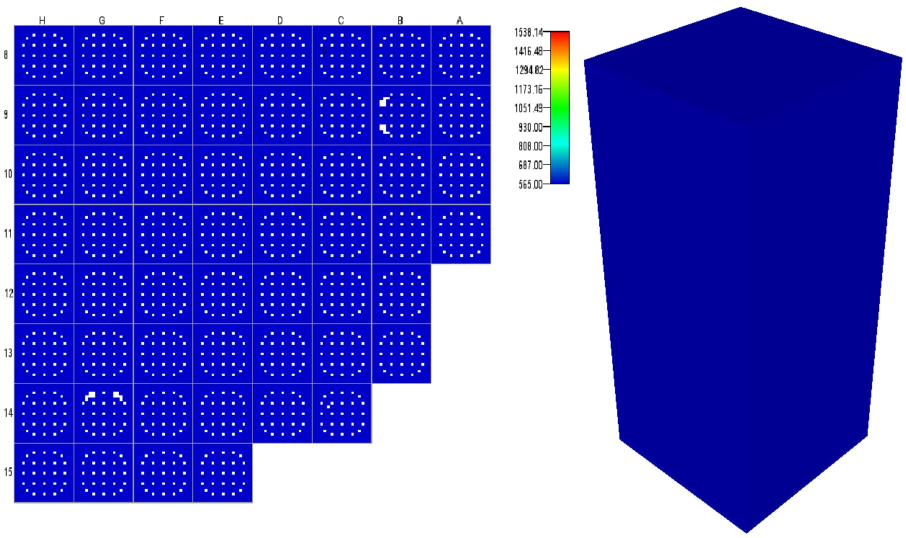
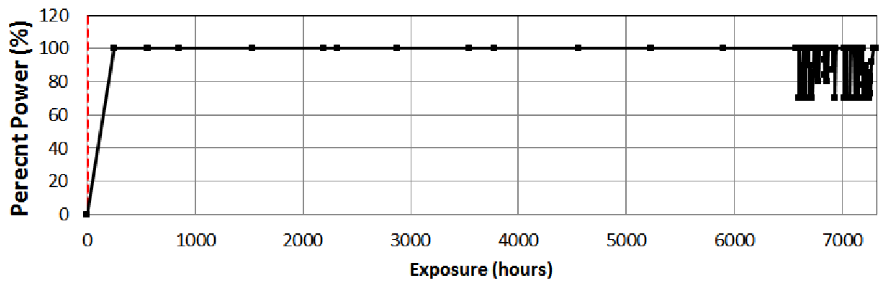
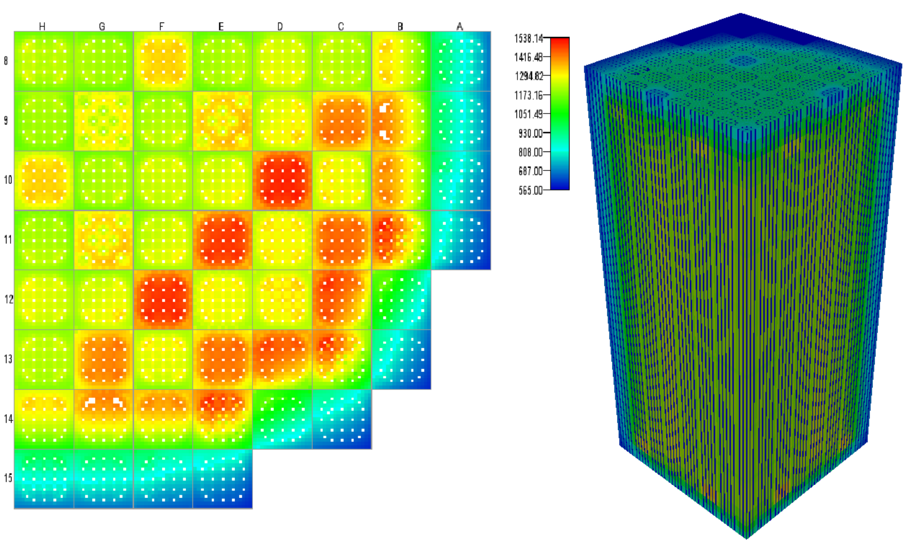
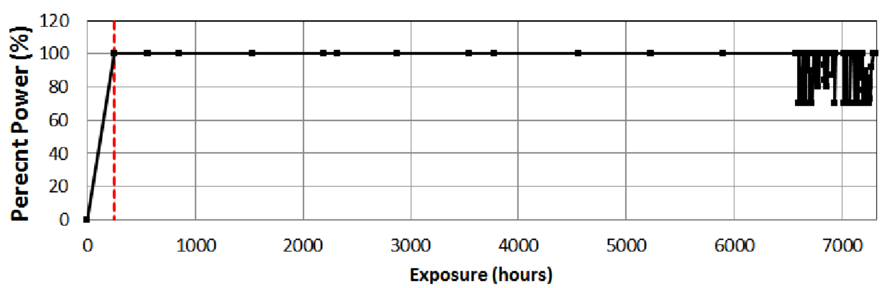
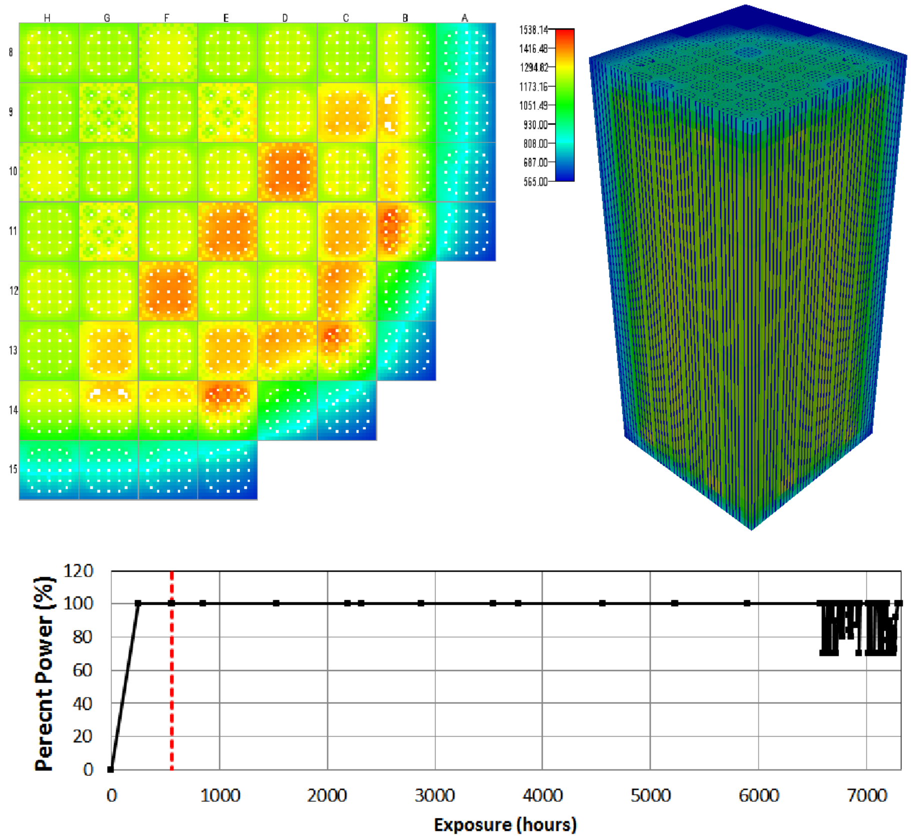
APPENDIX A – QUARTER CORE, MAXIMUM CENTERLINE FUEL TEMPERATURE RESULTS











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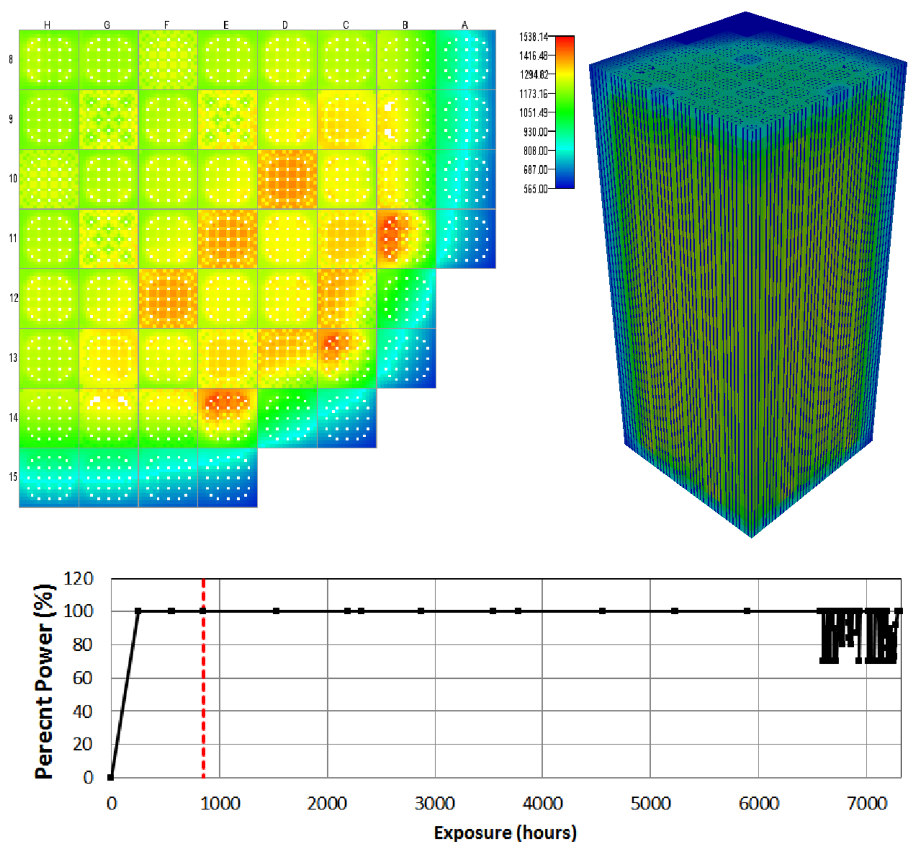

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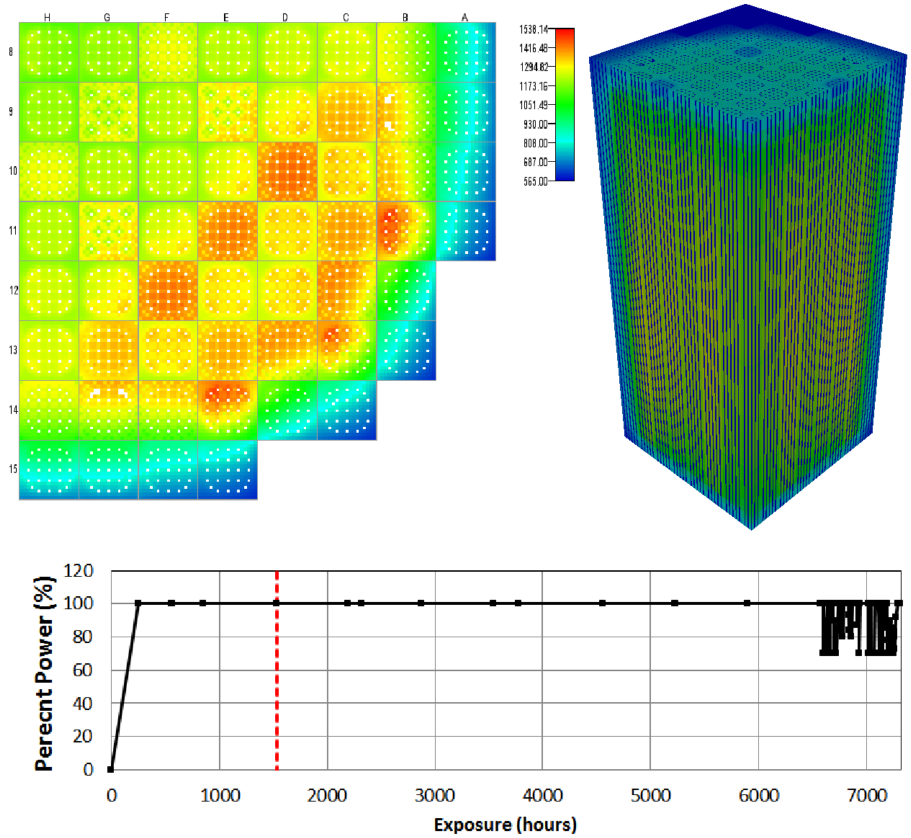
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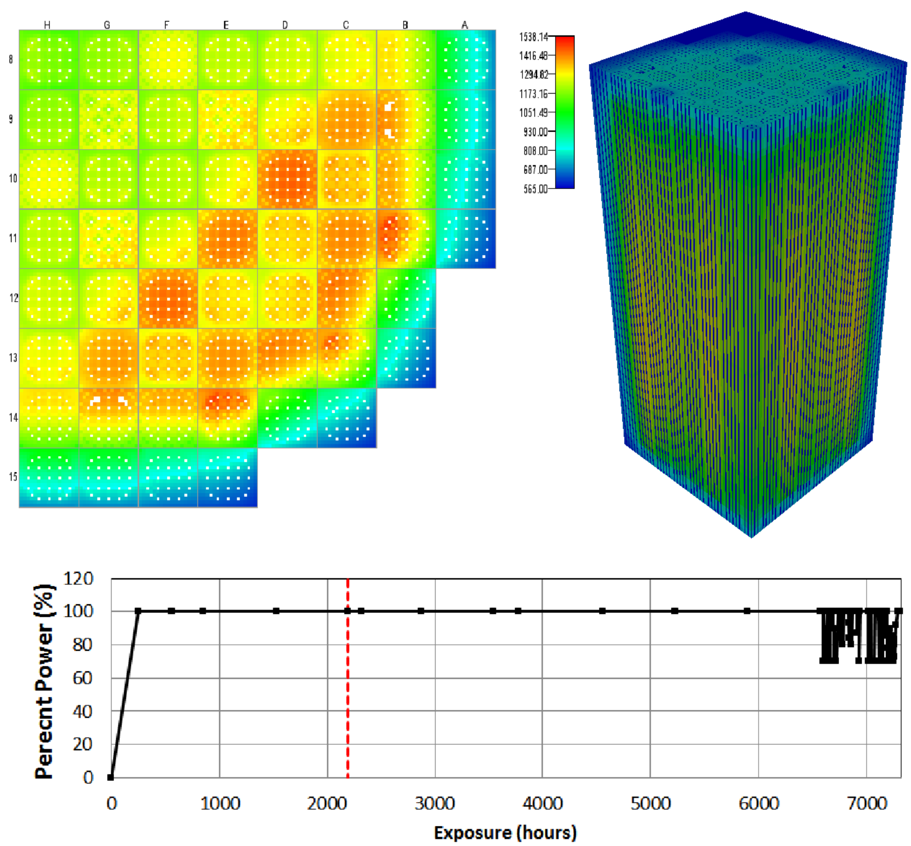
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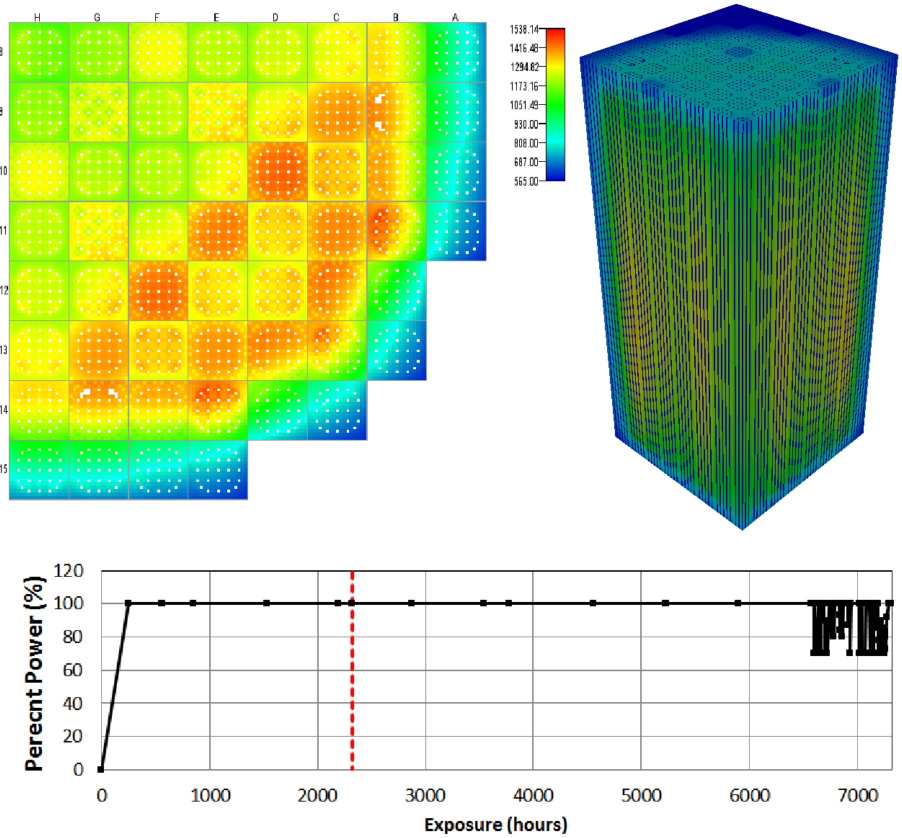
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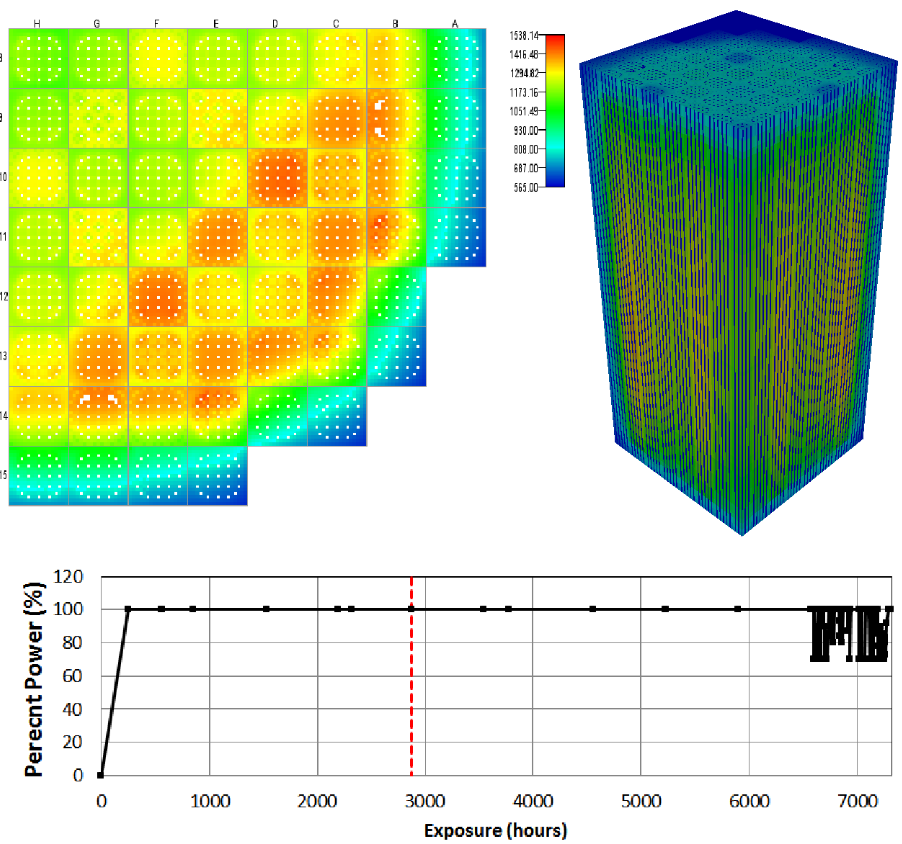
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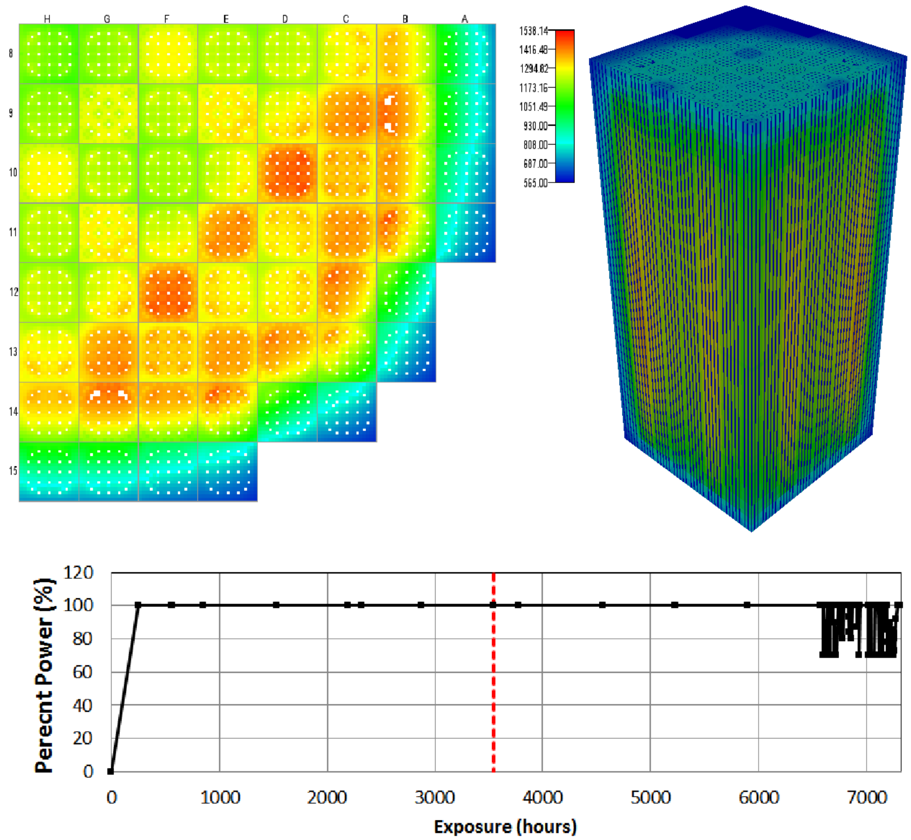
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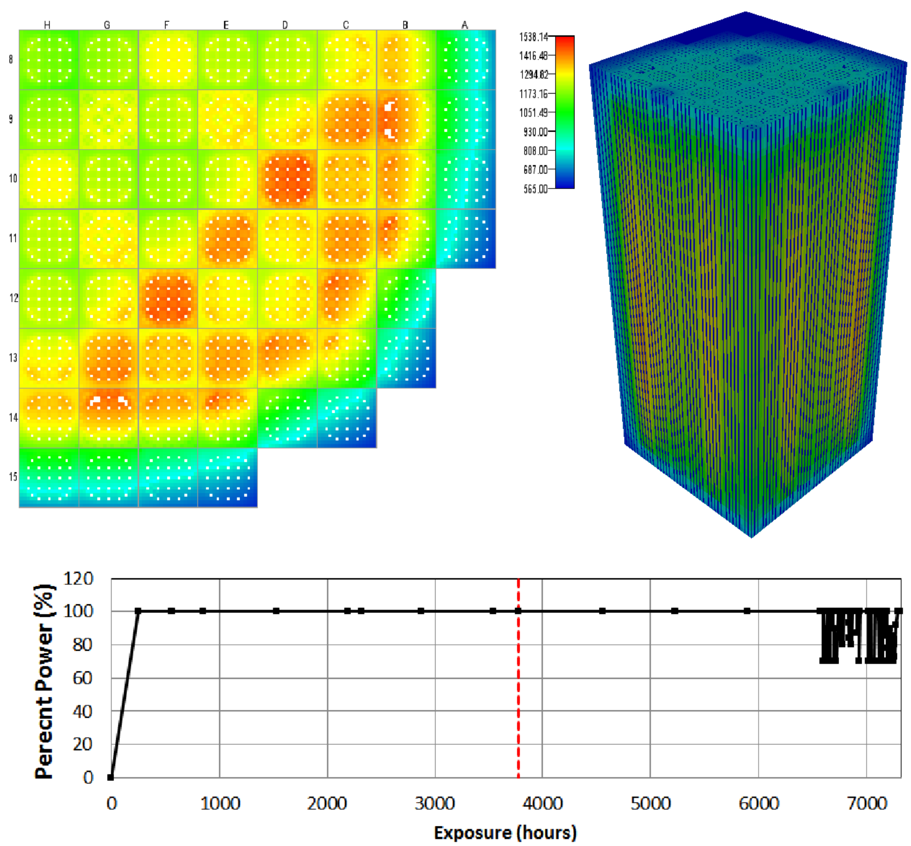
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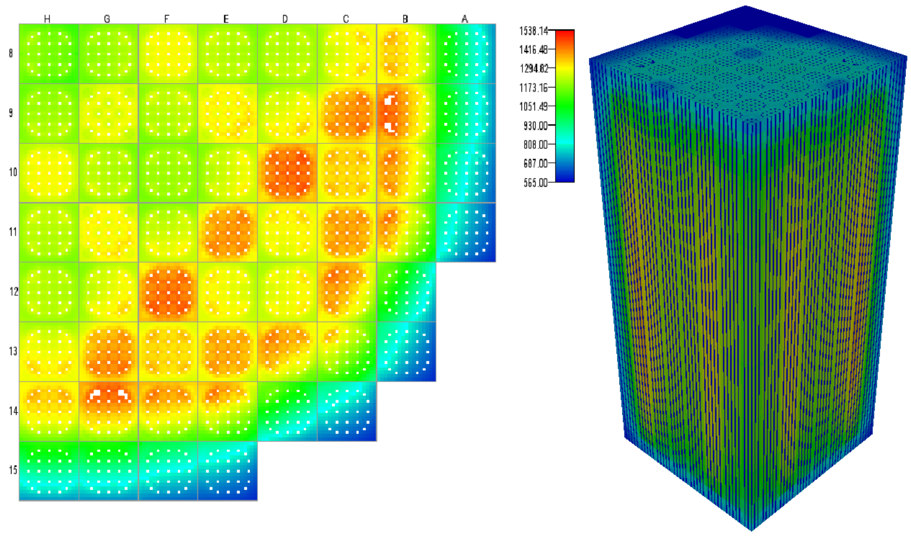

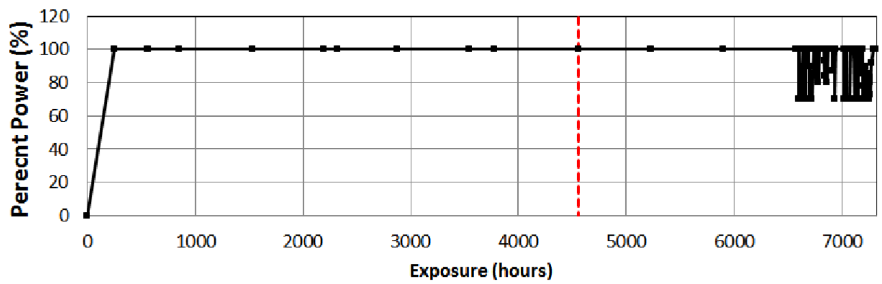
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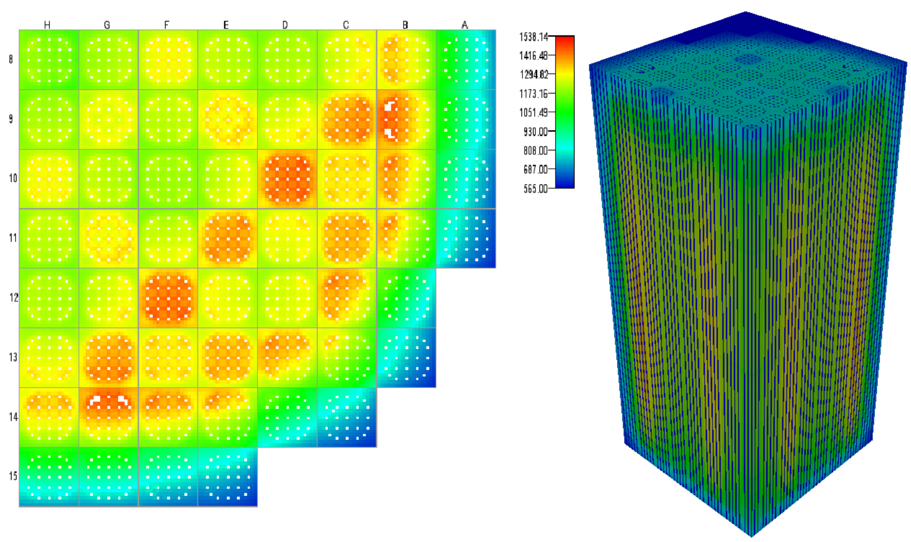

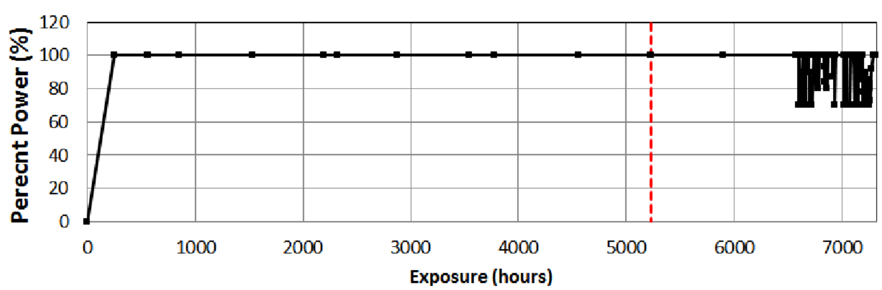
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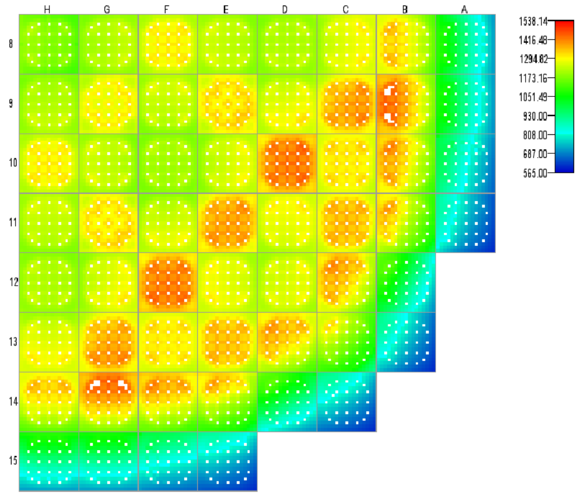
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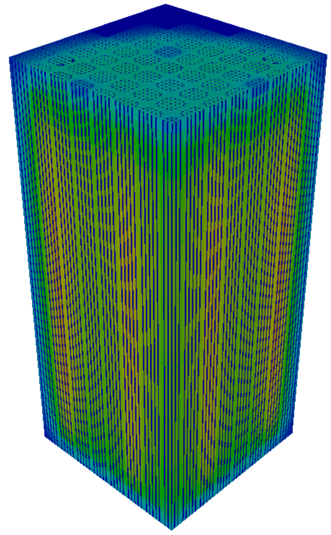

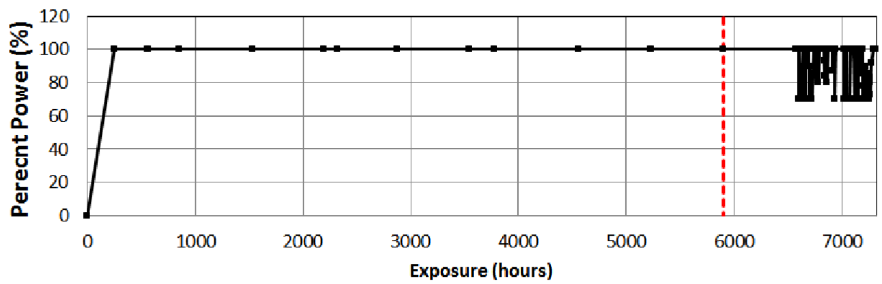
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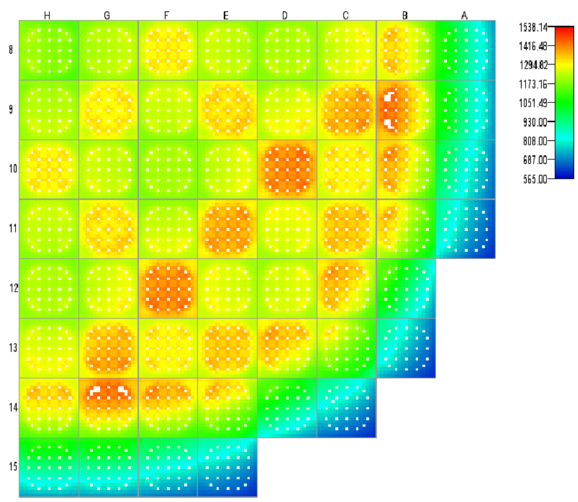
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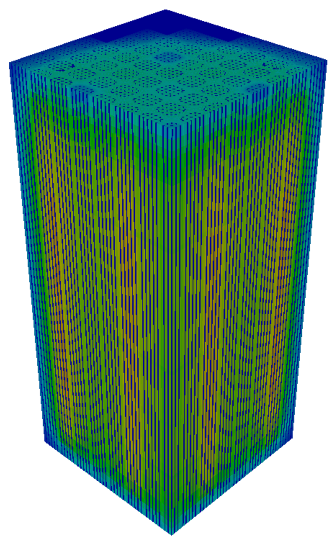

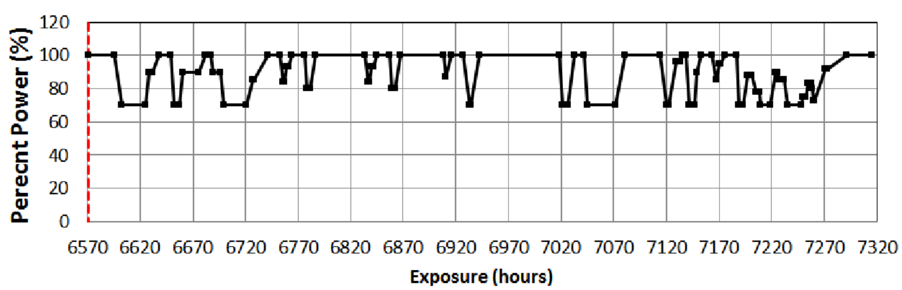
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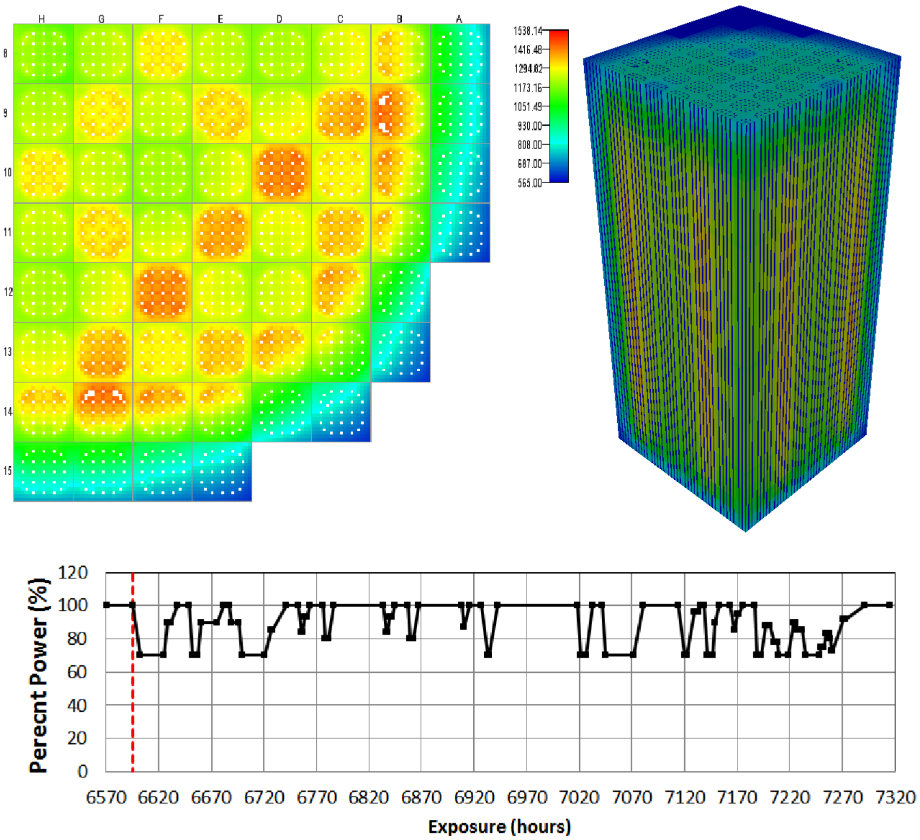
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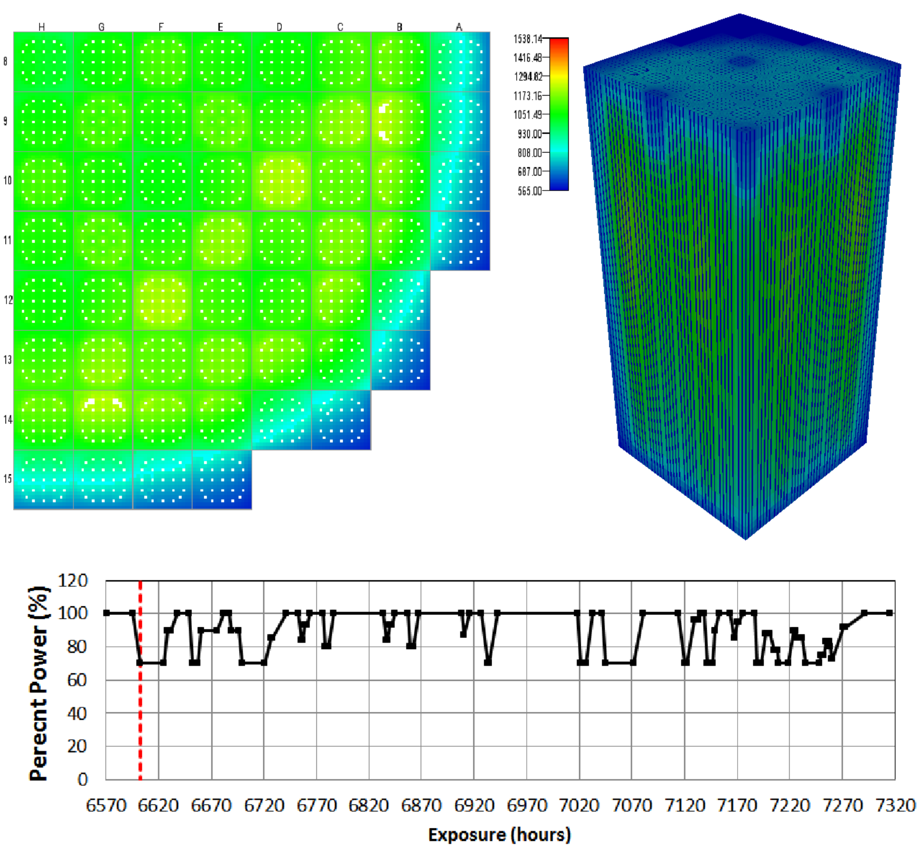
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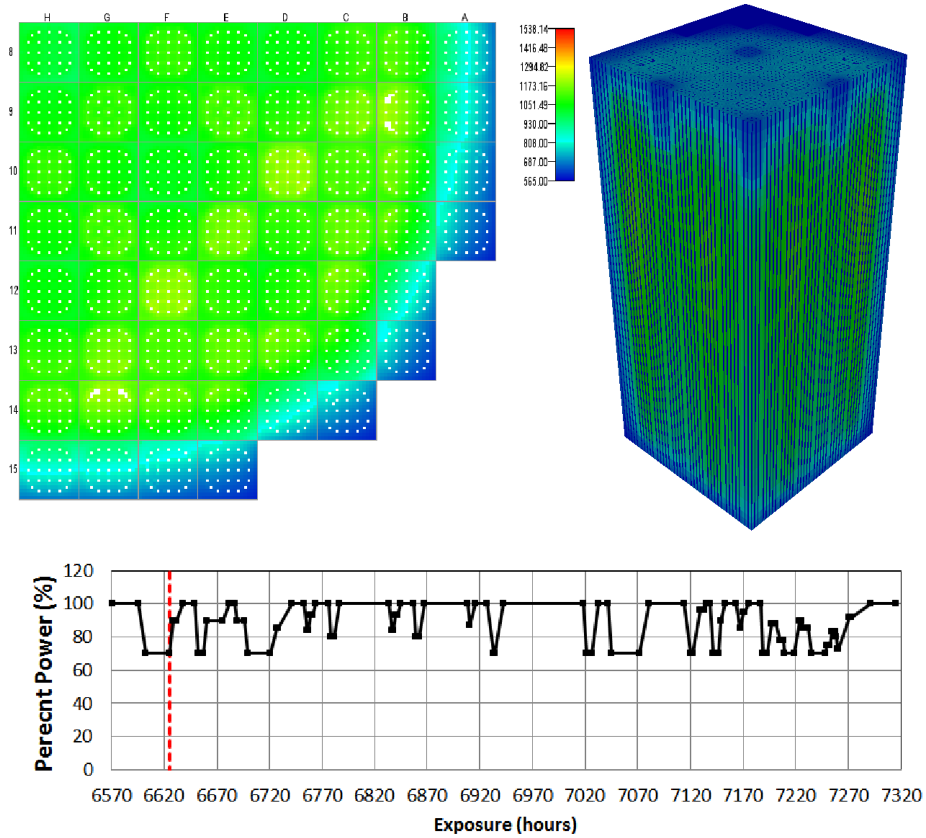
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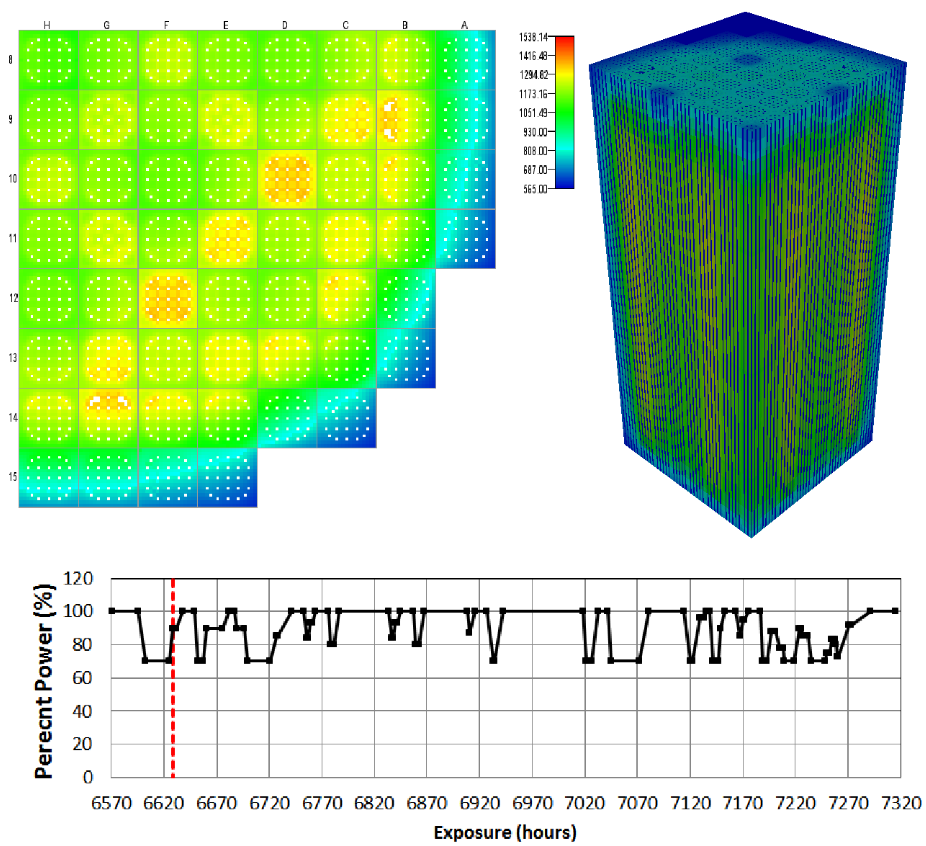
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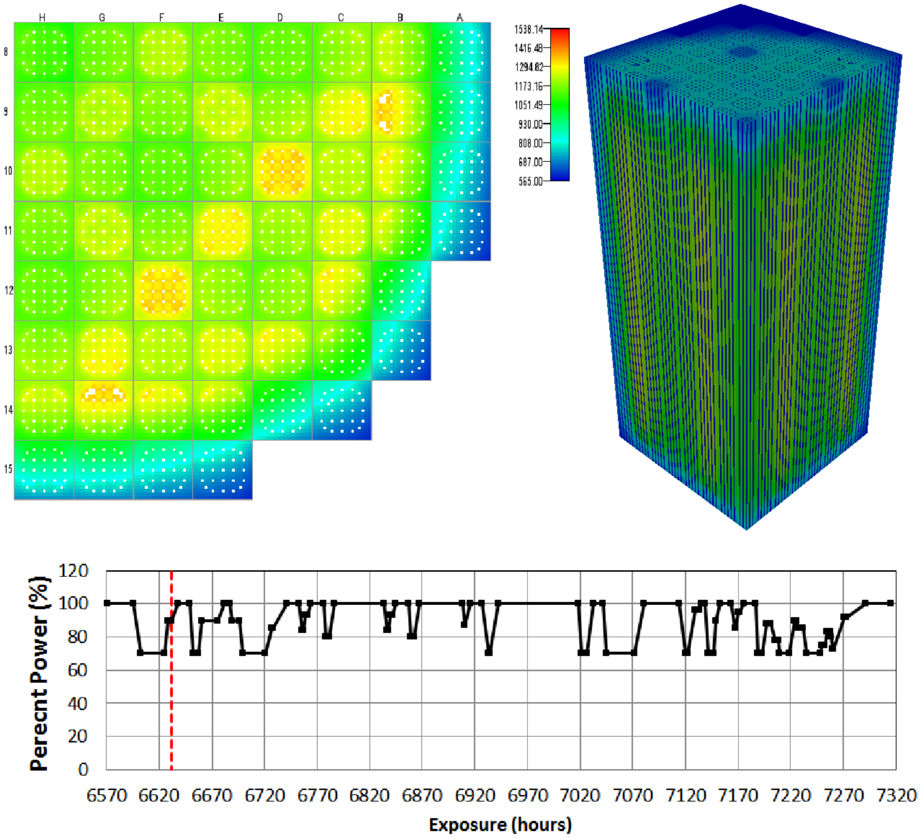
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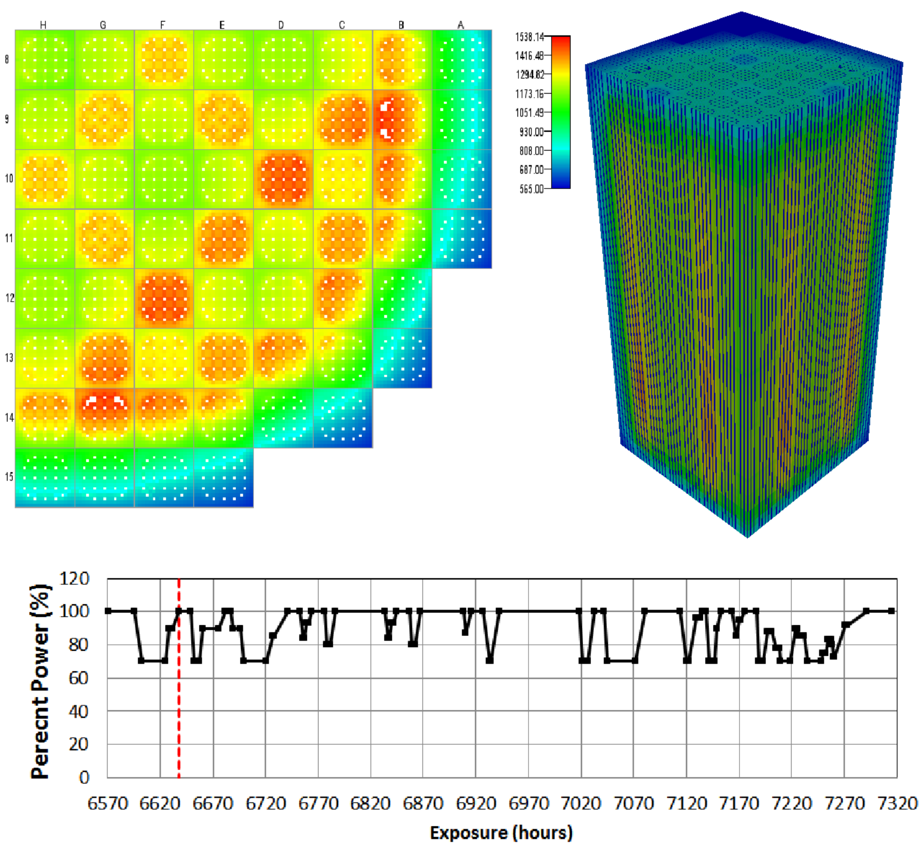
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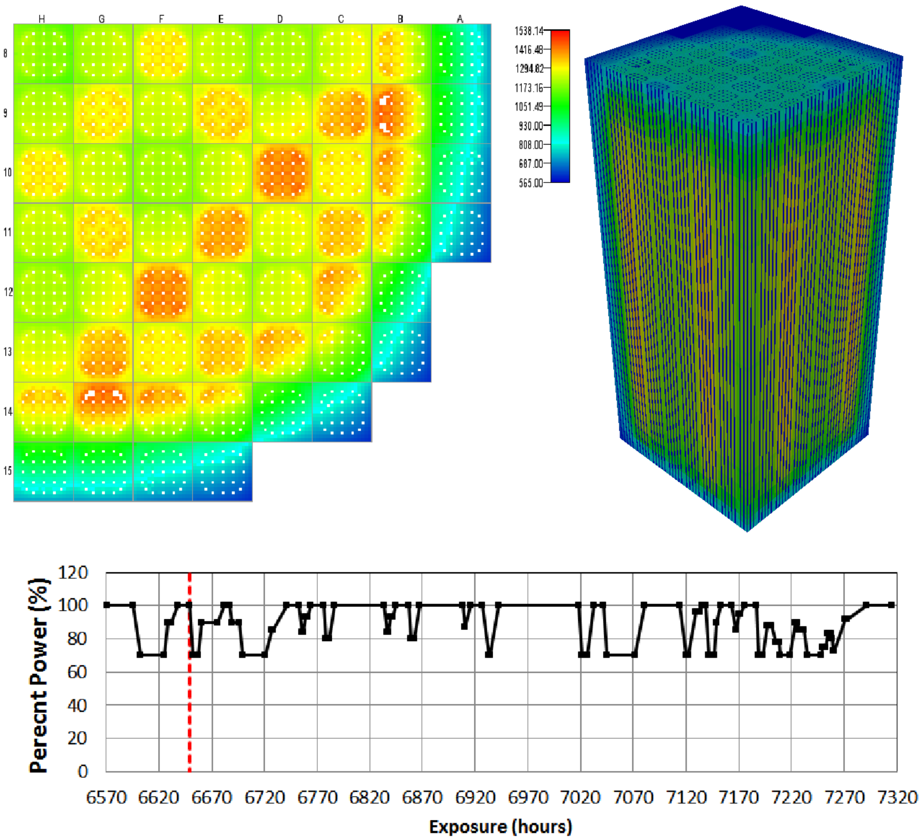
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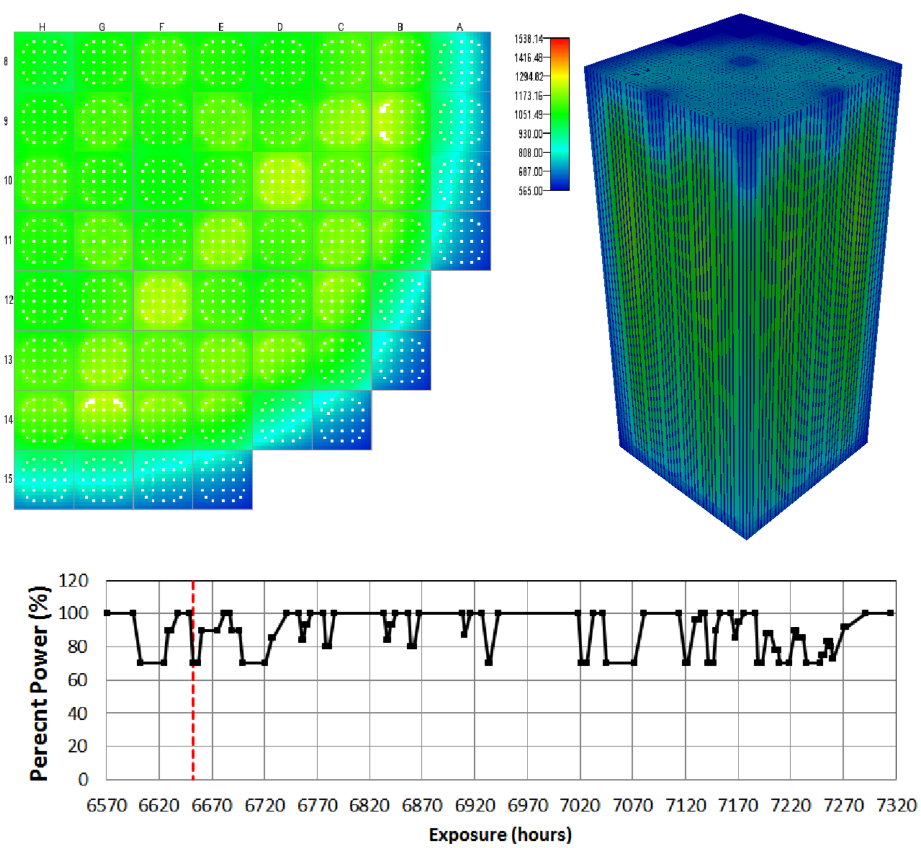
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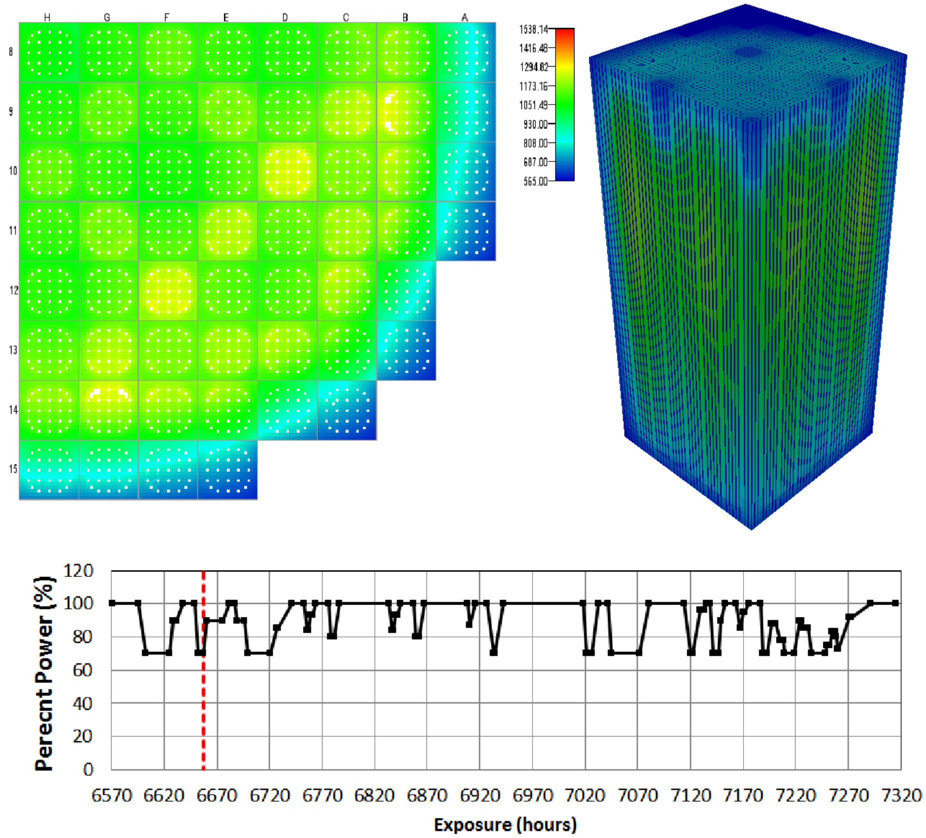
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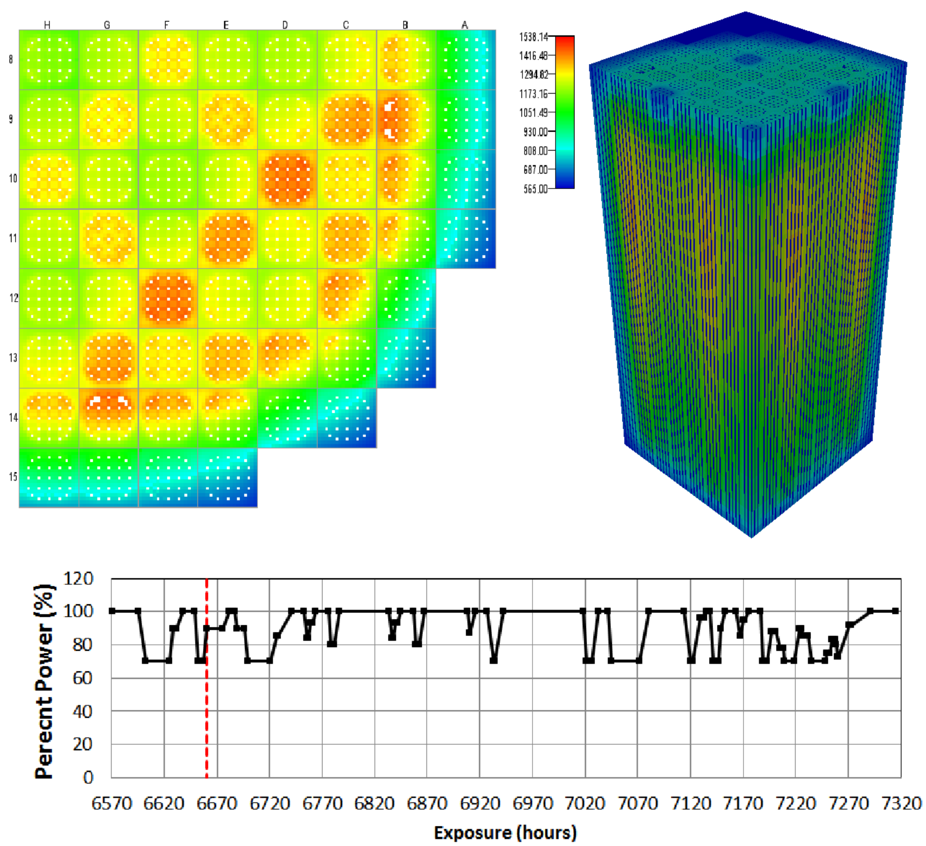
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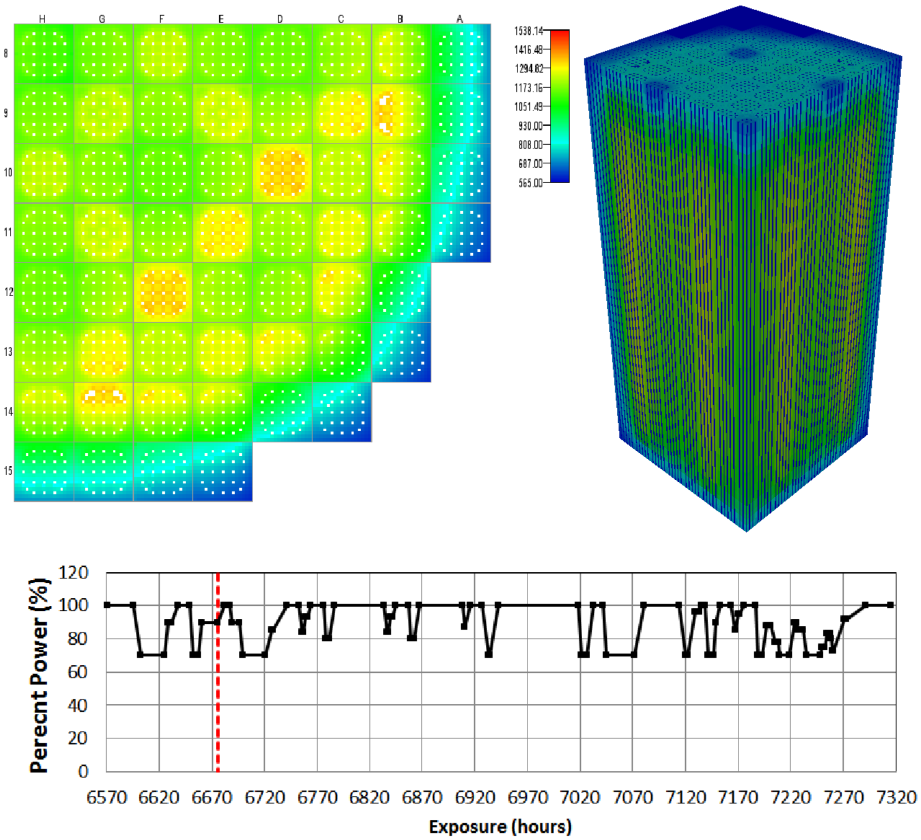
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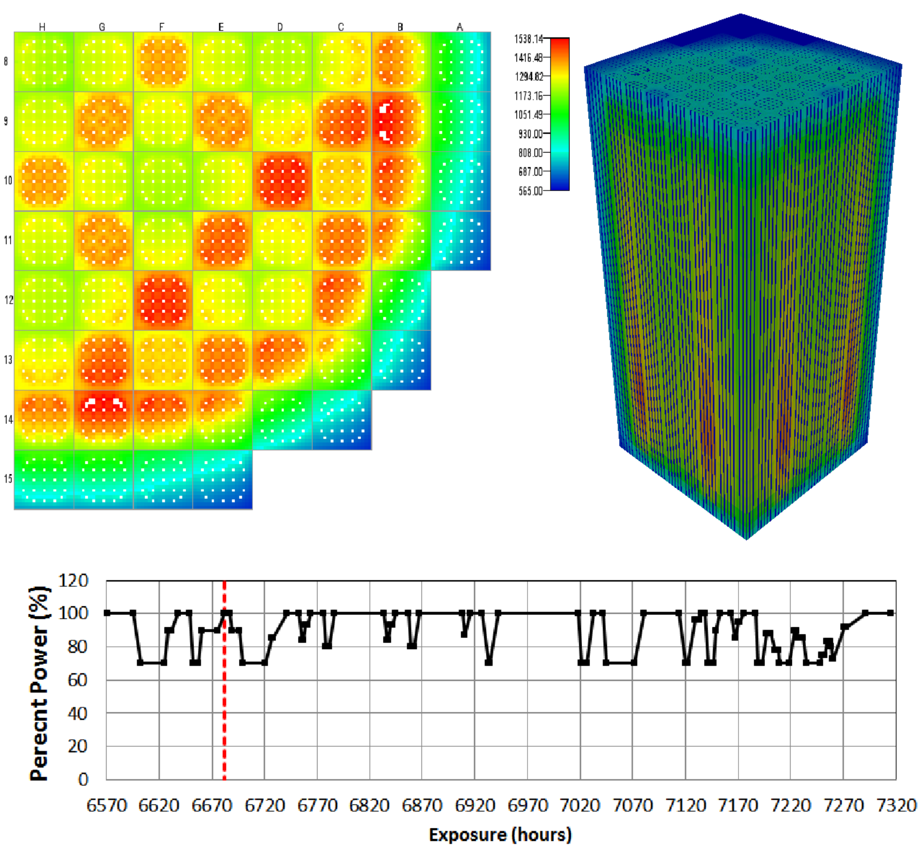
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1294.82
1173.16
1051.49
930.00
808.00
687.00
565.00
Perecnt Power (%)
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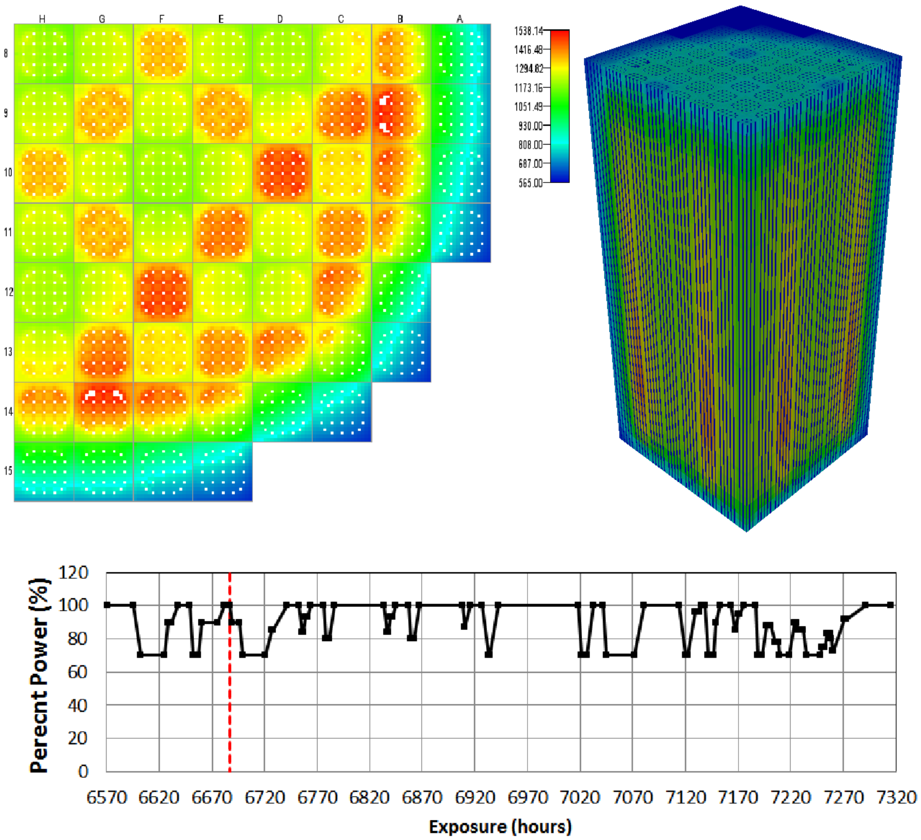
Exposure (hours)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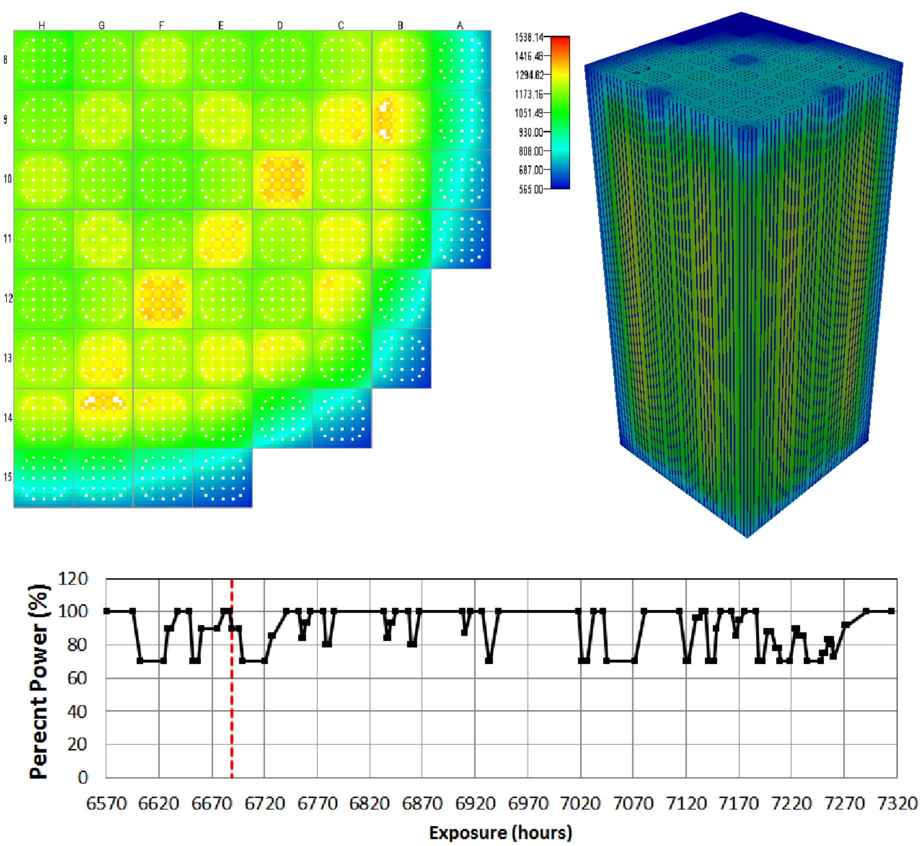
Perecnt Power (%)
Exposure (hours)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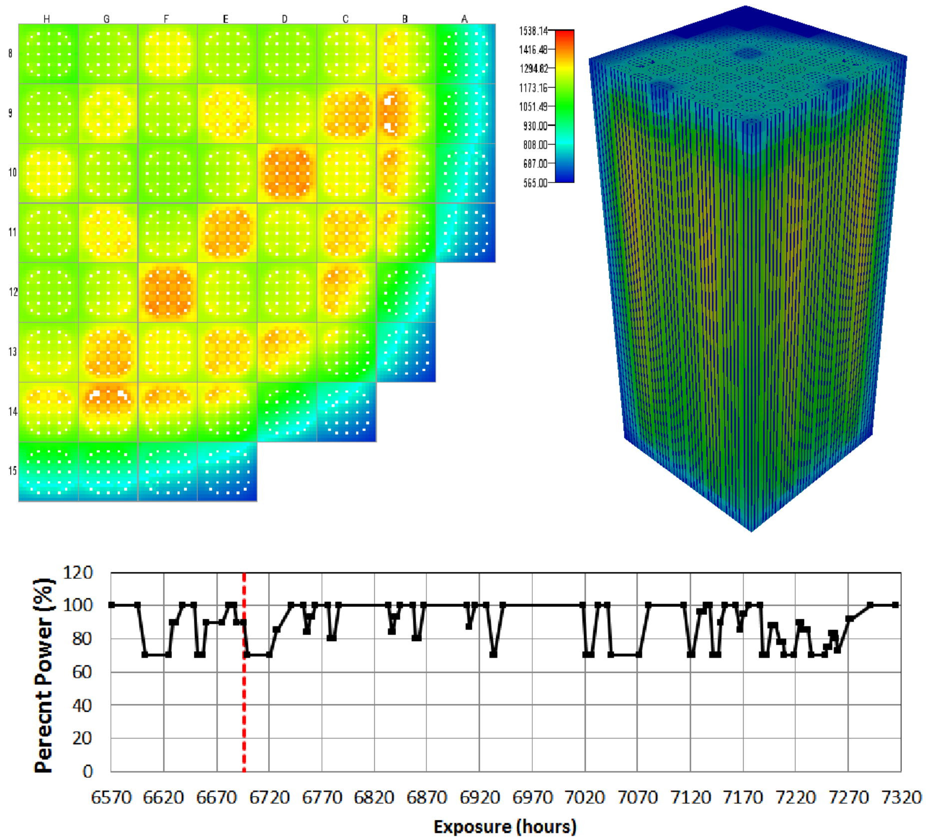
Perecnt Power (%)
Exposure (hours)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Perecnt Power (%)
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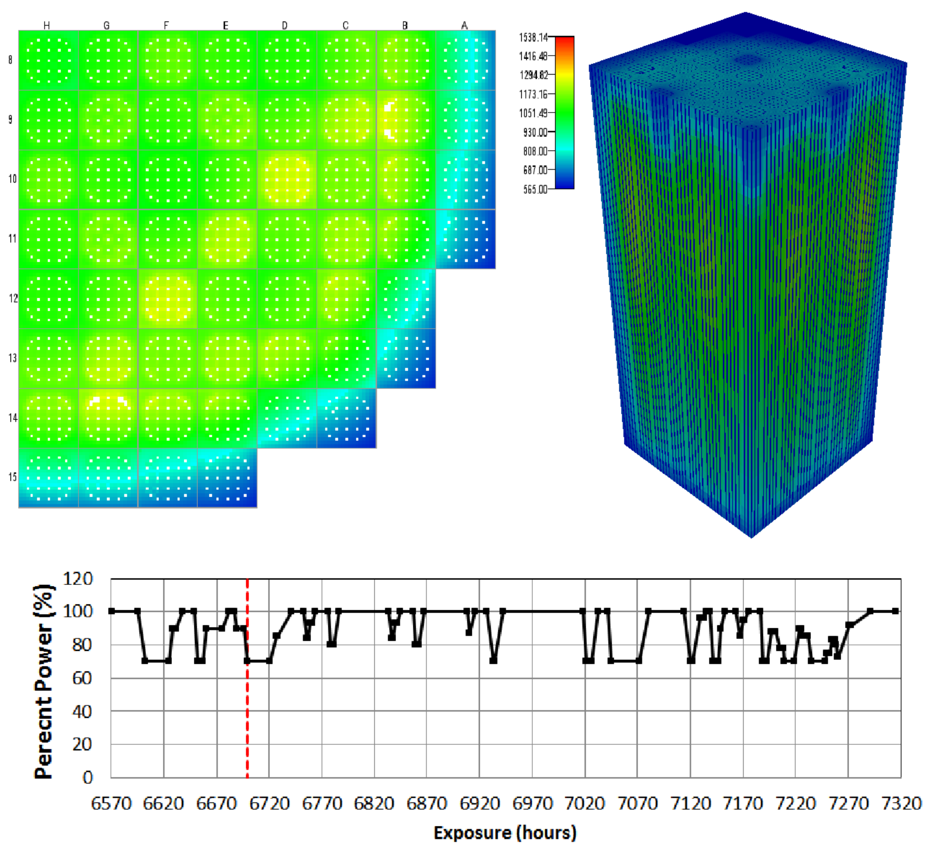
Exposure (hours)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Perecnt Power (%)
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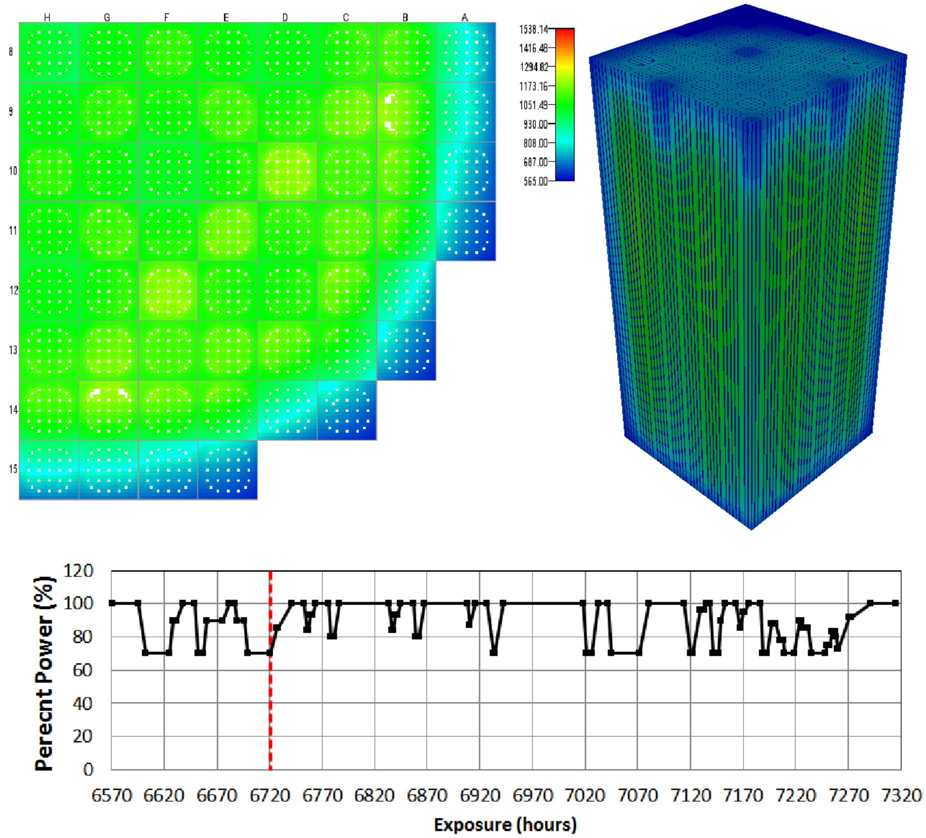
Exposure (hours)



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Perecnt Power (%)
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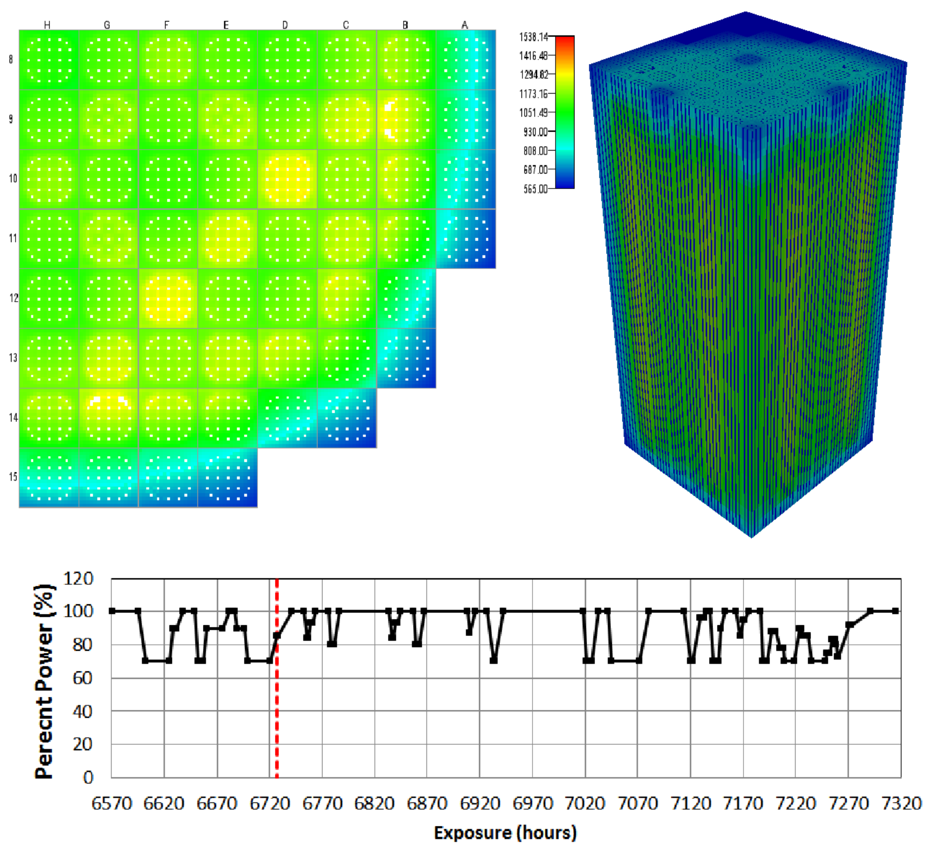
Exposure (hours)



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Perecnt Power (%)
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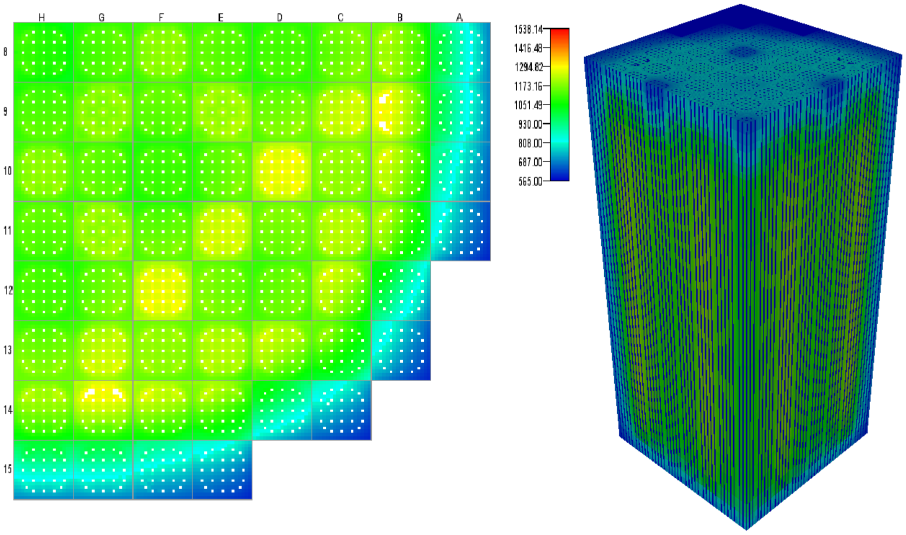
Exposure (hours)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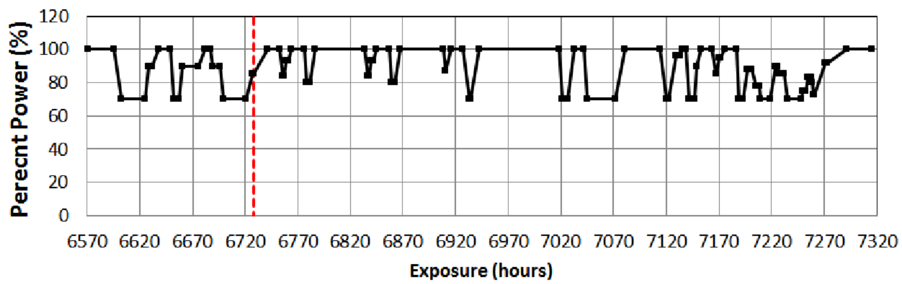
Perecnt Power (%)
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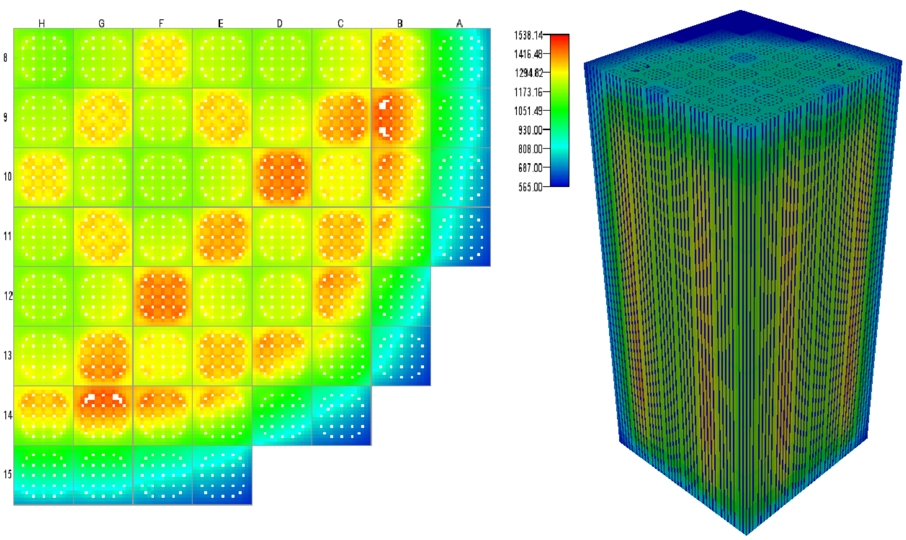
Exposure (hours)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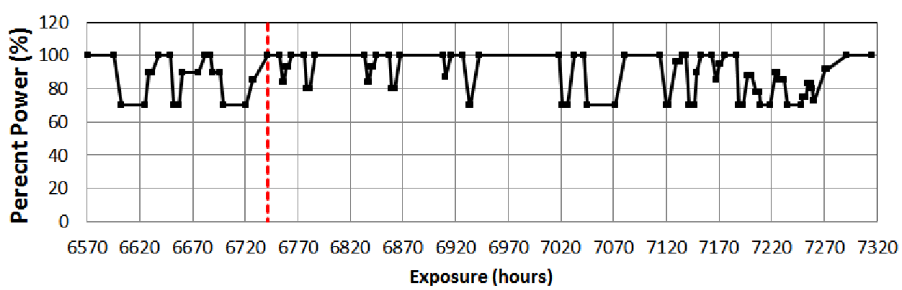
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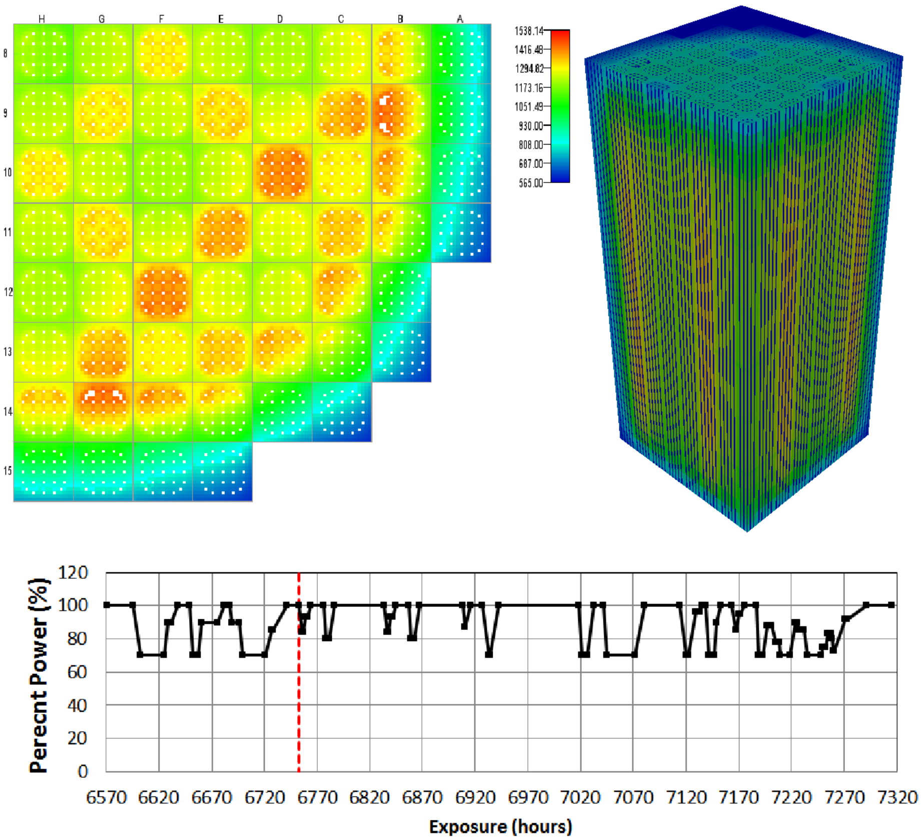
Exposure (hours)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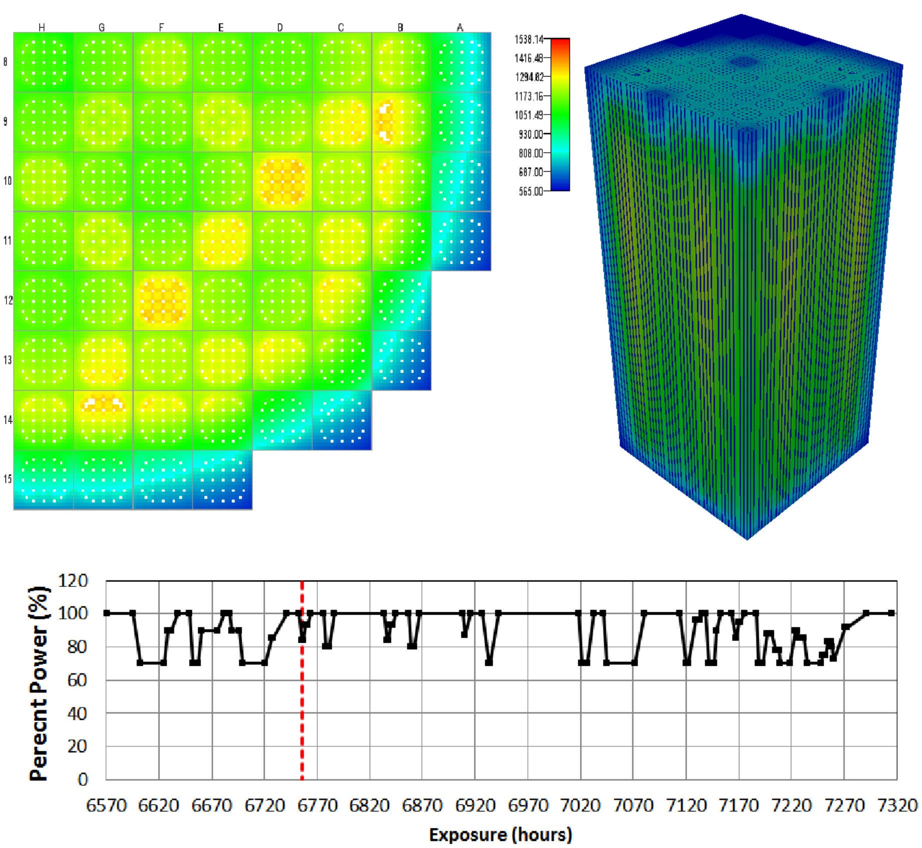
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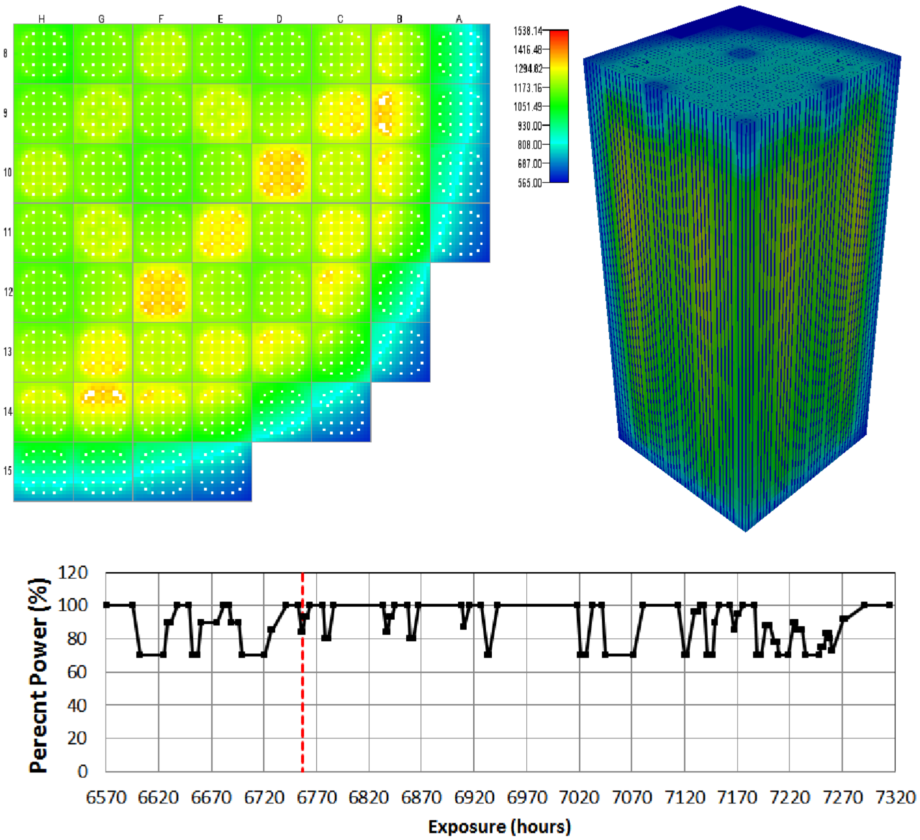
Exposure (hours)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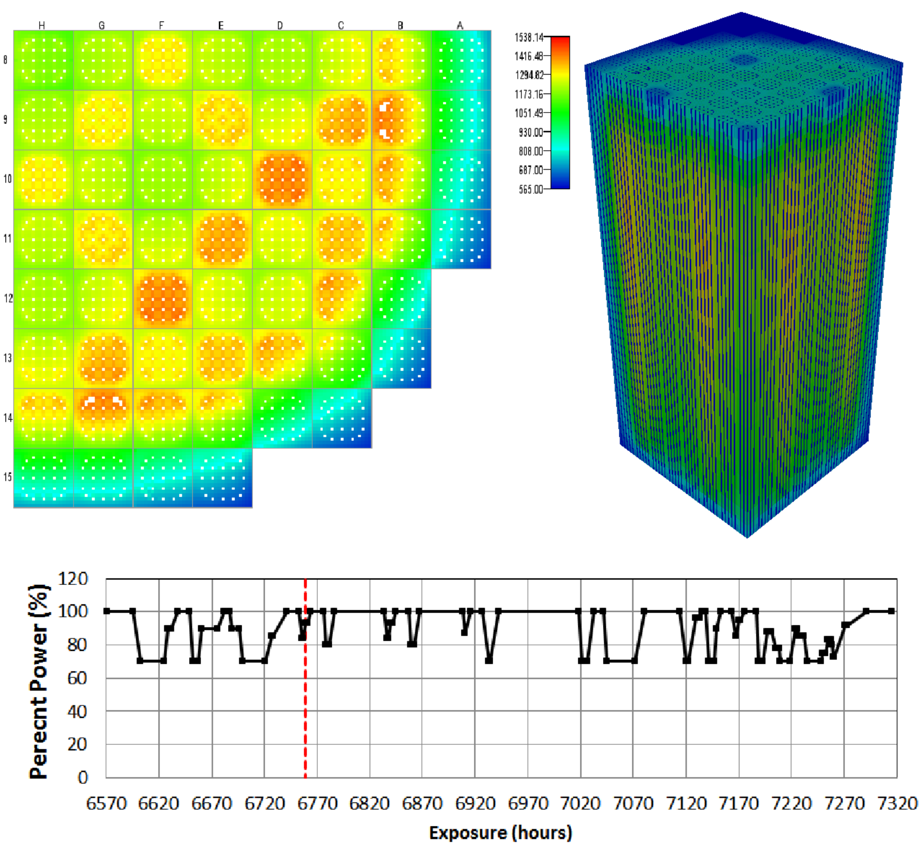
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Perecnt Power (%)
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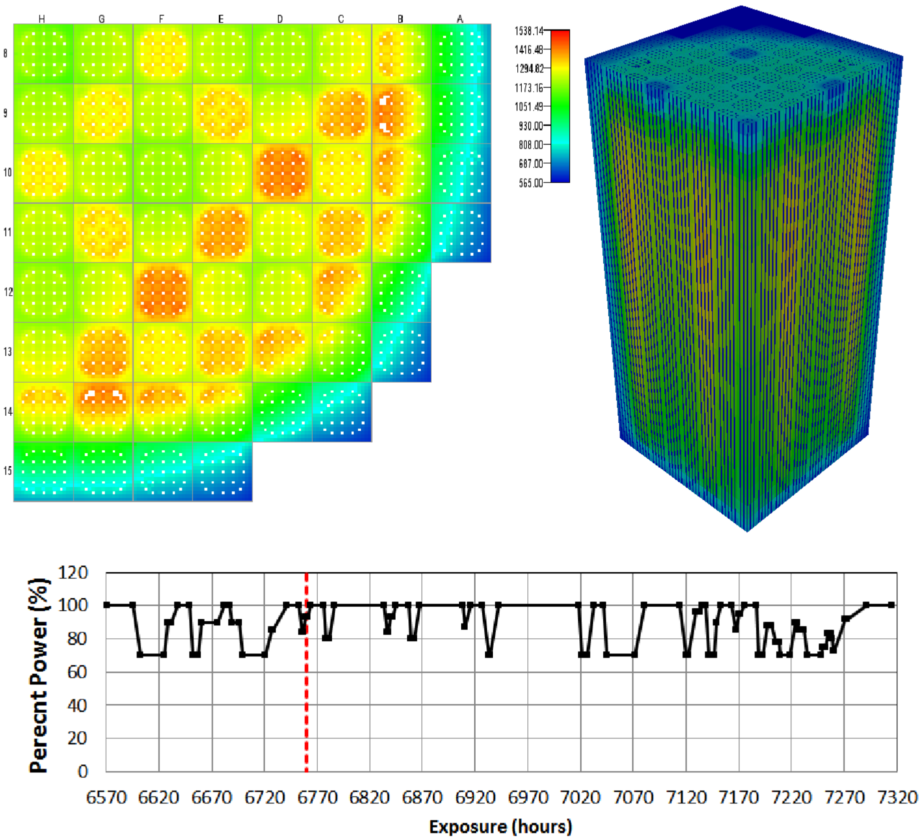
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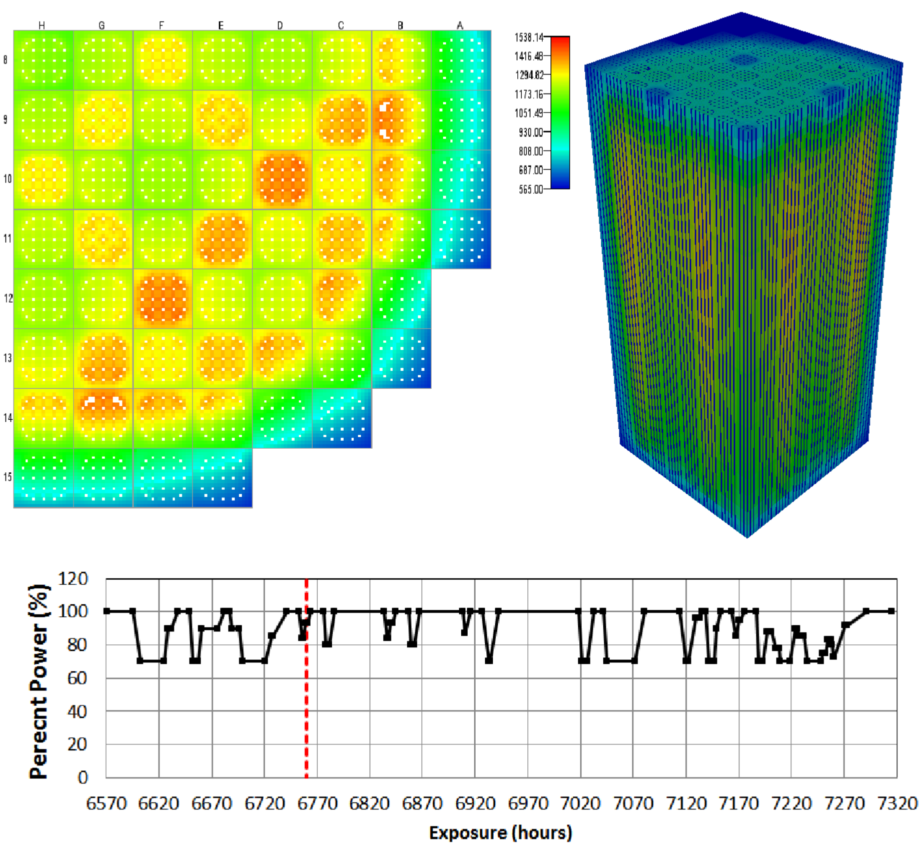
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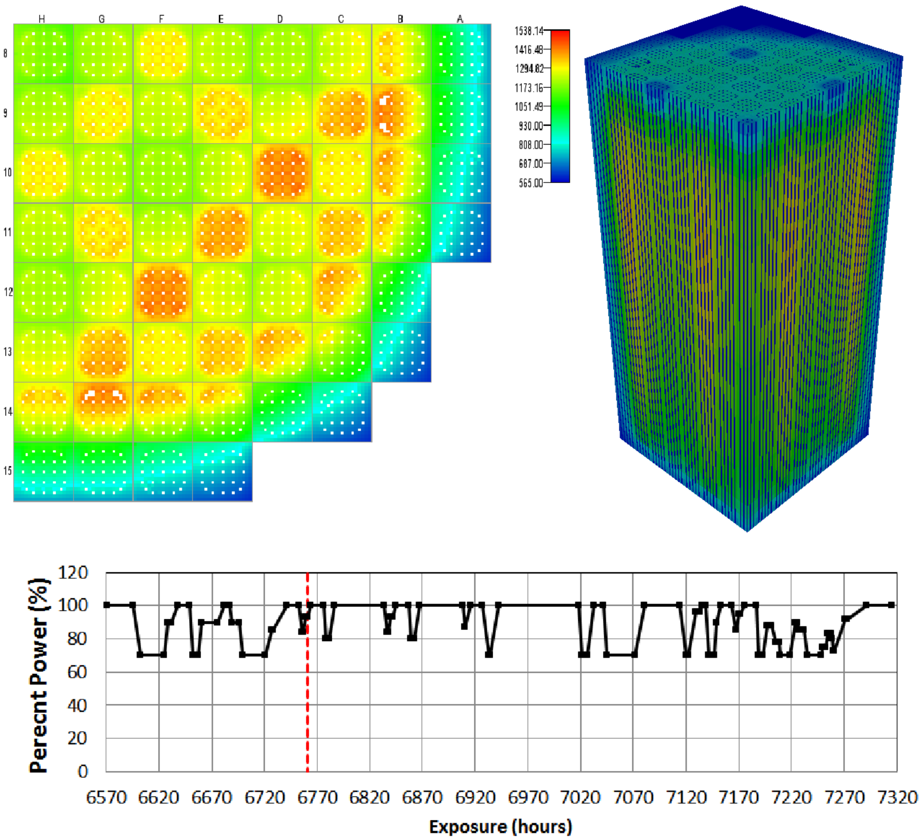
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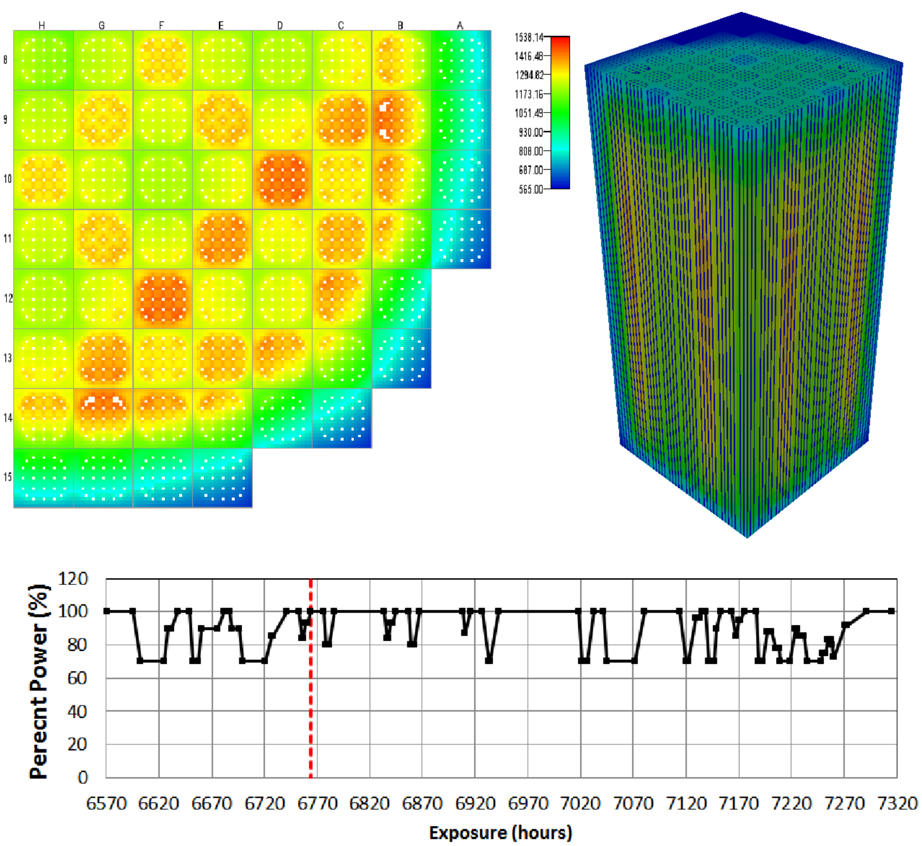
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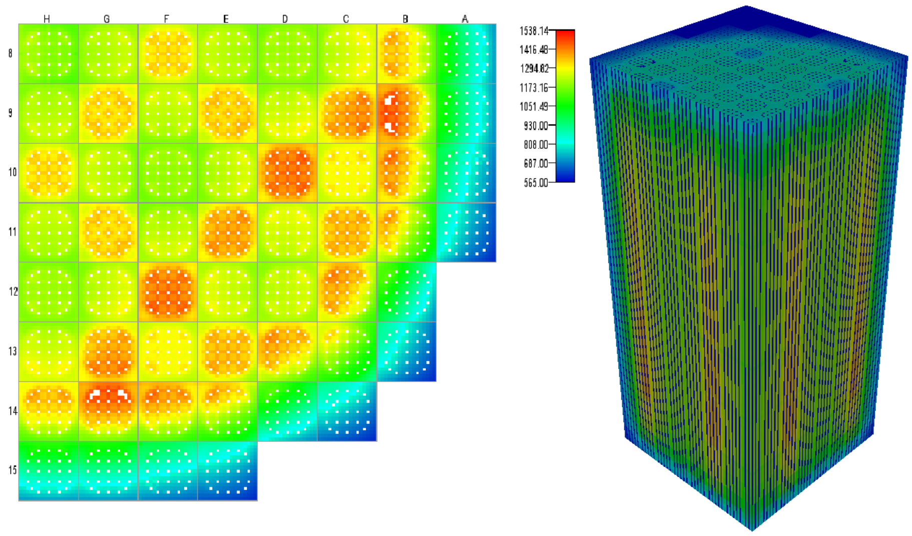

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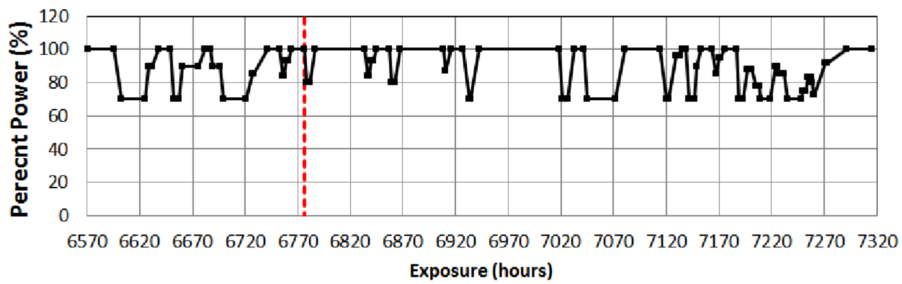

Perecnt Power (%)
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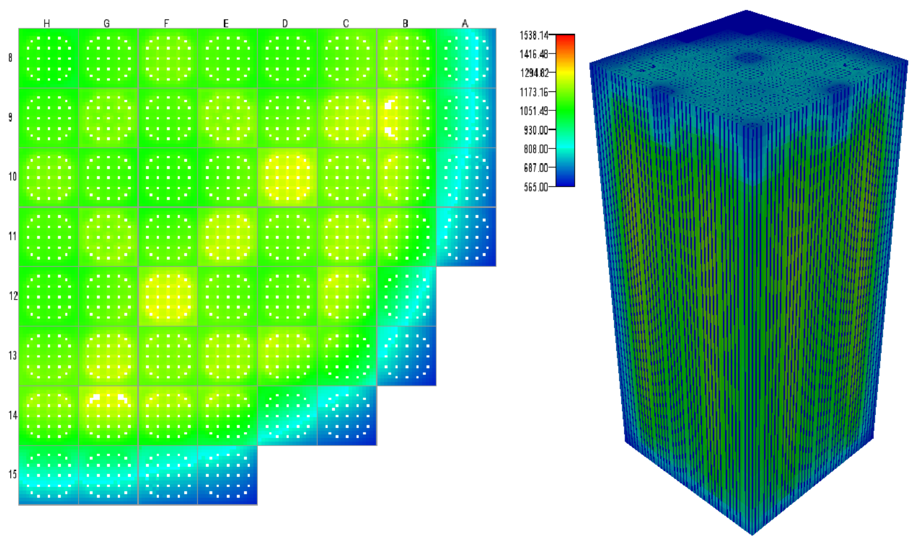

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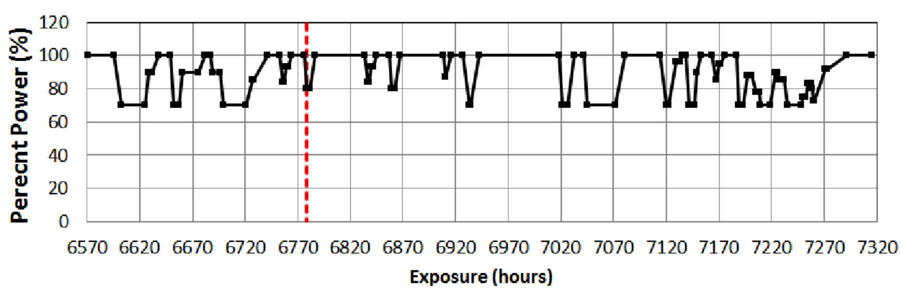

Perecnt Power (%)
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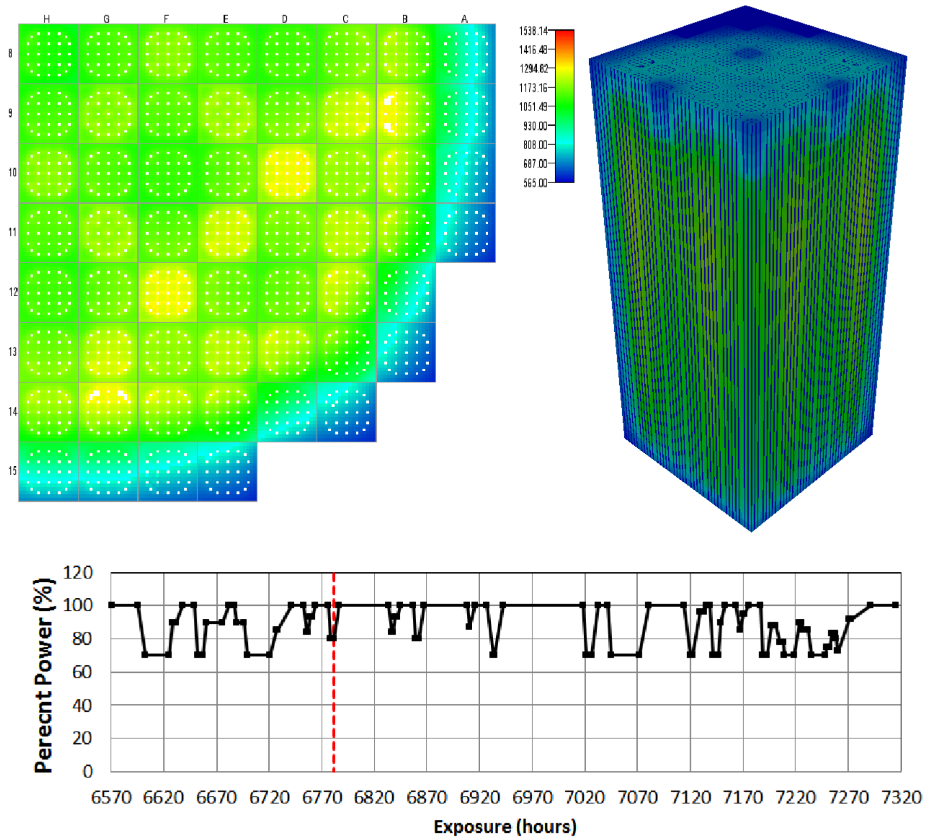
Exposure (hours)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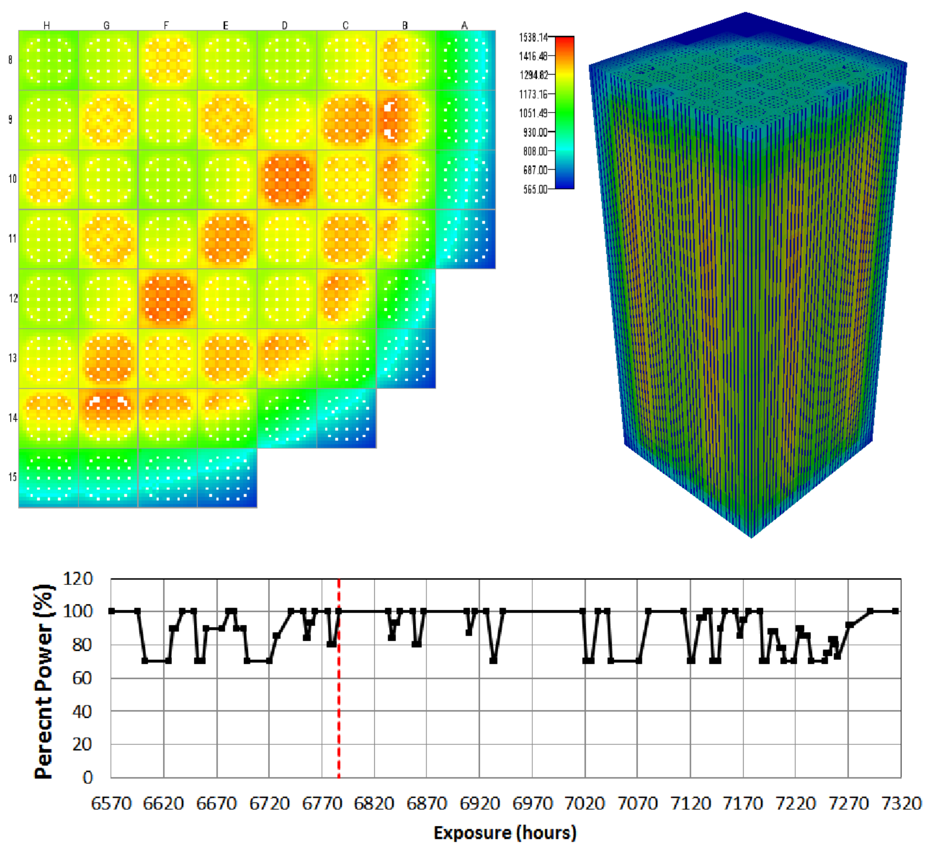
Exposure (hours)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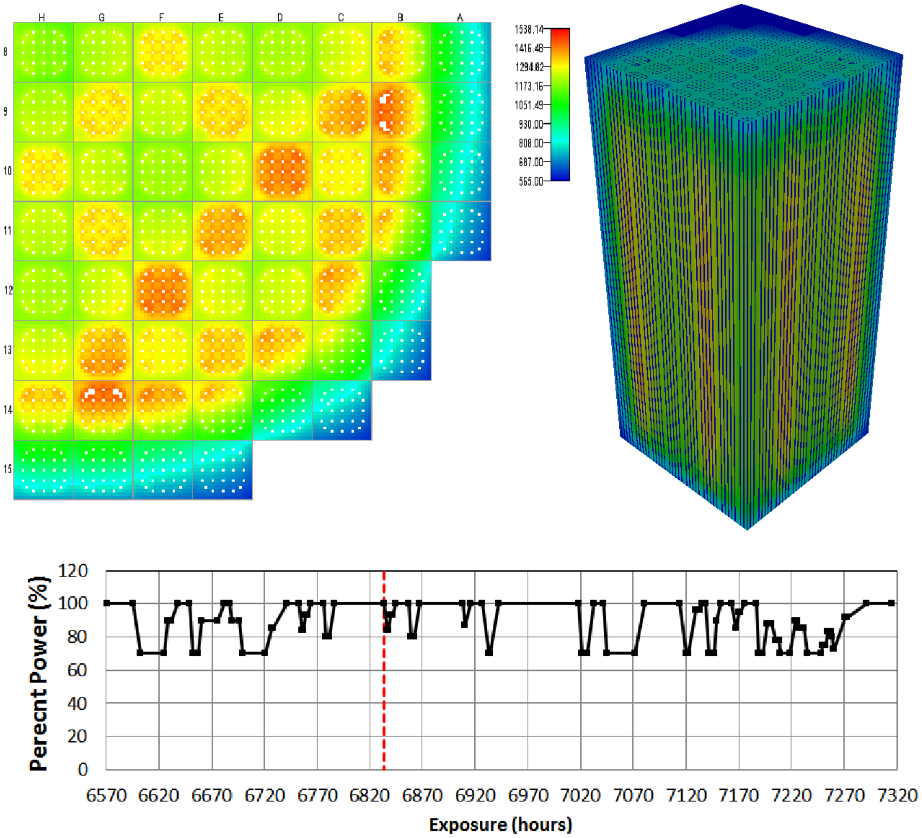
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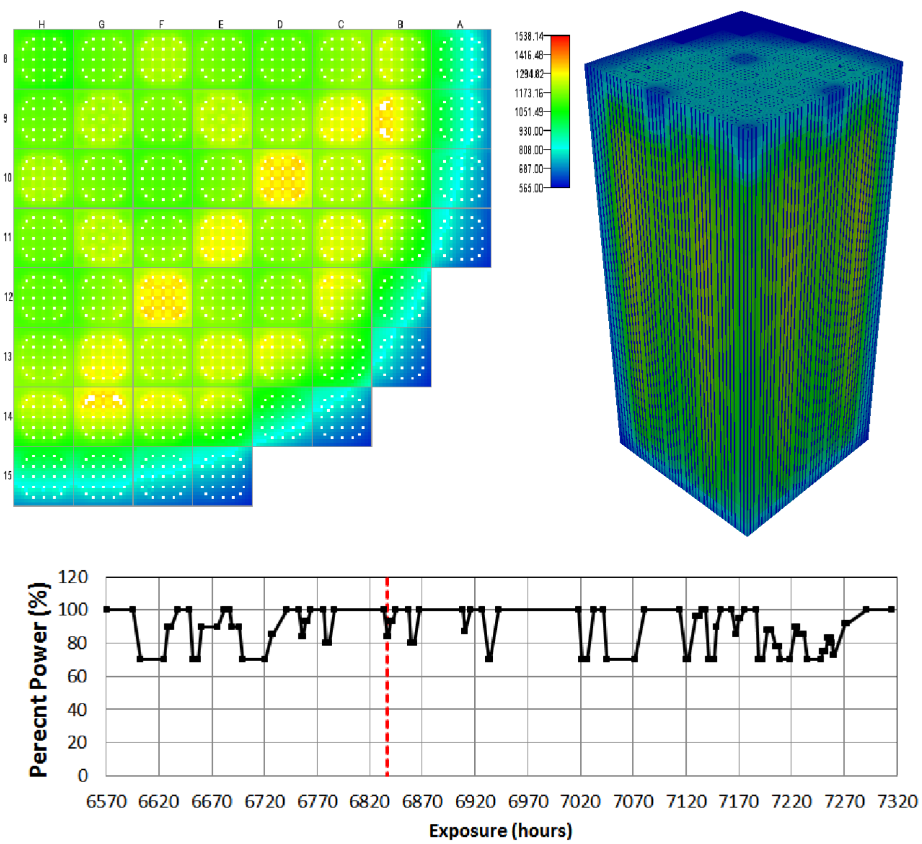
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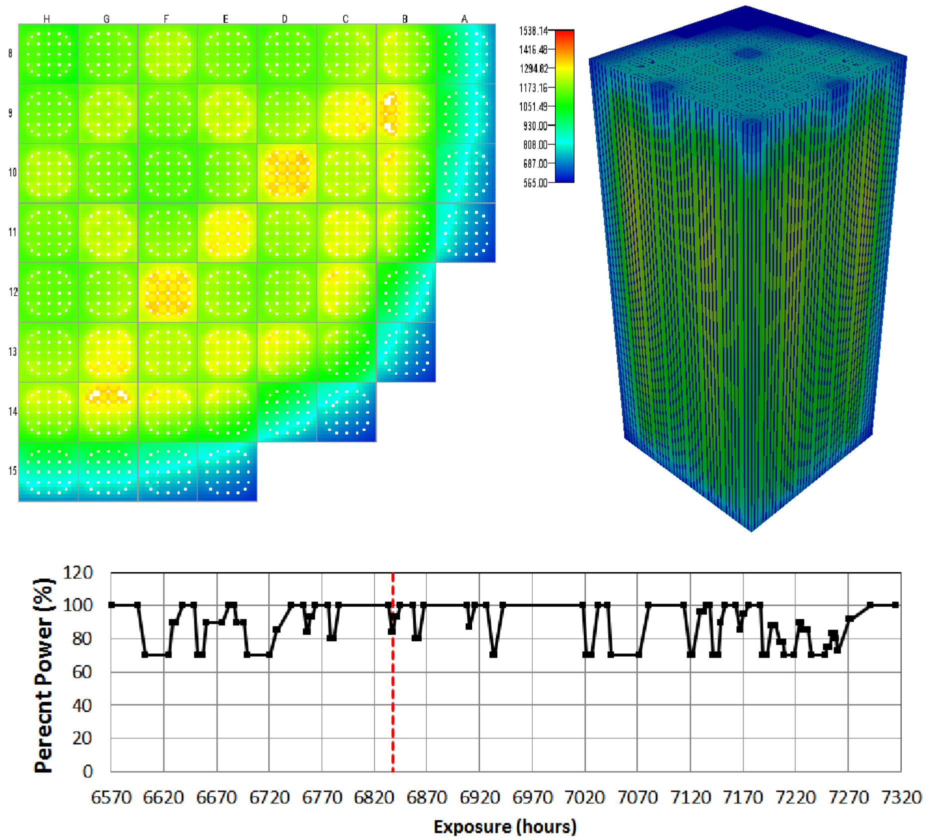
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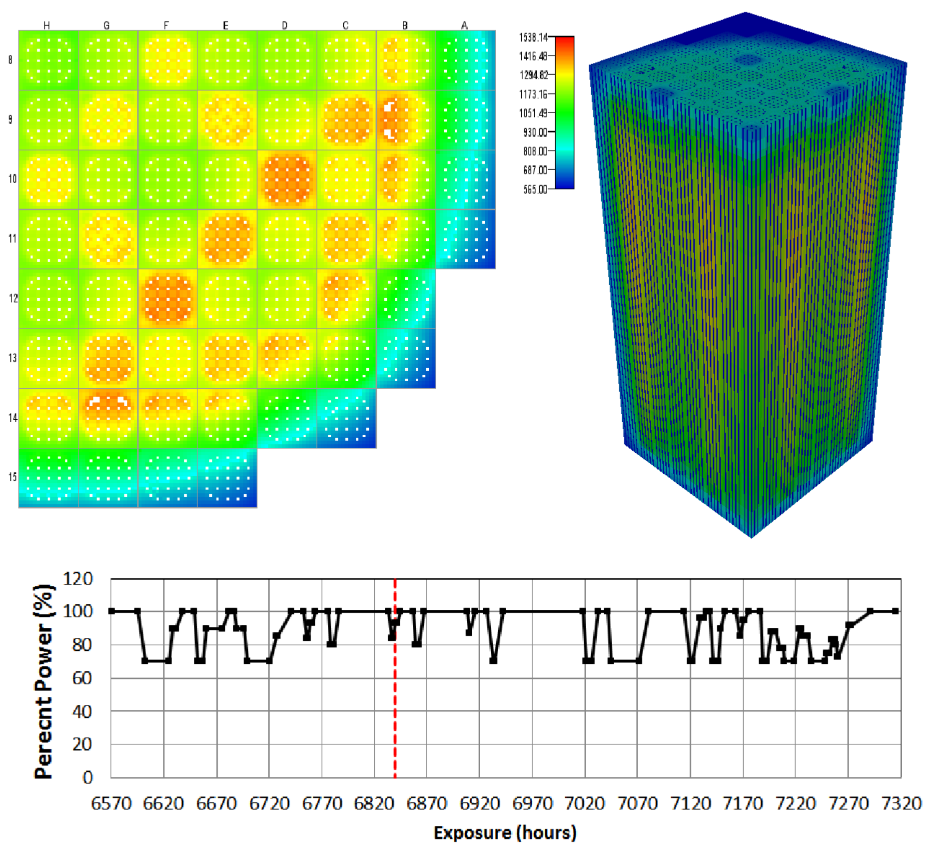
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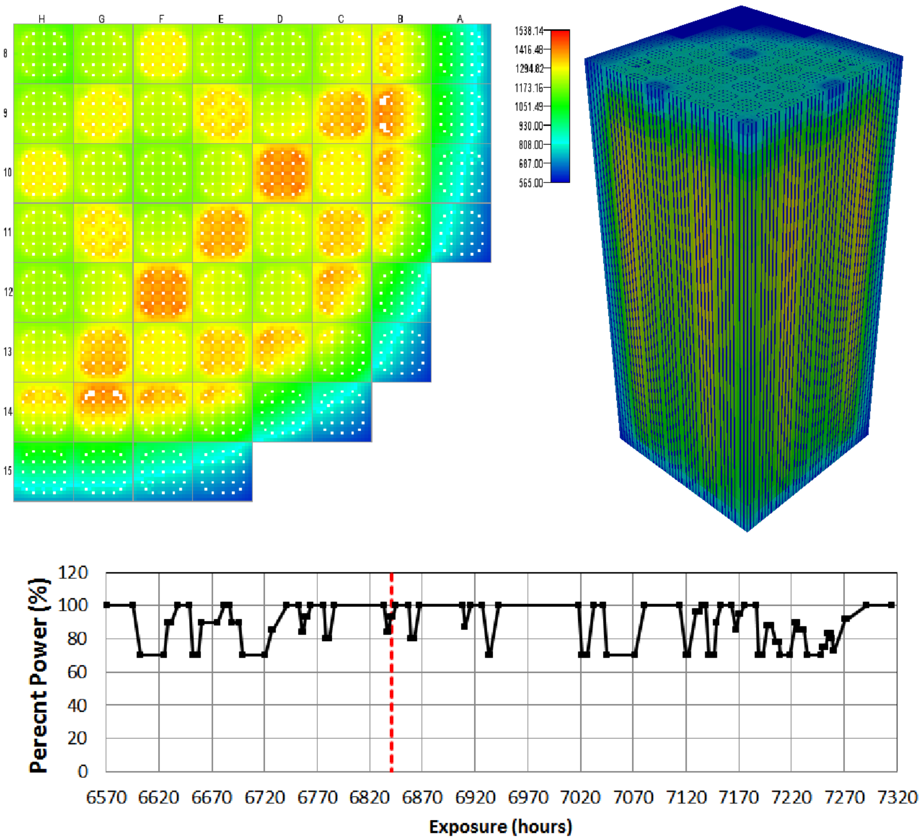
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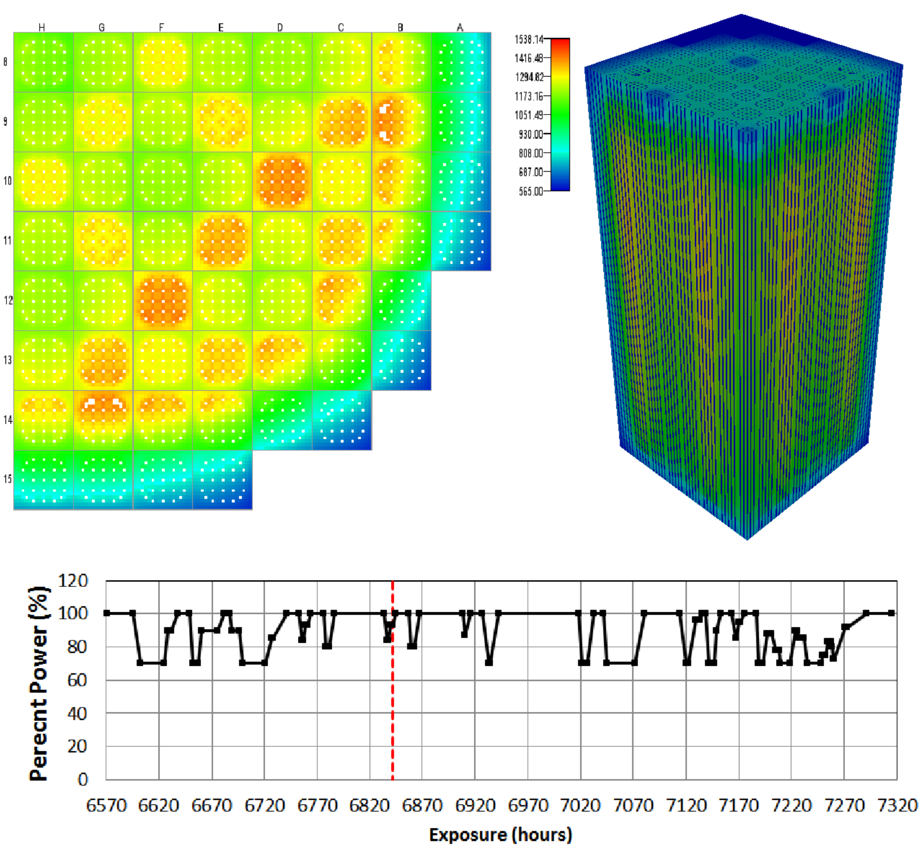
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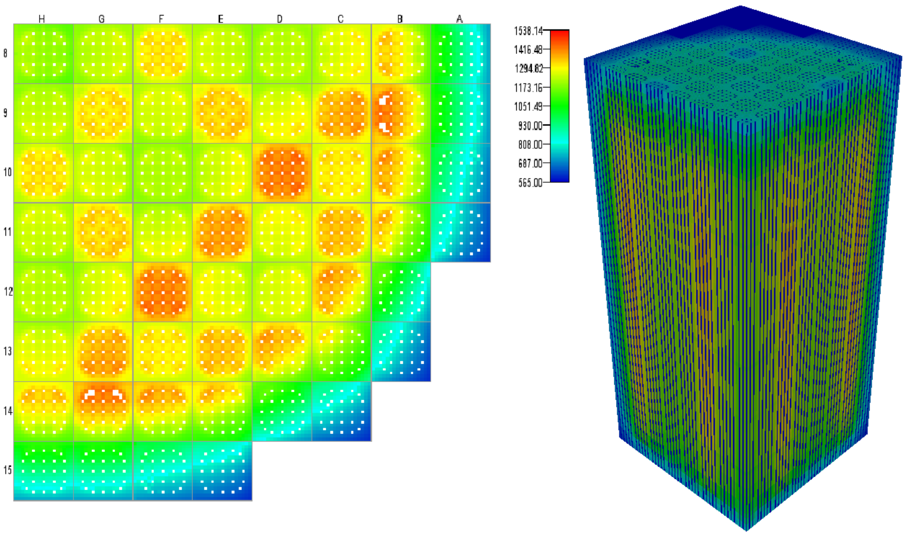

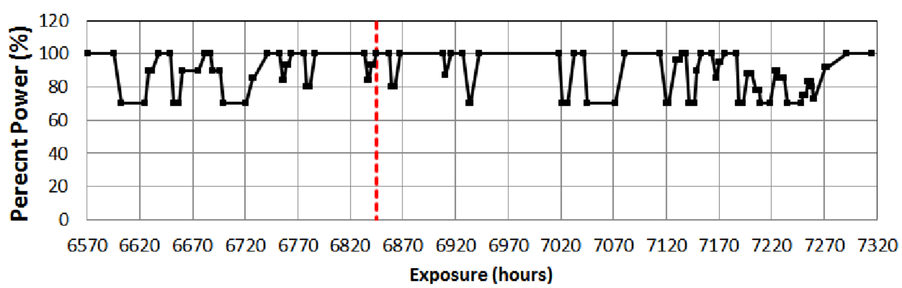
Perecnt Power (%)
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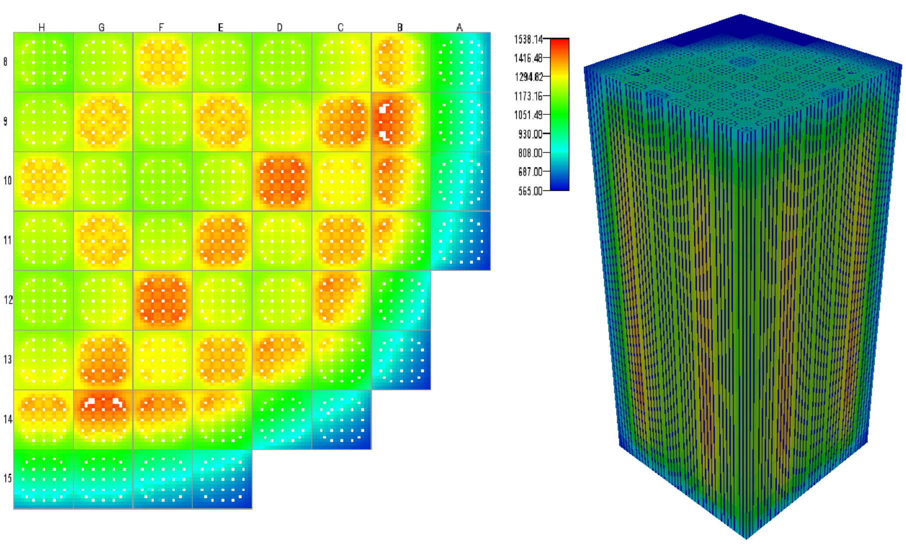

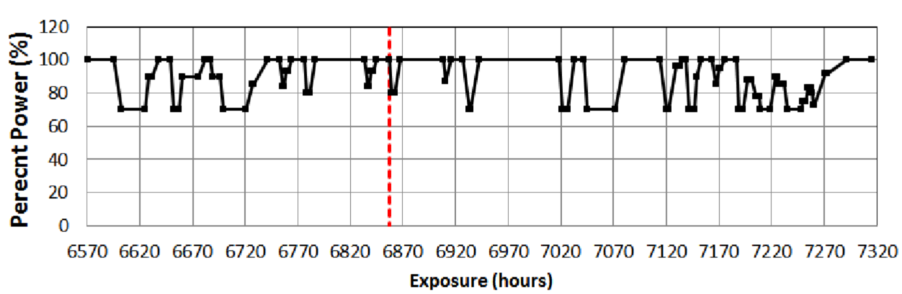
Perecnt Power (%)
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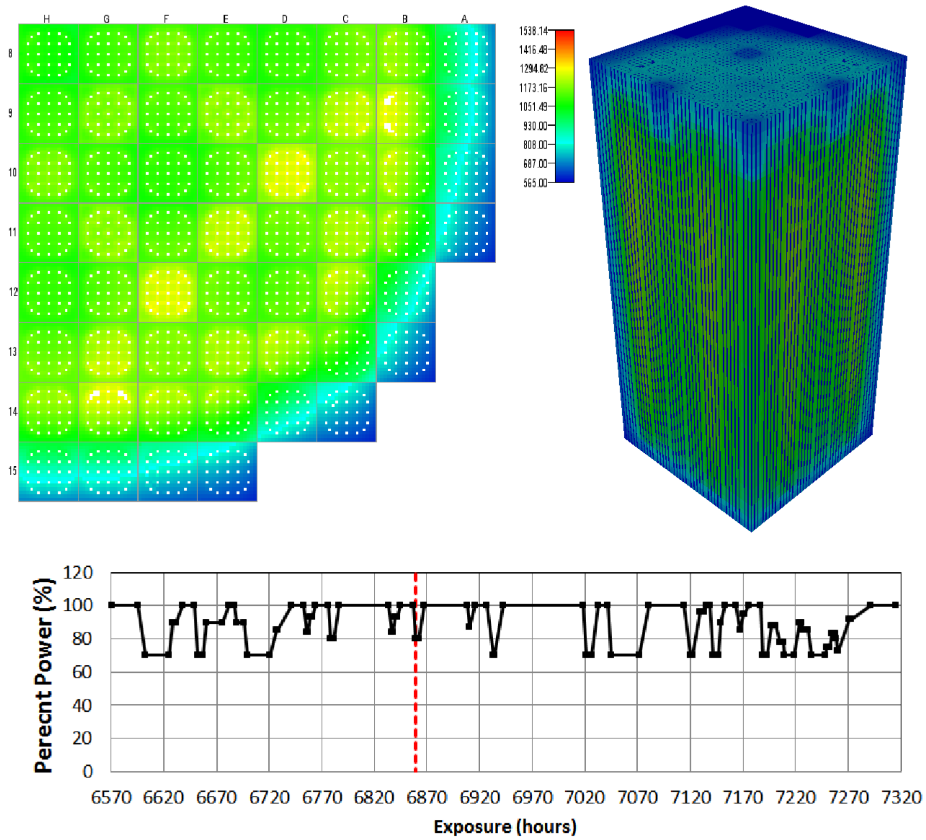
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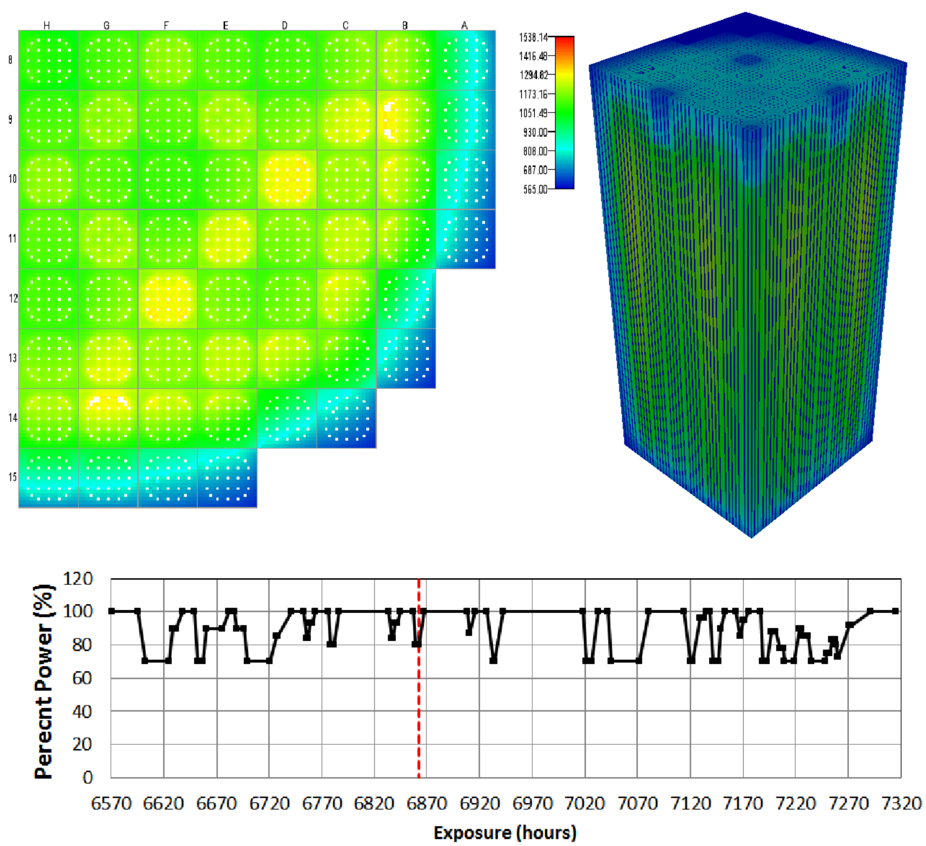
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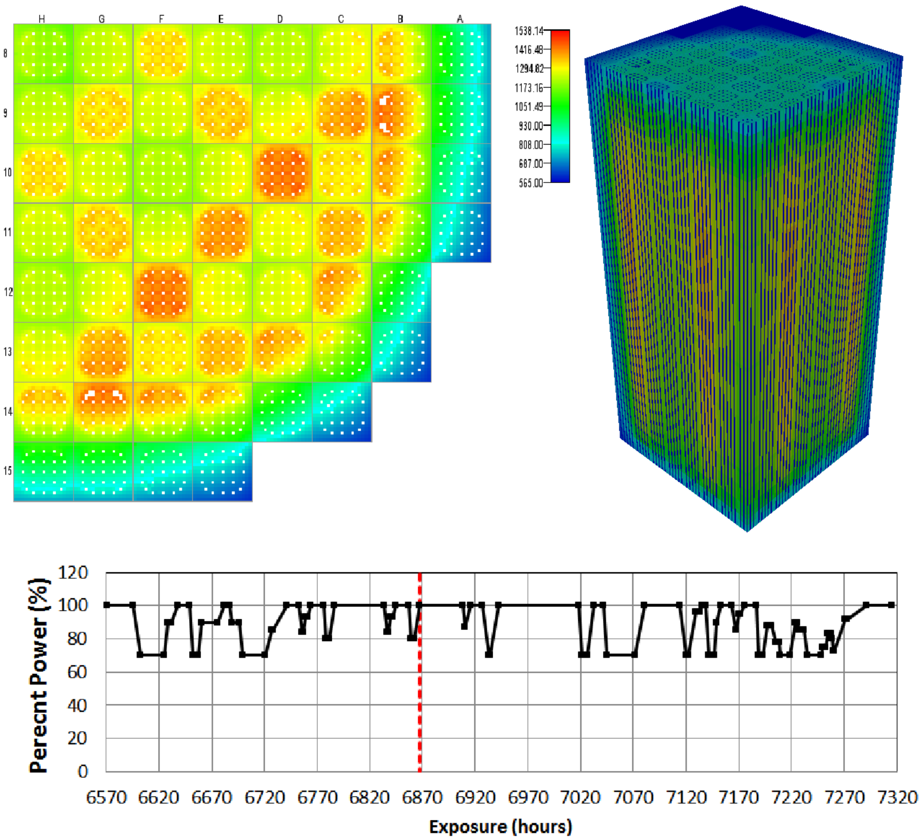
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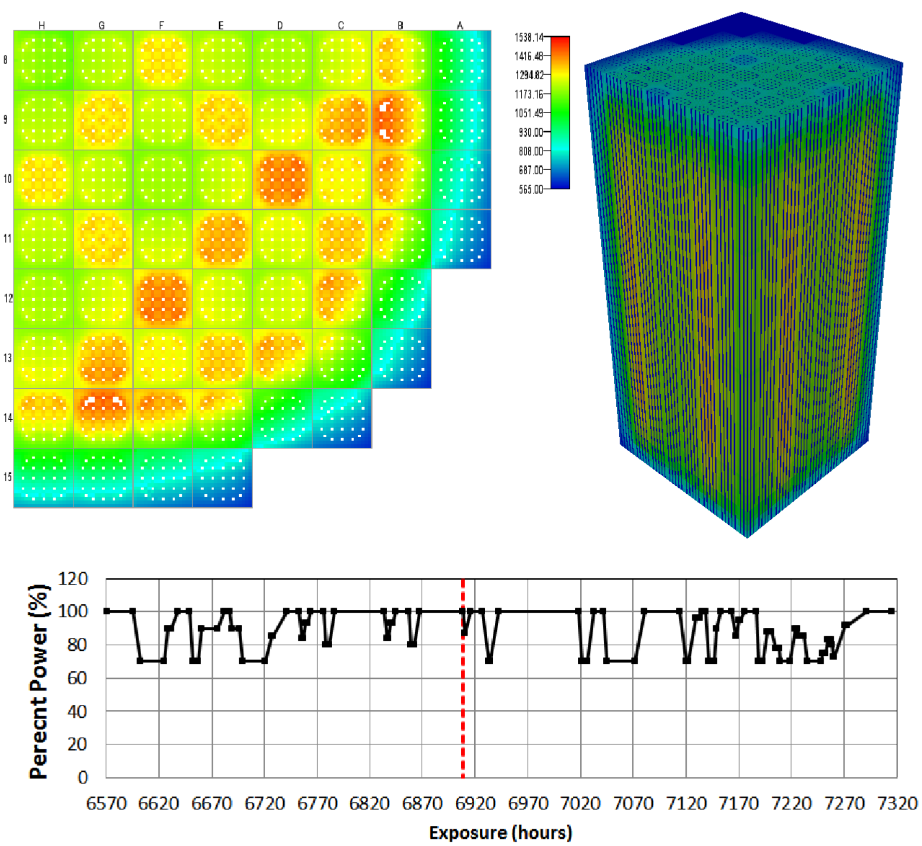
Exposure (hours)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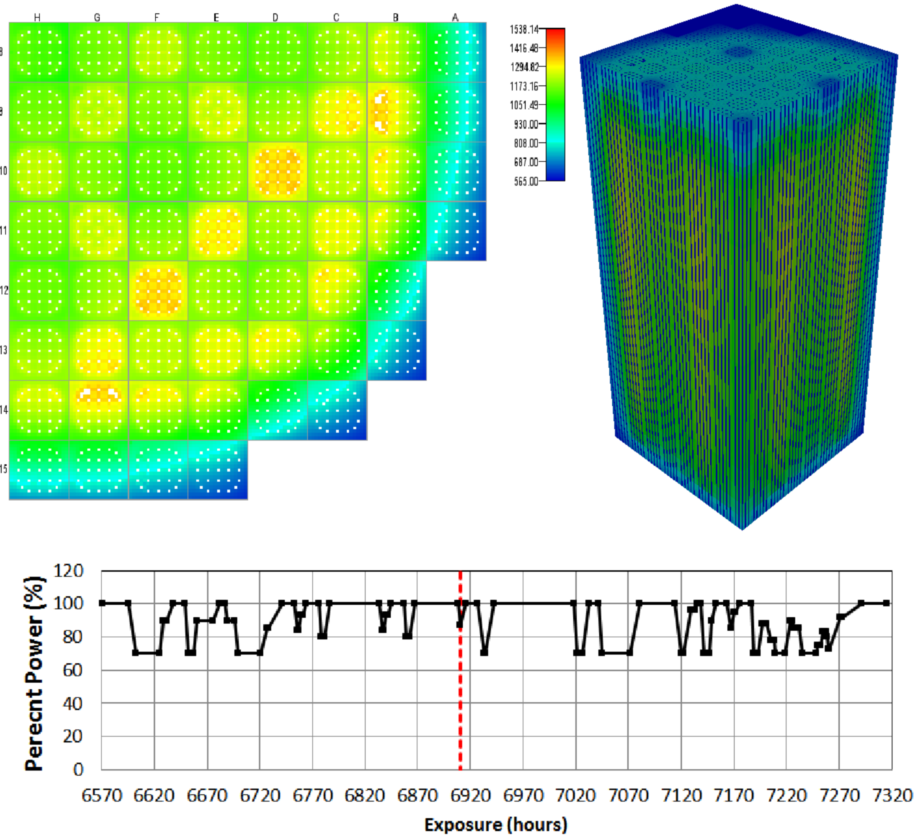
Exposure (hours)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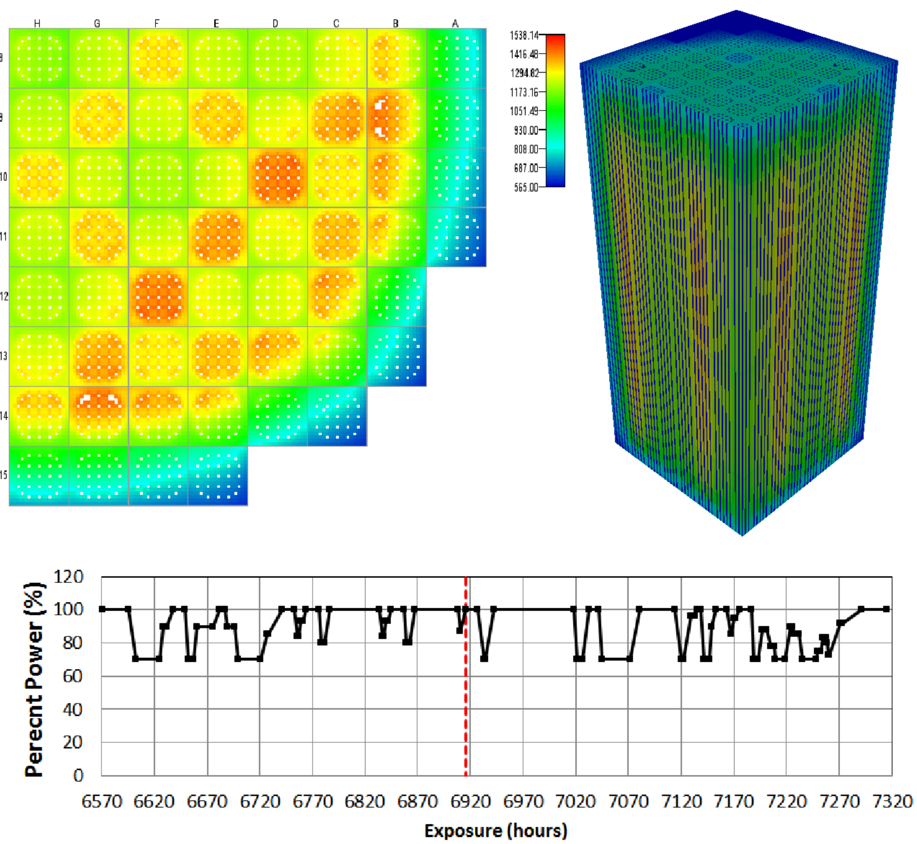
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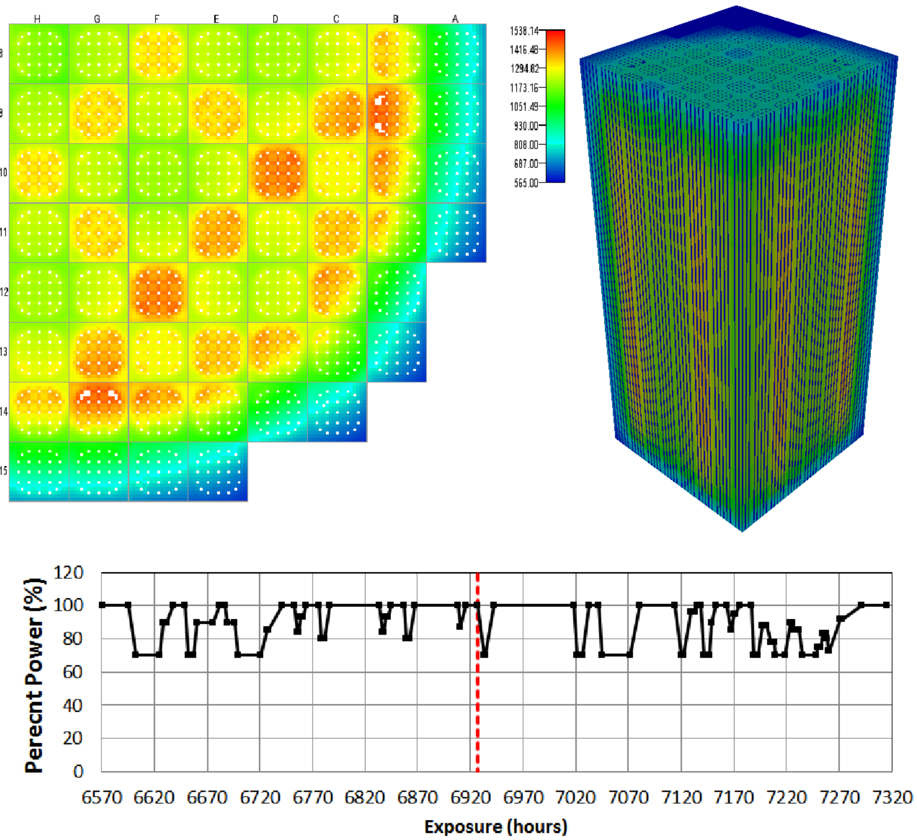
Exposure (hours)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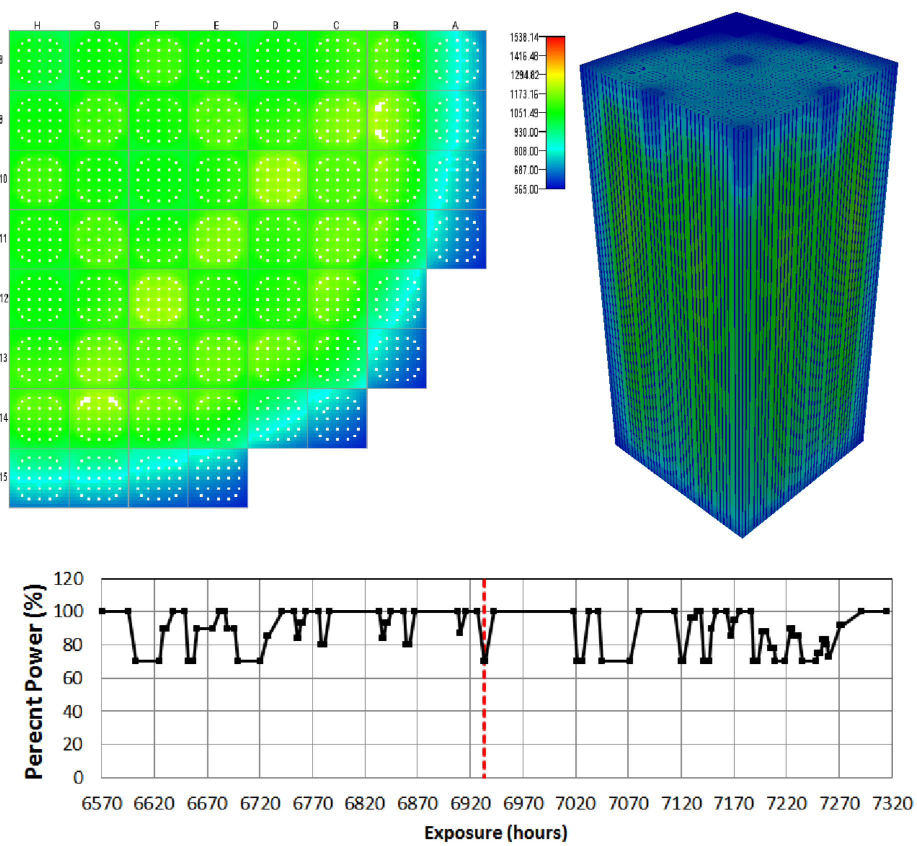
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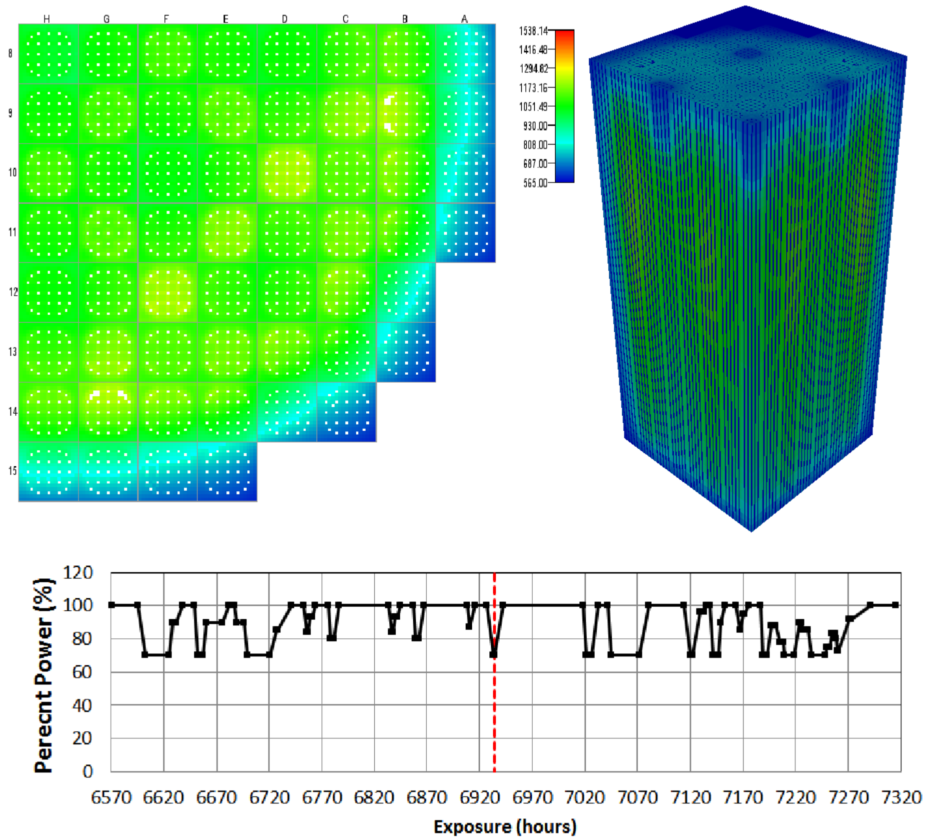
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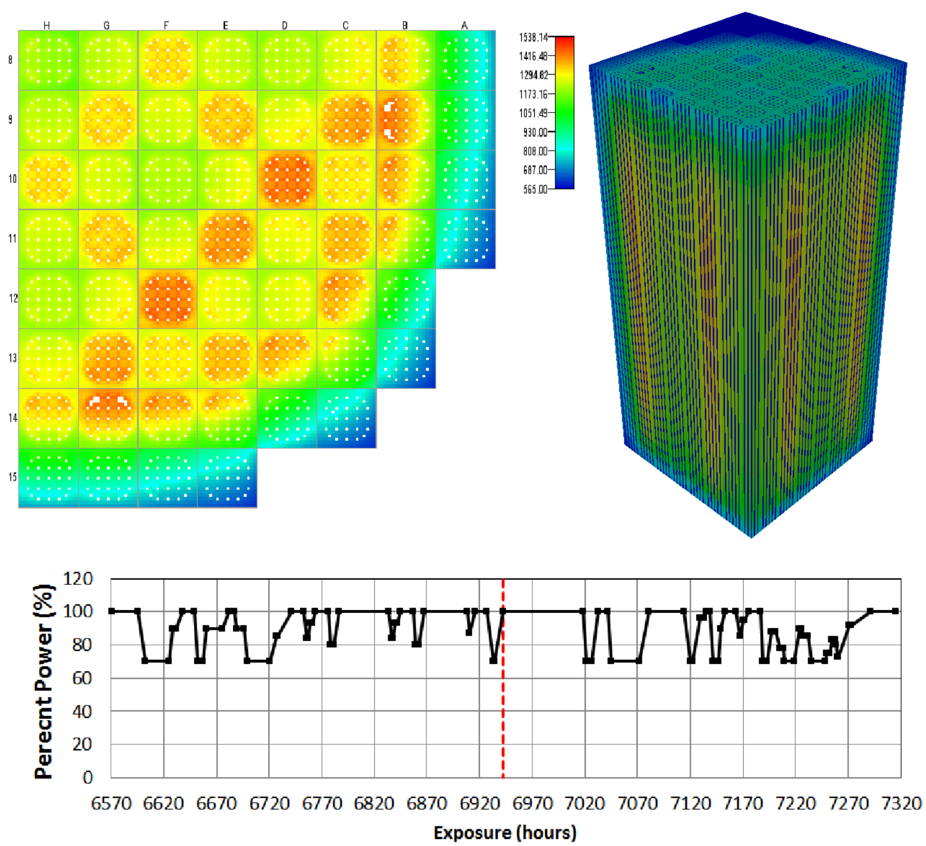
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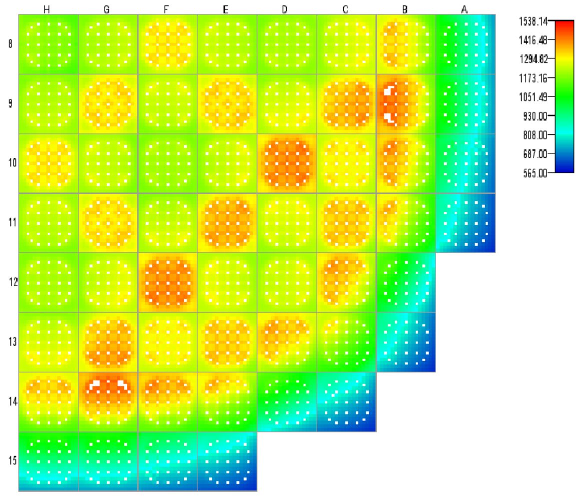
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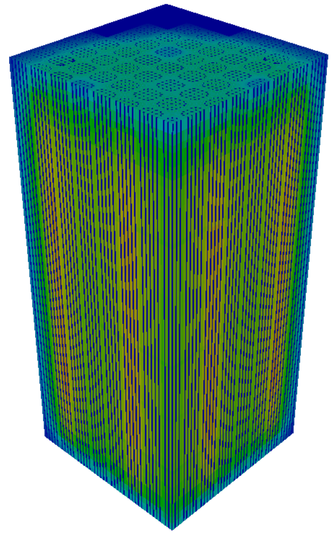

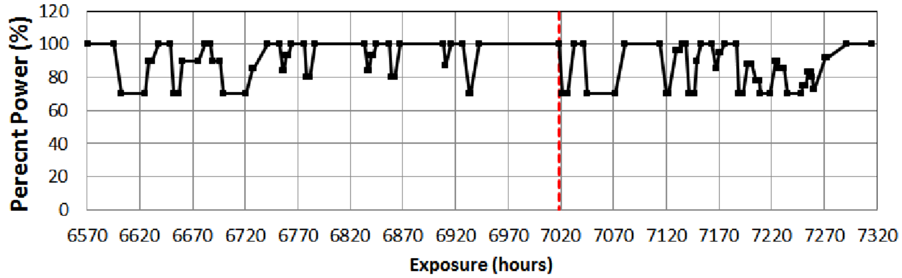
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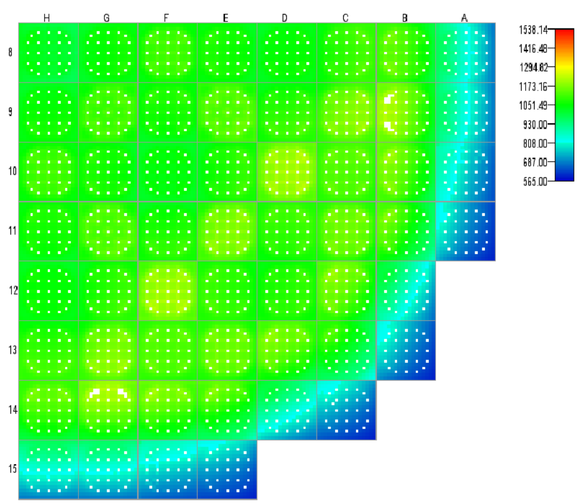
Exposure (hours)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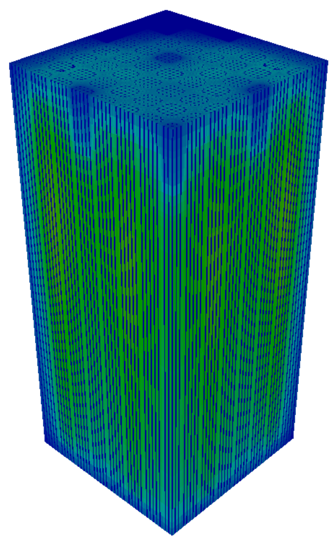

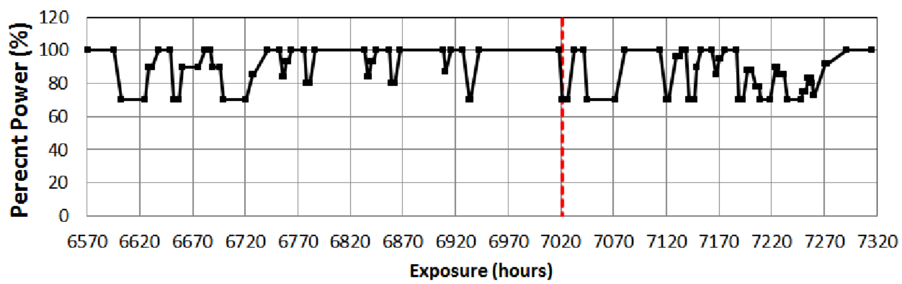
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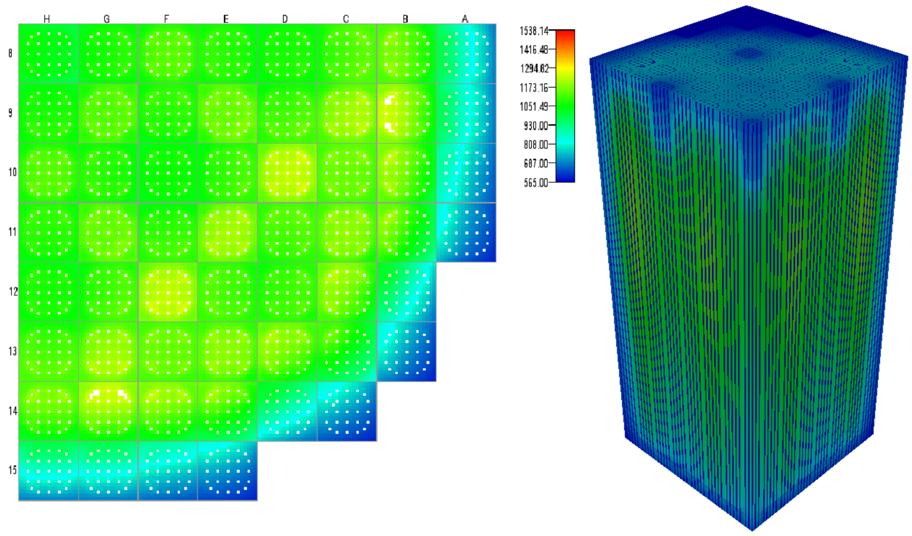
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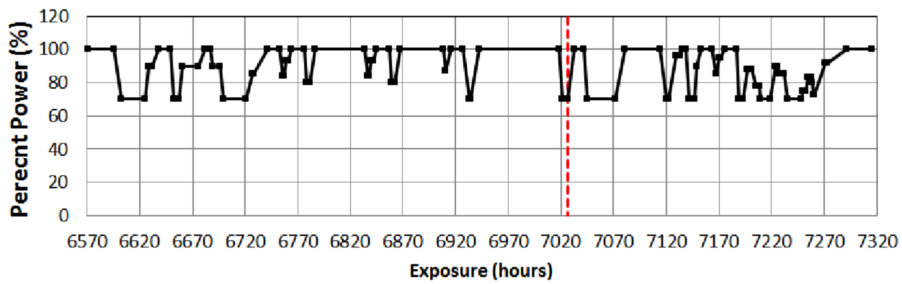
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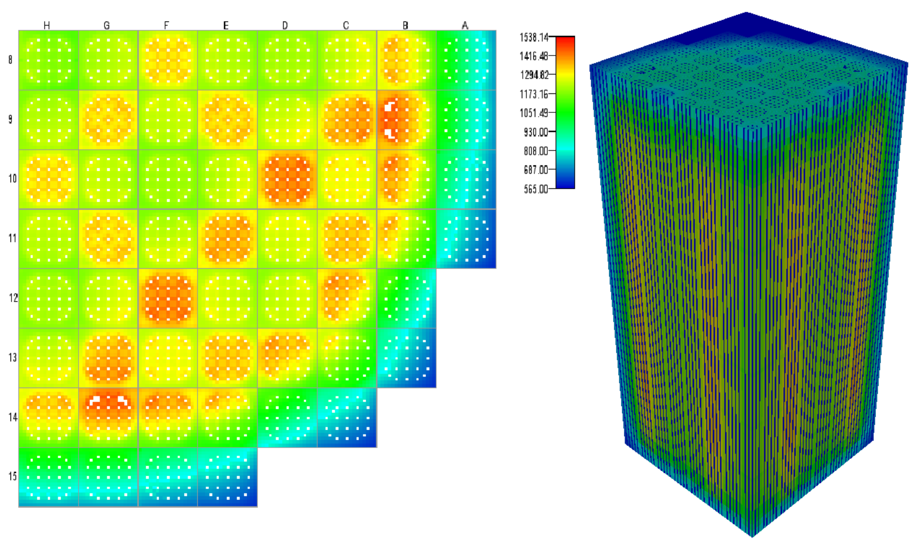
Exposure (hours)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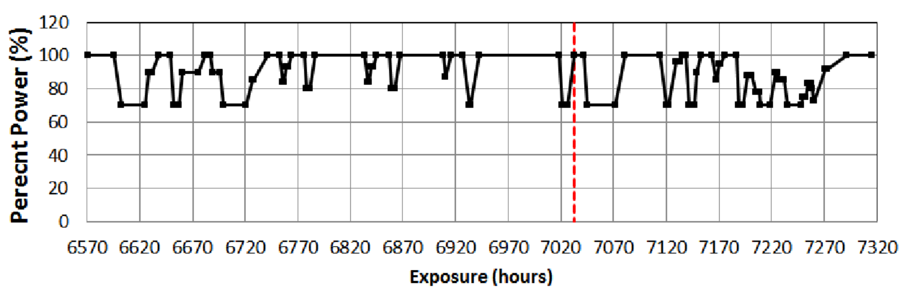
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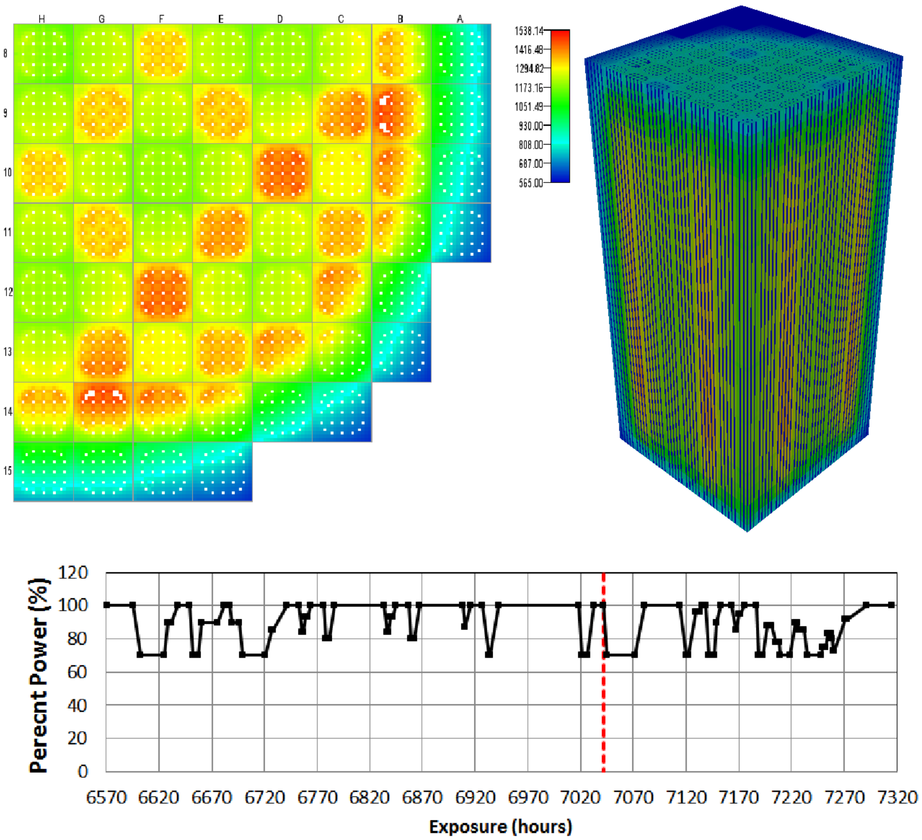
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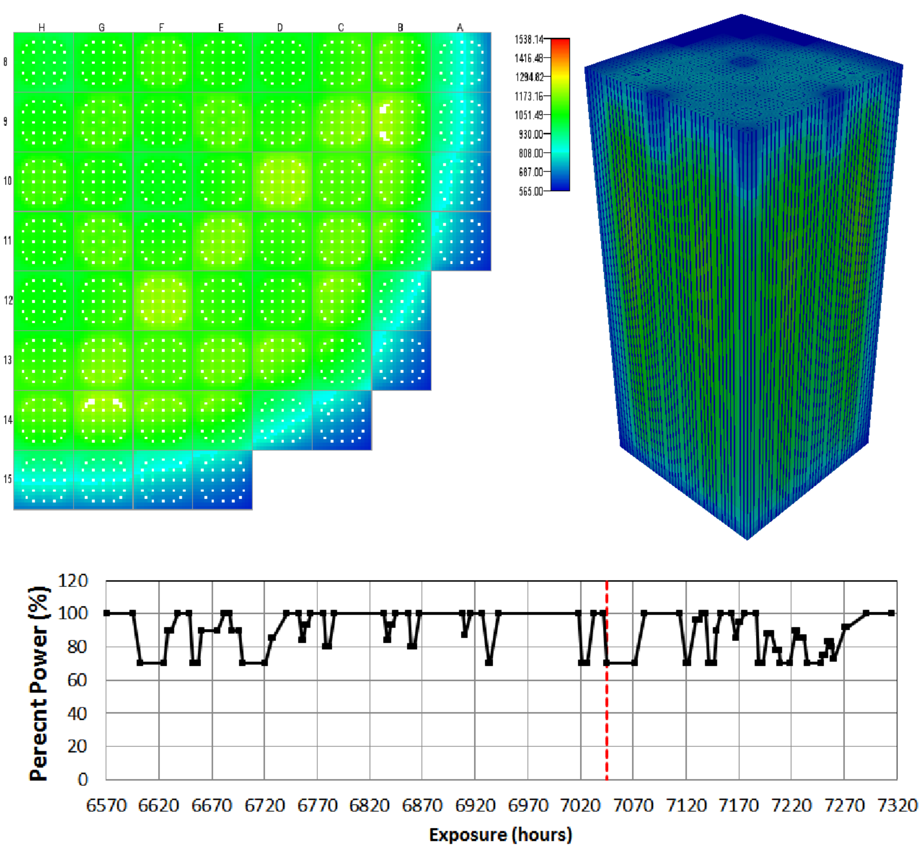
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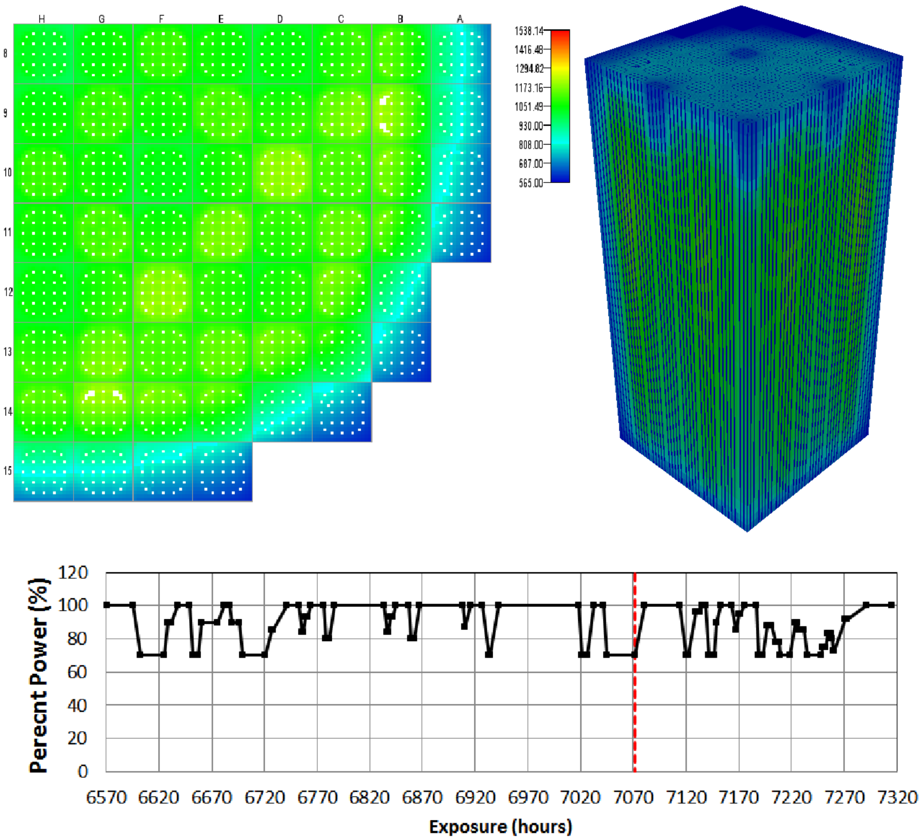
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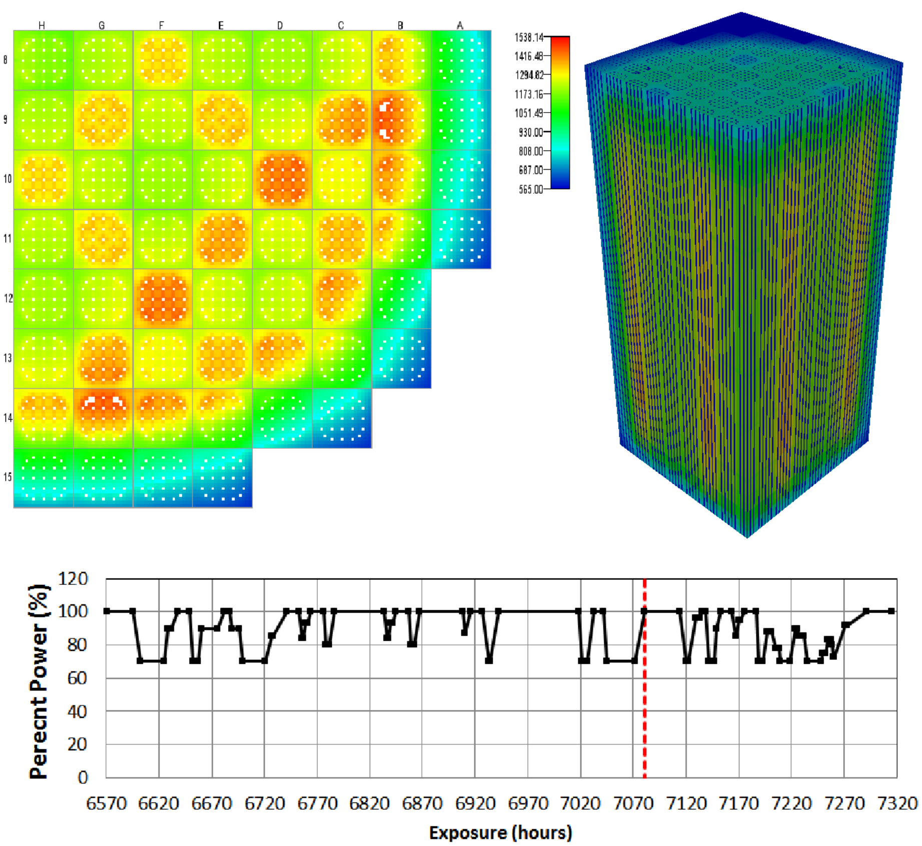
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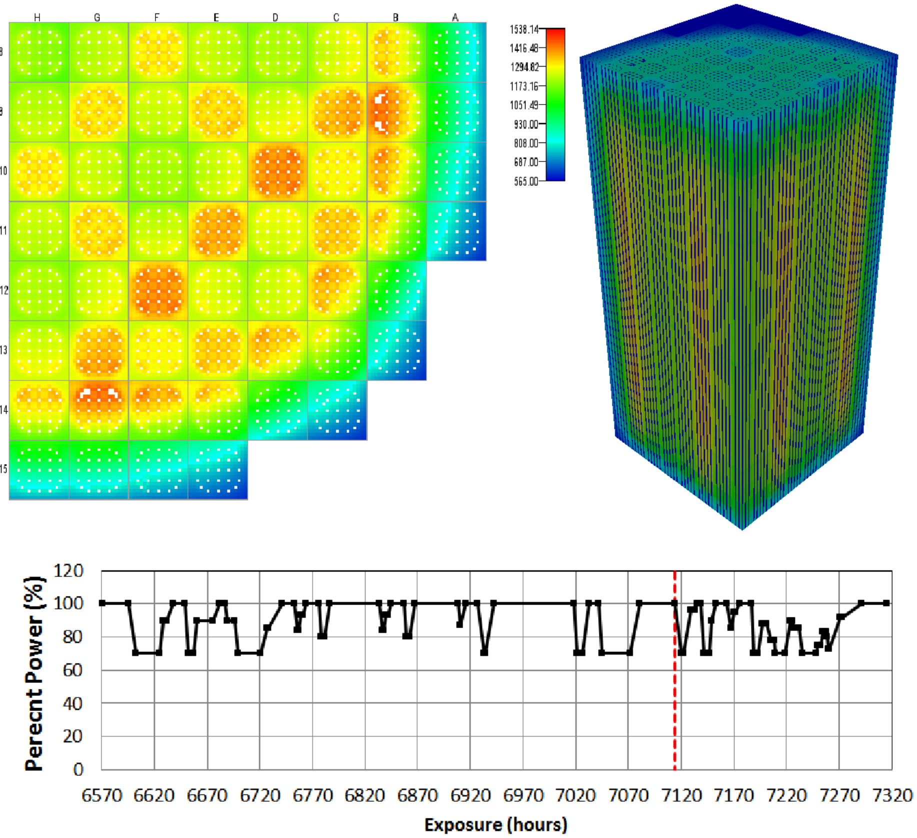
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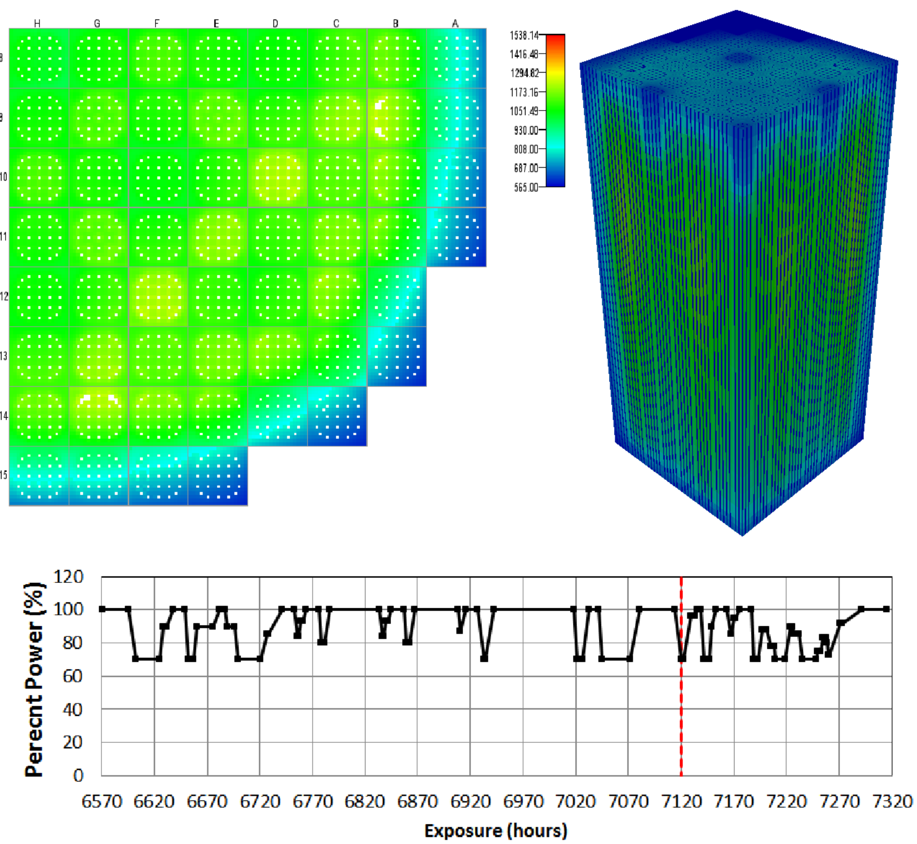
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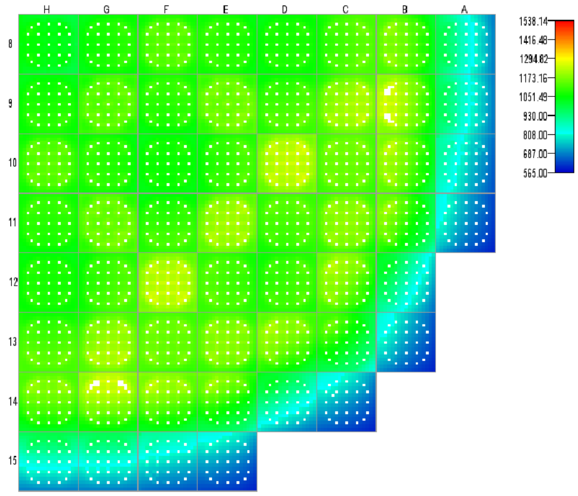
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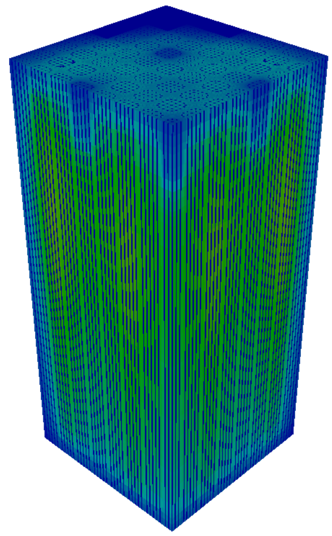

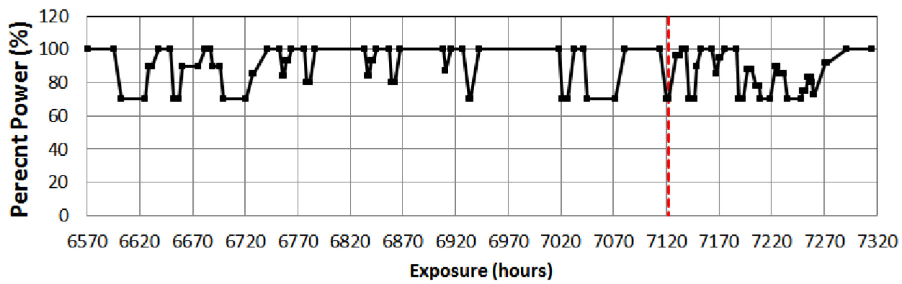
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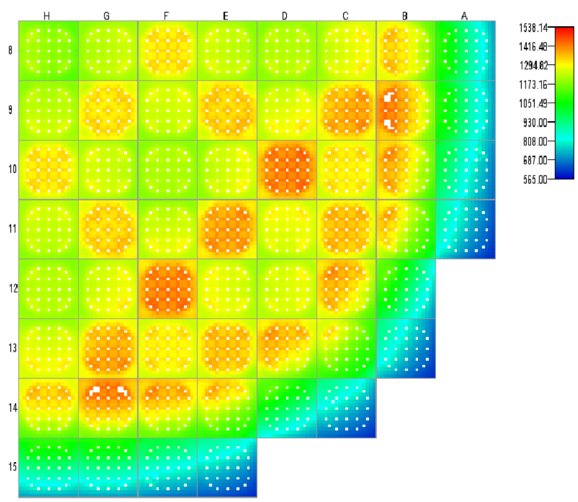
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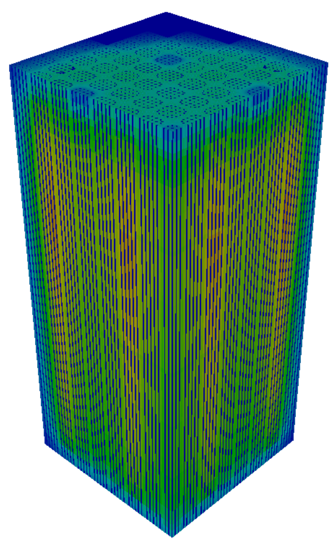

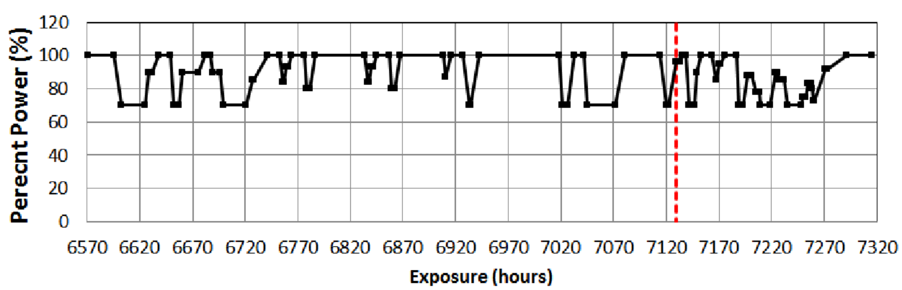
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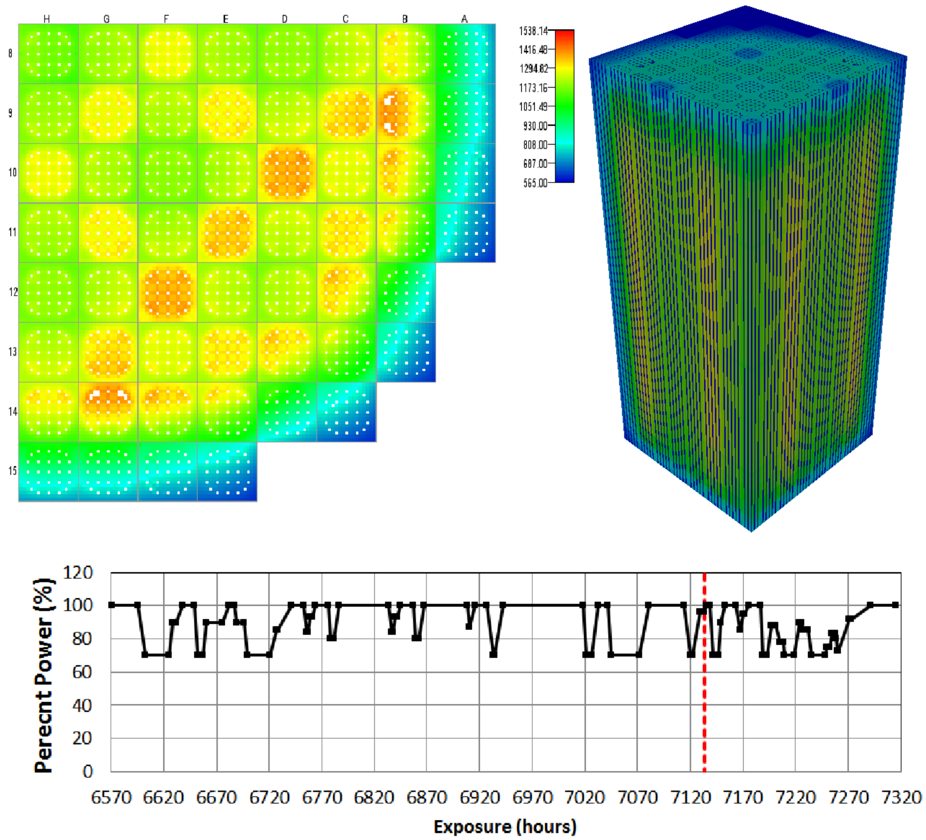
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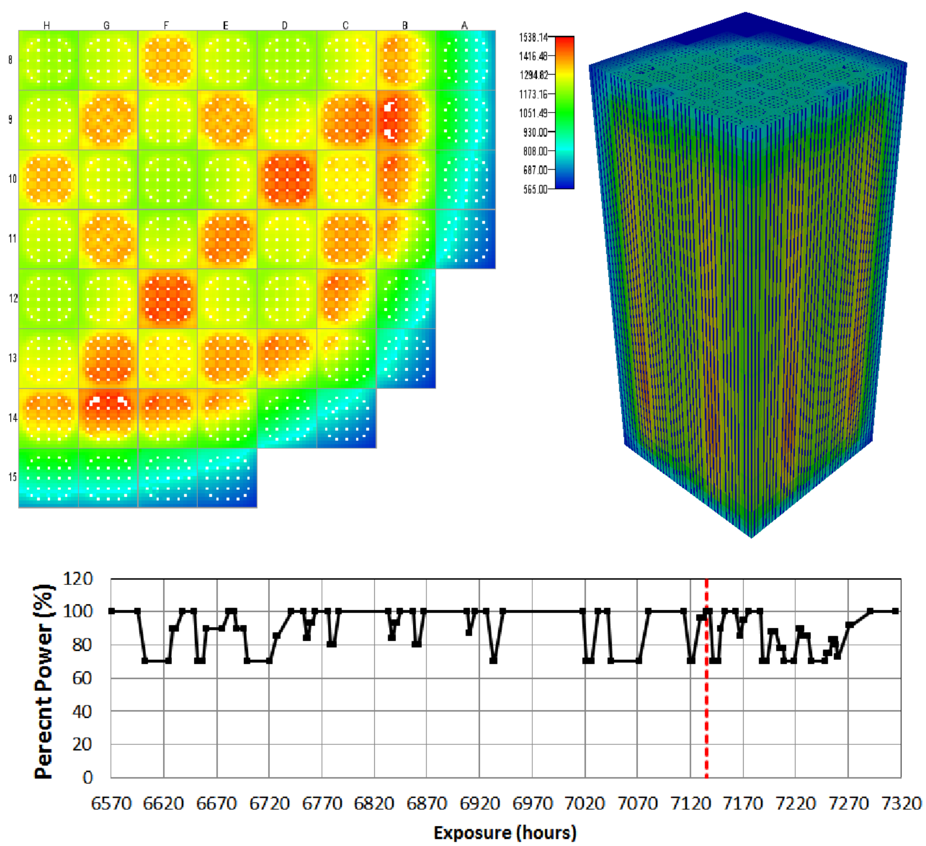
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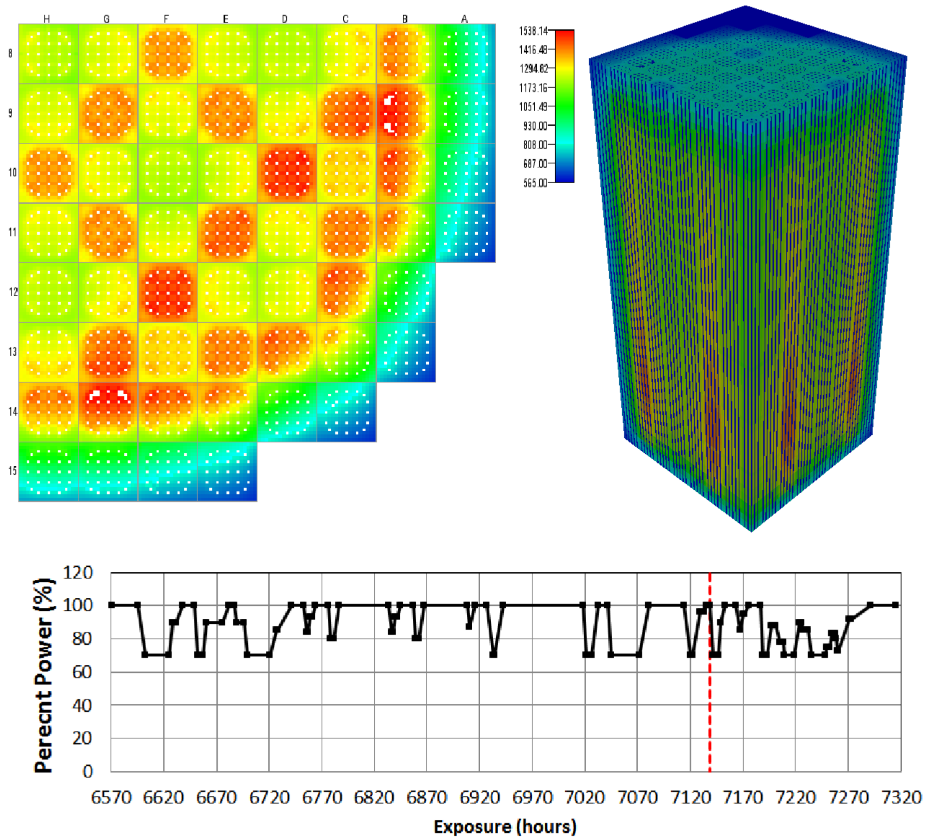

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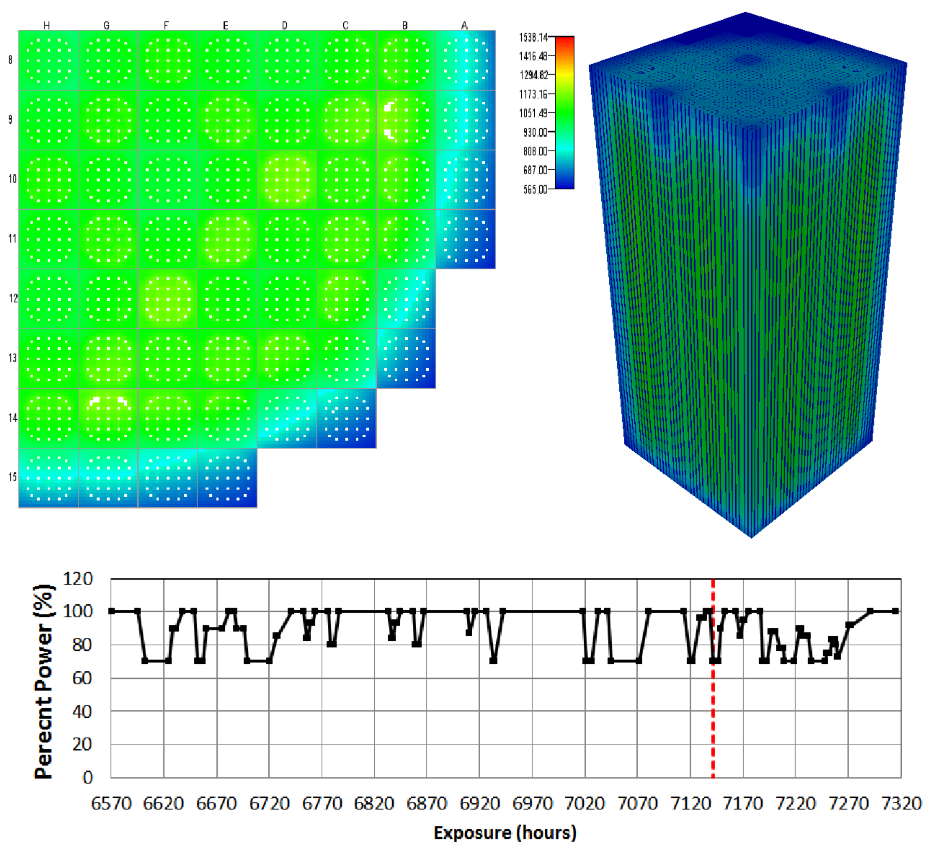

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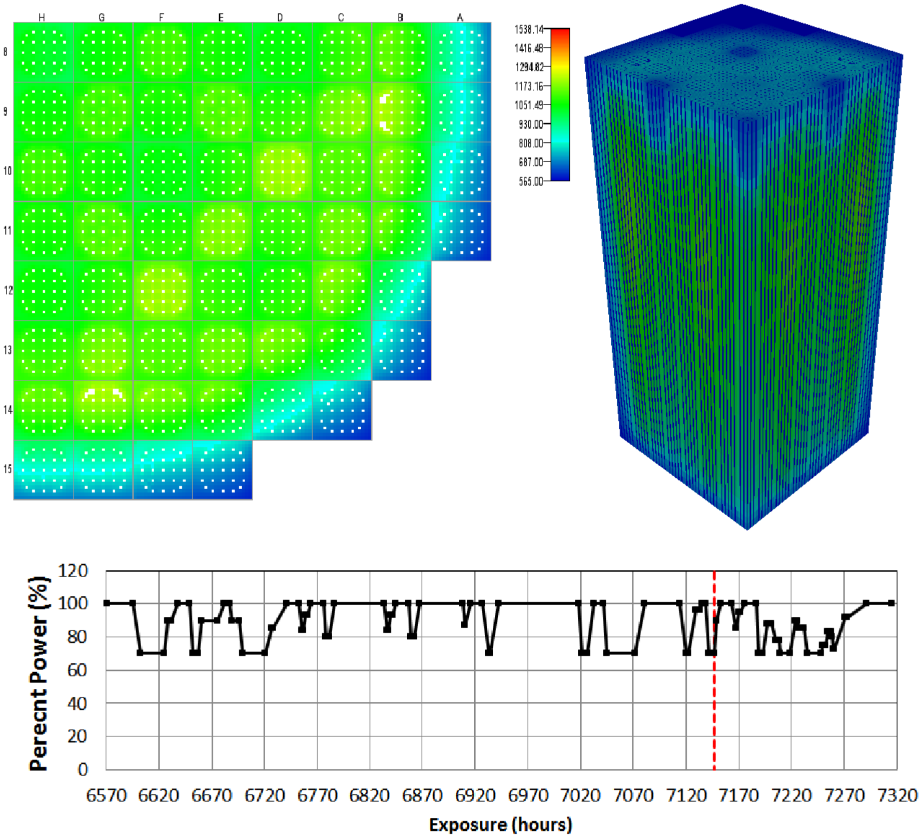
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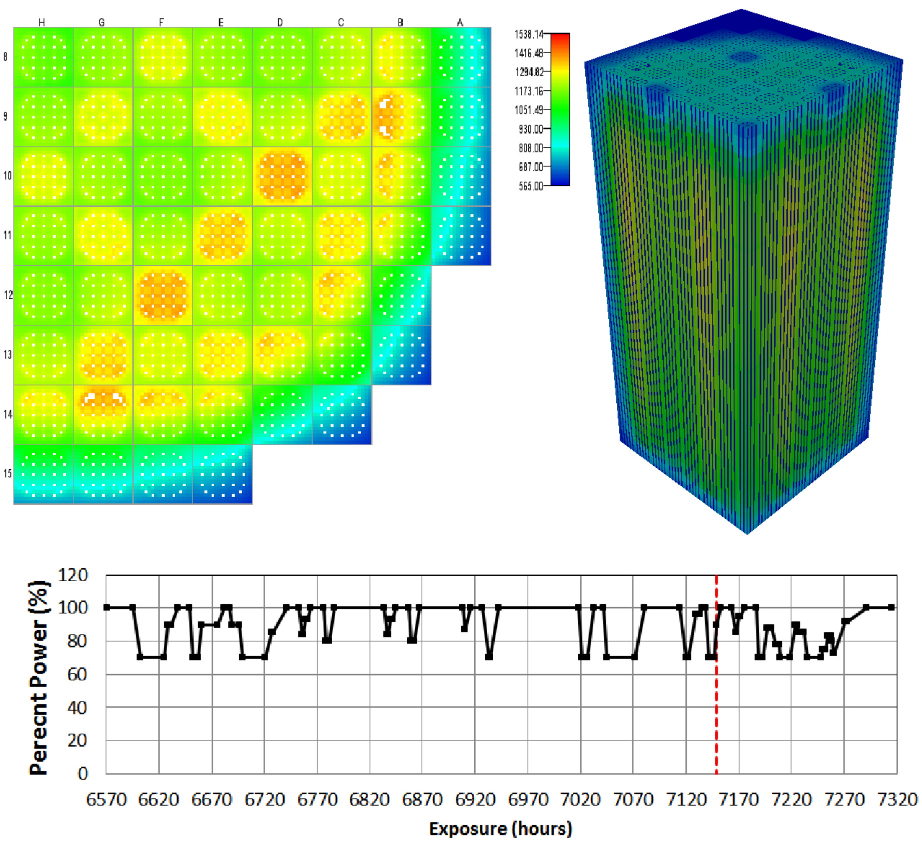
Exposure (hours)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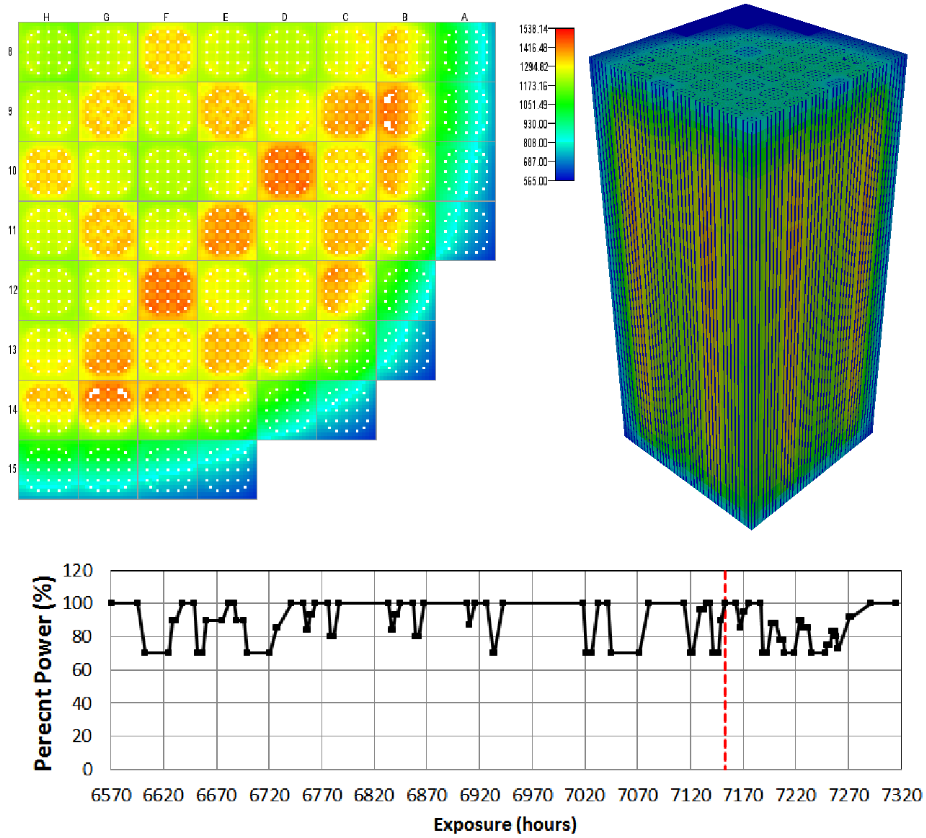
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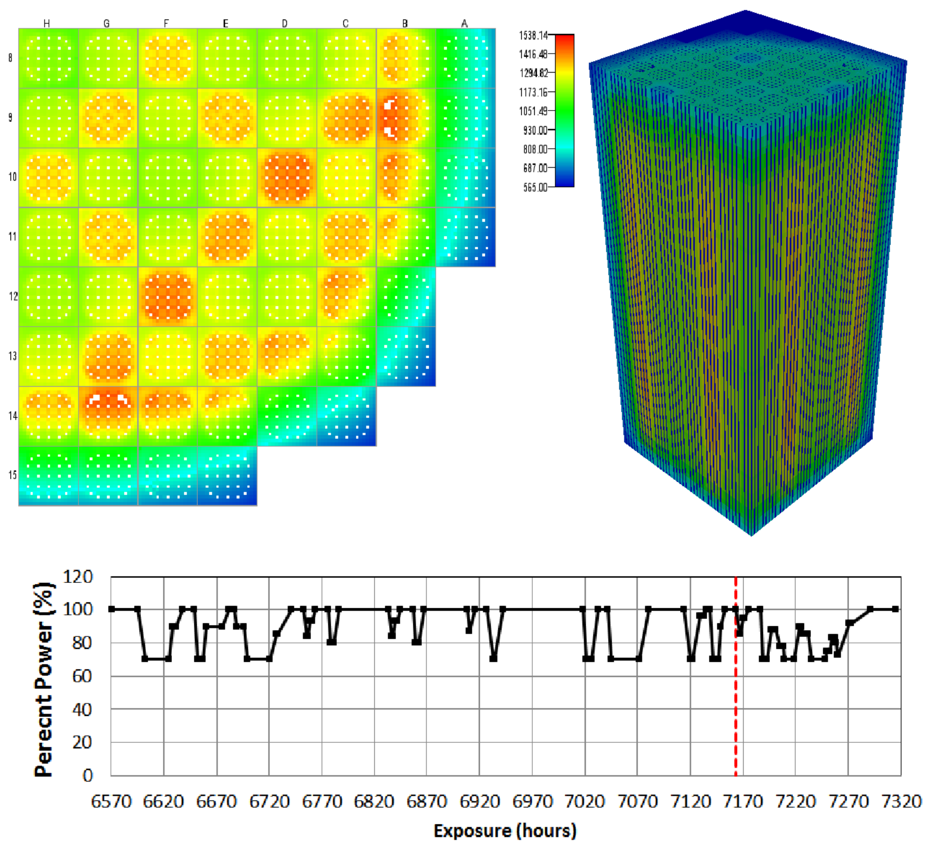
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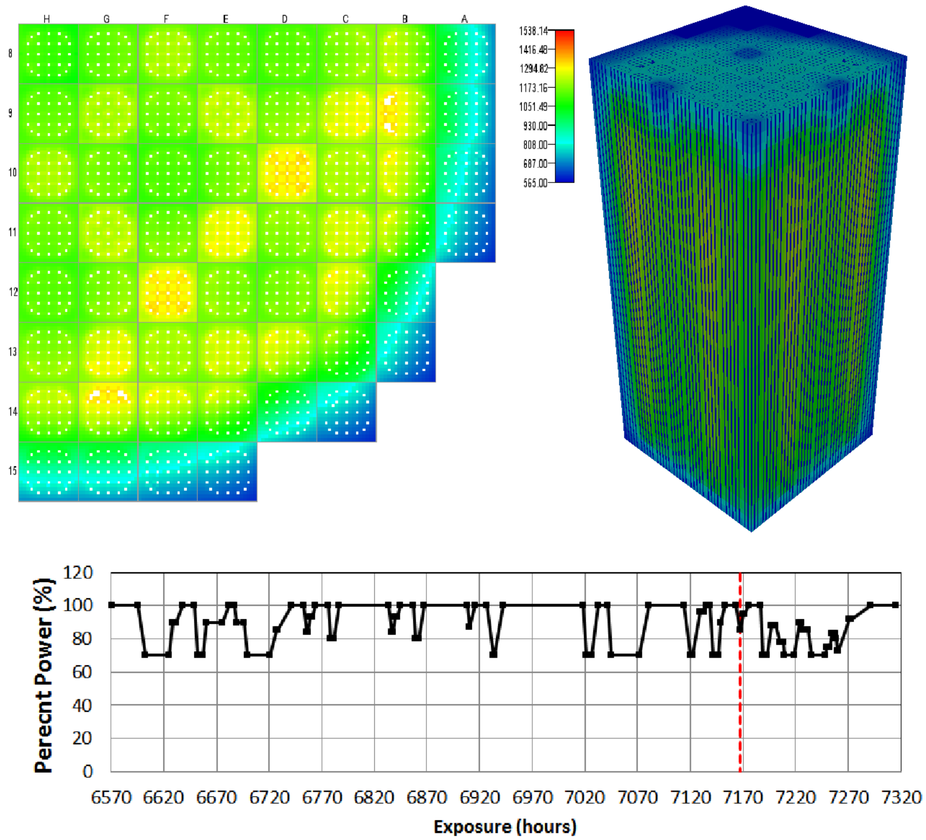
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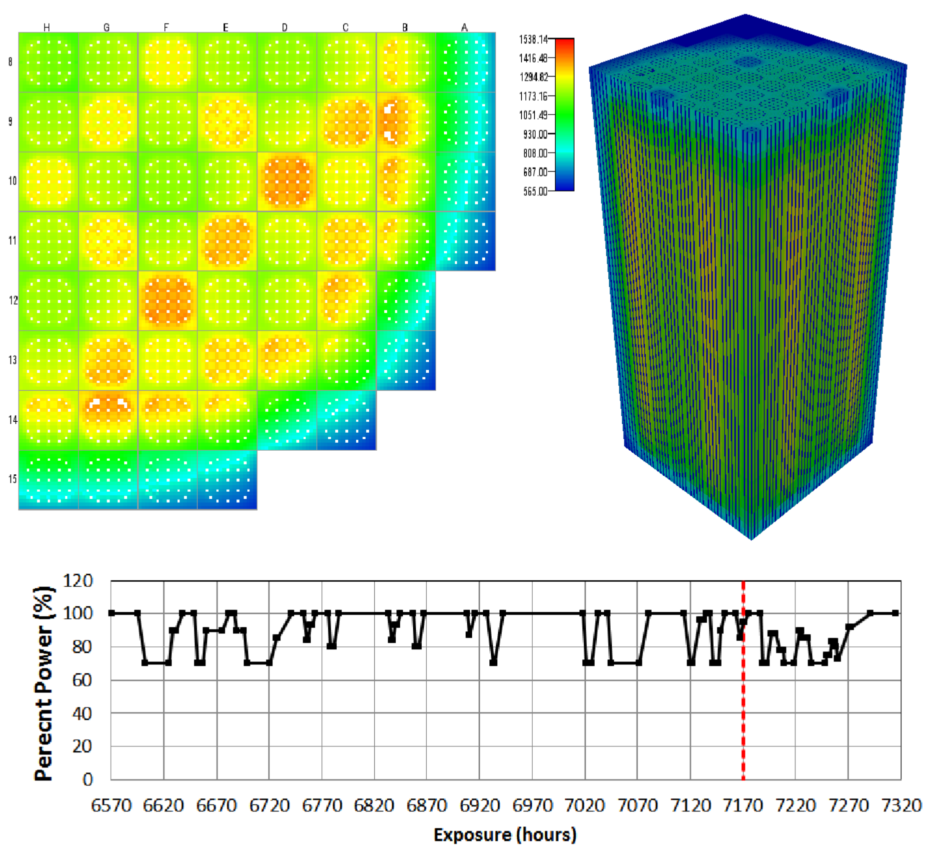
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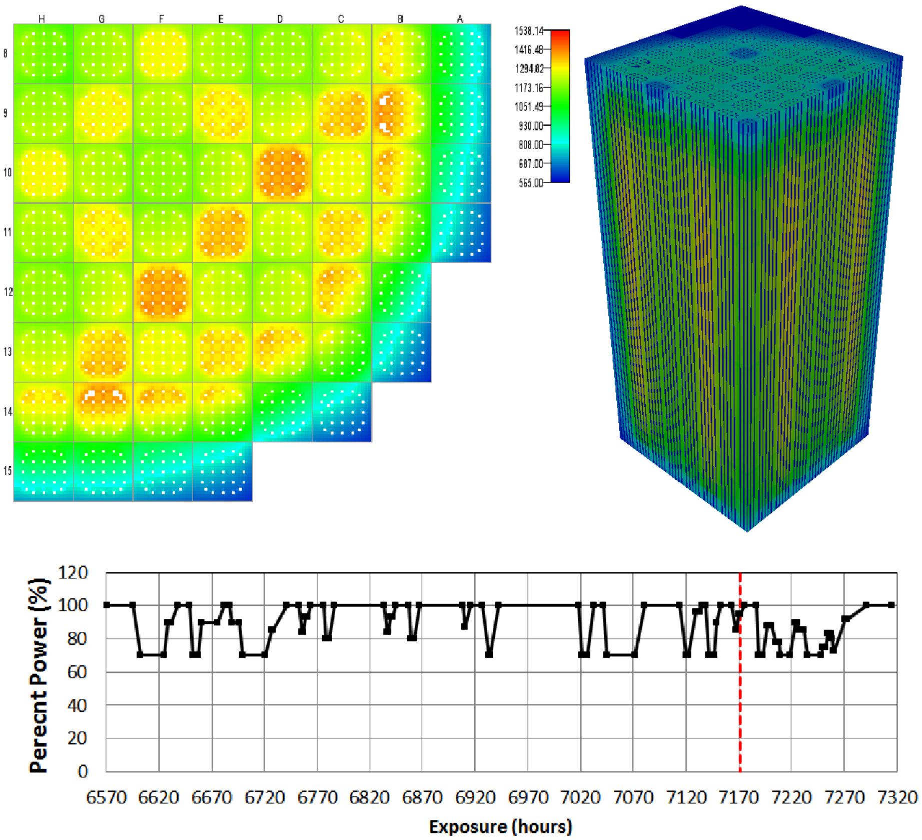
1416.48
1294.82
1173.16
1051.49
930.00
808.00
687.00
565.00
Perecnt Power (%)
120
100
80
60
40
20
0
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)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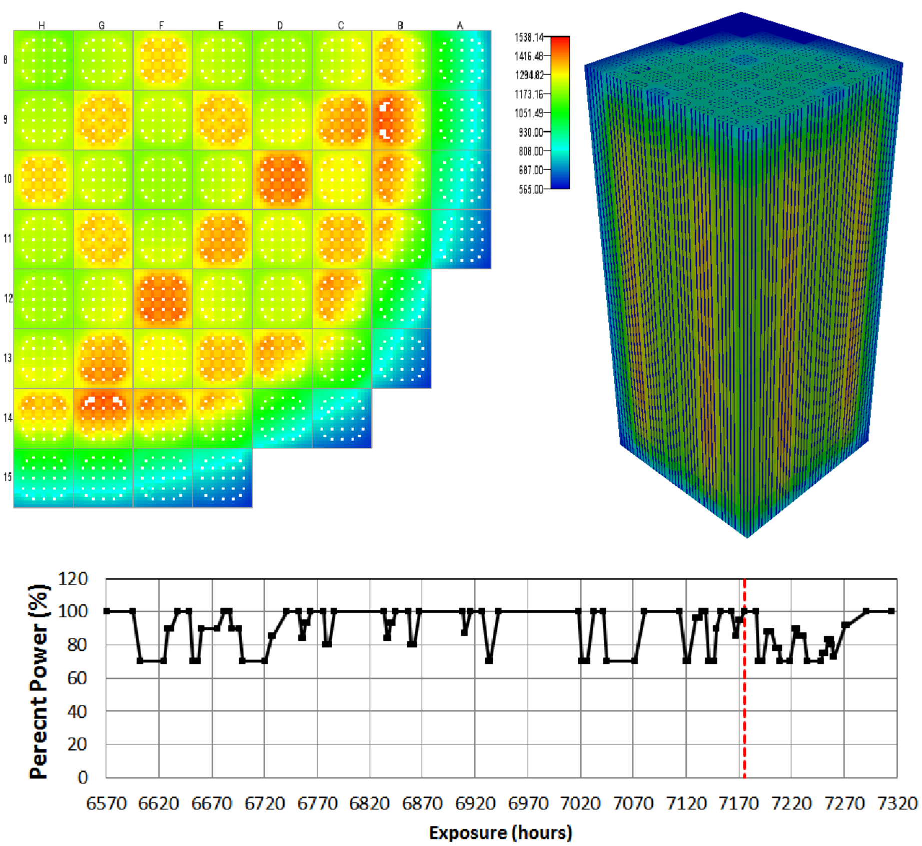
1538.14
1416.48
1294.82
1173.16
1051.49
930.00
808.00
687.00
565.00
Perecnt Power (%)
120
100
80
60
40
20
0
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)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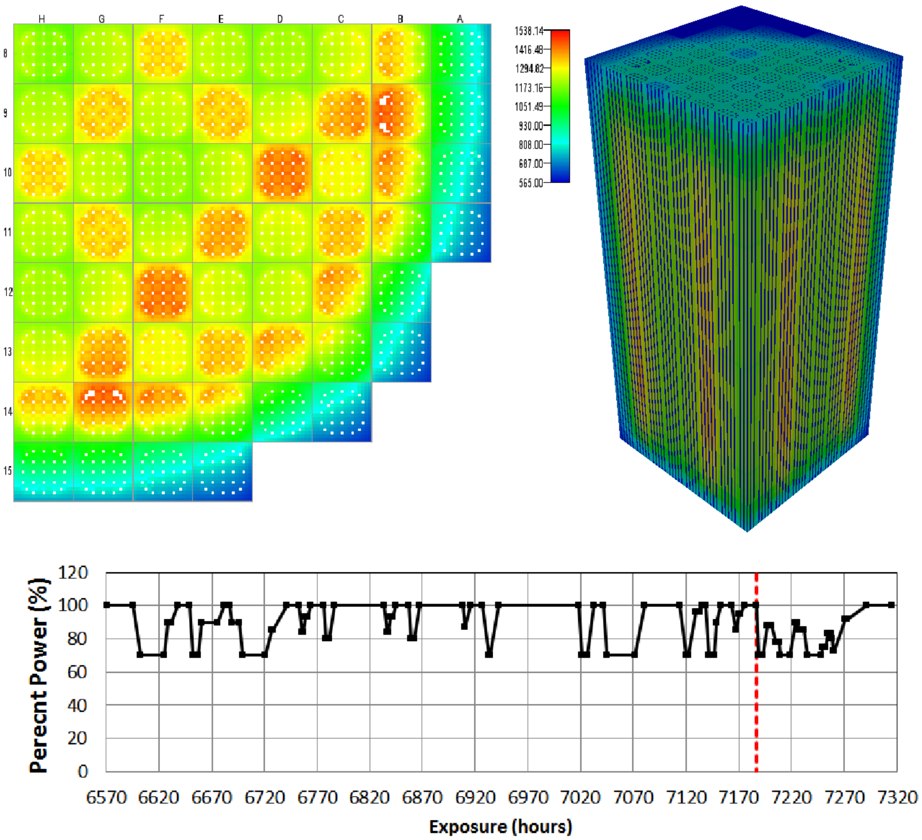
1538.14
1416.48
1294.82
1173.16
1051.49
930.00
808.00
687.00
565.00
Perecnt Power (%)
120
100
80
60
40
20
0
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)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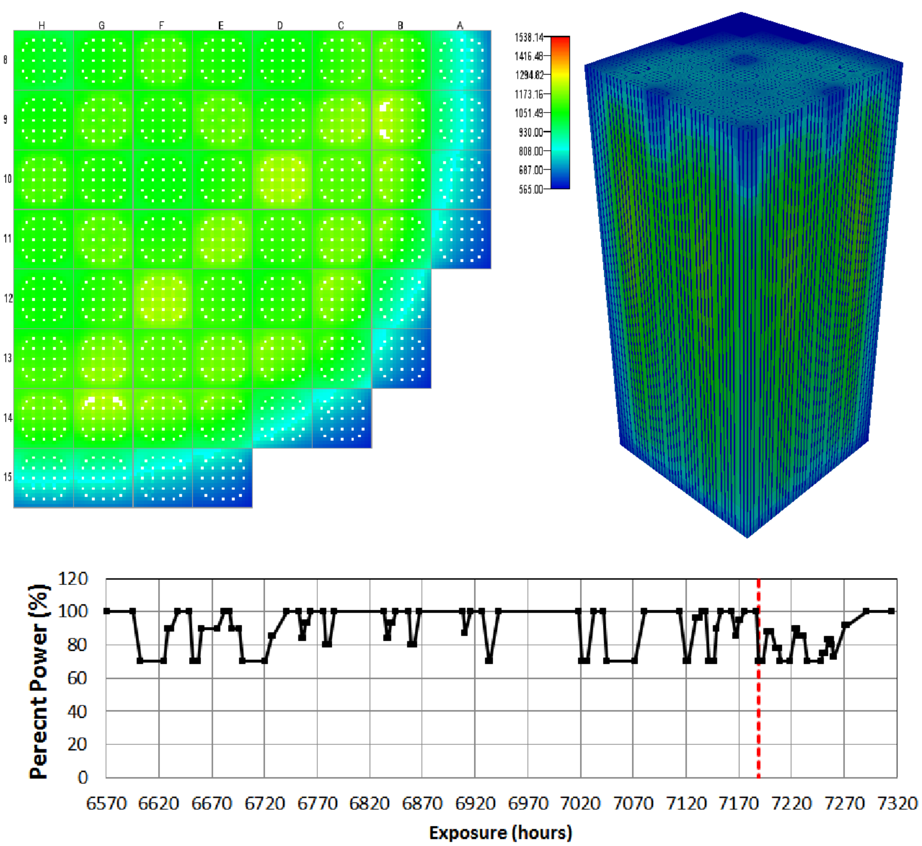
8 9 10 11 12 13 14 15
1538.14
1416.48
1294.82
1173.16
1051.49
930.00
808.00
687.00
565.00
Perecnt Power (%)
120 100 80 60 40 20 0
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)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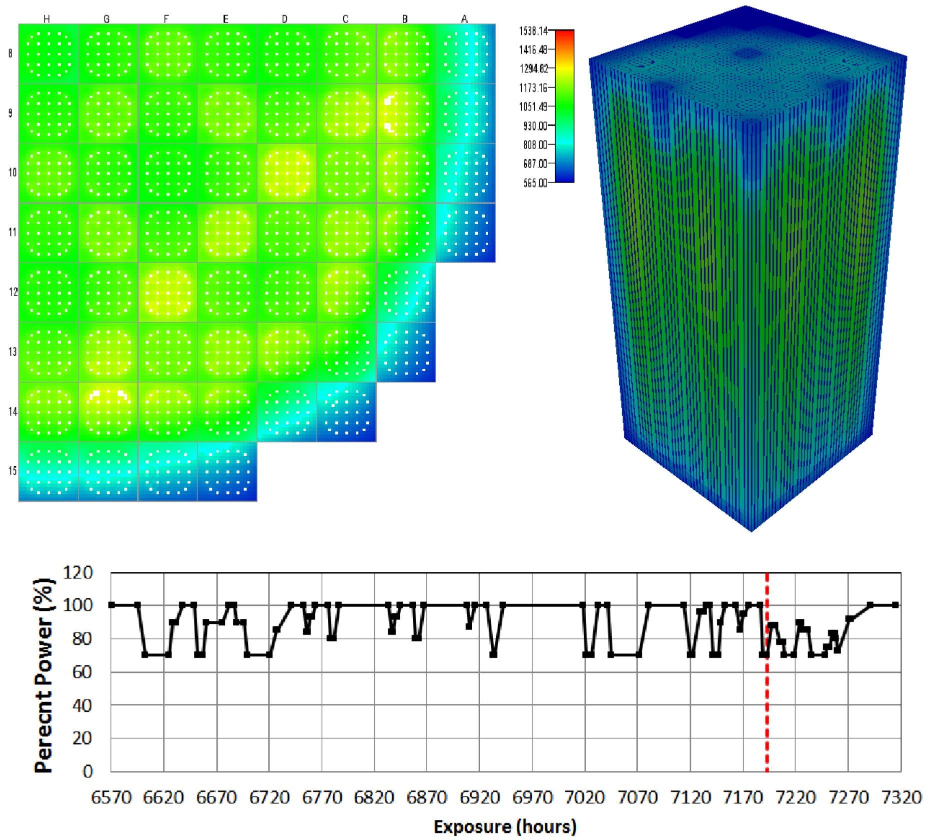
1416.48
1294.82
1173.16
1051.49
930.00
808.00
687.00
565.00
Perecnt Power (%)
120 100 80 60 40 20 0
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)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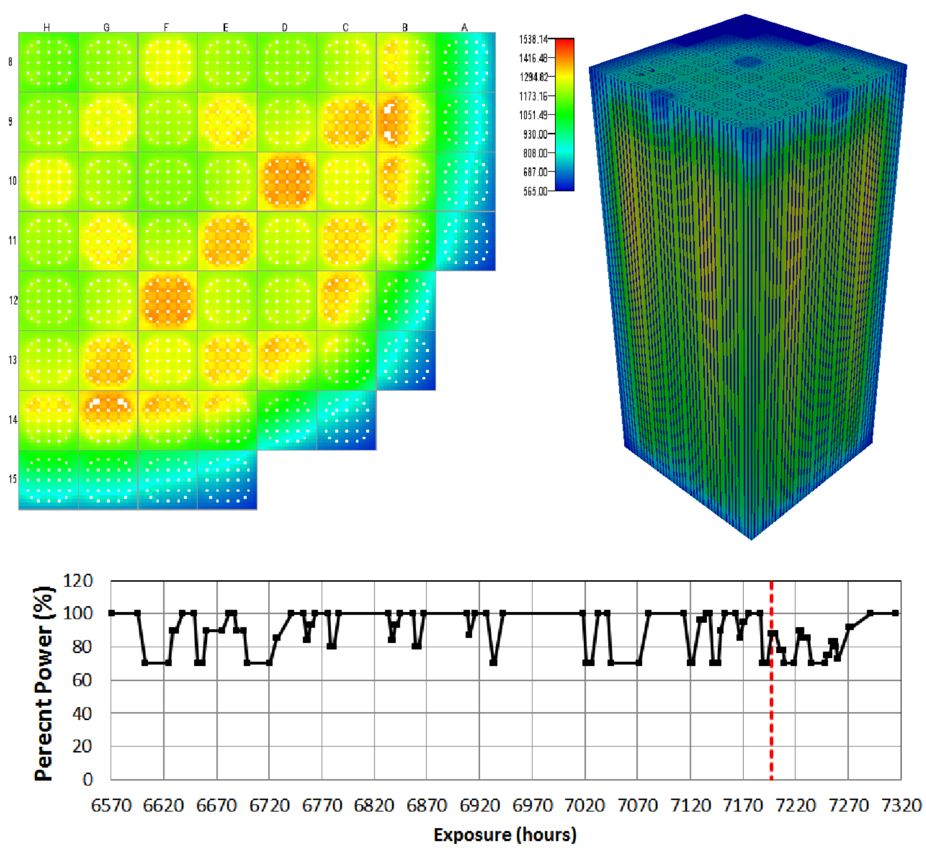
1416.48
1294.82
1173.16
1051.49
930.00
808.00
687.00
565.00
Perecnt Power (%)
0 20 40 60 80 100 120
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)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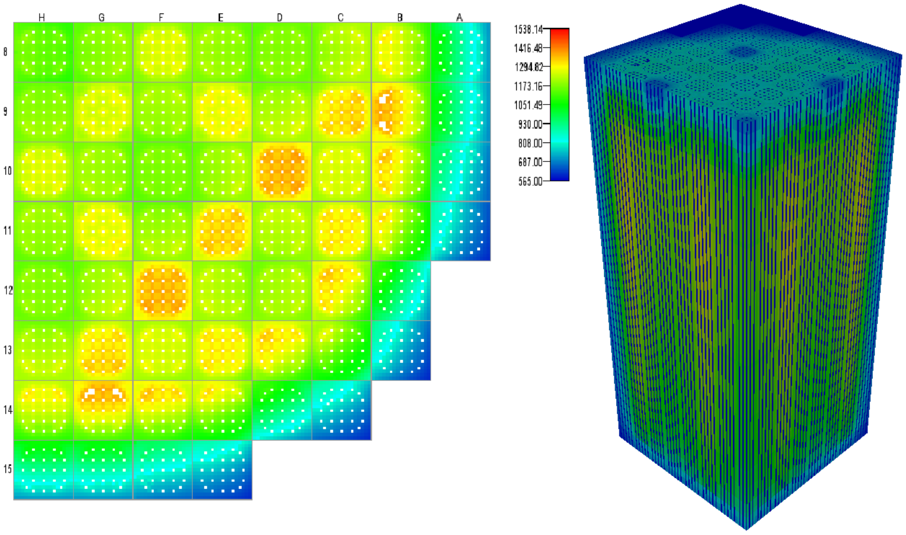
1416.48
1294.82
1173.16
1051.49
930.00
808.00
687.00
565.00
Perecnt Power (%)
0 20 40 60 80 100 120
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)


H G F E D C B A
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1538.14
1416.48
1294.82
1173.16
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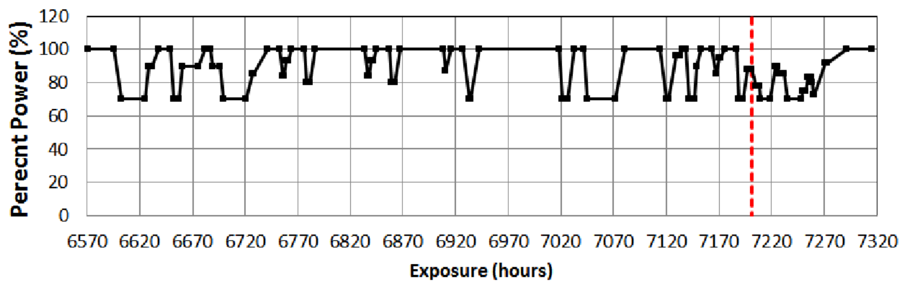
808.00
687.00
565.00


Perecnt Power (%)
0
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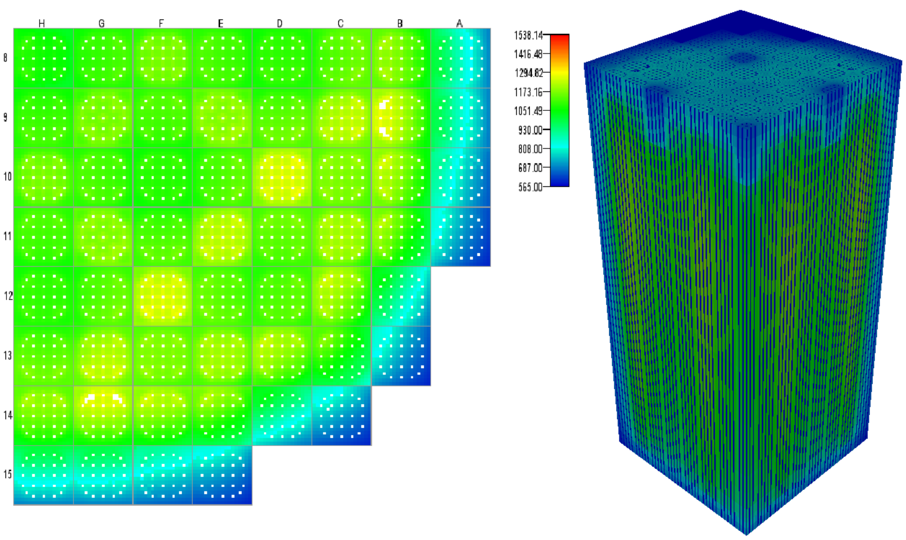
40
60
80
100
120
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)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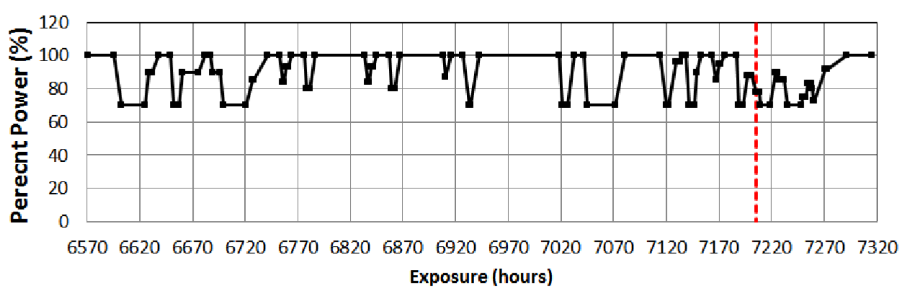
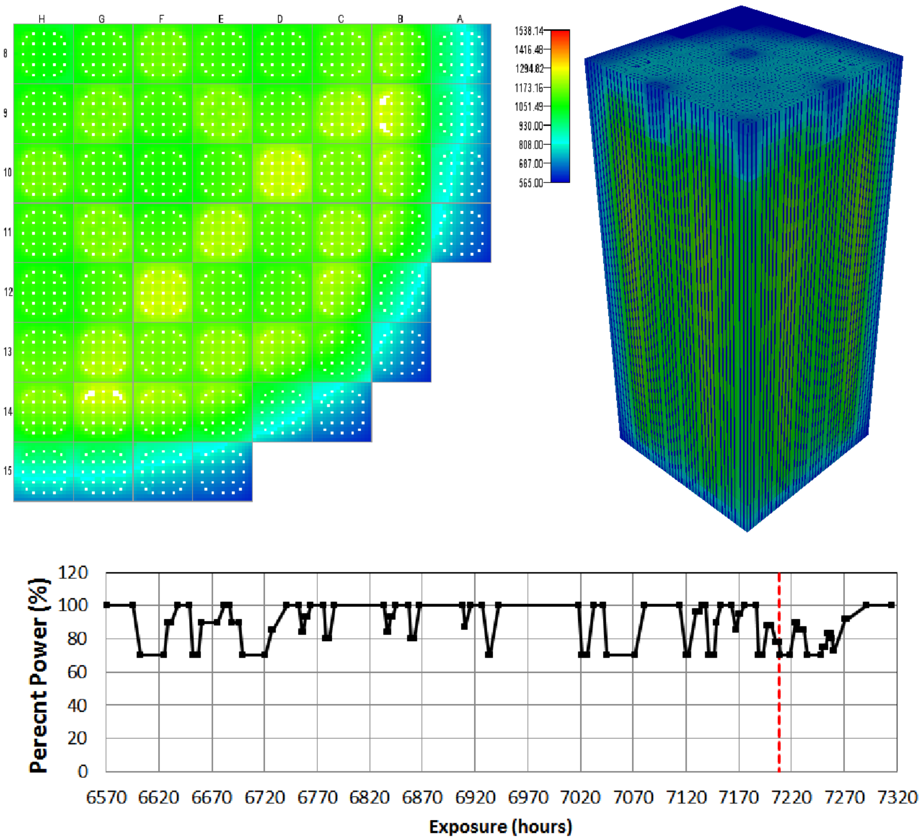
1173.16
1051.49
930.00
808.00
687.00
565.00


Perecnt Power (%)
0
20
40
60
80
100
120
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)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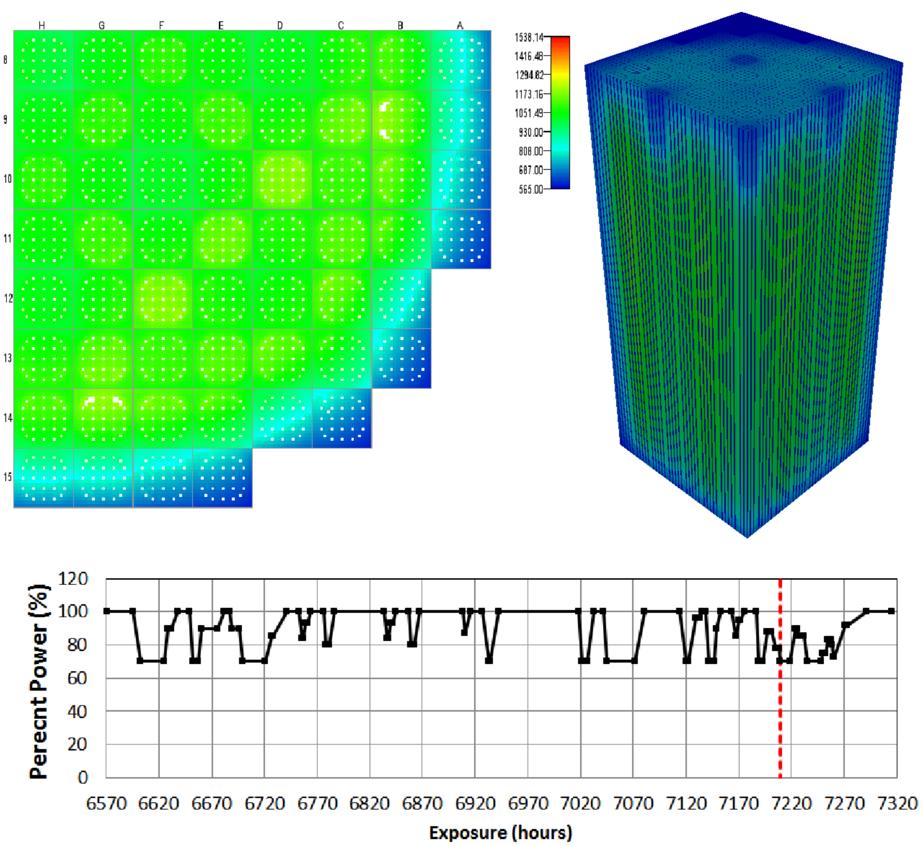
1538.14
1416.48
1294.82
1173.16
1051.49
930.00
808.00
687.00
565.00
Perecnt Power (%)
120
100
80
60
40
20
0
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)


H G F E D C B A
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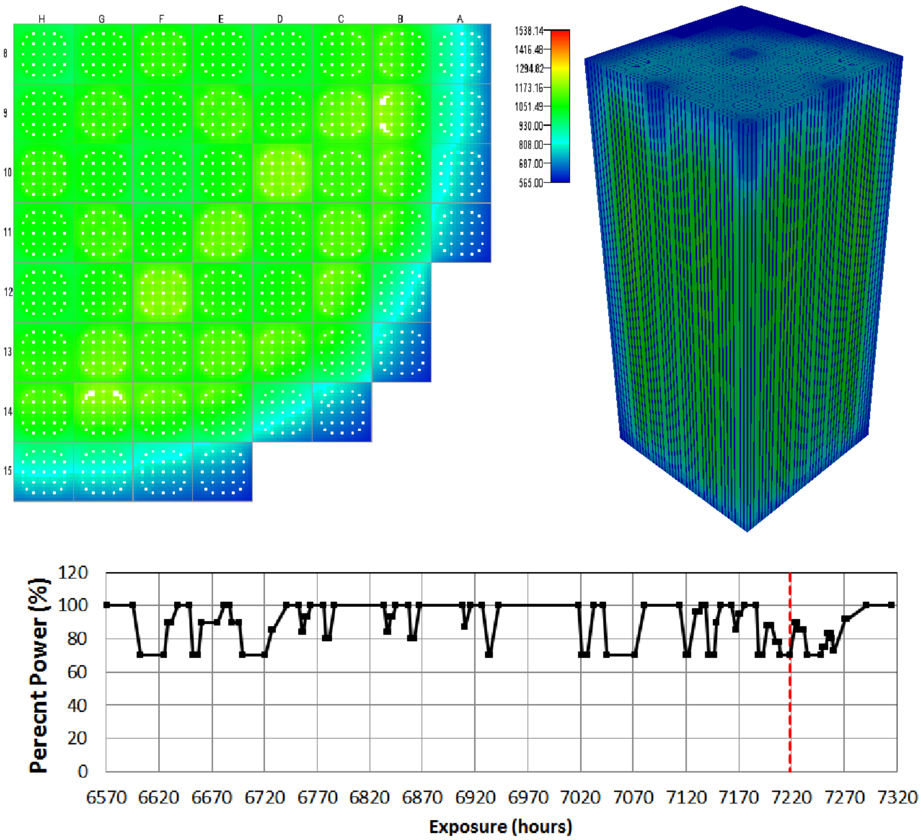
15
1538.14
1416.48
1294.82
1173.16
1051.49
930.00
808.00
687.00
565.00
Perecnt Power (%)
120
100
80
60
40
20
0
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)


H G F E D C B A
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10
11
12
13
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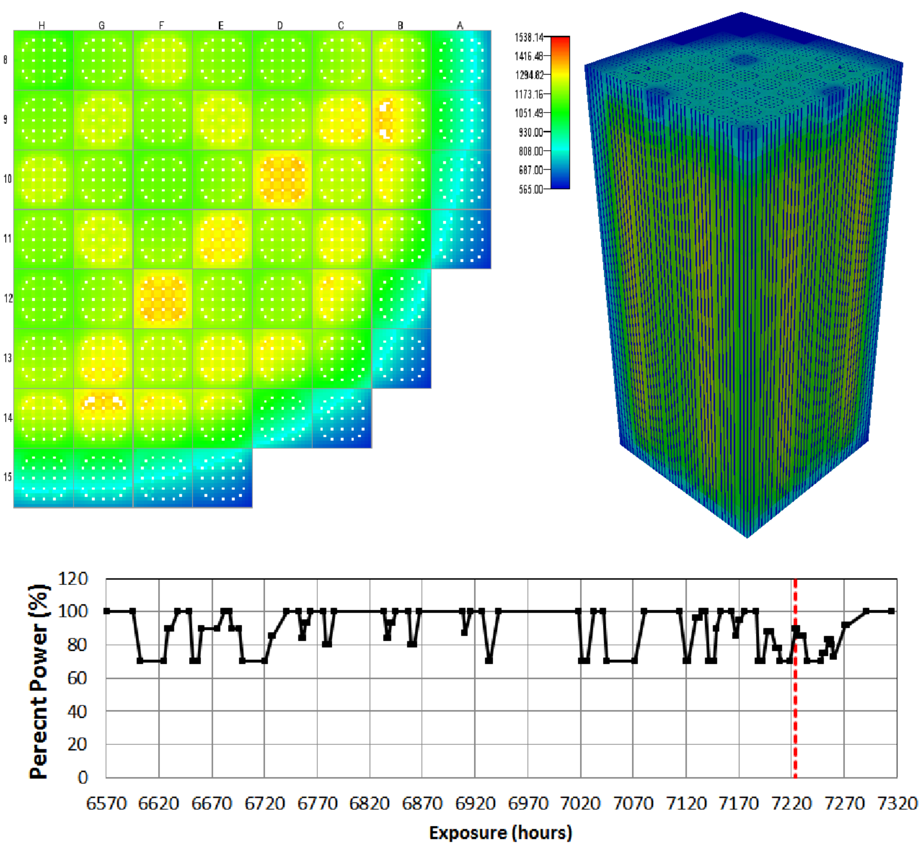
15
1538.14
1416.48
1294.82
1173.16
1051.49
930.00
808.00
687.00
565.00
Perecnt Power (%)
120
100
80
60
40
20
0
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)


H G F E D C B A
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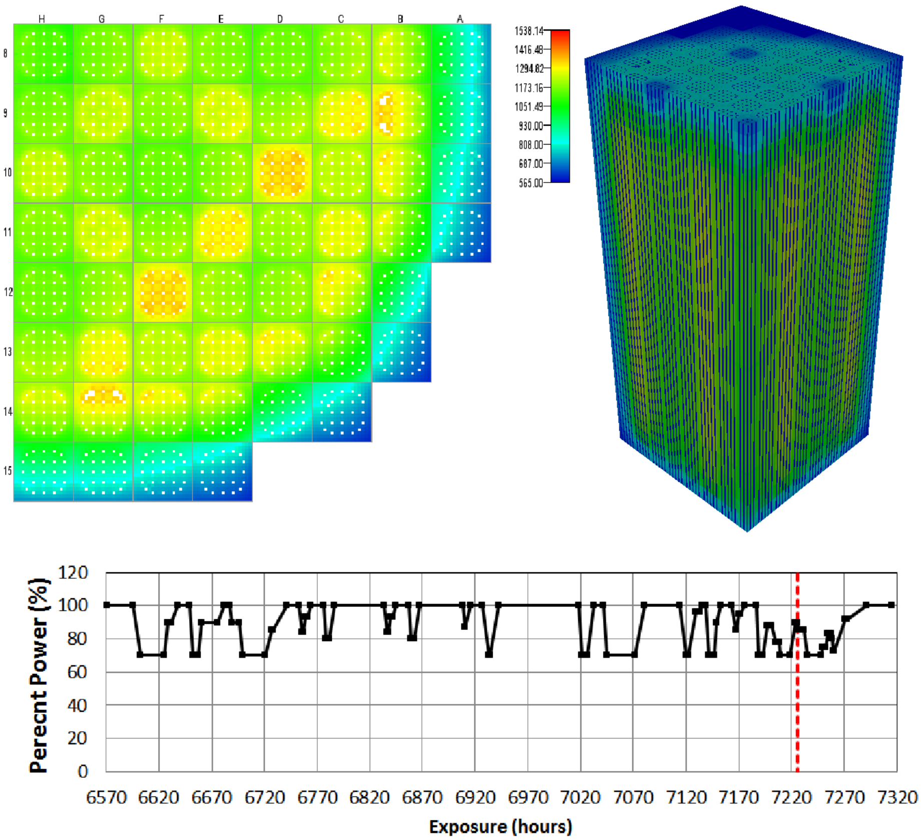
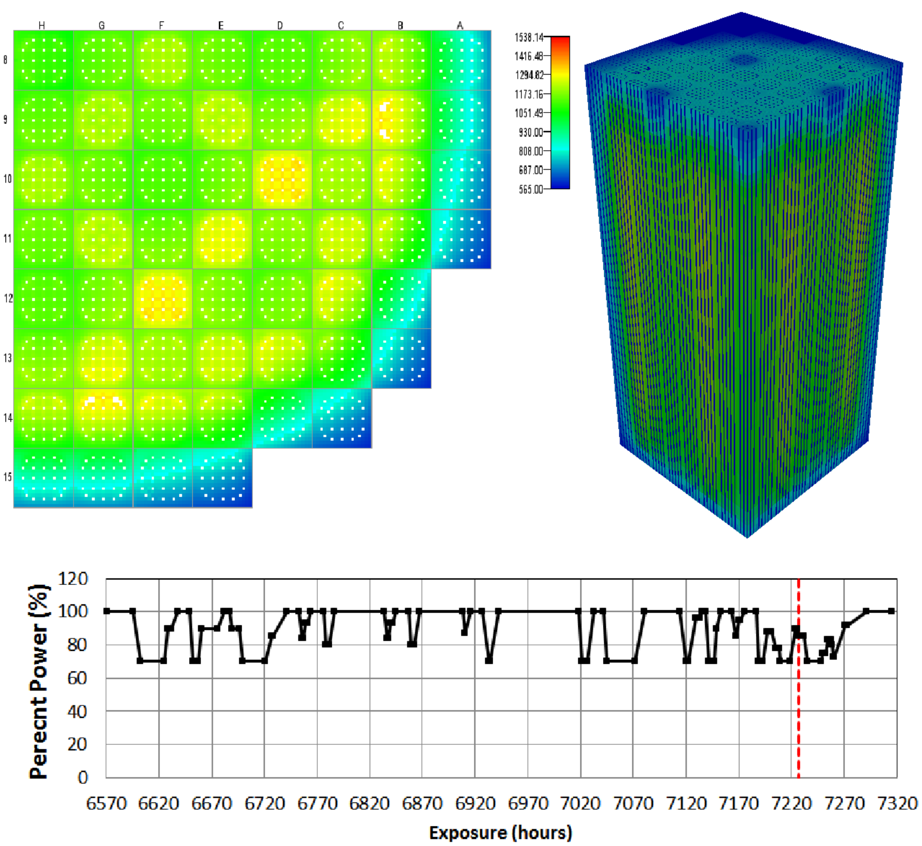
1538.14
1416.48
1294.82
1173.16
1051.49
930.00
808.00
687.00
565.00
Perecnt Power (%)
120
100
80
60
40
20
0
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)


H G F E D C B A
8 9 10 11 12 13 14 15
1538.14
1416.48
1294.82
1173.16
1051.49
930.00
808.00
687.00
565.00
Perecnt Power (%)
0 20 40 60 80 100 120
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)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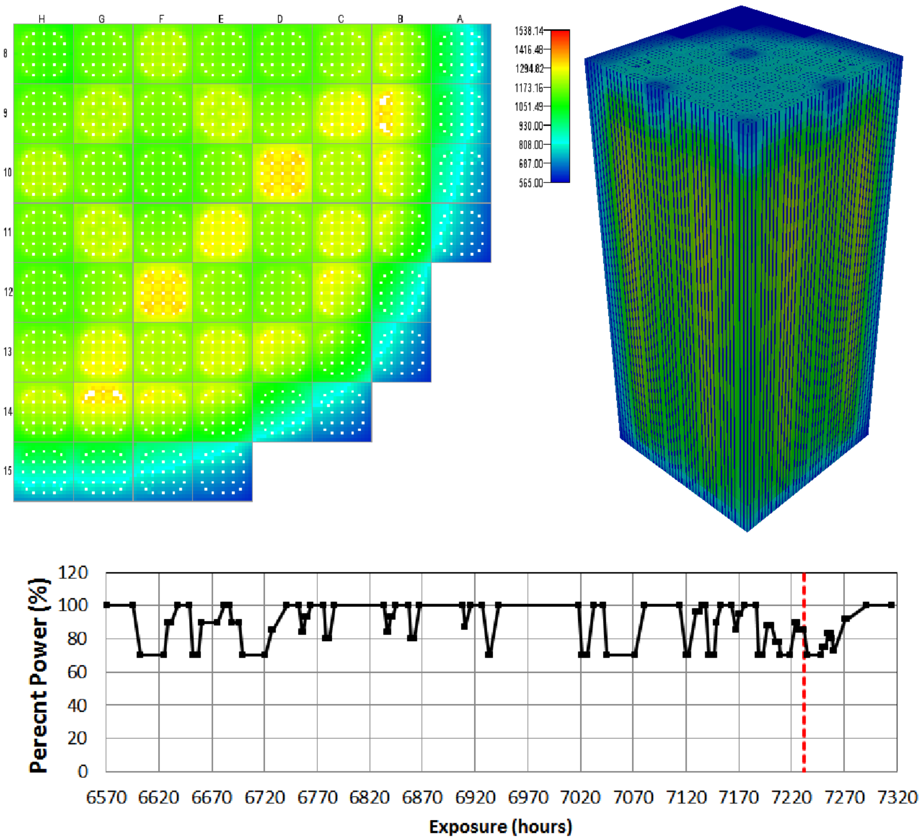
1538.14
1416.48
1294.82
1173.16
1051.49
930.00
808.00
687.00
565.00
Perecnt Power (%)
0 20 40 60 80 100 120
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)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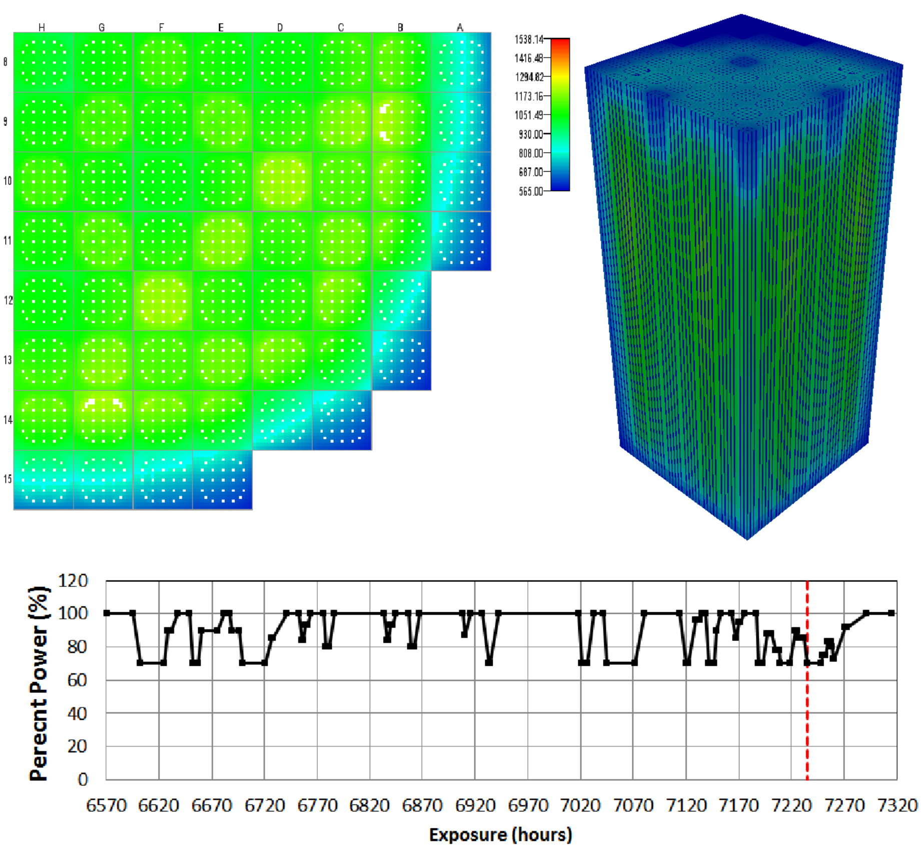
15
1538.14
1416.48
1294.82
1173.16
1051.49
930.00
808.00
687.00
565.00
Perecnt Power (%)
0
20
40
60
80
100
120
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)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10
11
12
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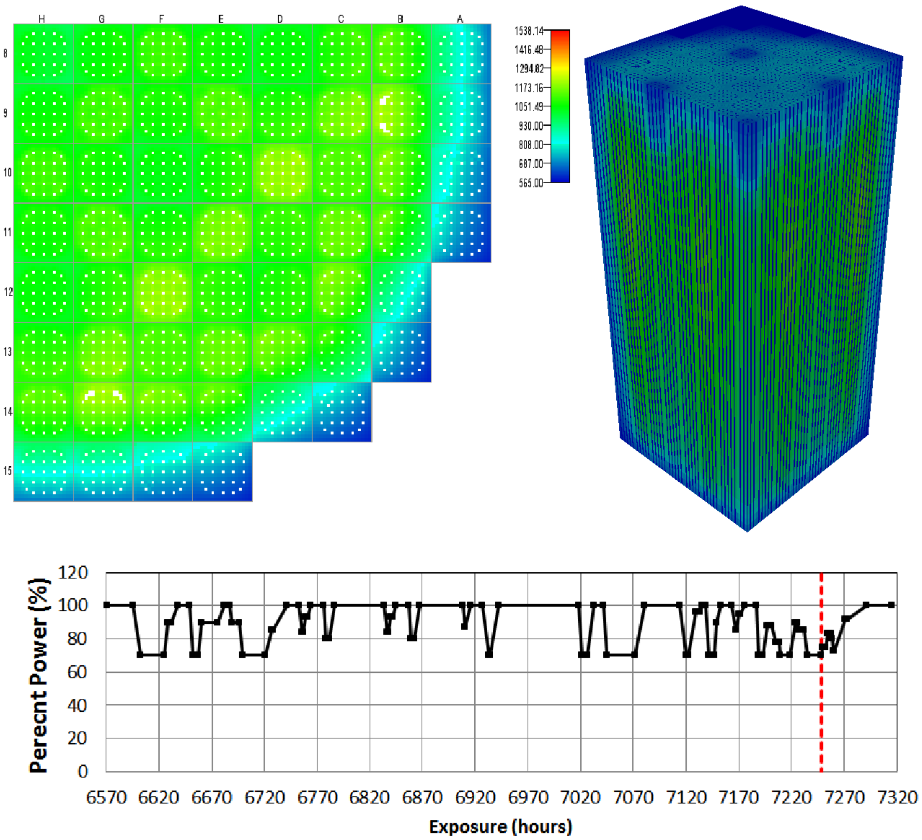
14
15
1538.14
1416.48
1294.82
1173.16
1051.49
930.00
808.00
687.00
565.00
Perecnt Power (%)
0
20
40
60
80
100
120
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)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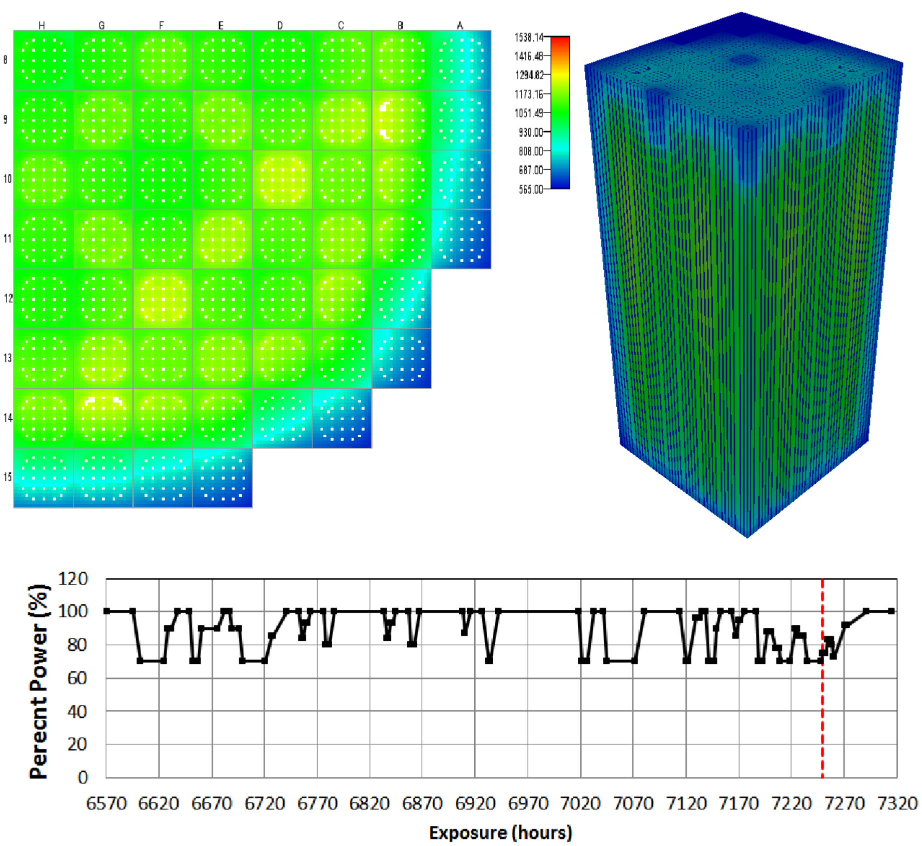
12
13
14
15
1538.14
1416.48
1294.82
1173.16
1051.49
930.00
808.00
687.00
565.00
Perecnt Power (%)
120
100
80
60
40
20
0
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)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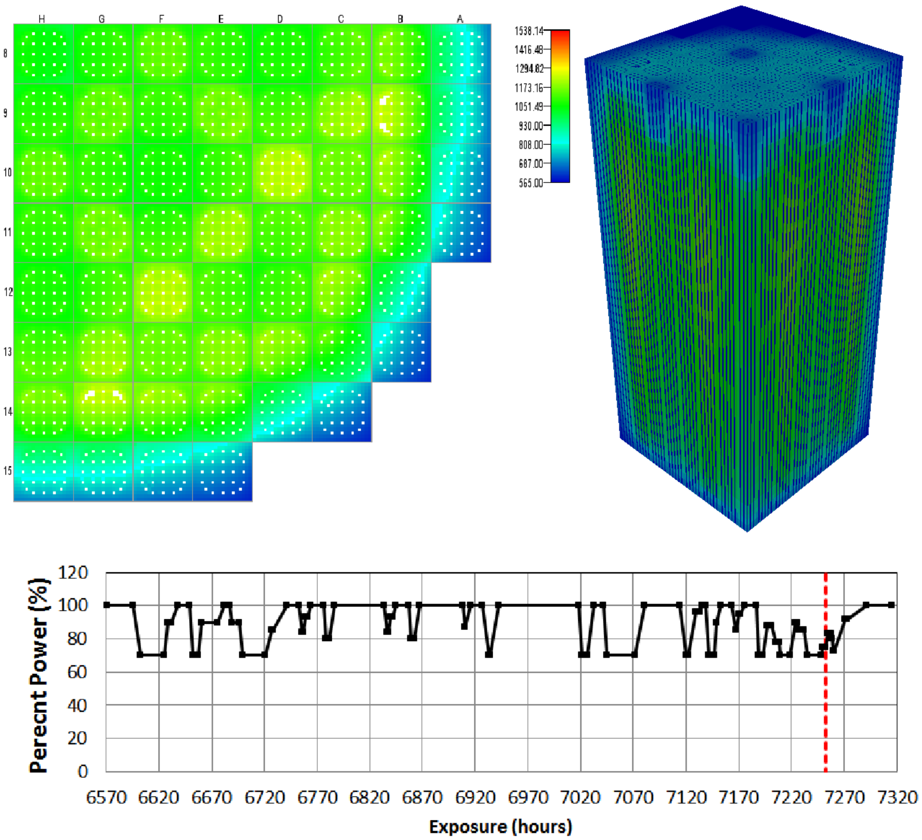
14
15
1538.14
1416.48
1294.82
1173.16
1051.49
930.00
808.00
687.00
565.00
Perecnt Power (%)
120
100
80
60
40
20
0
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)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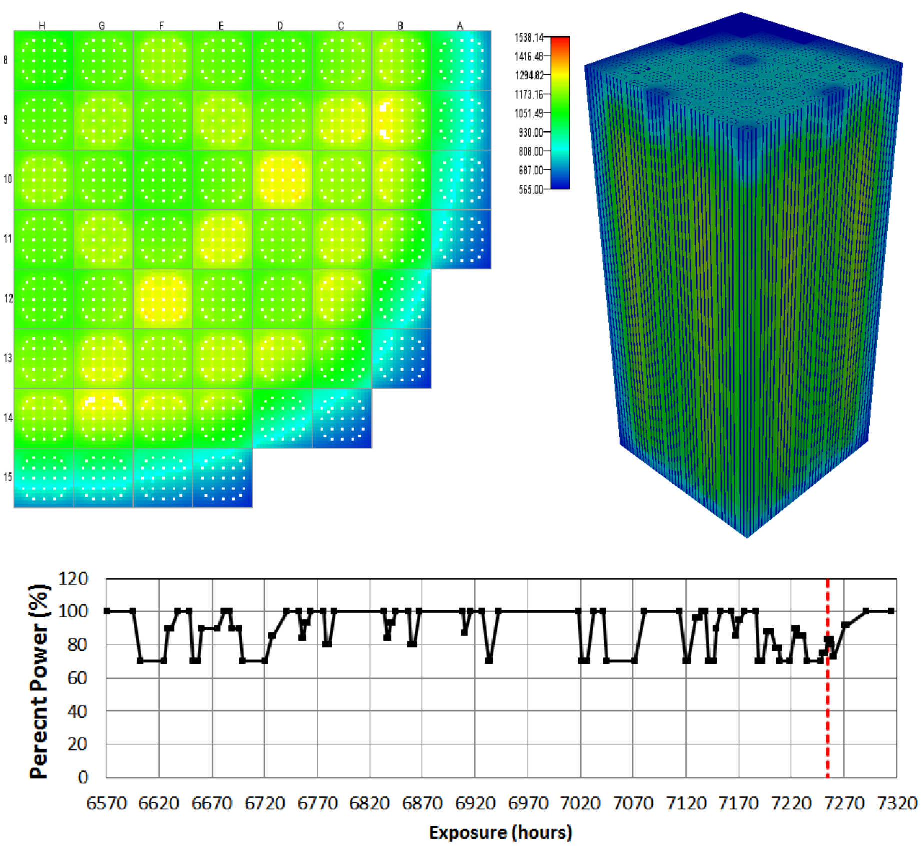
1538.14
1416.48
1294.82
1173.16
1051.49
930.00
808.00
687.00
565.00
Perecnt Power (%)
120 100 80 60 40 20 0
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)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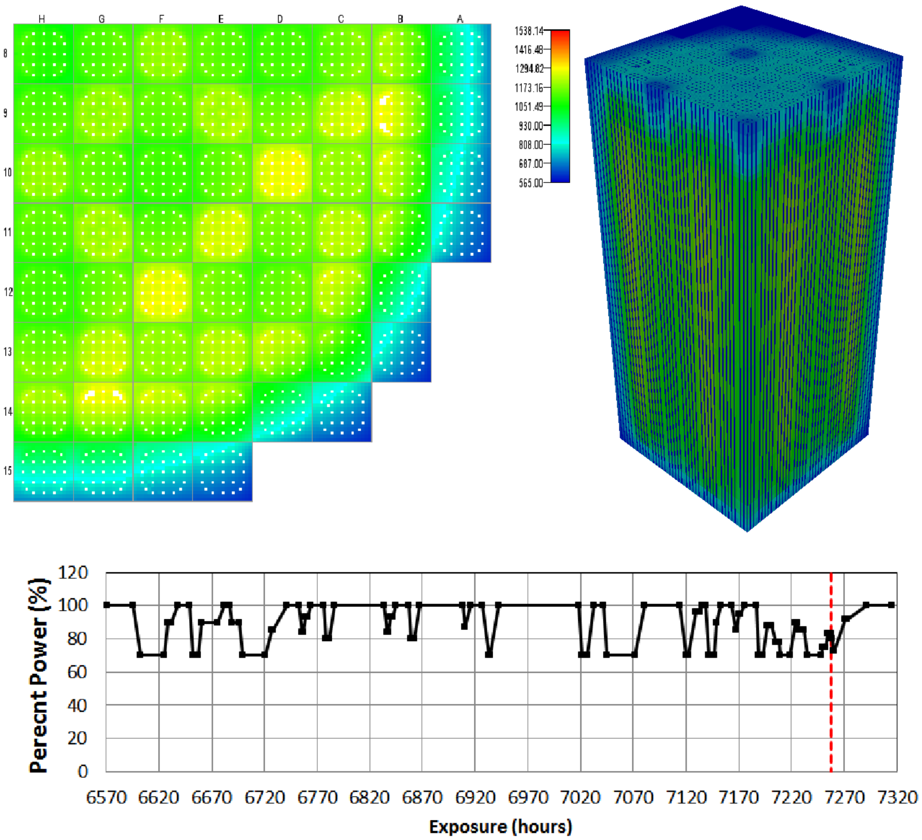
1294.82
1173.16
1051.49
930.00
808.00
687.00
565.00
Perecnt Power (%)
120 100 80 60 40 20 0
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)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14
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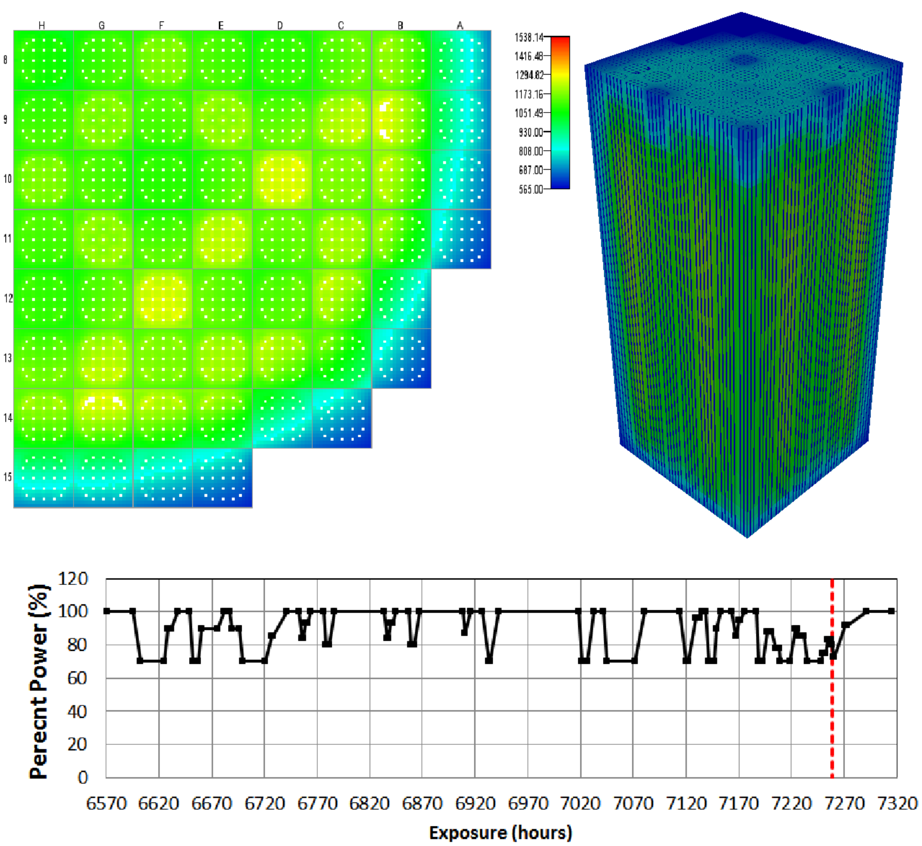
1538.14
1416.48
1294.82
1173.16
1051.49
930.00
808.00
687.00
565.00
Perecnt Power (%)
120
100
80
60
40
20
0
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)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11
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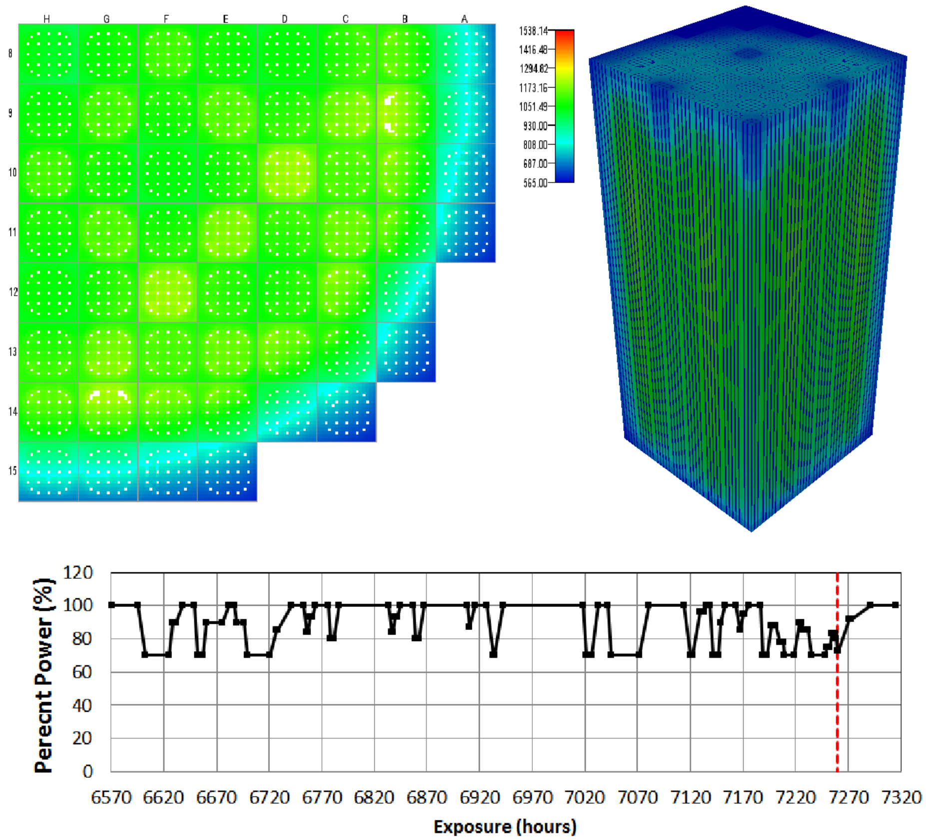
14
15
1538.14
1416.48
1294.82
1173.16
1051.49
930.00
808.00
687.00
565.00
Perecnt Power (%)
120
100
80
60
40
20
0
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)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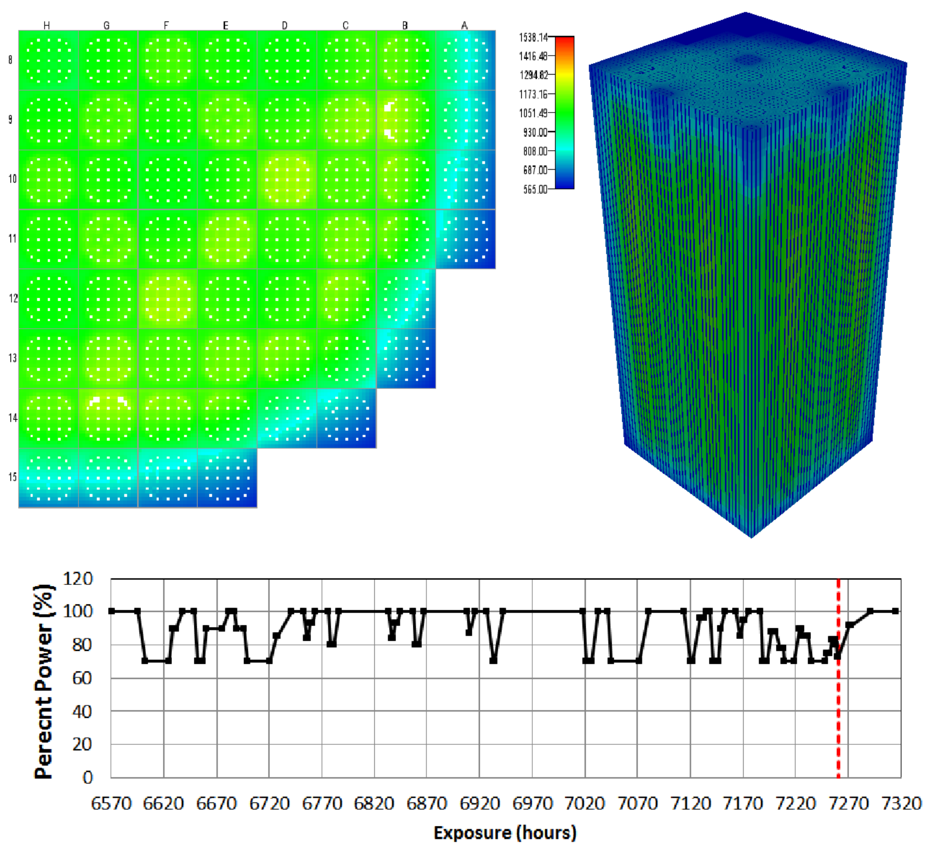
1538.14
1416.48
1294.82
1173.16
1051.49
930.00
808.00
687.00
565.00
Perecnt Power (%)
120 100 80 60 40 20 0
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)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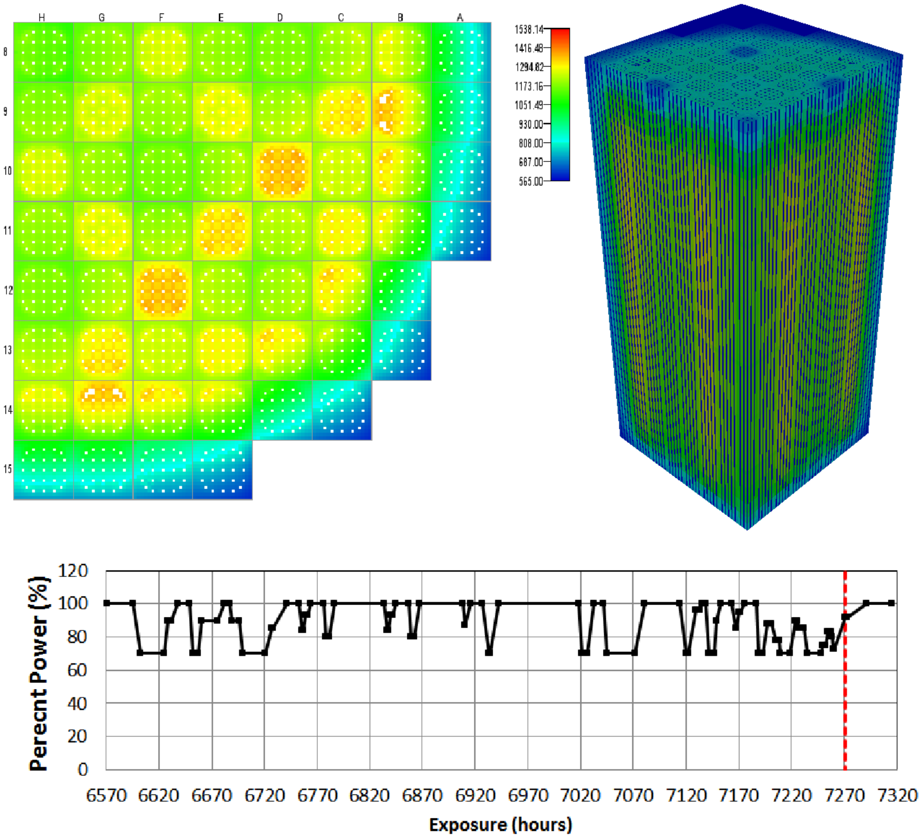
1538.14
1416.48
1294.82
1173.16
1051.49
930.00
808.00
687.00
565.00
Perecnt Power (%)
120 100 80 60 40 20 0
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)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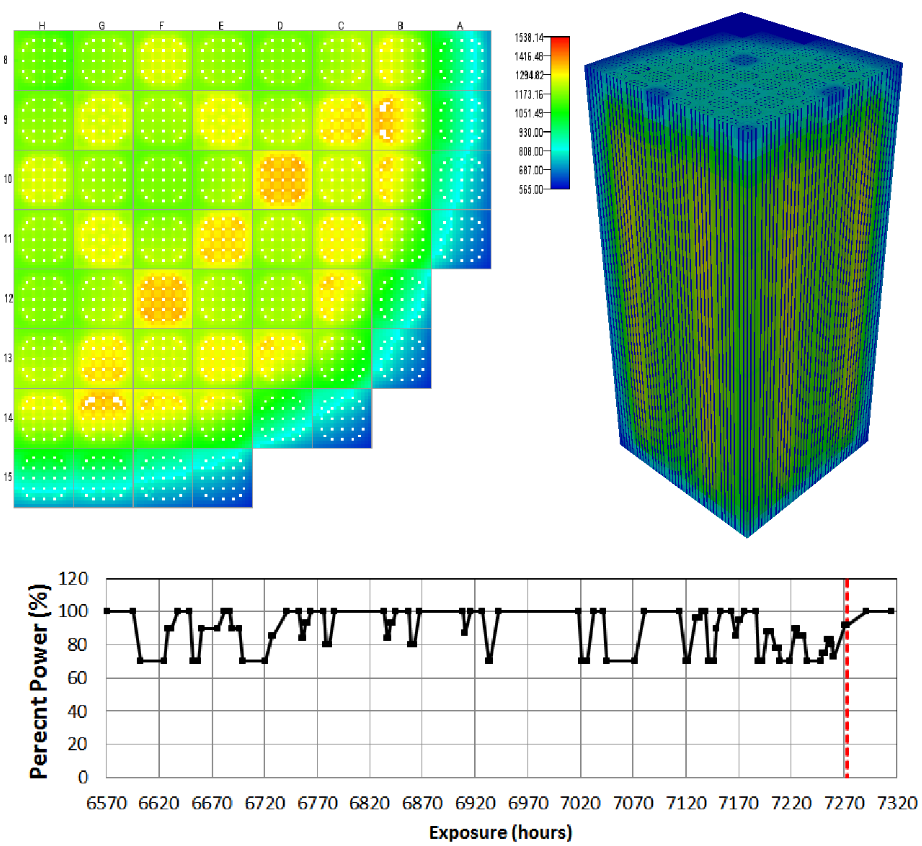
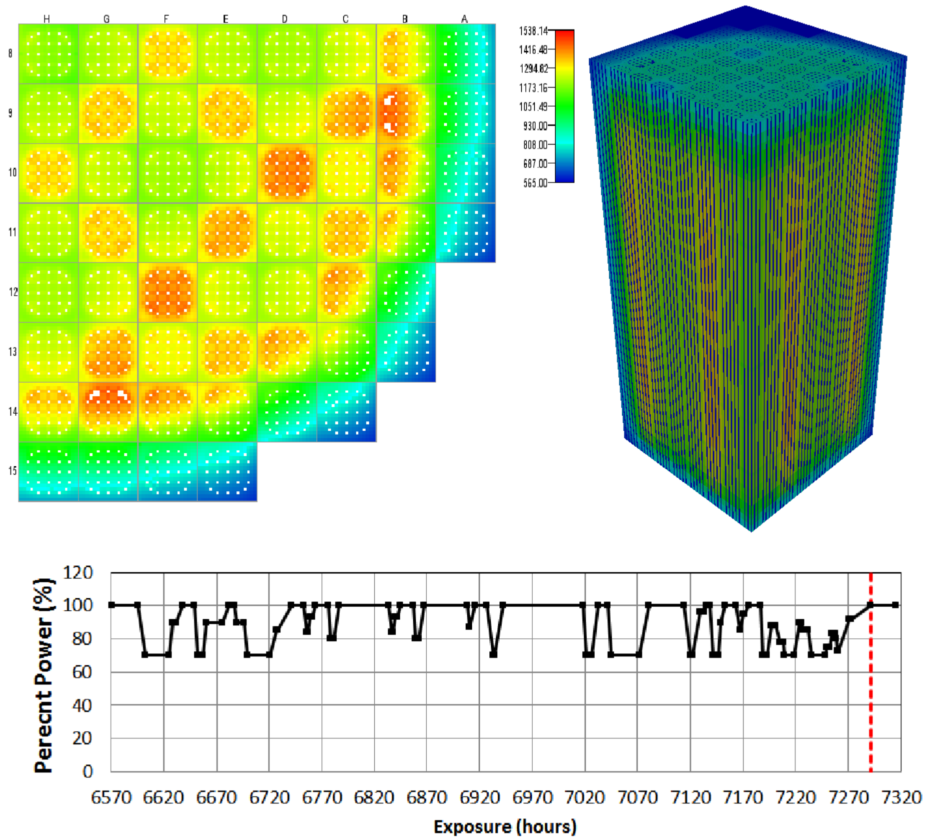
8 9 10 11 12 13 14 15
1538.14
1416.48
1294.82
1173.16
1051.49
930.00
808.00
687.00
565.00
Perecnt Power (%)
0 20 40 60 80 100 120
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)


H G F E D C B A
8 9 10 11 12 13 14 15
1538.14
1416.48
1294.82
1173.16
1051.49
930.00
808.00
687.00
565.00
Perecnt Power (%)
0 20 40 60 80 100 120
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)


H
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F
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D
C
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A
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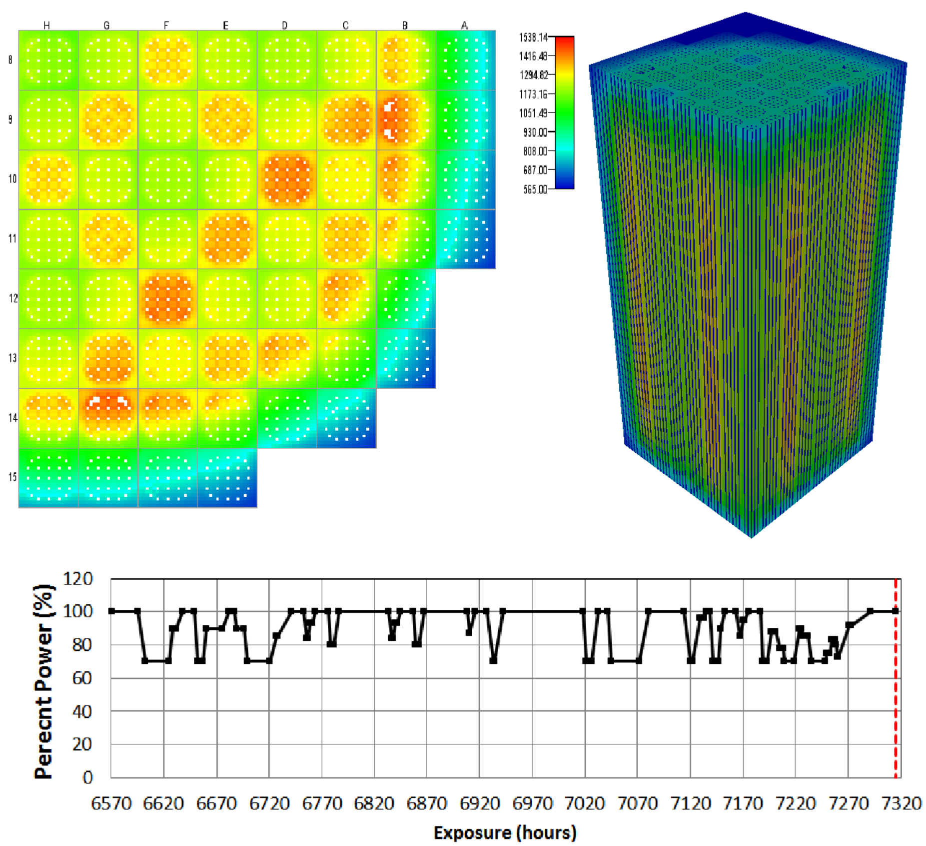
12
13
14
15
1538.14
1416.48
1294.82
1173.16
1051.49
930.00
808.00
687.00
565.00
Perecnt Power (%)
120
100
80
60
40
20
0
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)


H
G
F
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8
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11
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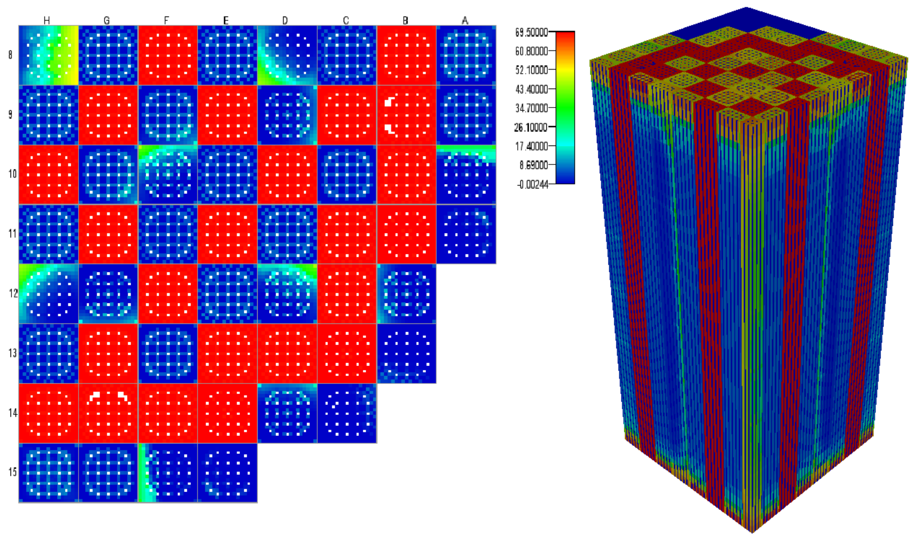
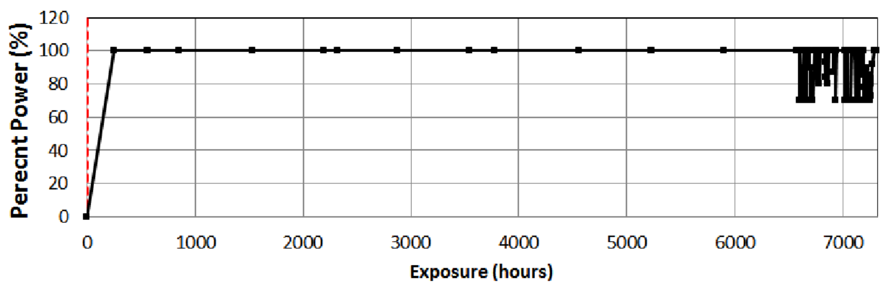
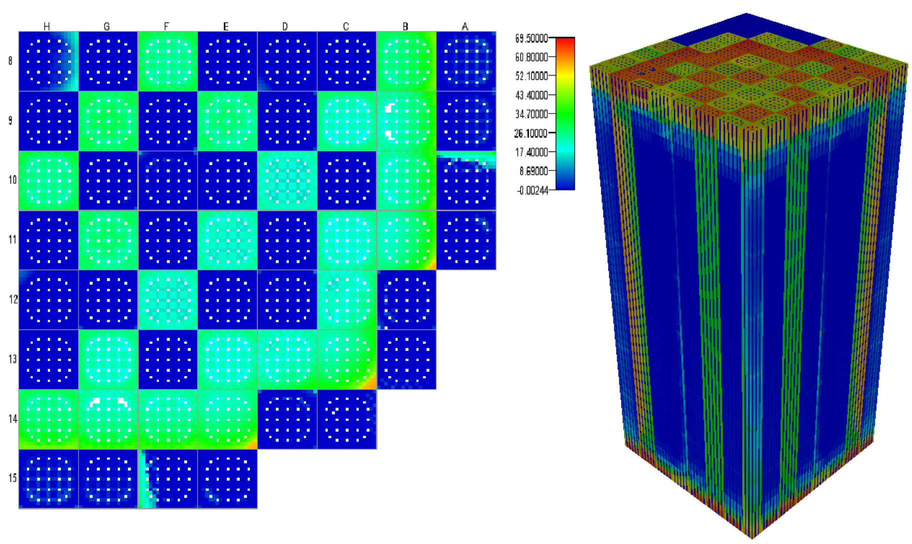
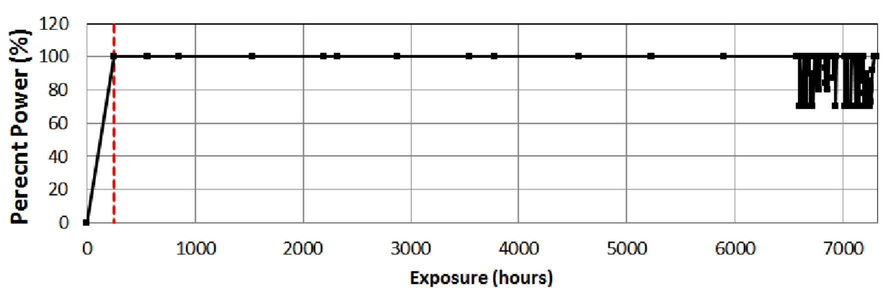
14
15
1538.14
1416.48
1294.82
1173.16
1051.49
930.00
808.00
687.00
565.00
Perecnt Power (%)
120
100
80
60
40
20
0
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)

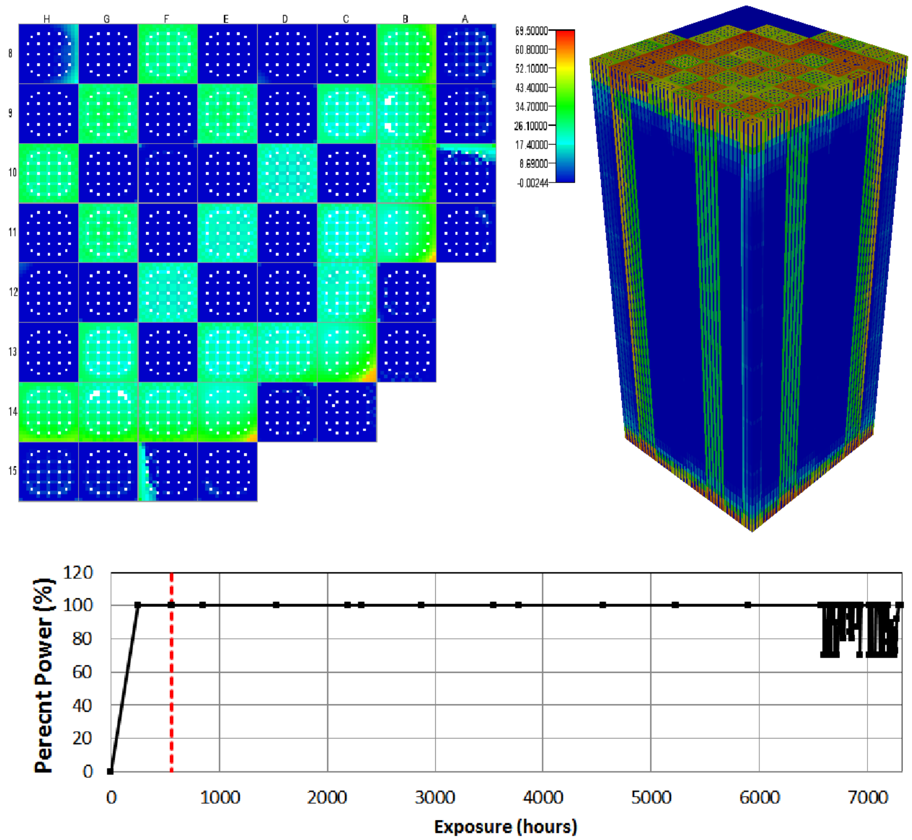
APPENDIX B - QUARTER CORE, FUEL-CLAD GAP THICKNESS RESULTS

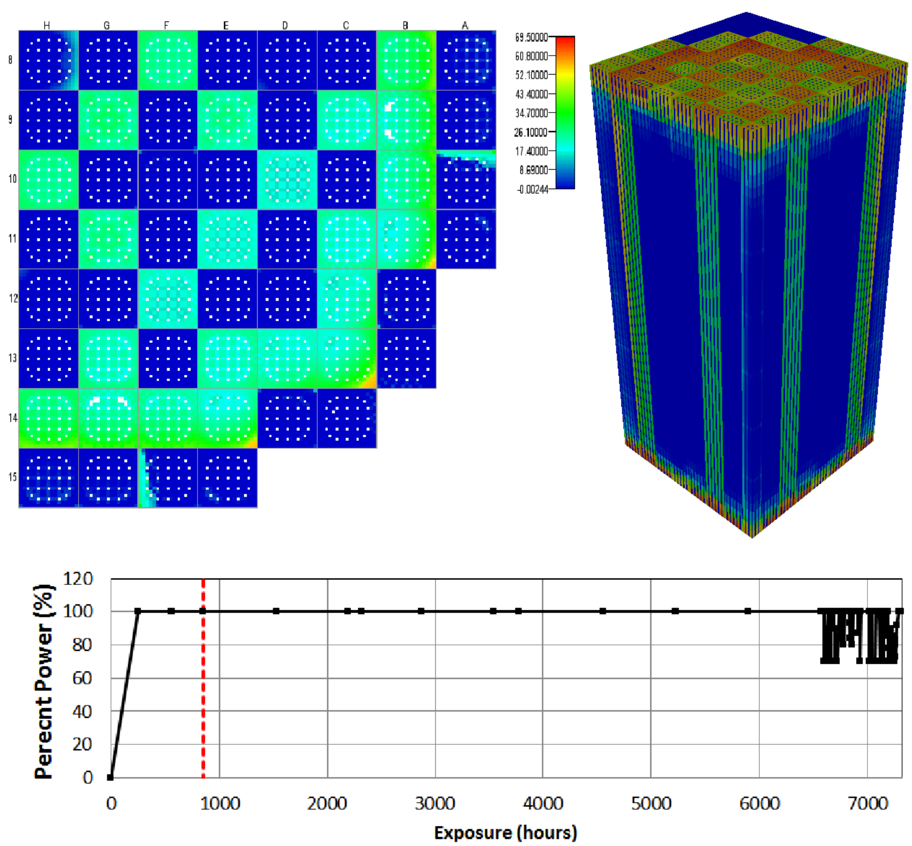


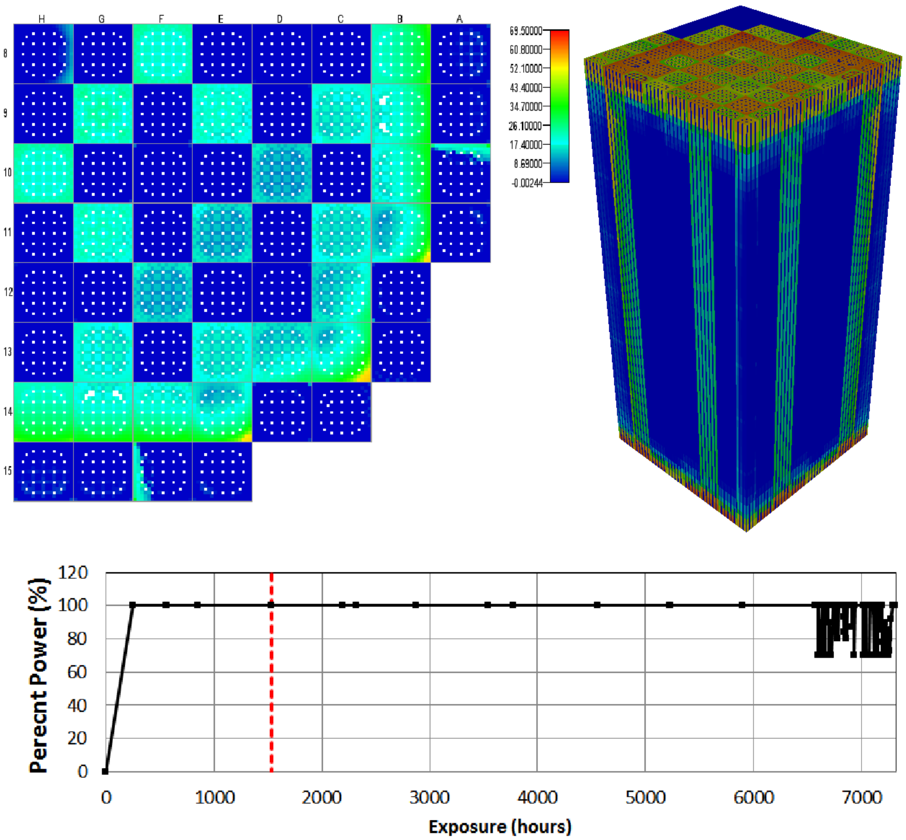







H G F E D C B A
8 9 10 11 12 13 14 15
69.50000
60.80000
52.10000
43.40000
34.70000
26.10000
17.40000
8.68000
-0.00244
Perecnt Power (%)
120 100 80 60 40 20 0
0 1000 2000 3000 4000 5000 6000 7000
Exposure (hours)


H G F E D C B A
8 9 10 11 12 13 14 15
69.50000
60.80000
52.10000
43.40000
34.70000
26.10000
17.40000
8.68000
-0.00244
Perecnt Power (%)
120 100 80 60 40 20 0
0 1000 2000 3000 4000 5000 6000 7000
Exposure (hours)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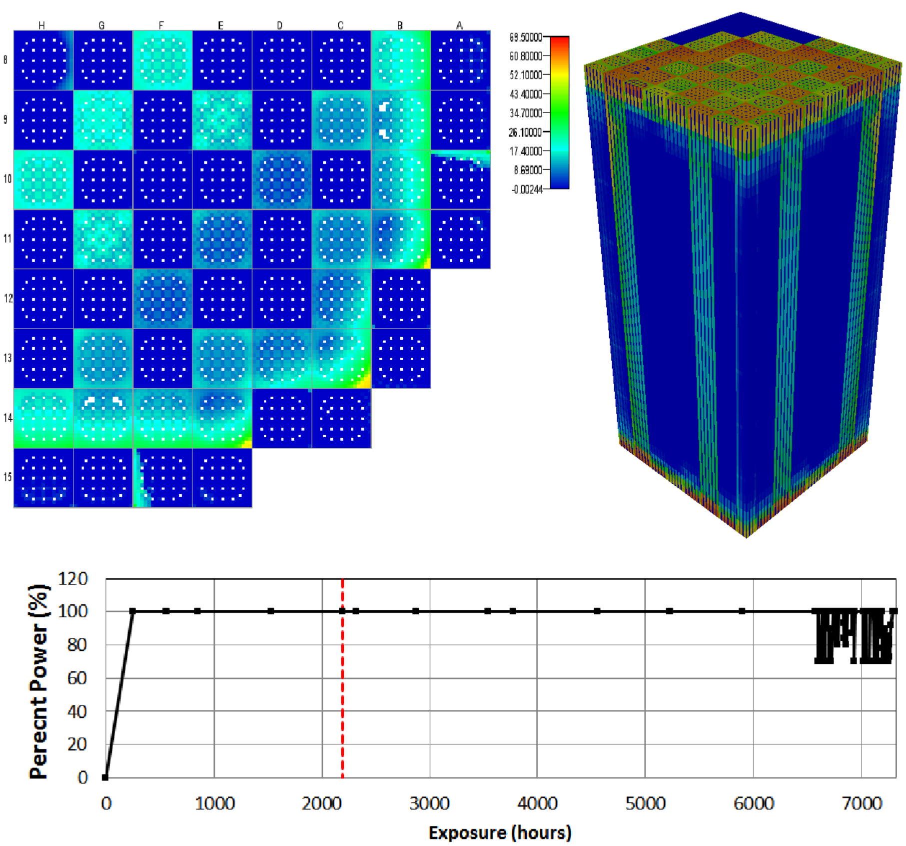
60.80000
52.10000
43.40000
34.70000
26.10000
17.40000
8.68000
-0.00244
Perecnt Power (%)
120 100 80 60 40 20 0
0 1000 2000 3000 4000 5000 6000 7000
Exposure (hours)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Perecnt Power (%)
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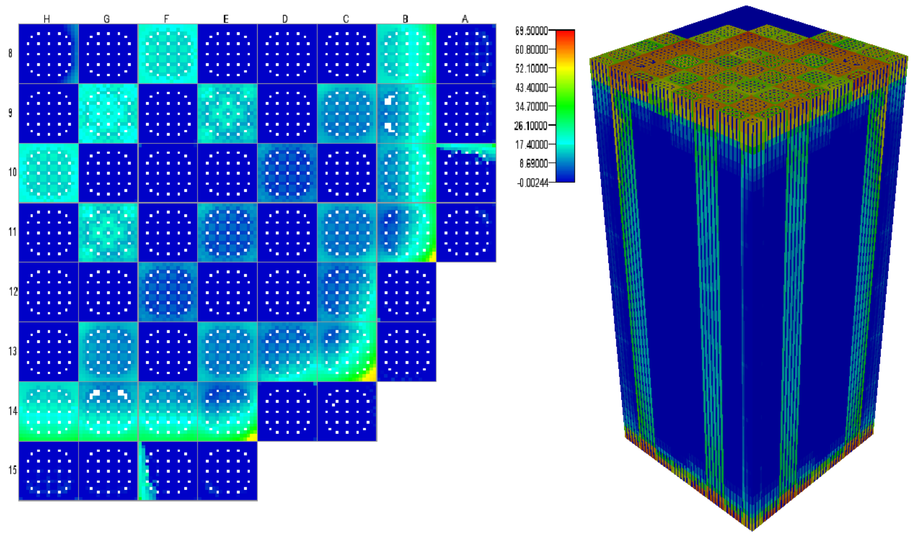
Exposure (hours)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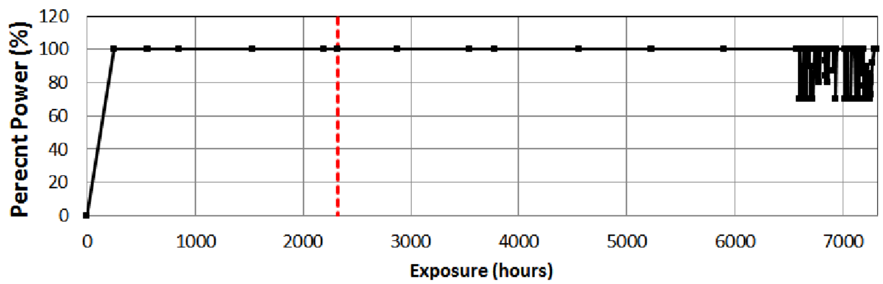
Perecnt Power (%)
Exposure (hours)
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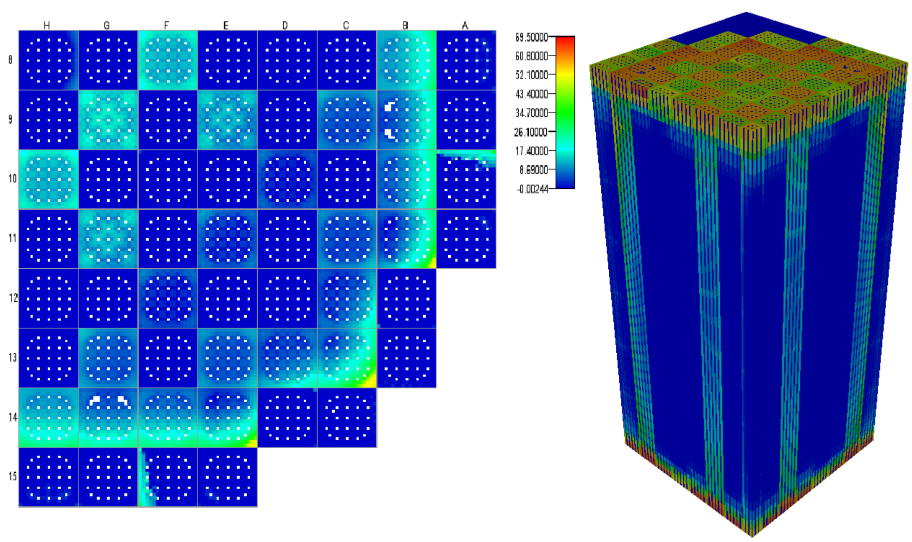
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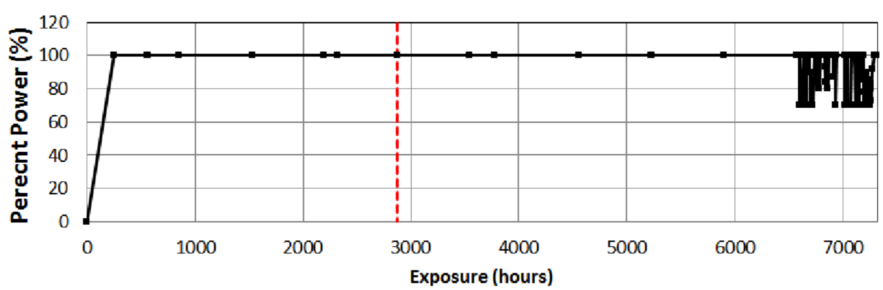
Perecnt Power (%)
Exposure (hours)
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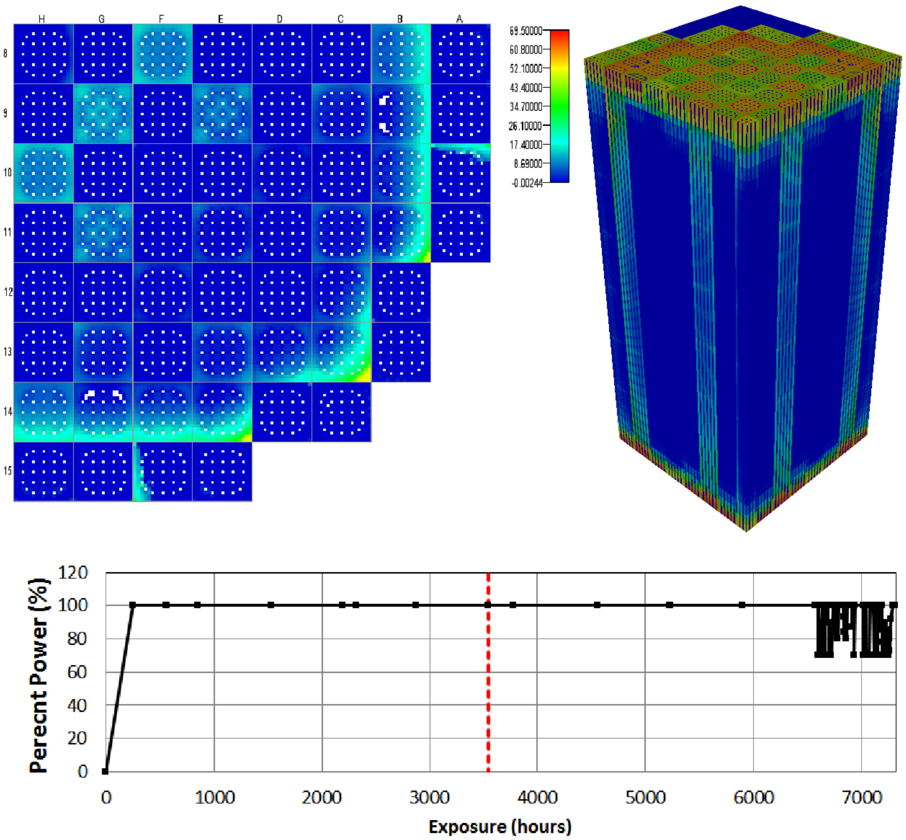
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Perecnt Power (%)
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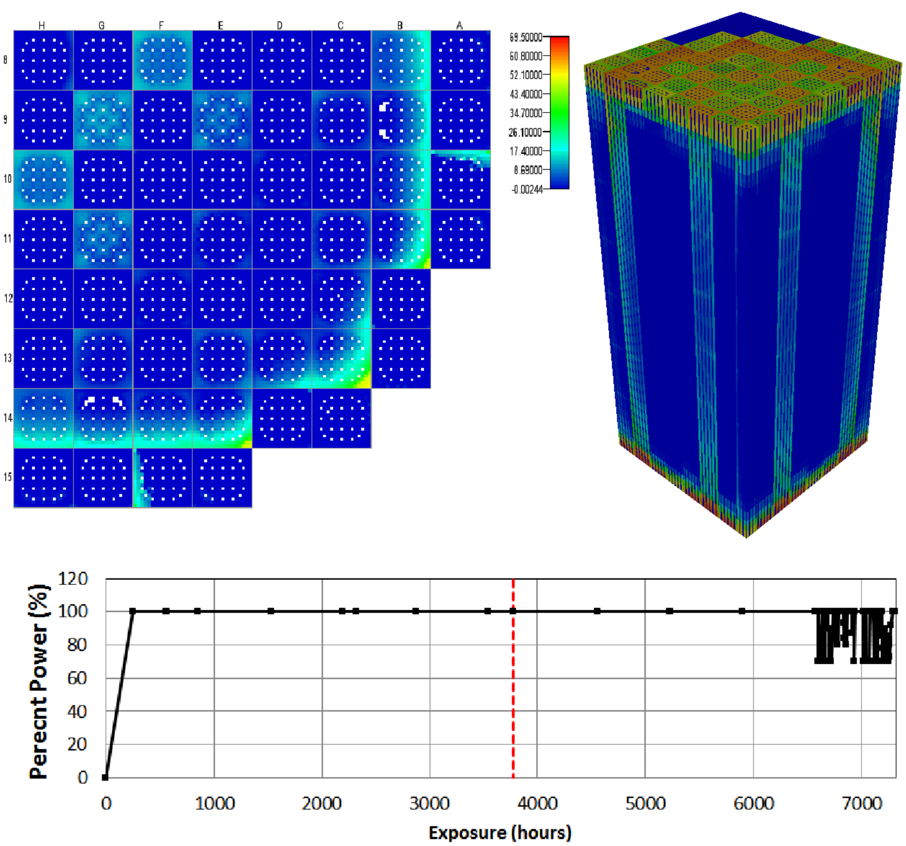
Exposure (hours)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Perecnt Power (%)
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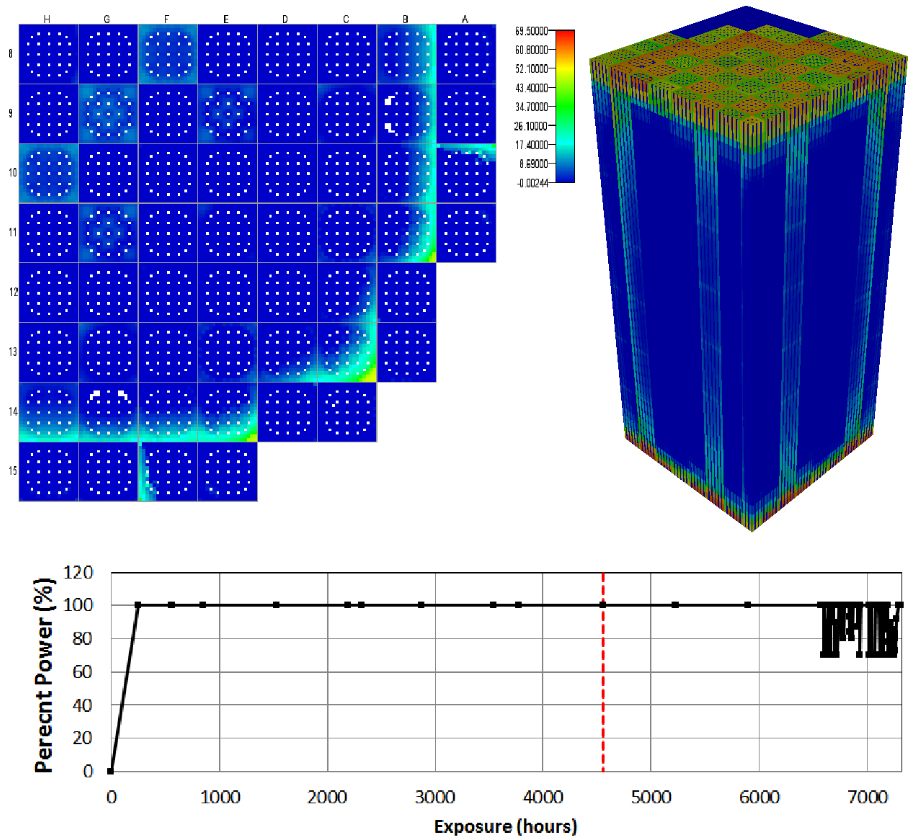
Exposure (hours)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17.40000
8.69000
-0.00244
Perecnt Power (%)
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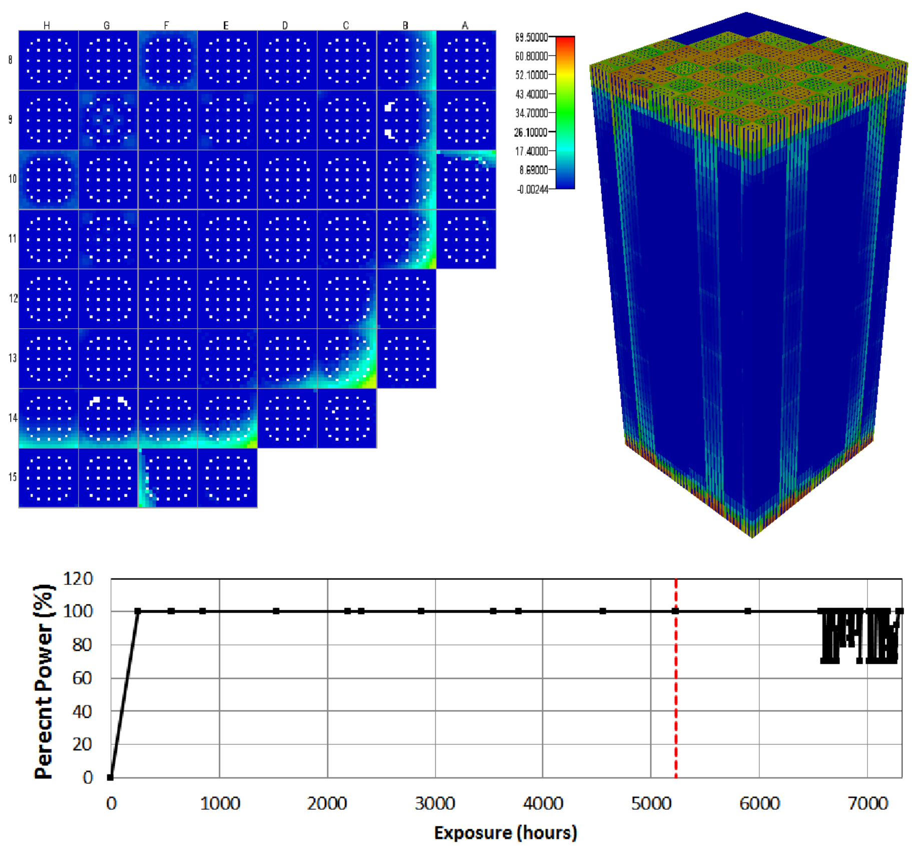
Exposure (hours)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17.40000
8.69000
-0.00244
Perecnt Power (%)
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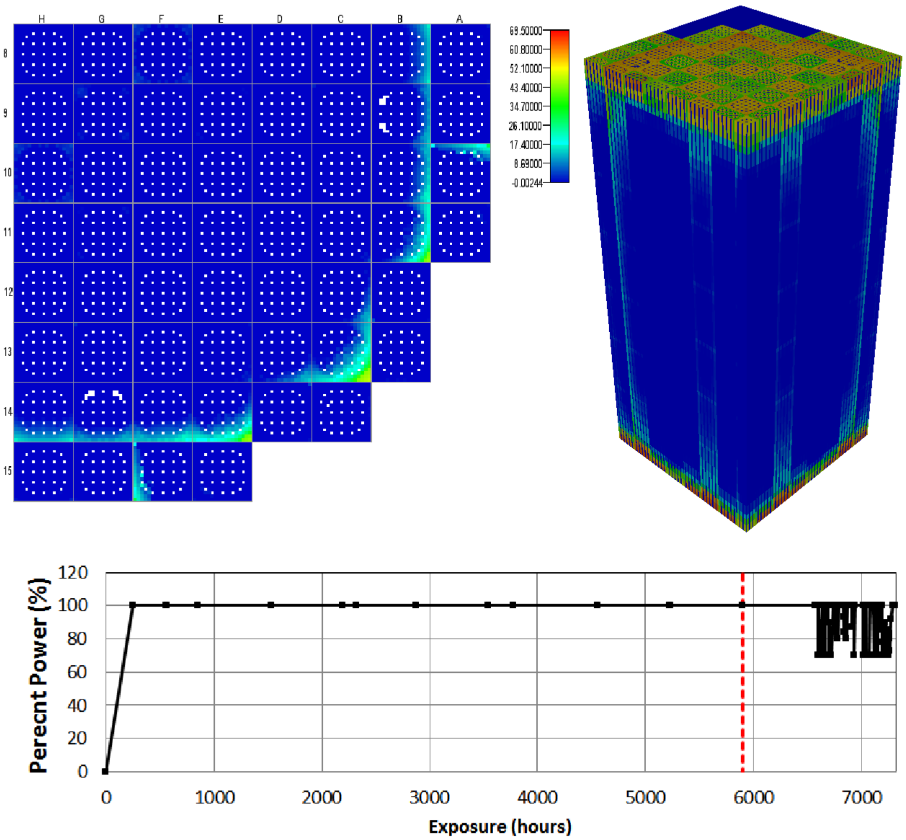
Exposure (hours)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-0.00244
Perecnt Power (%)
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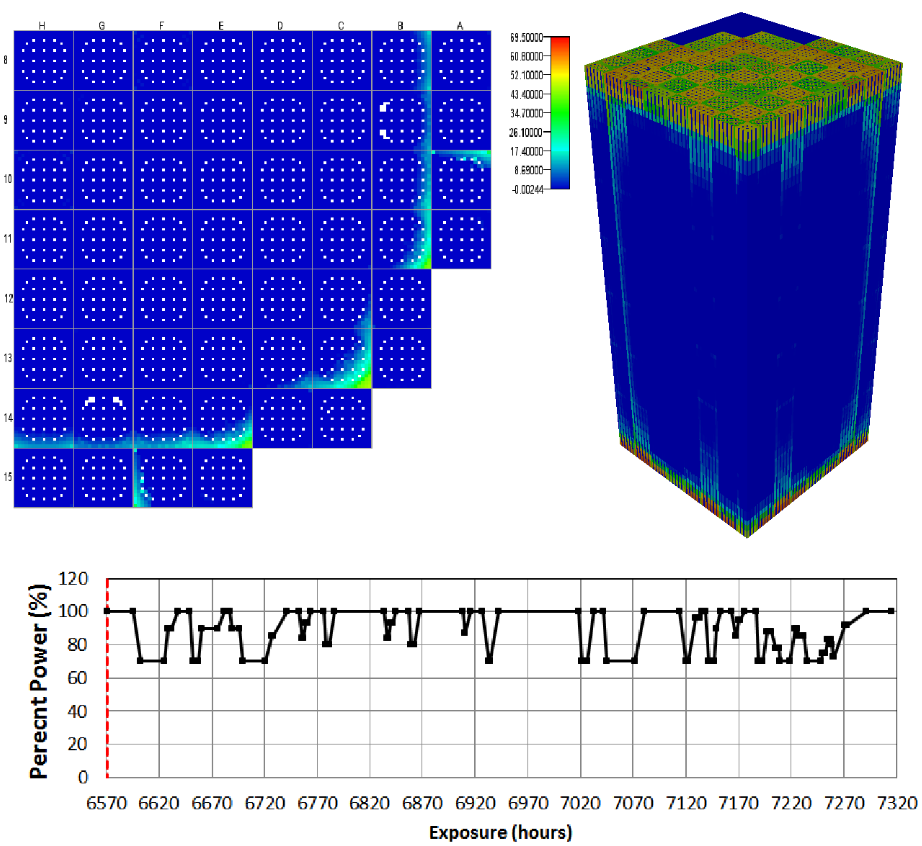
Exposure (hours)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52.10000
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34.70000
26.10000
17.40000
8.68000
-0.00244
Perecnt Power (%)
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7070
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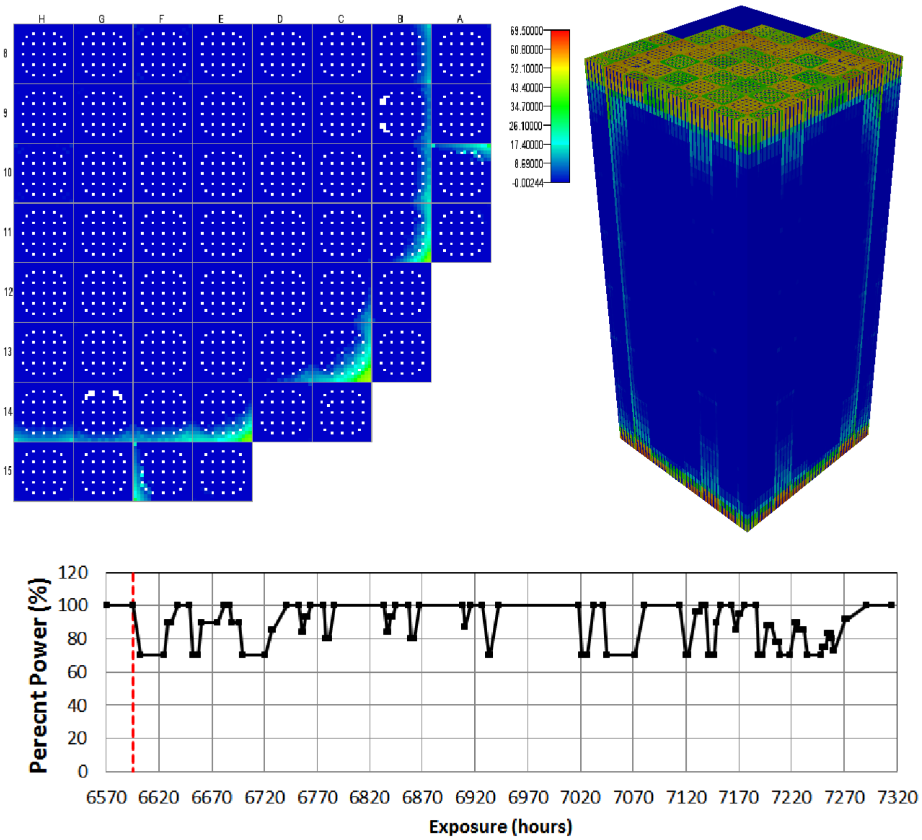
7170
7220
7270
7320
Exposure (hours)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-0.00244
Perecnt Power (%)
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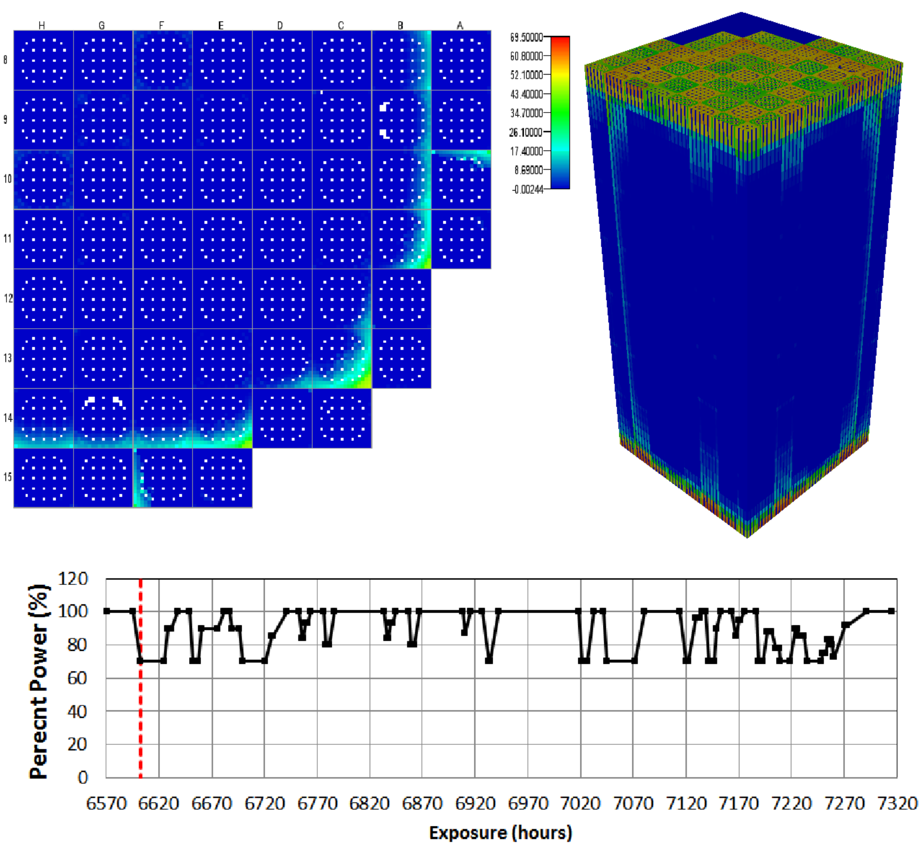
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)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Perecnt Power (%)
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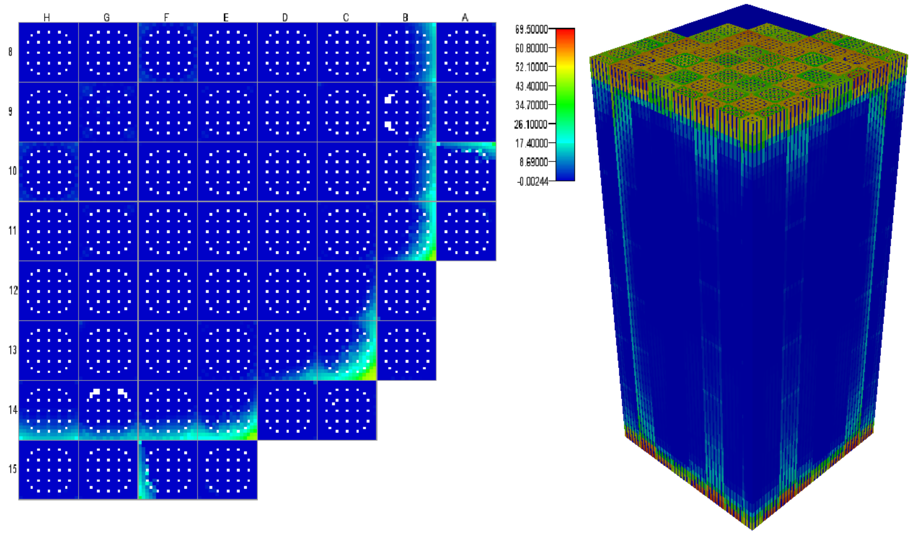
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)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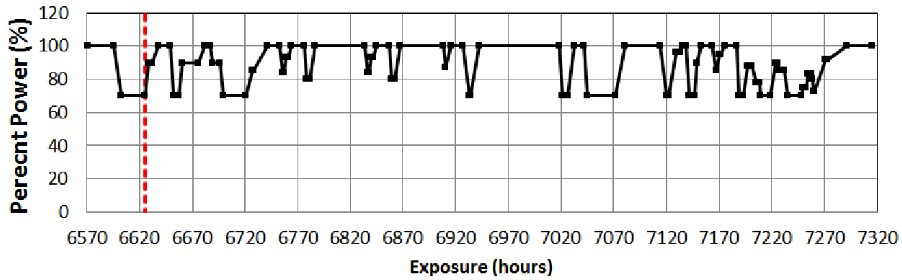
Perecnt Power (%)
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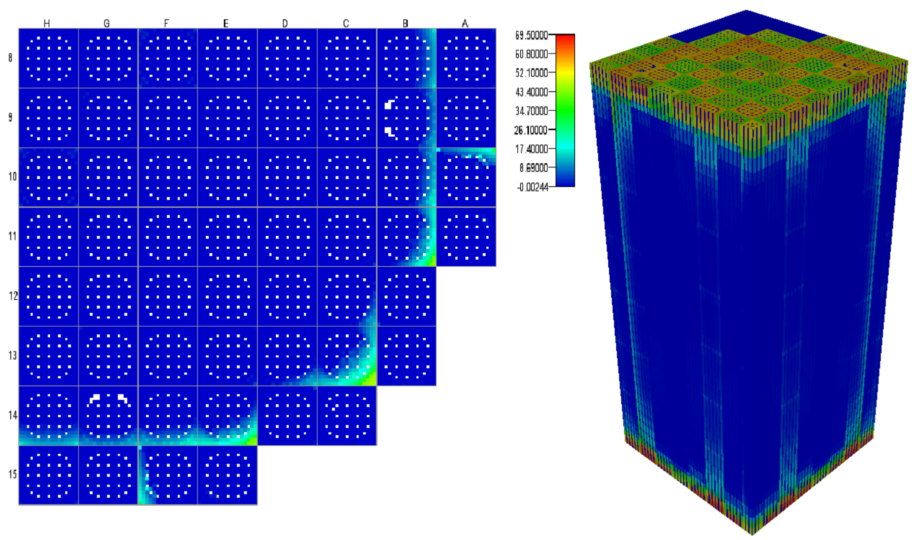
Exposure (hours)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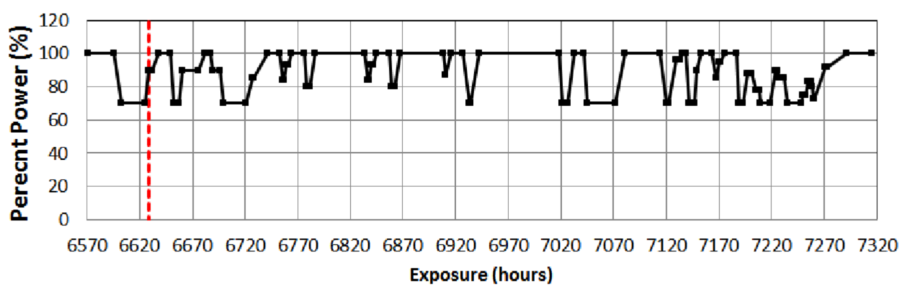
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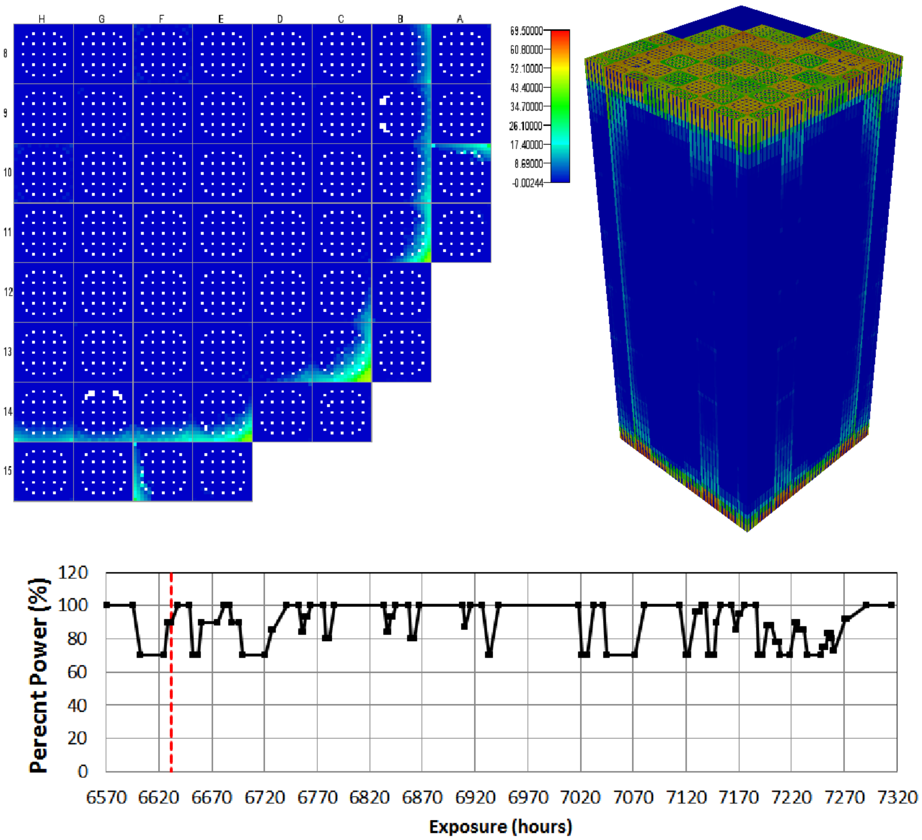
Exposure (hours)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Perecnt Power (%)
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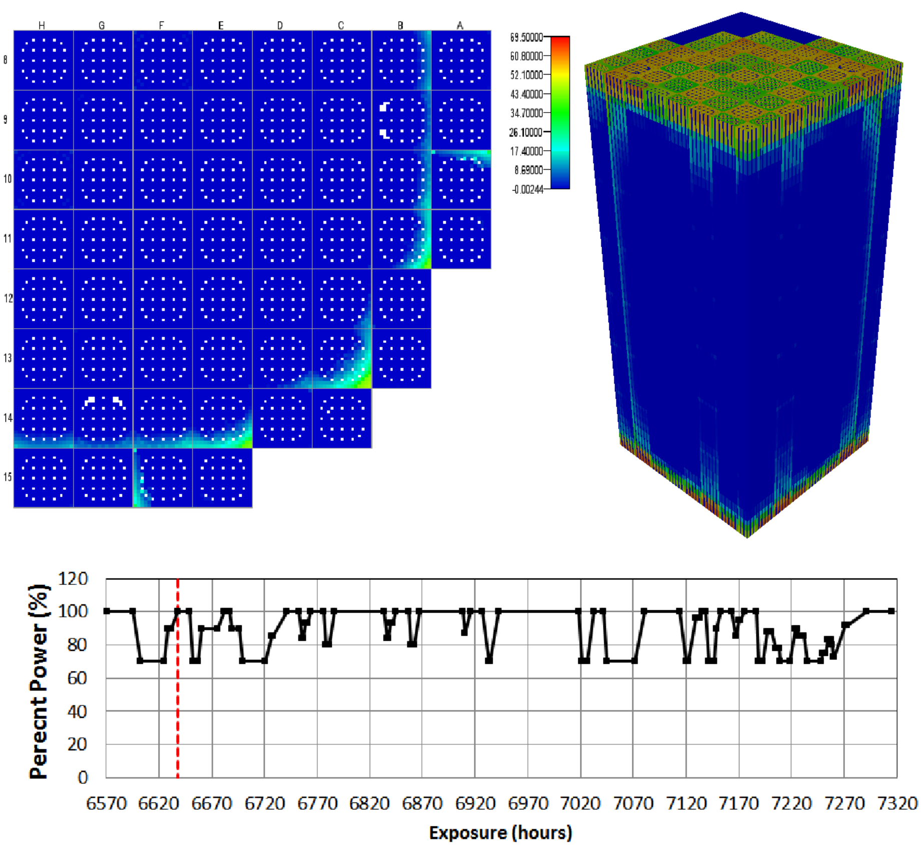
Exposure (hours)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Perecnt Power (%)
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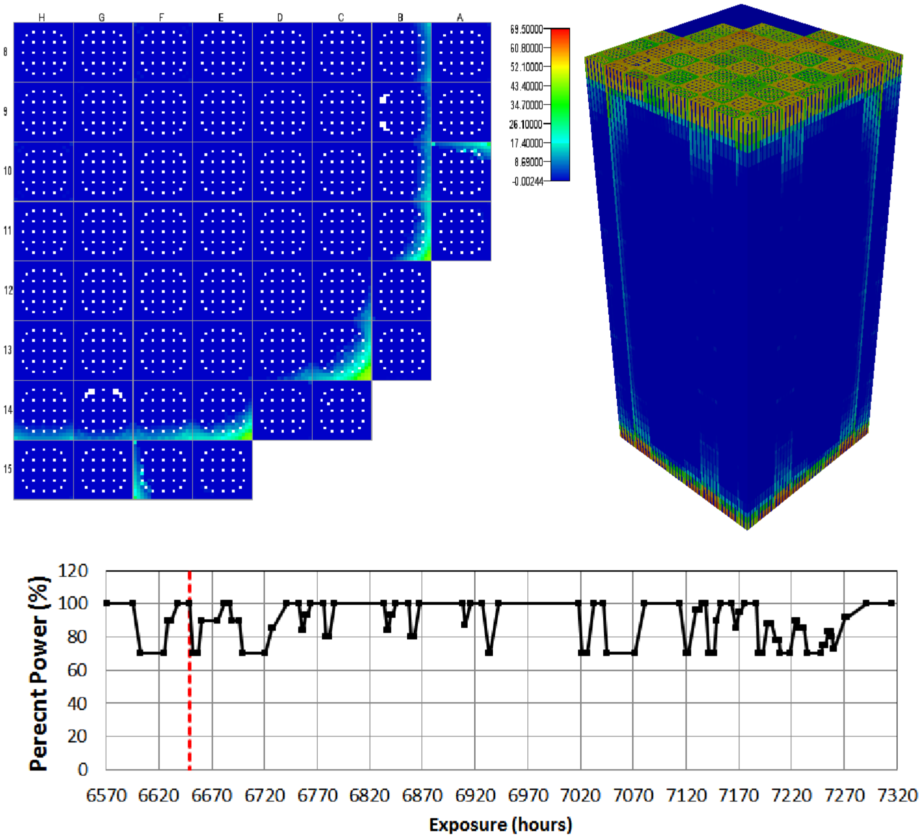
Exposure (hours)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Perecnt Power (%)
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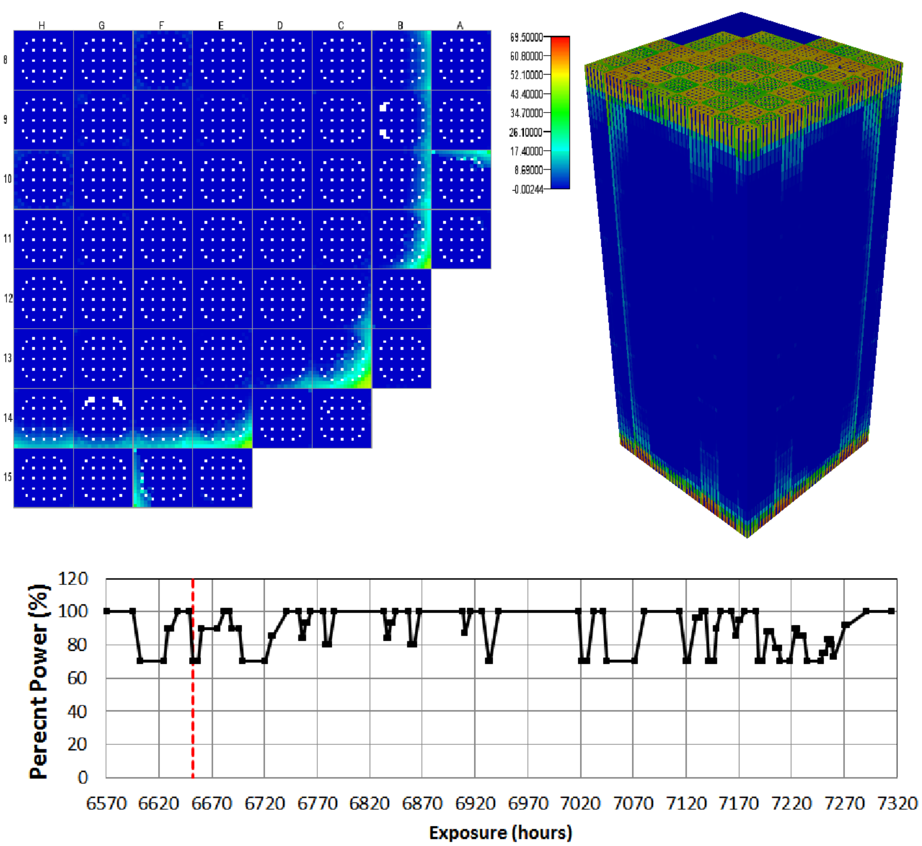
Exposure (hours)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Perecnt Power (%)
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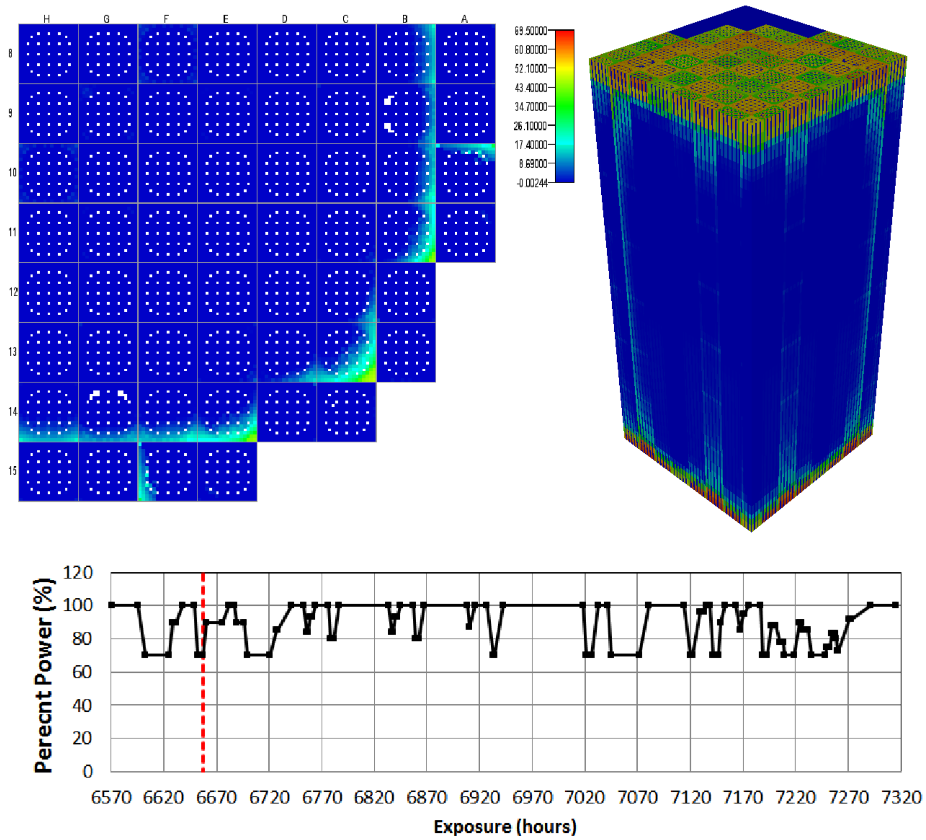
Exposure (hours)



H G F E D C B A
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Perecnt Power (%)
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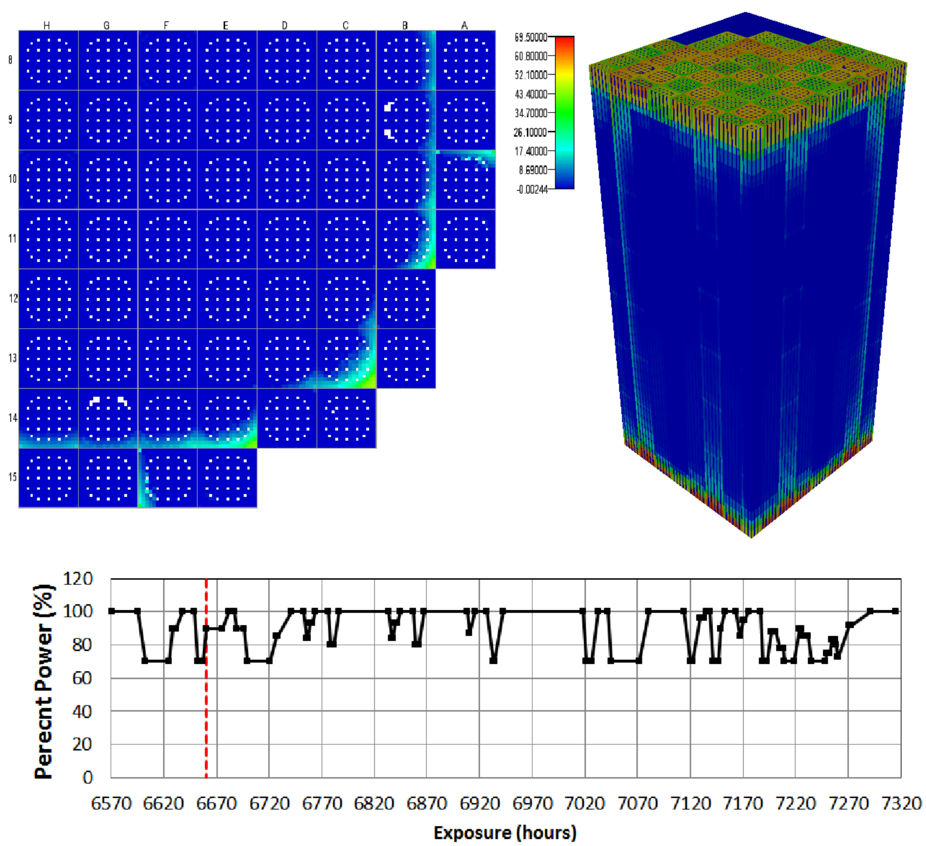
Exposure (hours)



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Perecnt Power (%)
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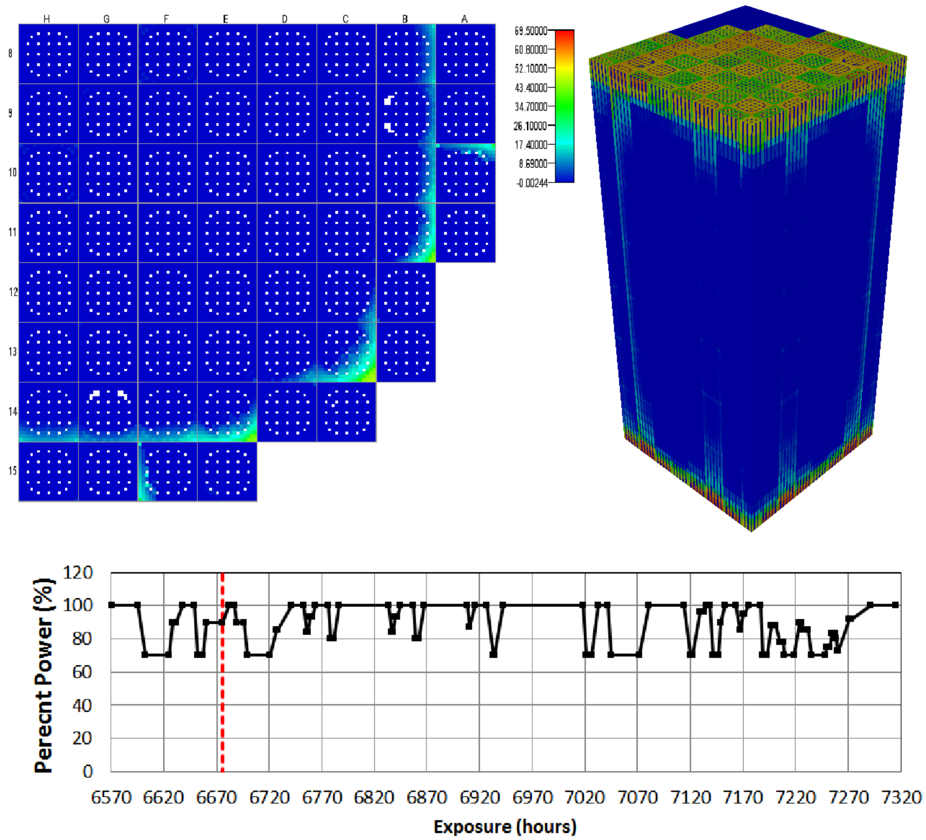
Exposure (hours)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Perecnt Power (%)
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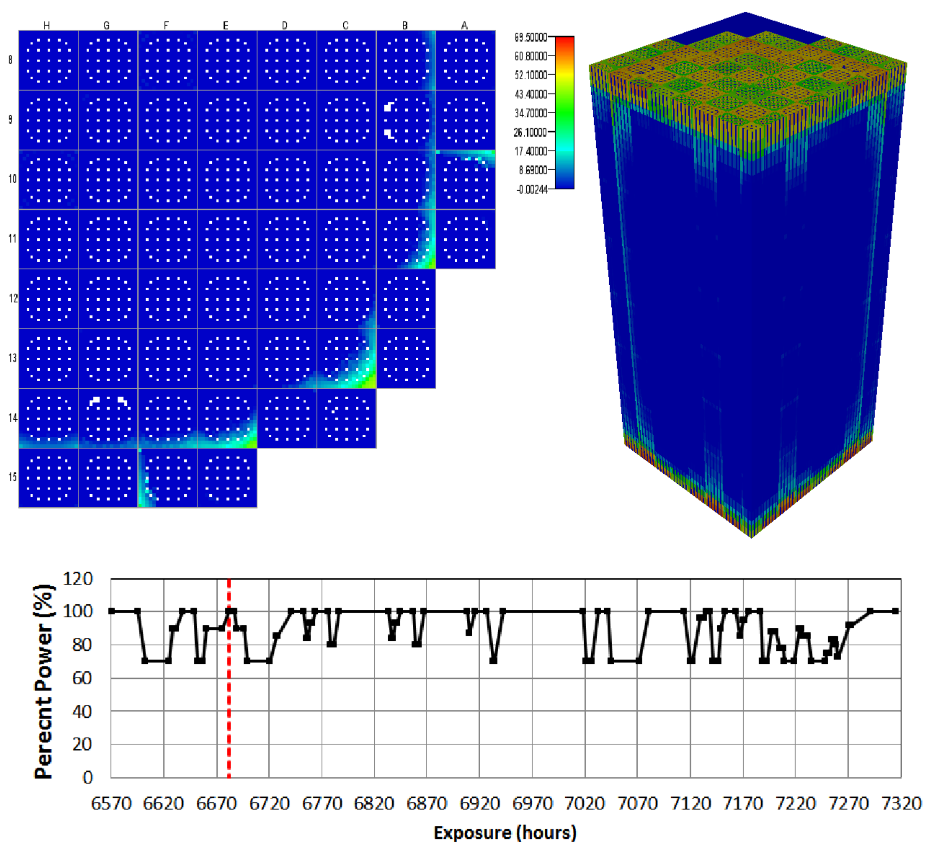
Exposure (hours)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Perecnt Power (%)
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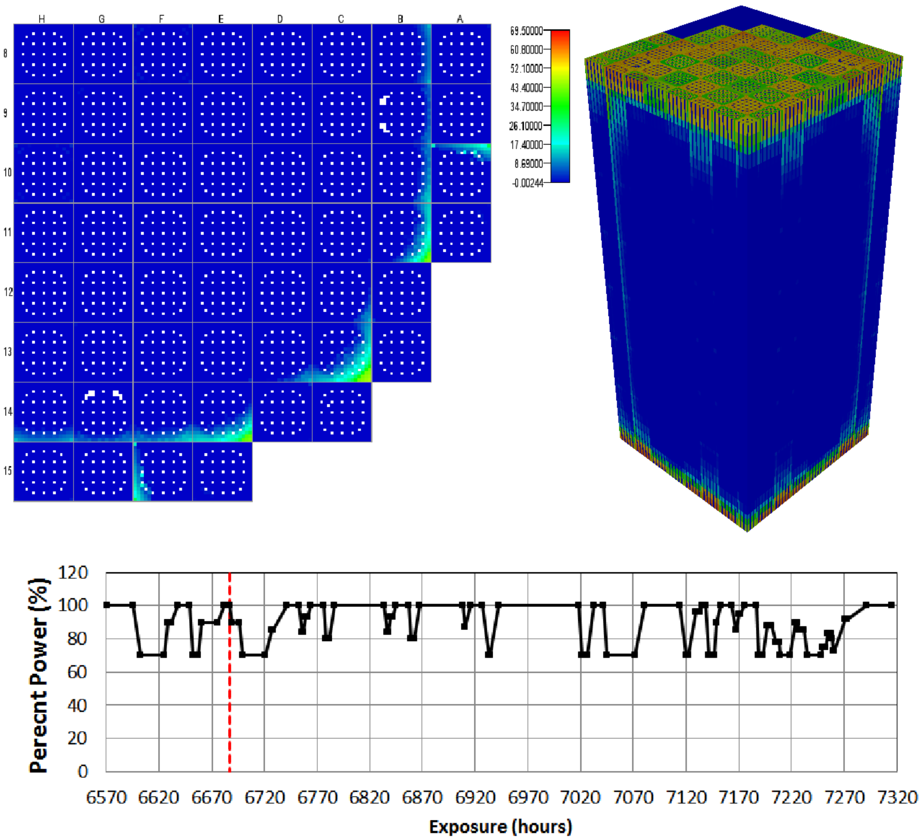
Exposure (hours)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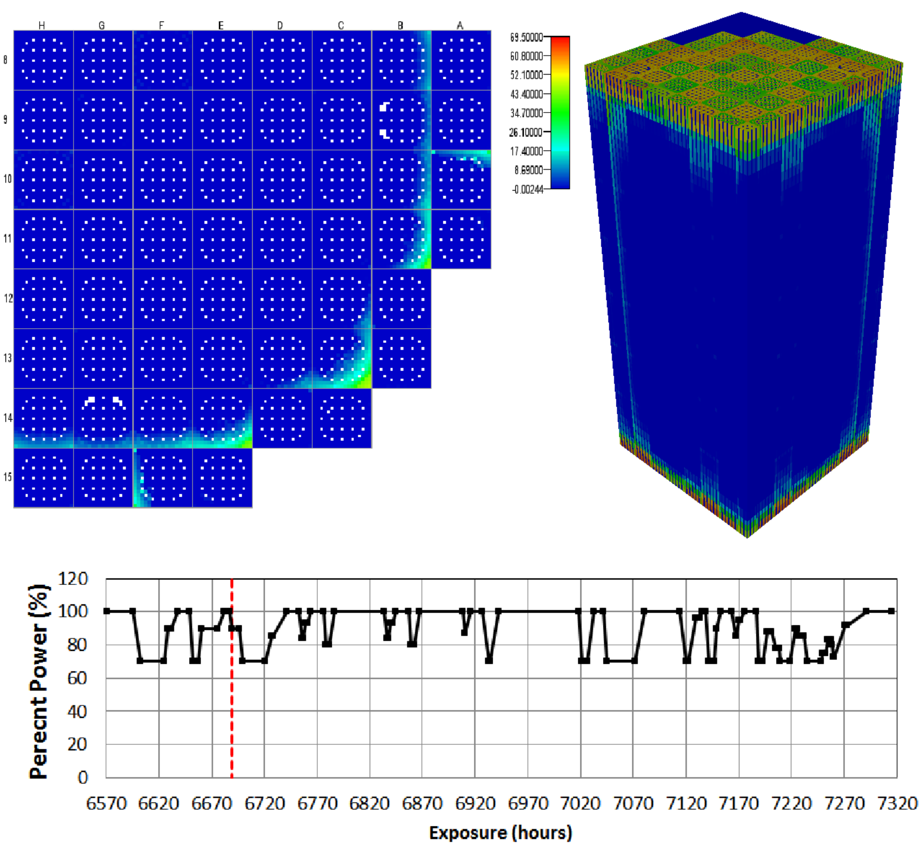
Exposure (hours)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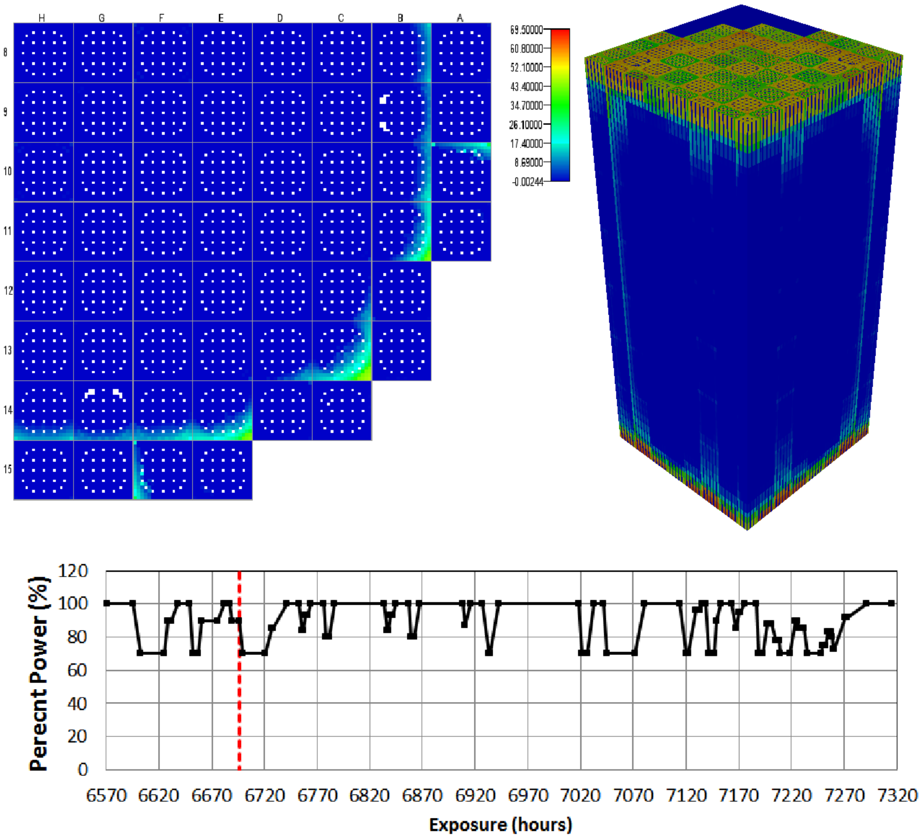
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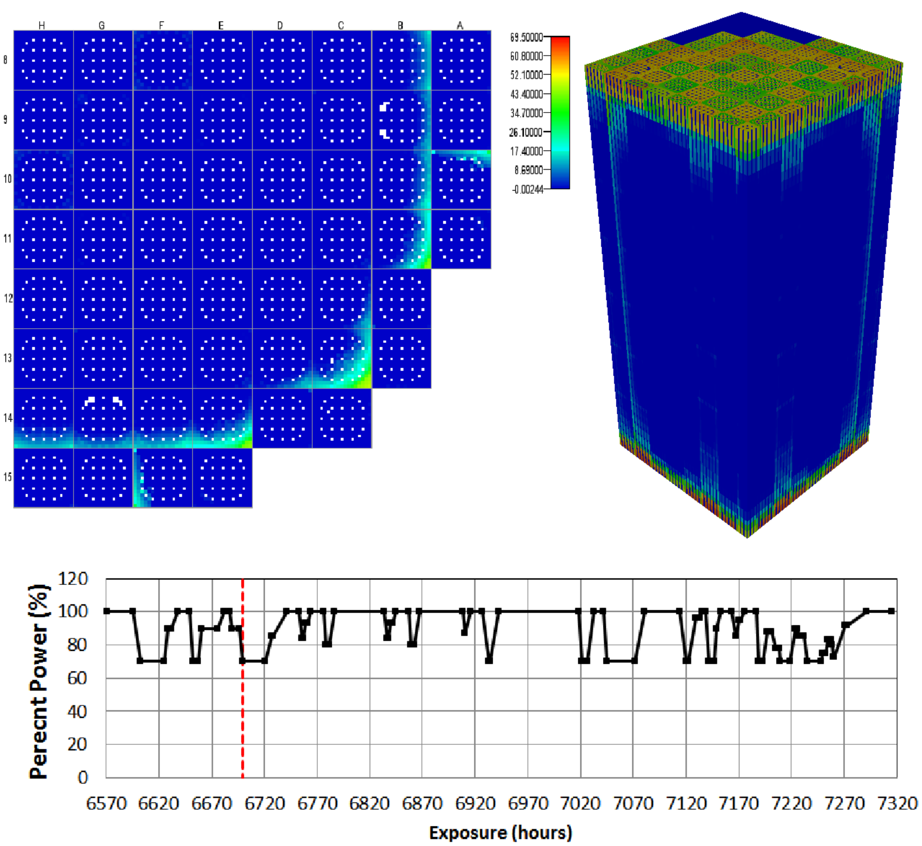
Exposure (hours)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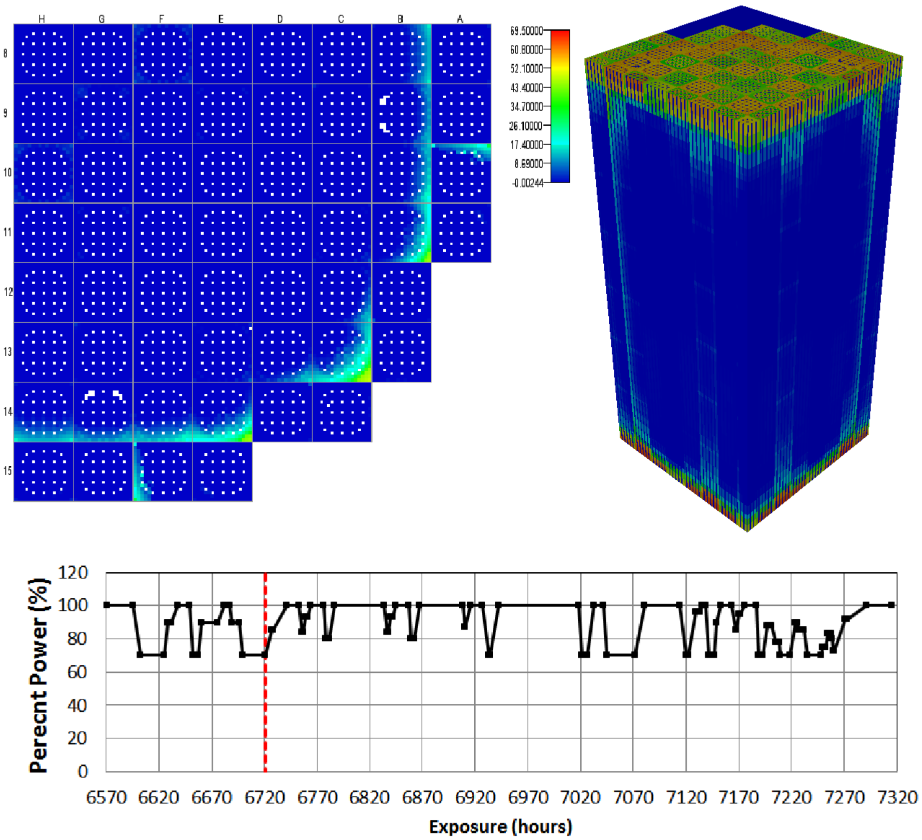
Exposure (hours)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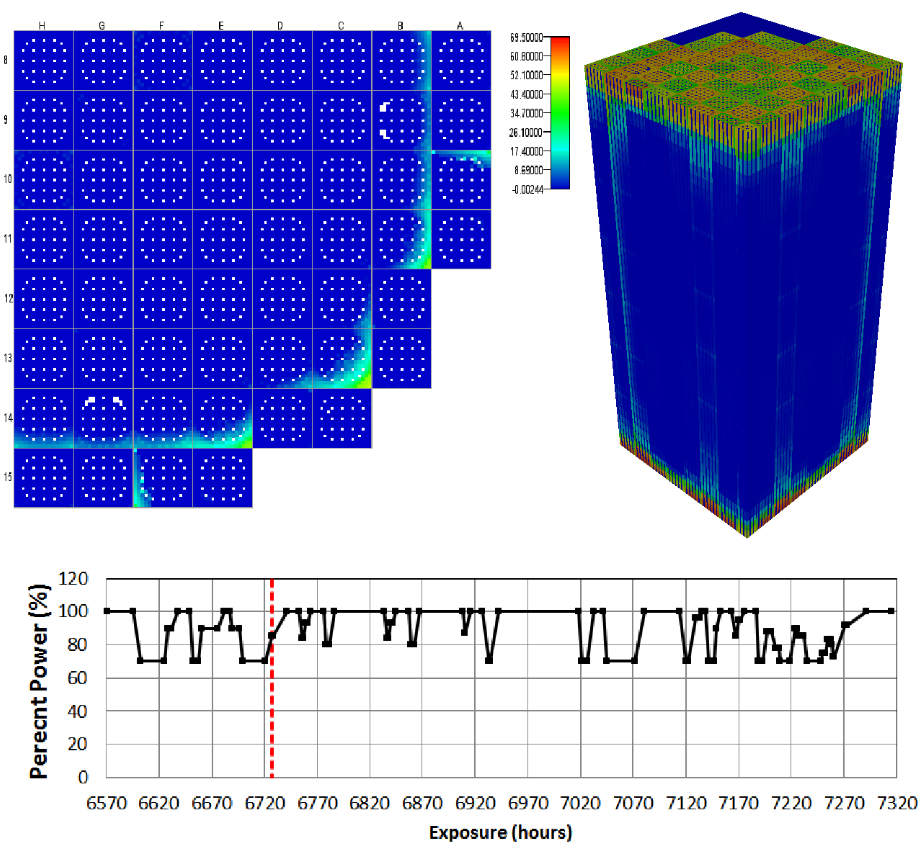
Exposure (hours)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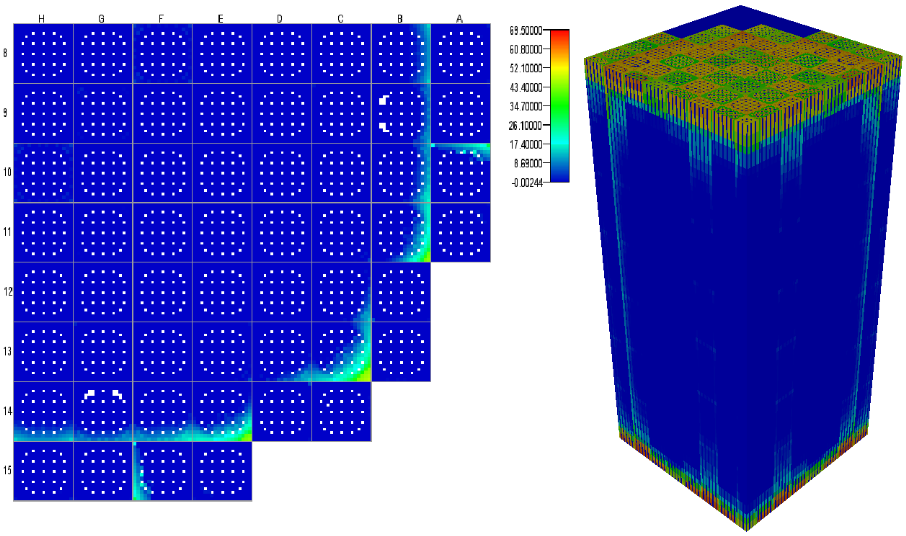
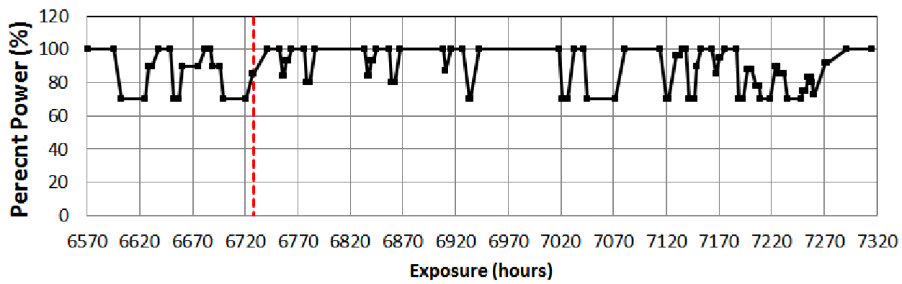
Exposure (hours)




Perecnt Power (%)
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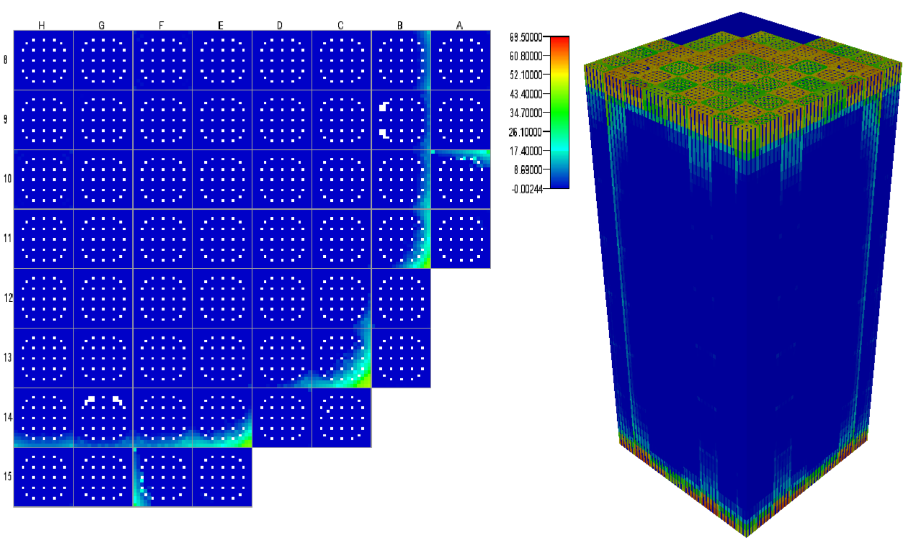
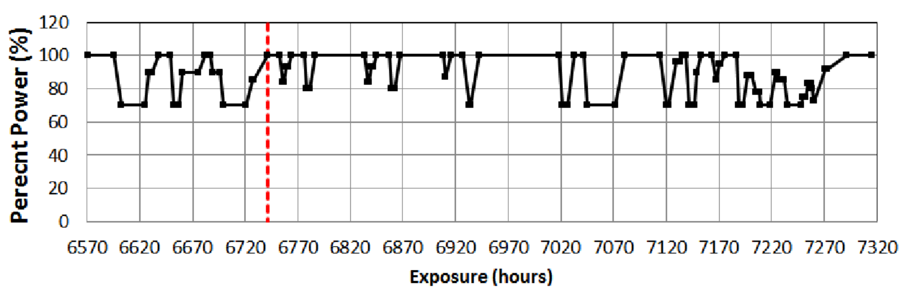
Exposure (hours)




Perecnt Power (%)
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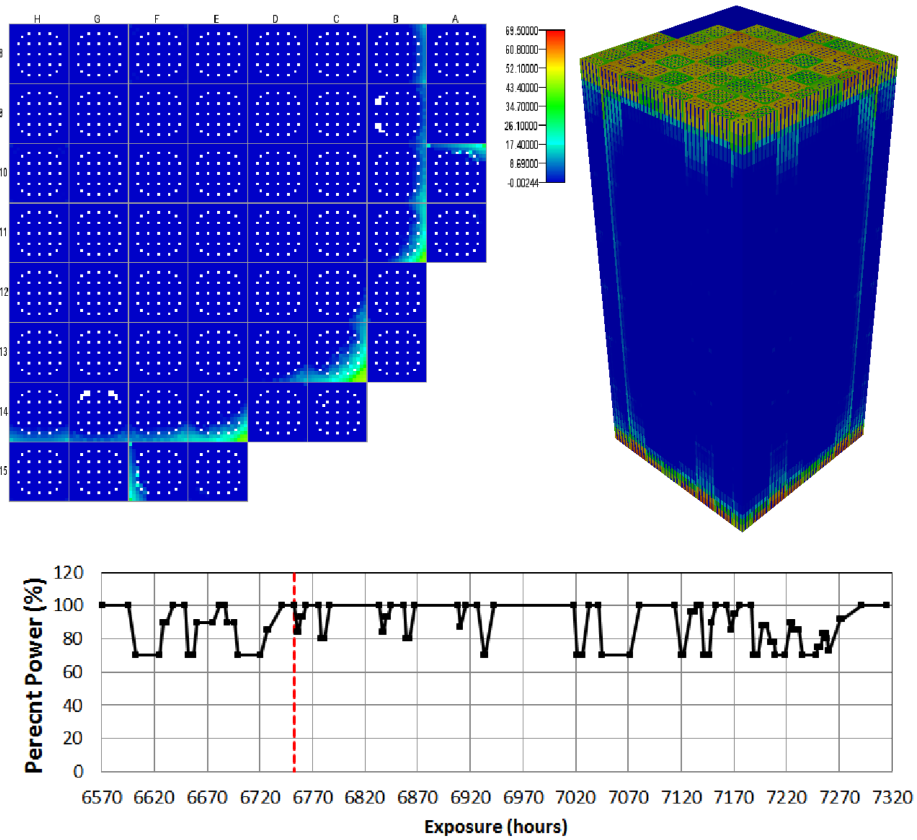
Exposure (hours)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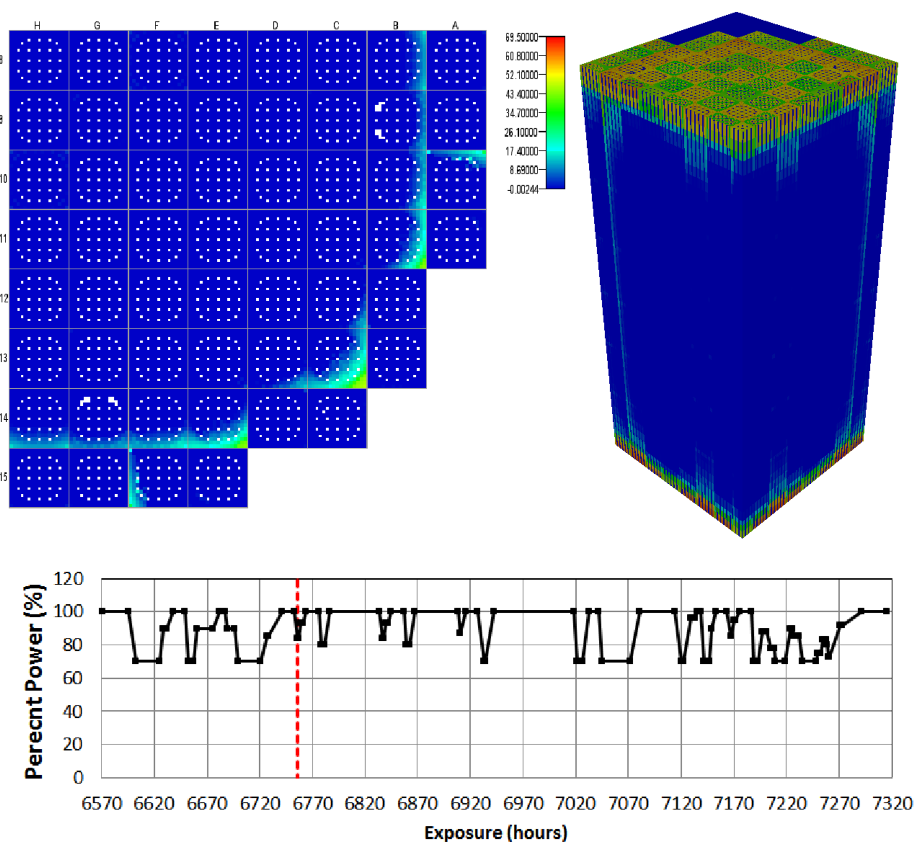
Exposure (hours)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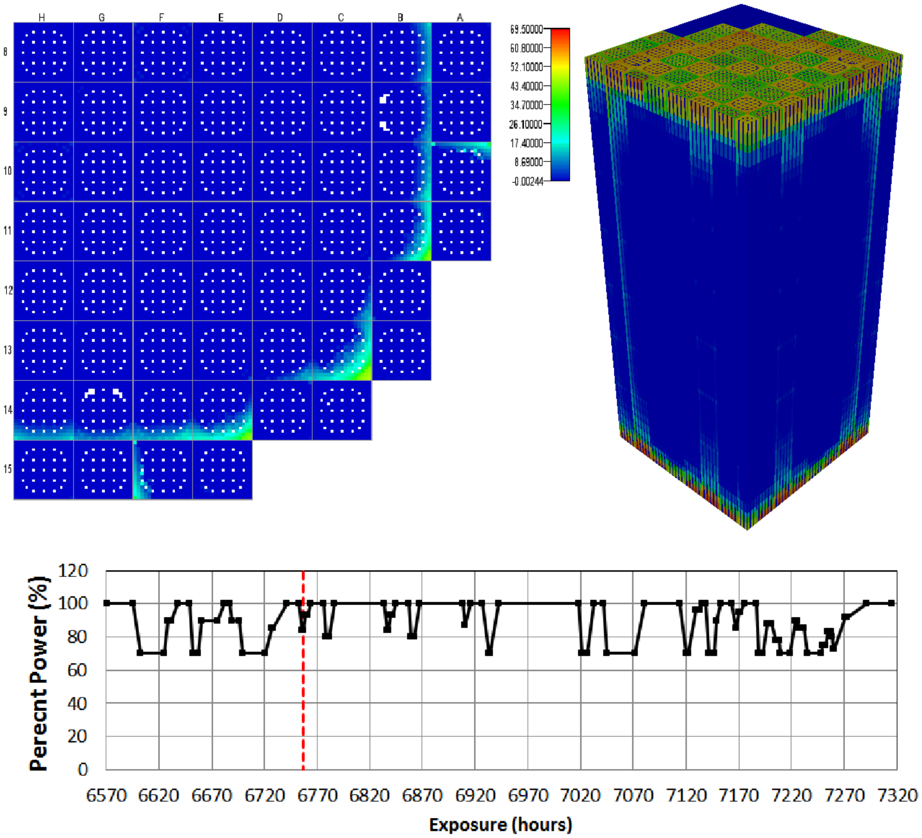
Exposure (hours)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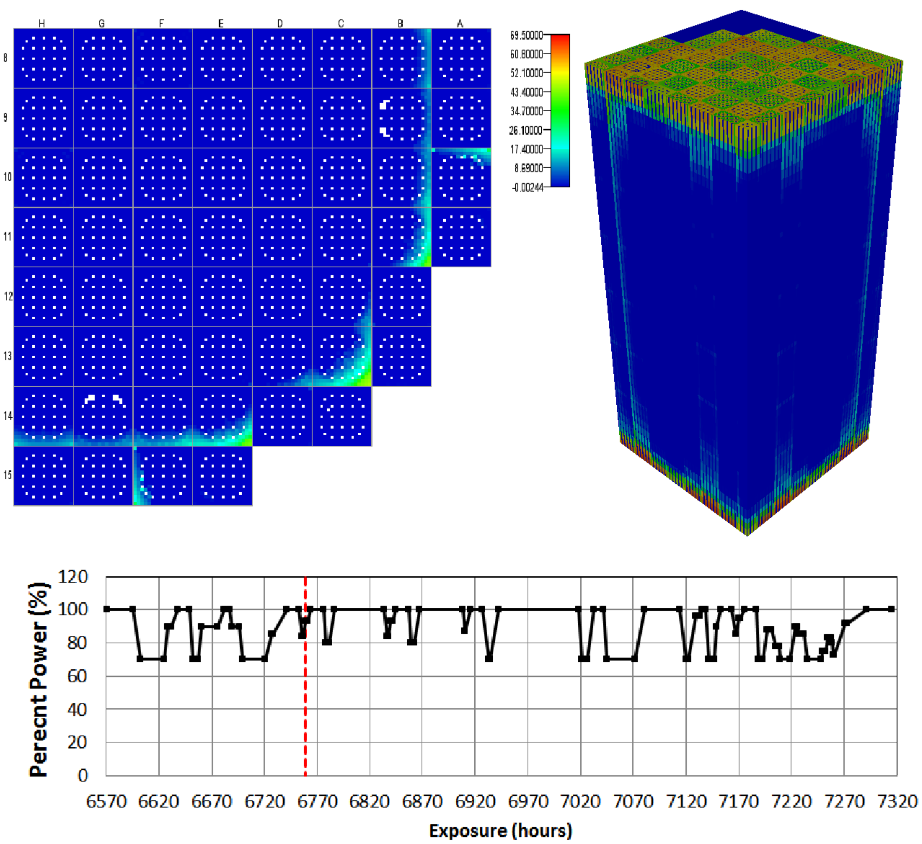
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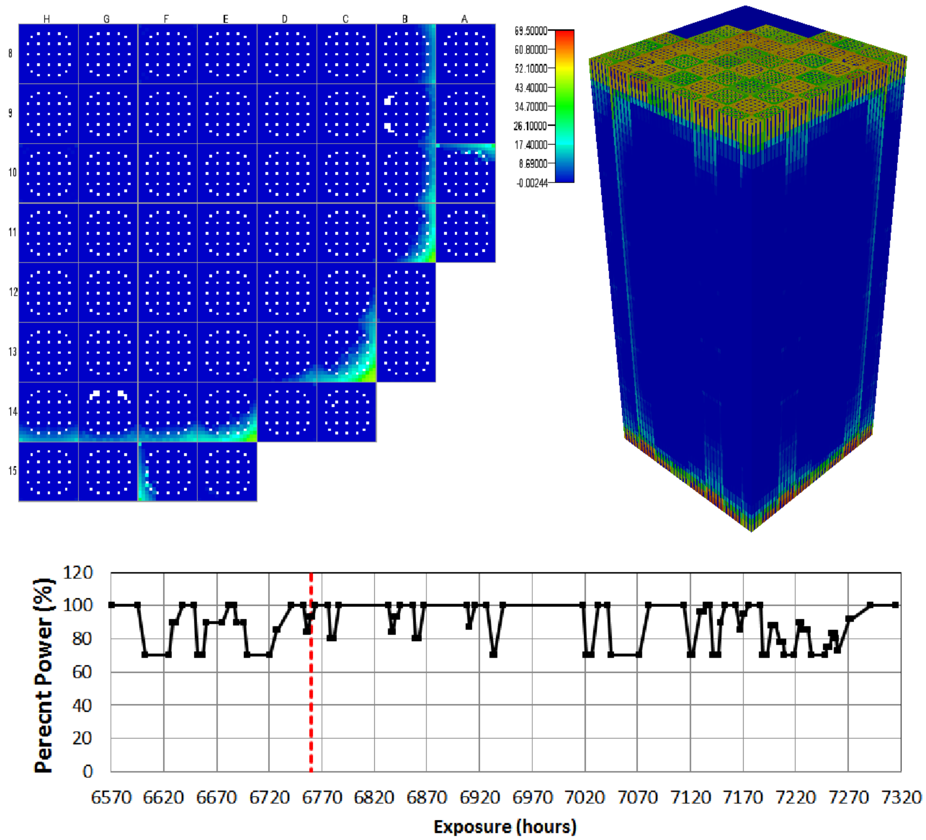
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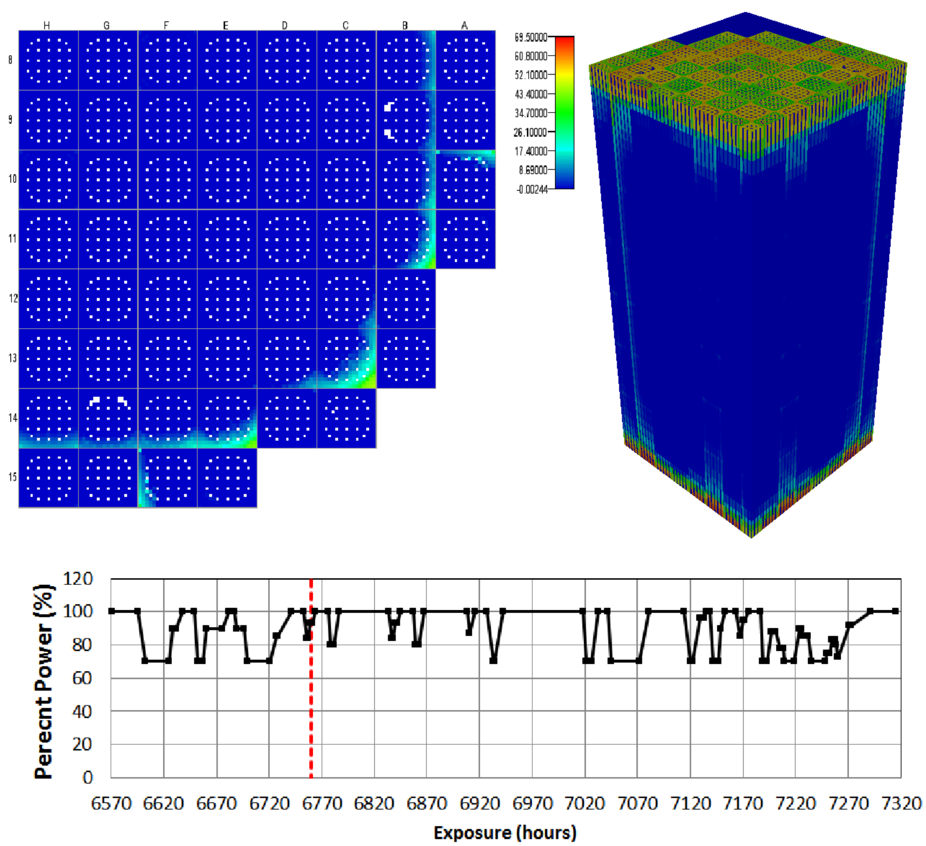
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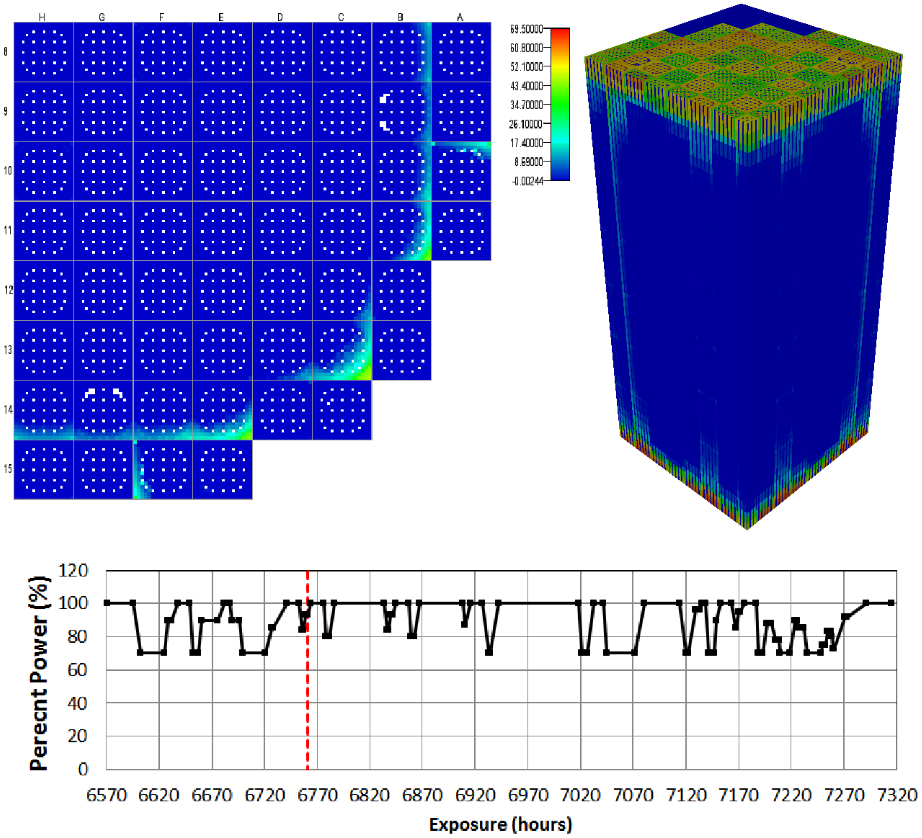
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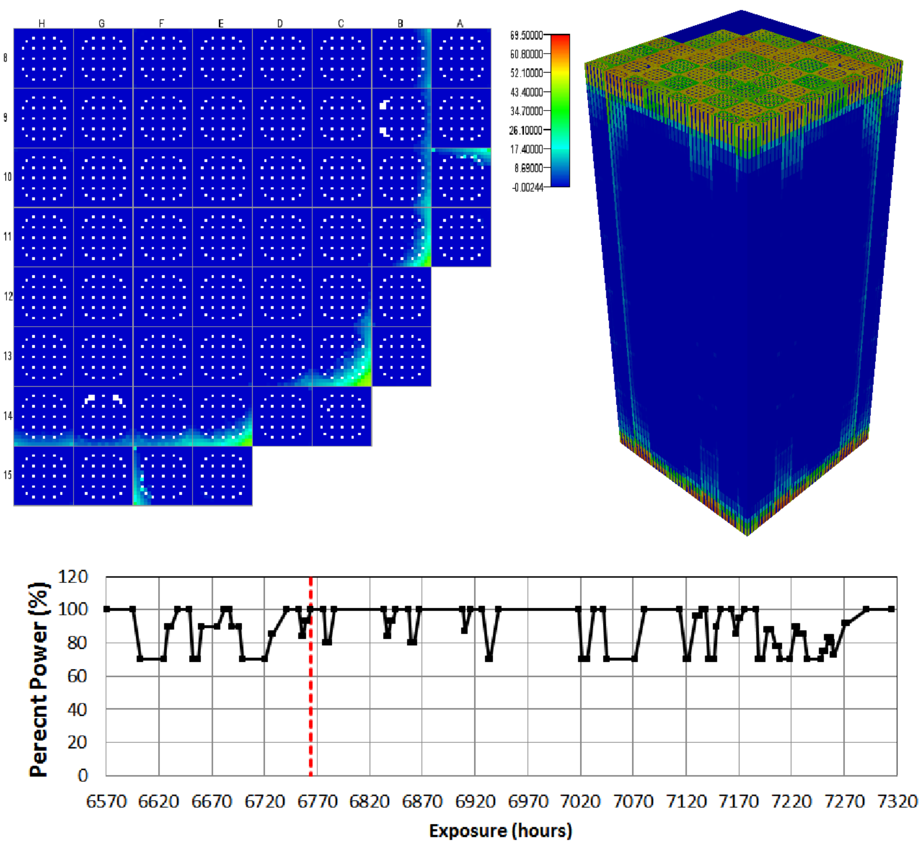
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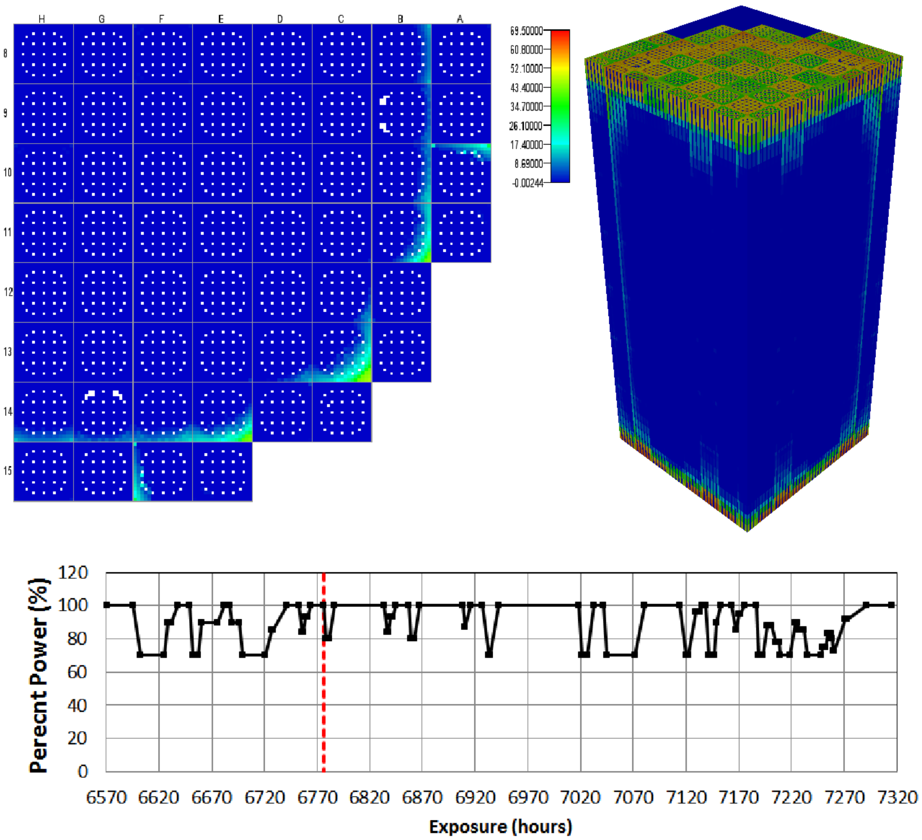
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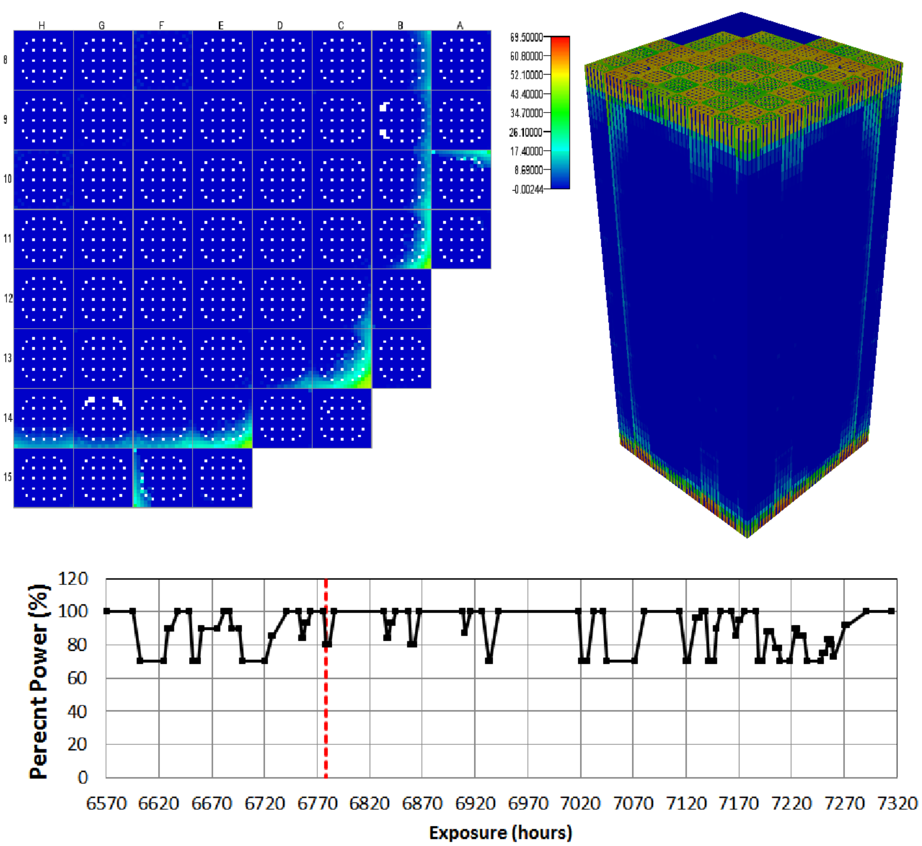
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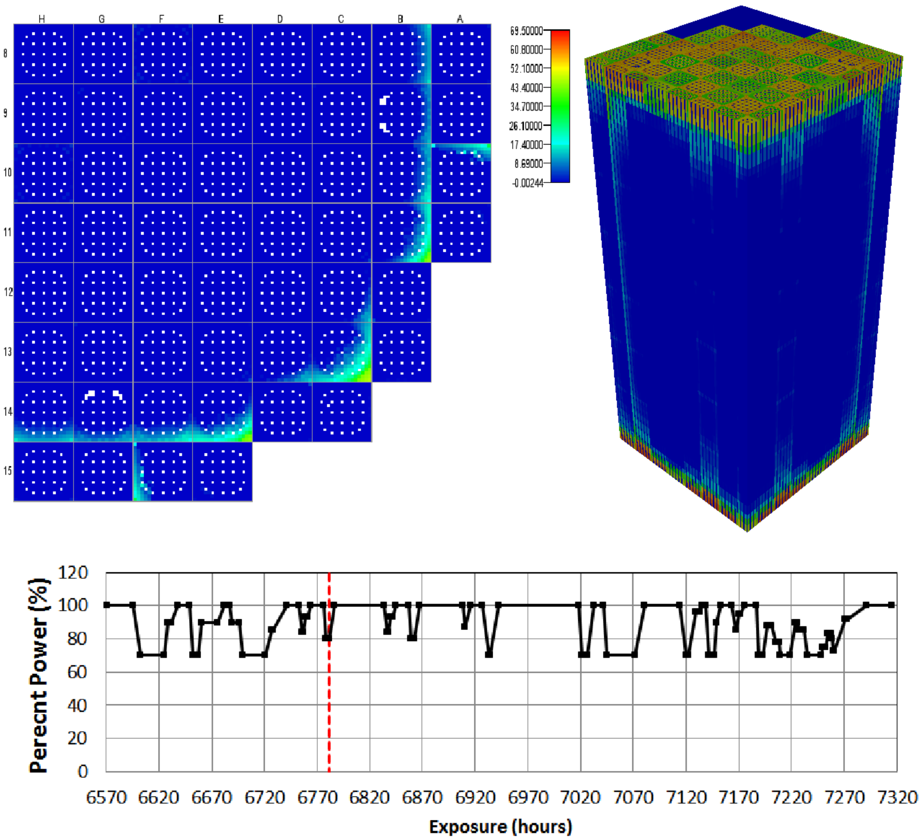
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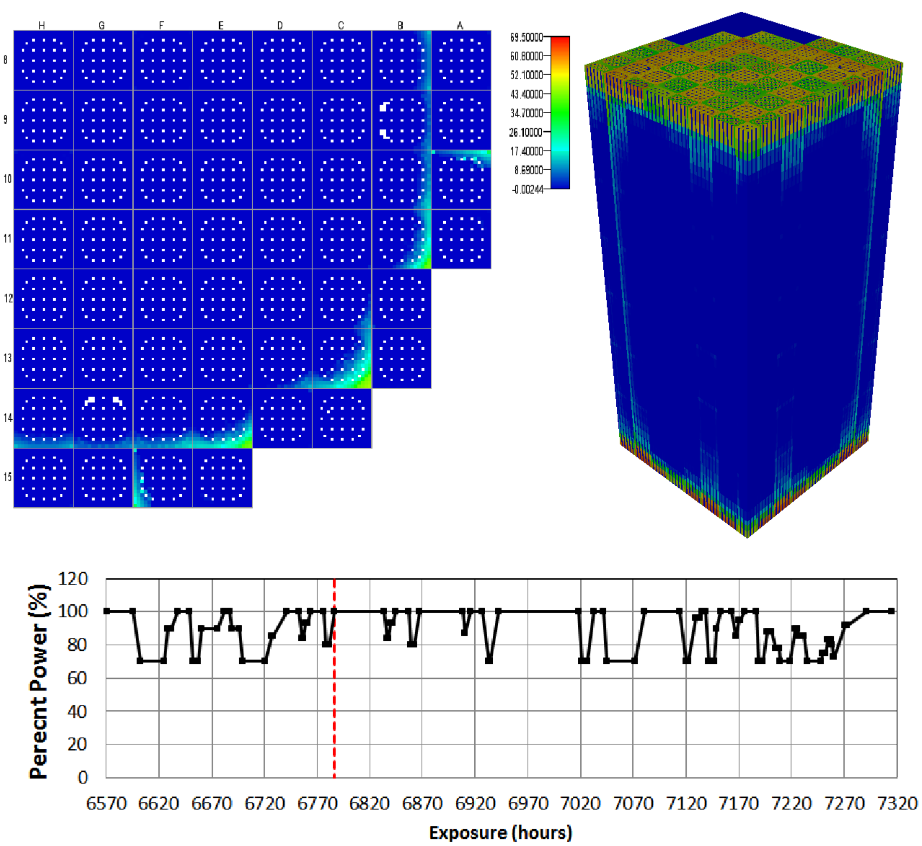
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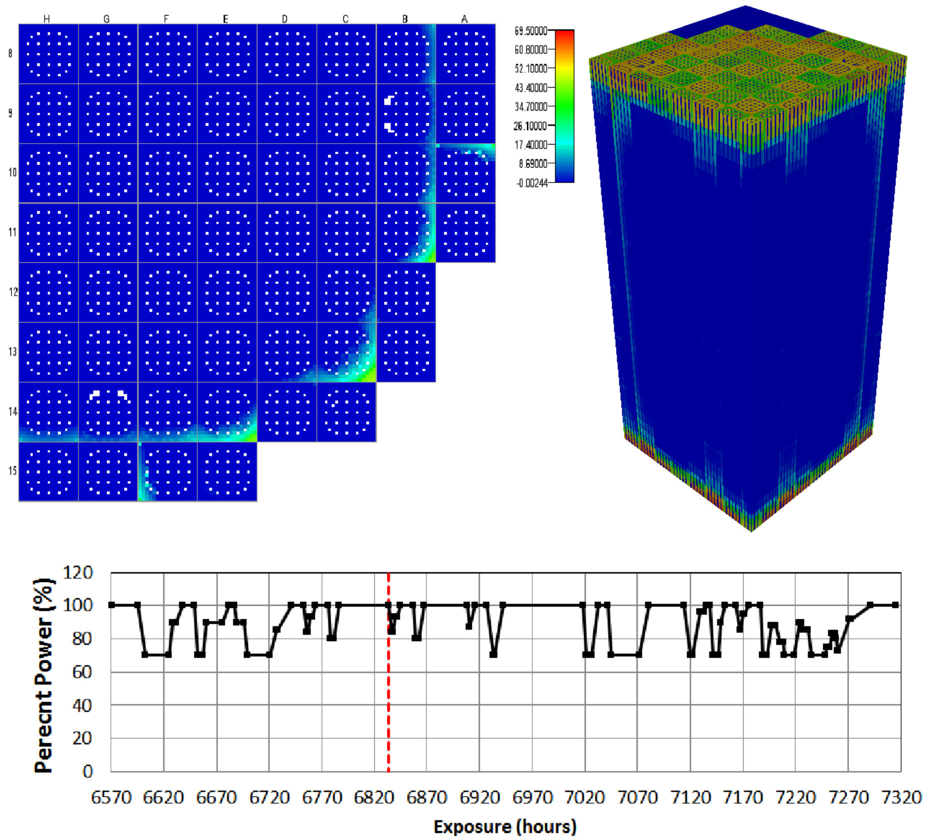

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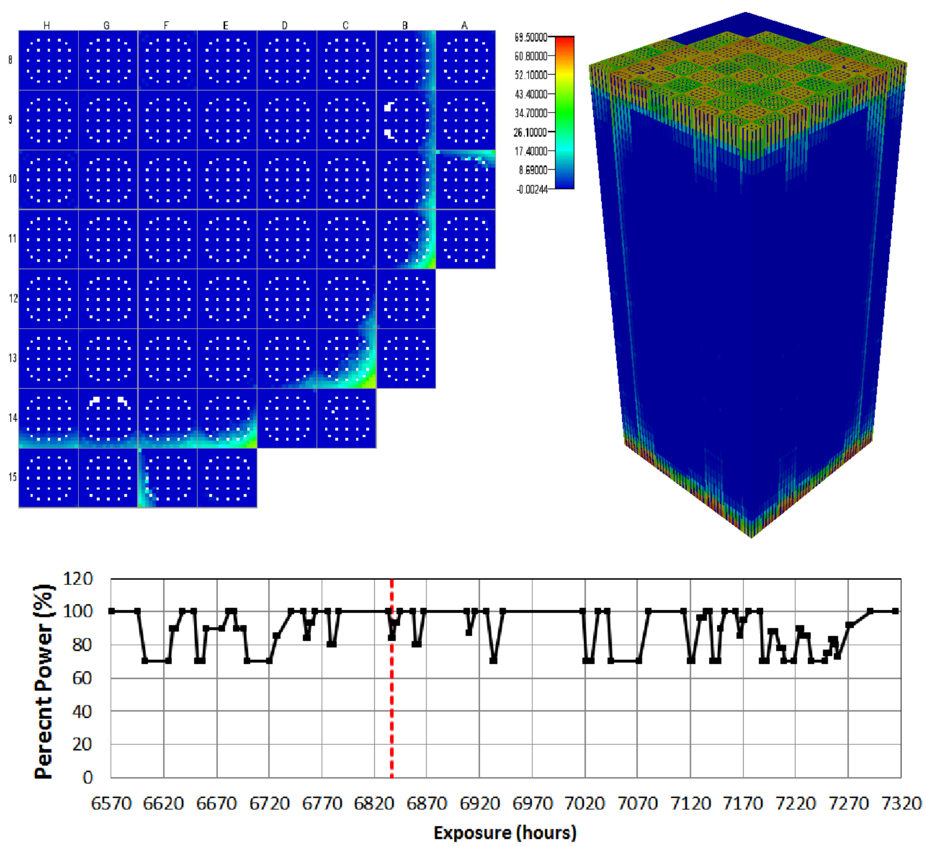

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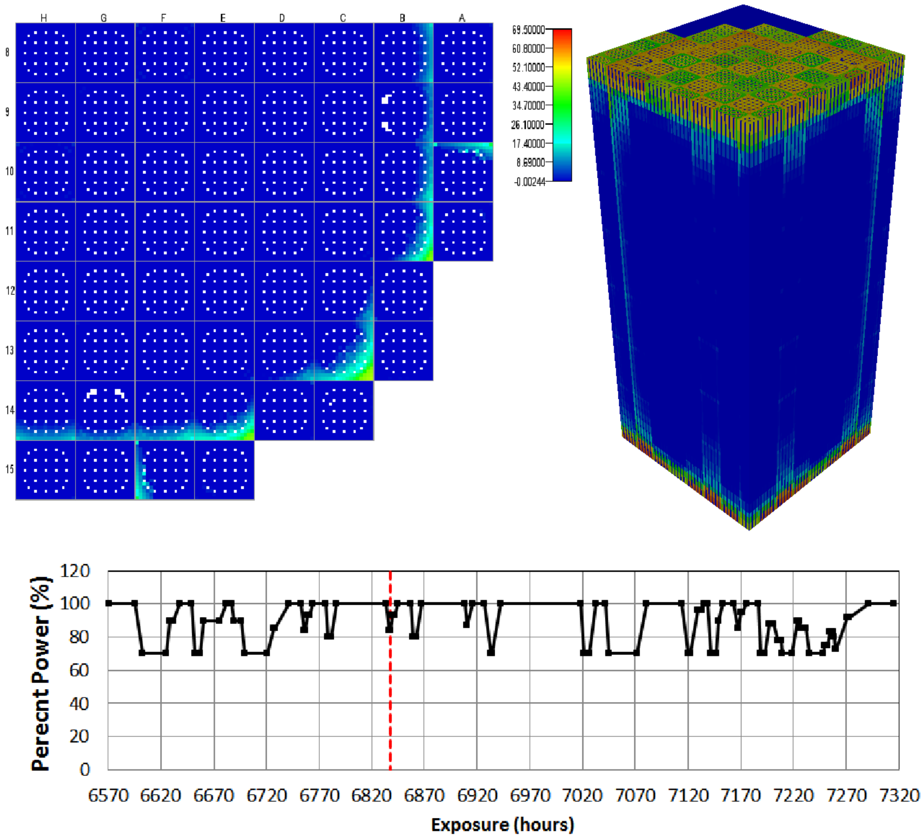
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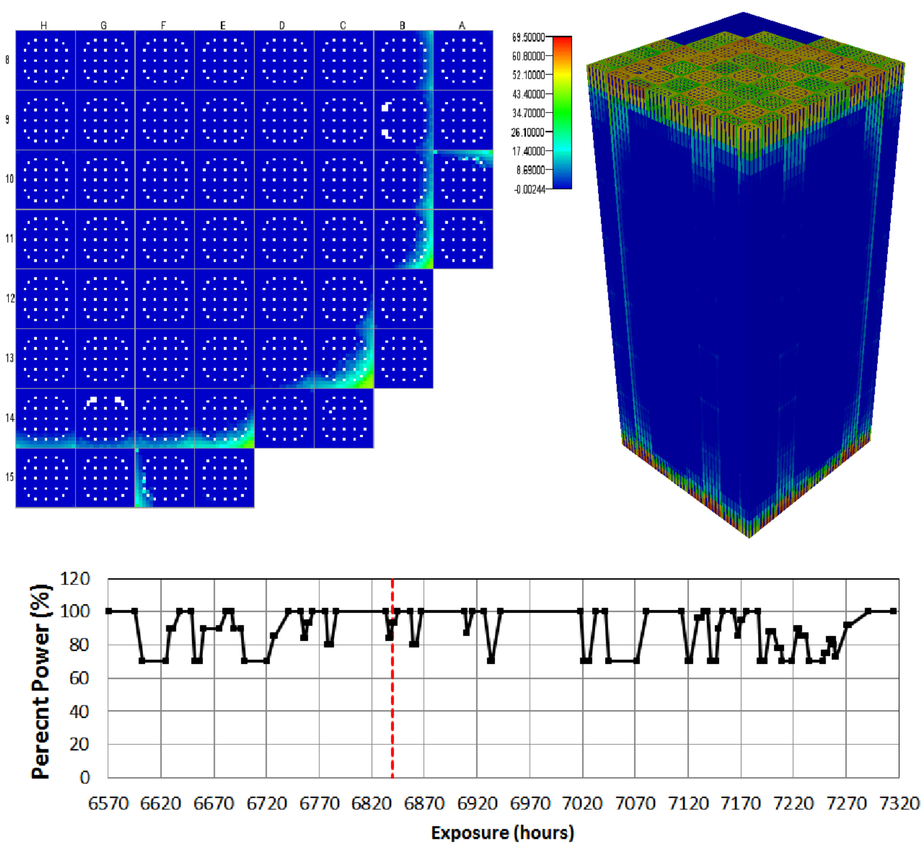
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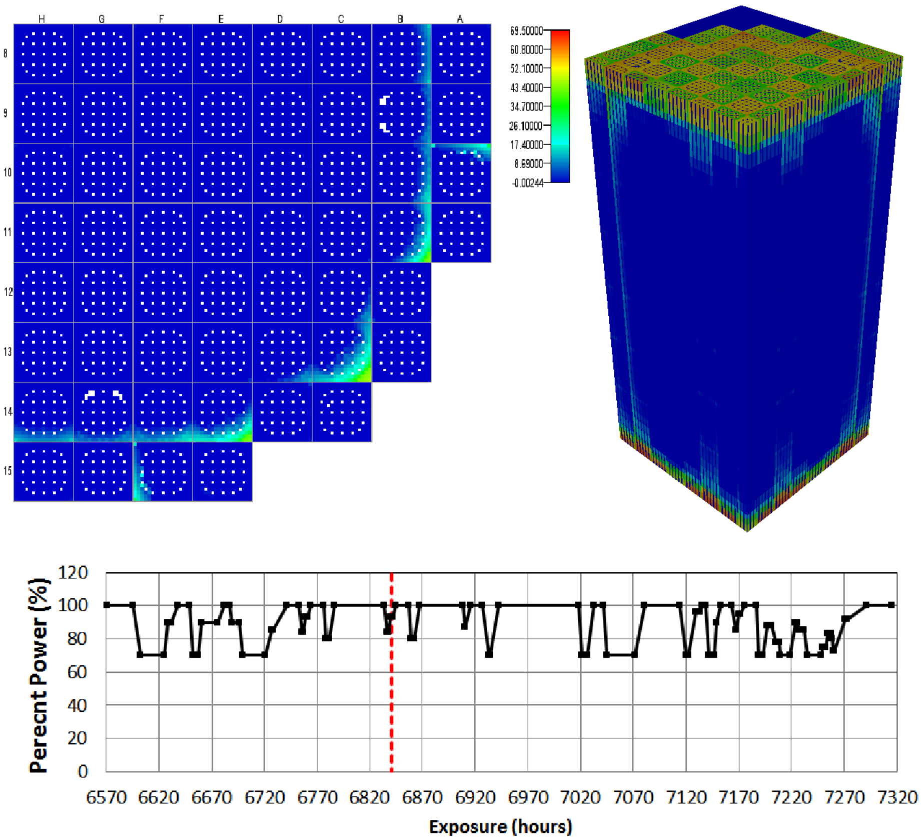
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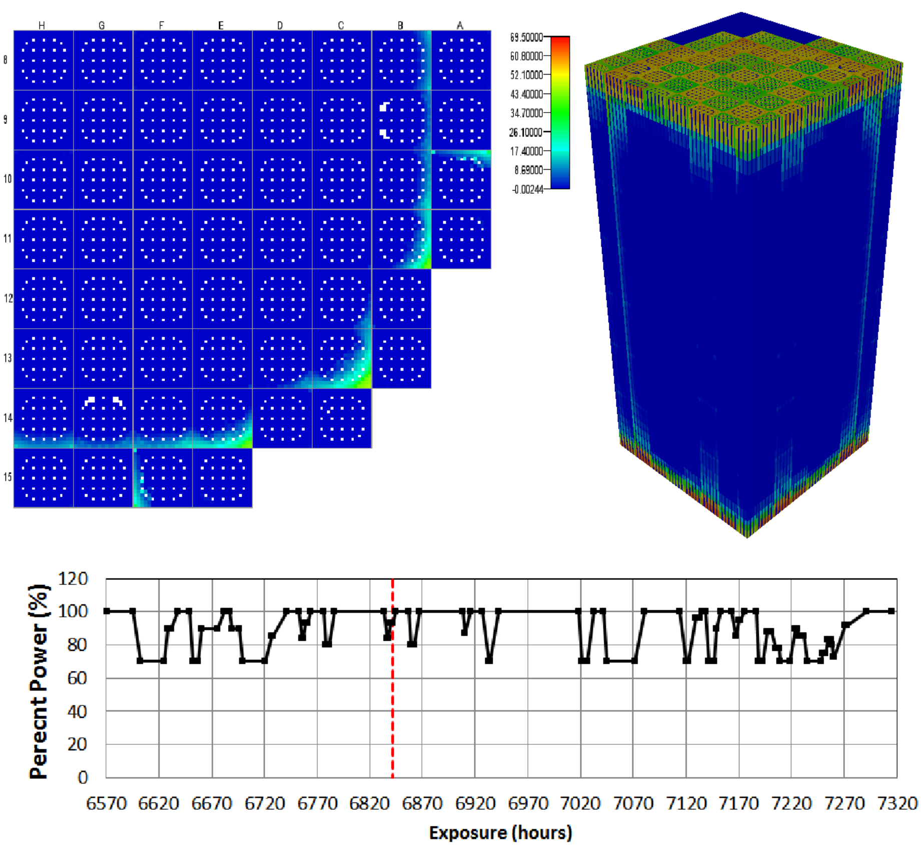
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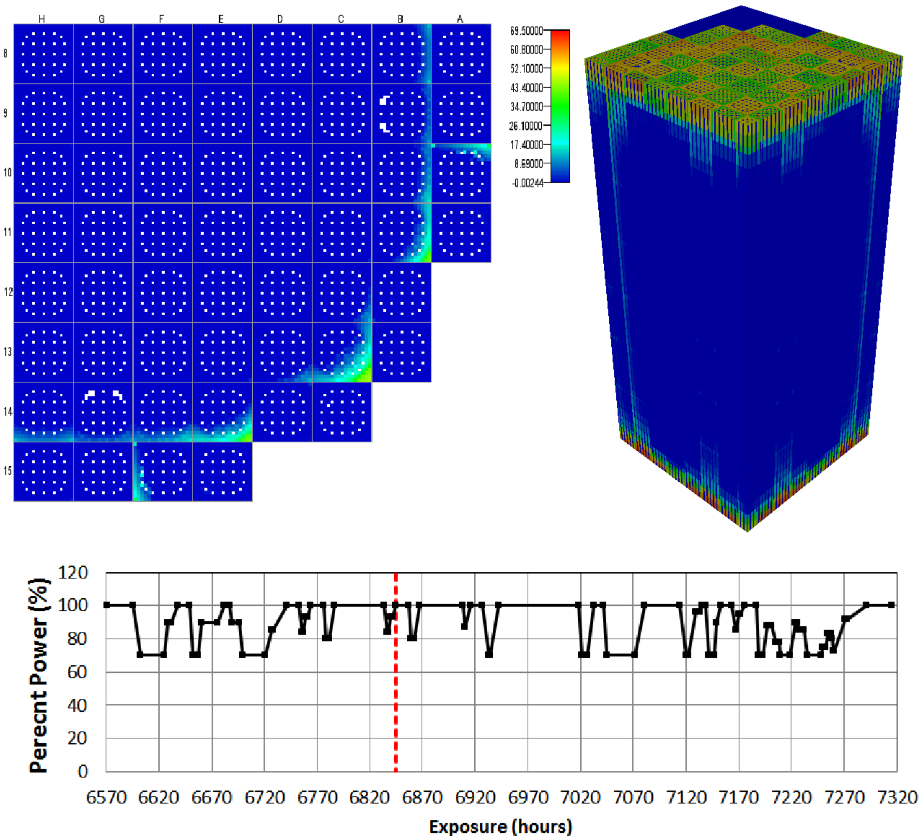
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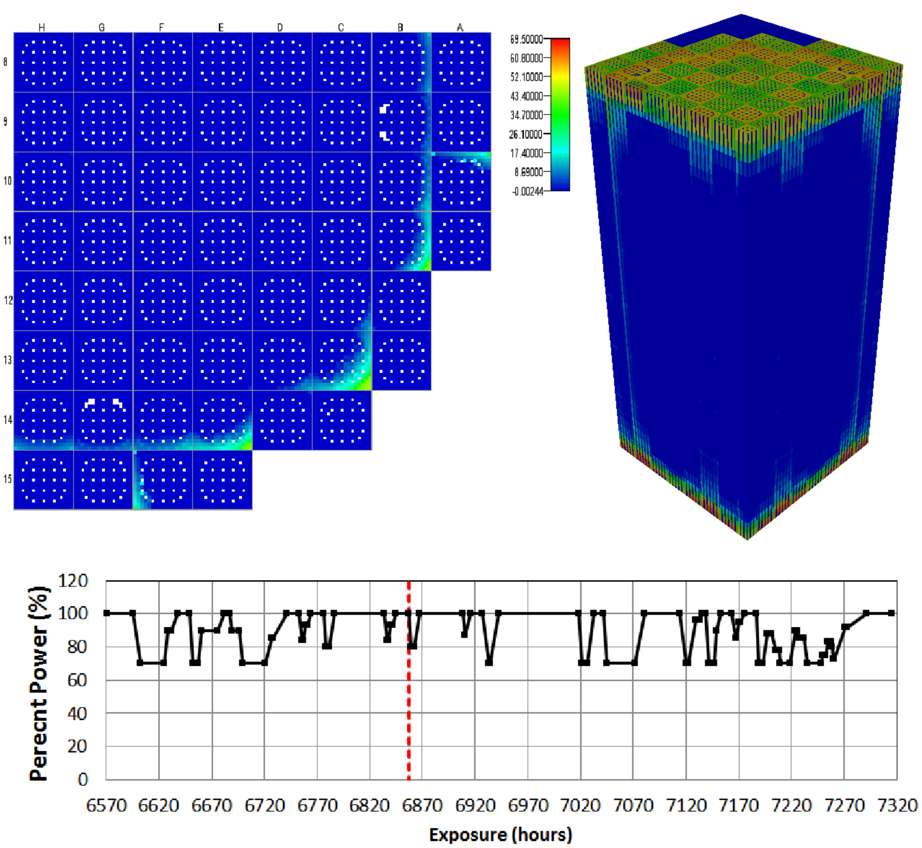
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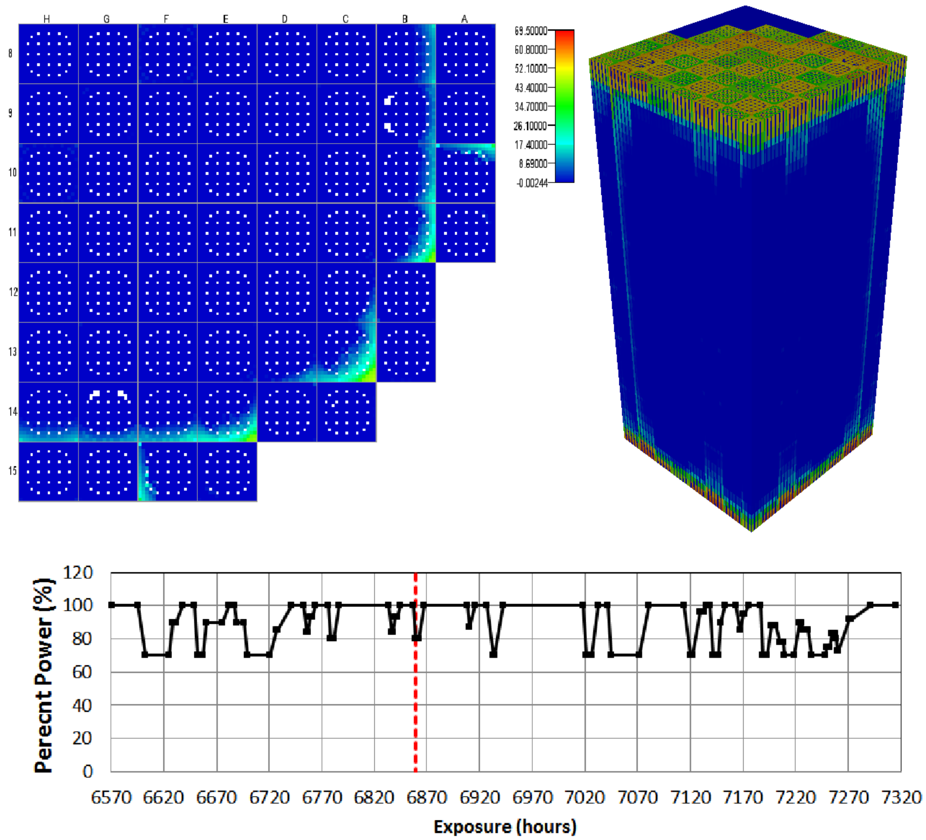
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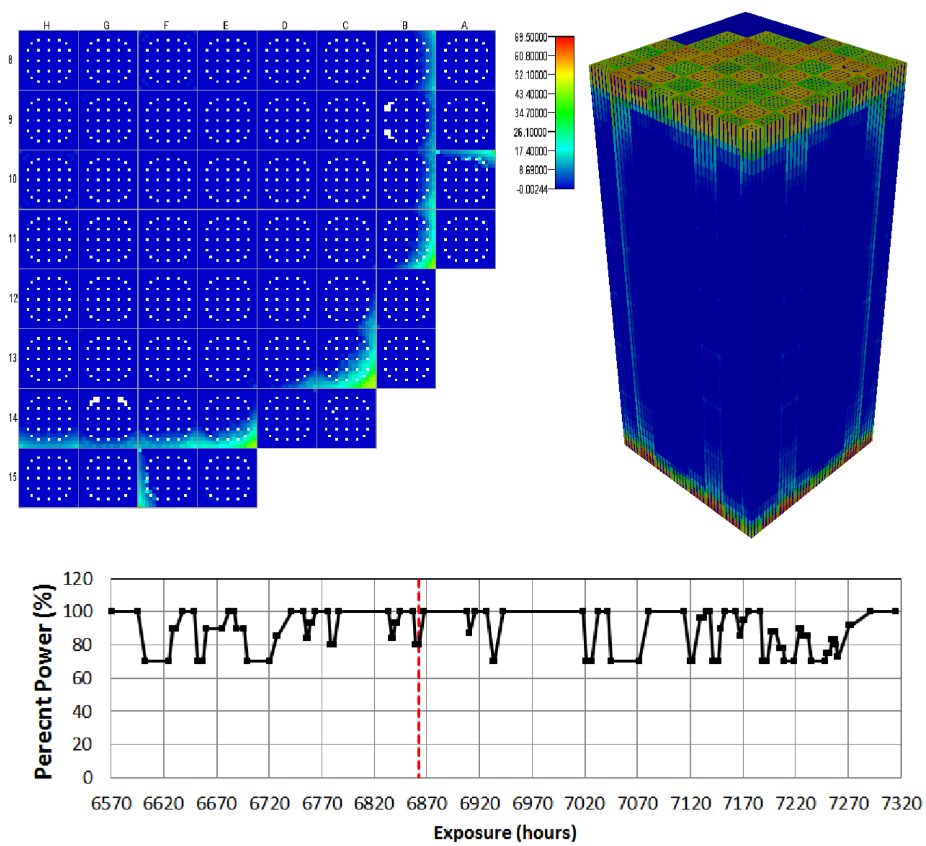
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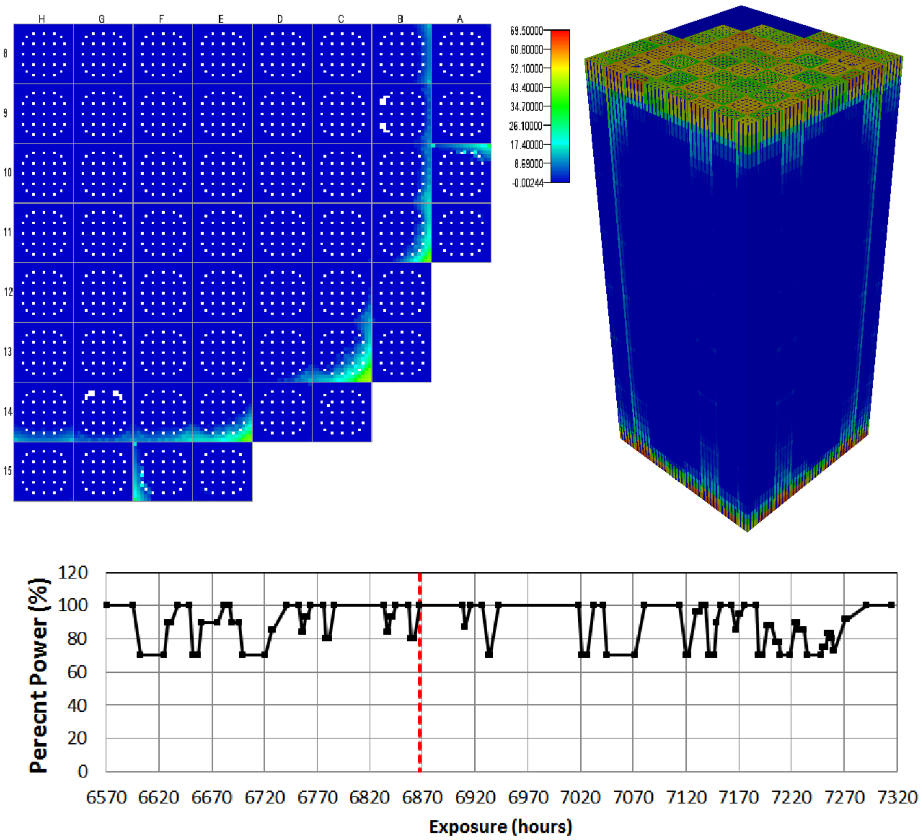
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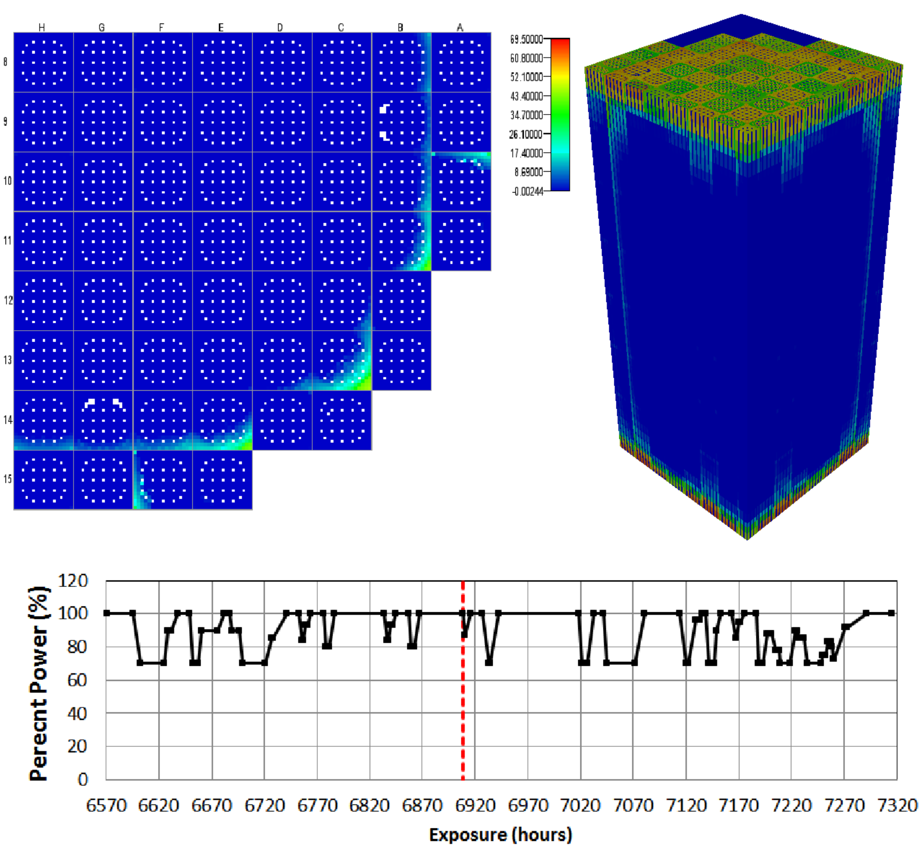
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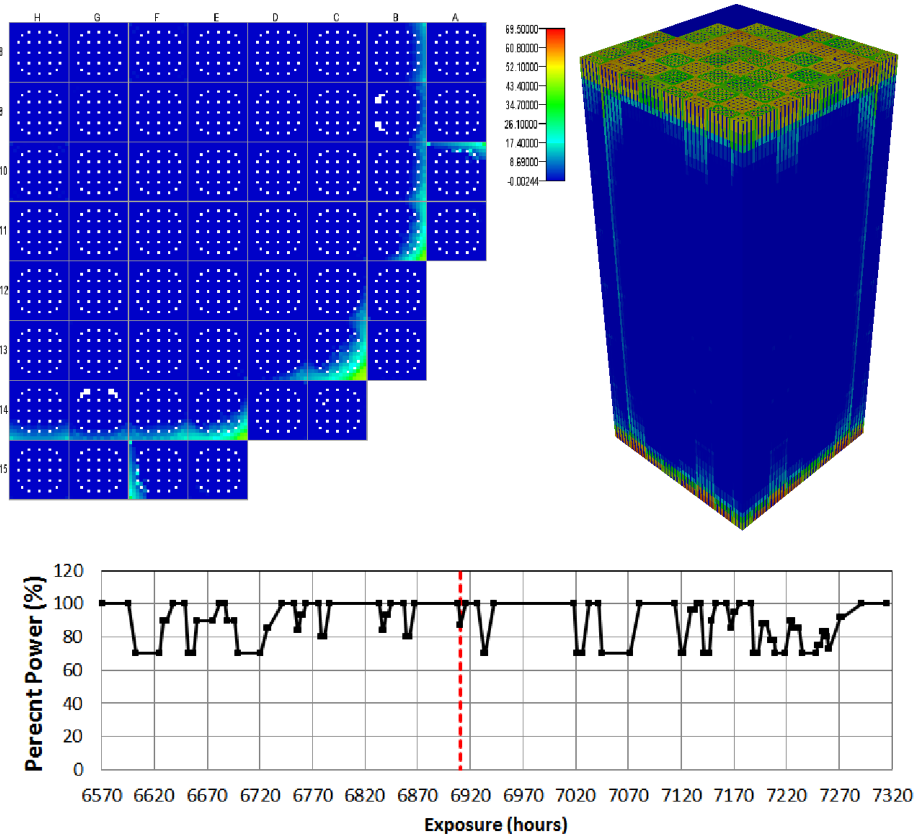
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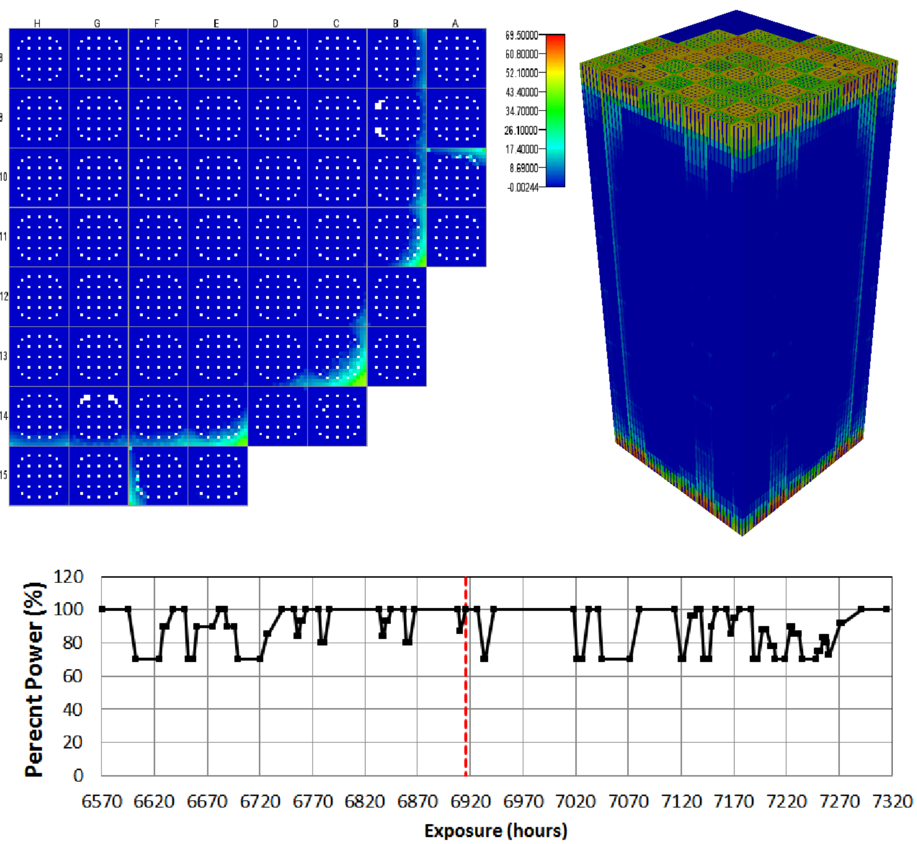
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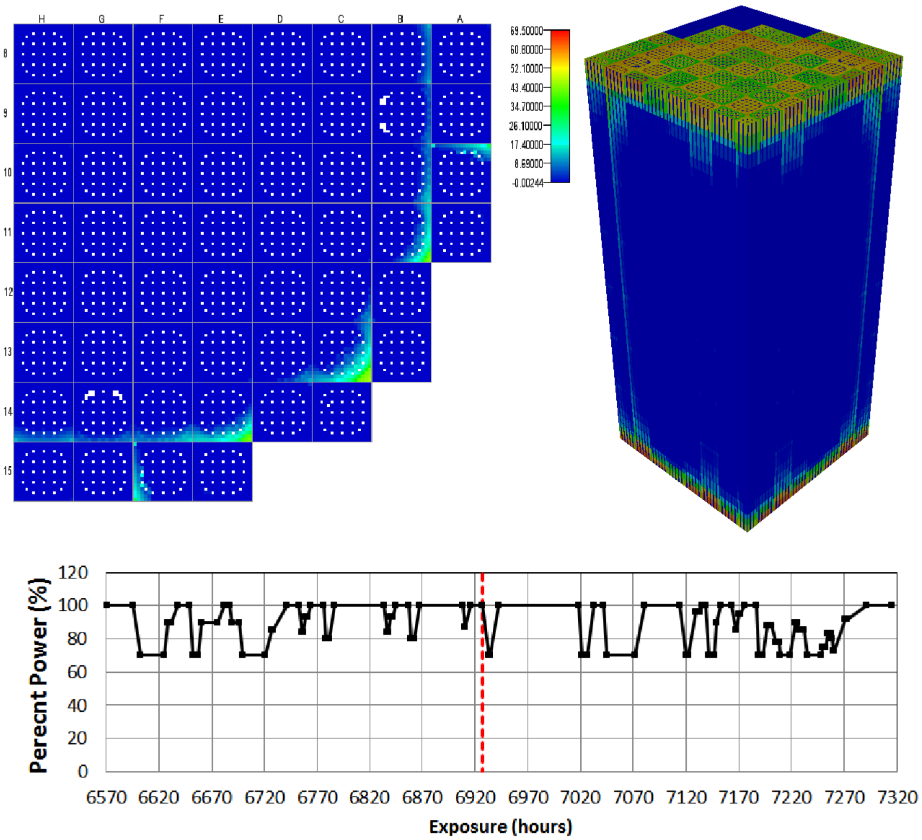
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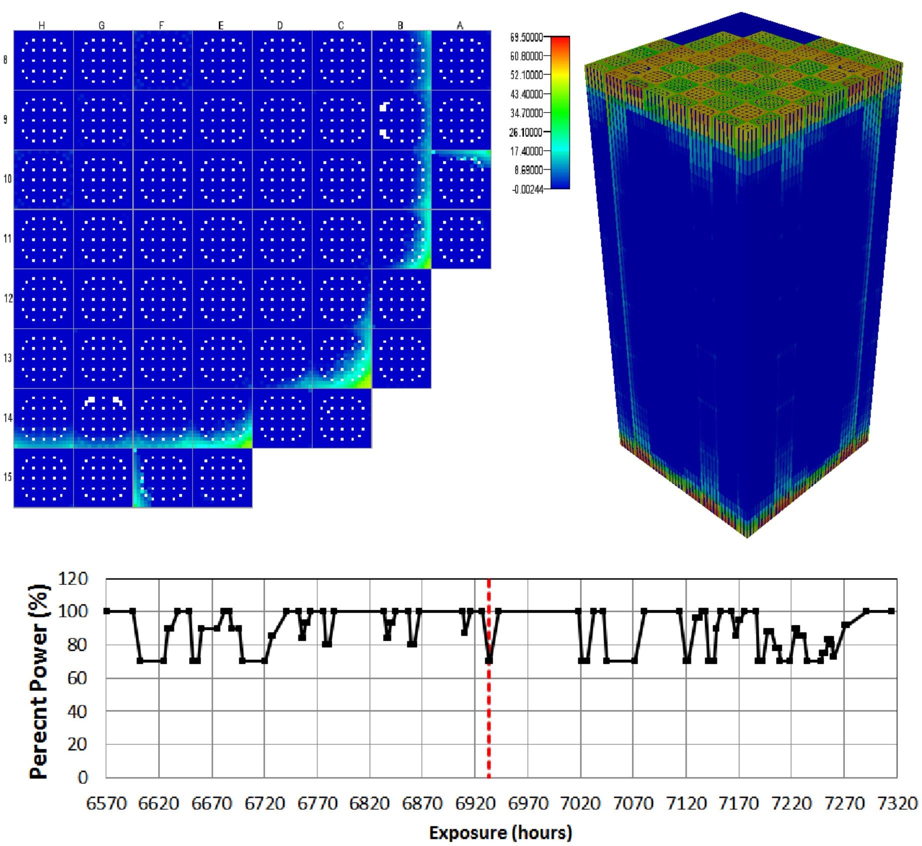
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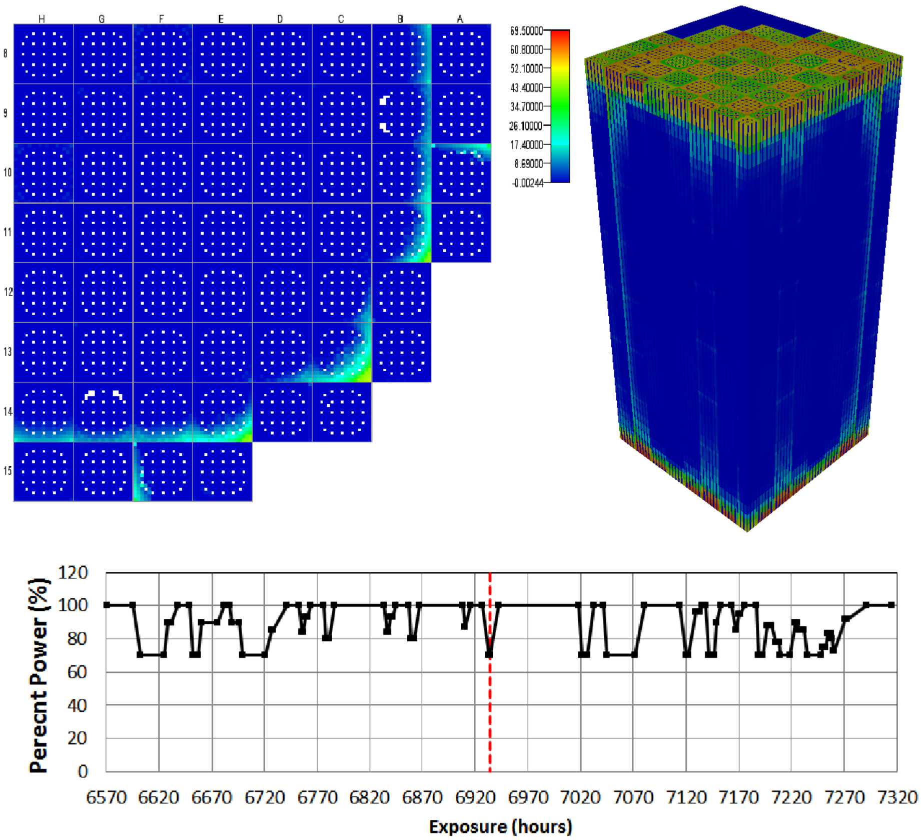
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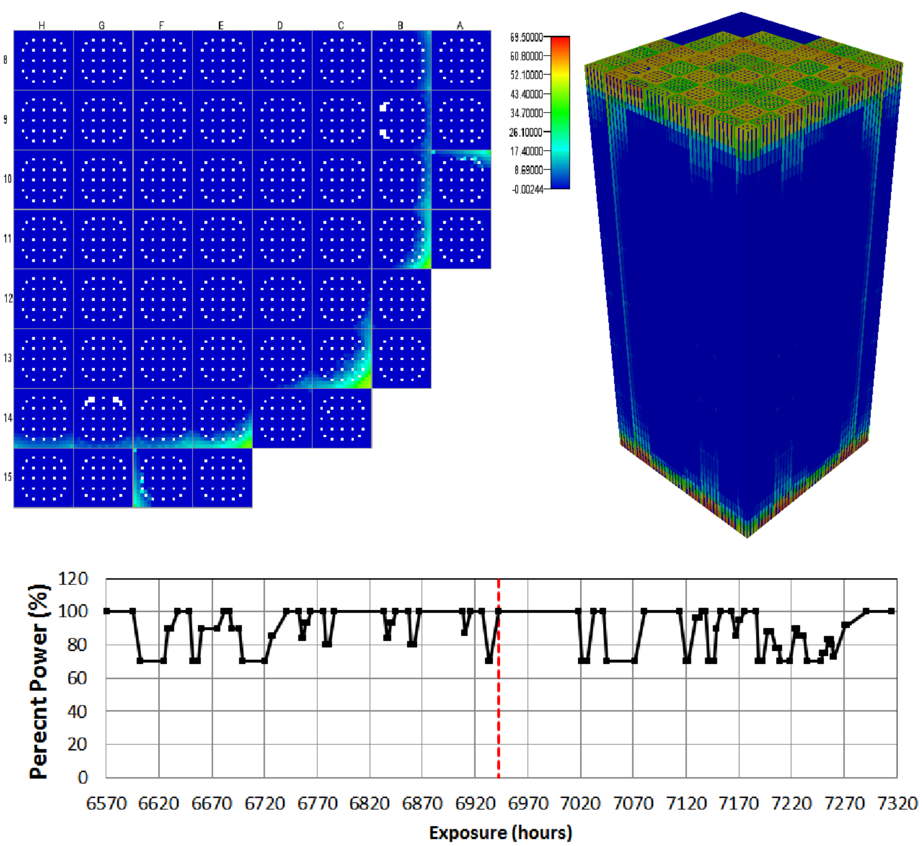
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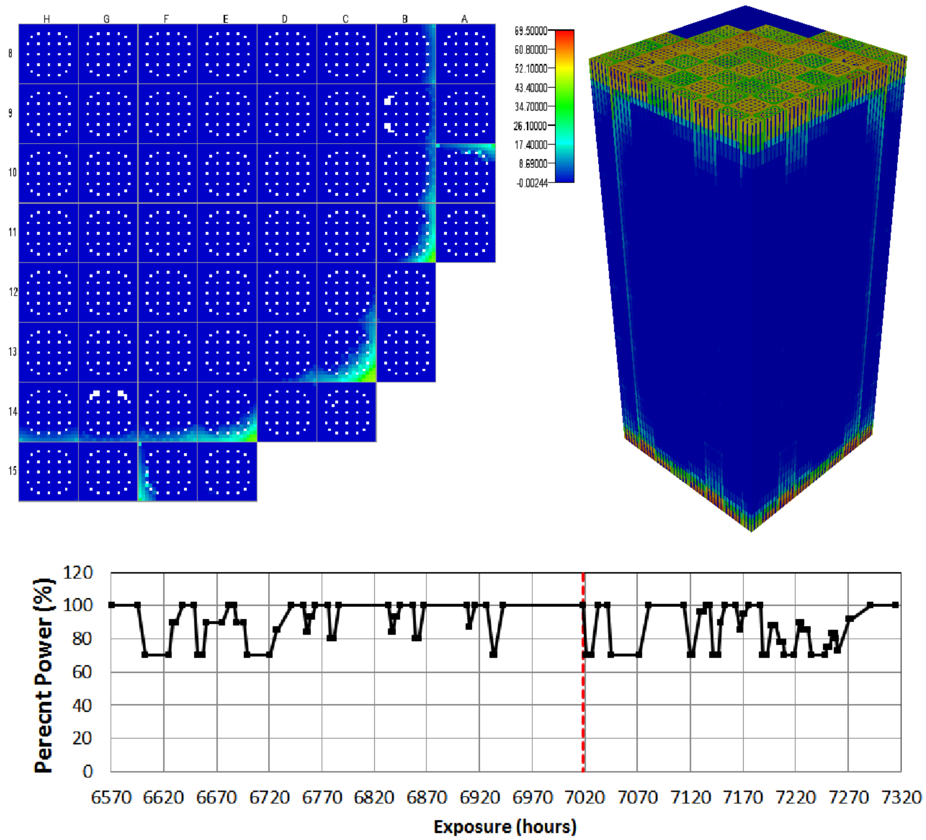
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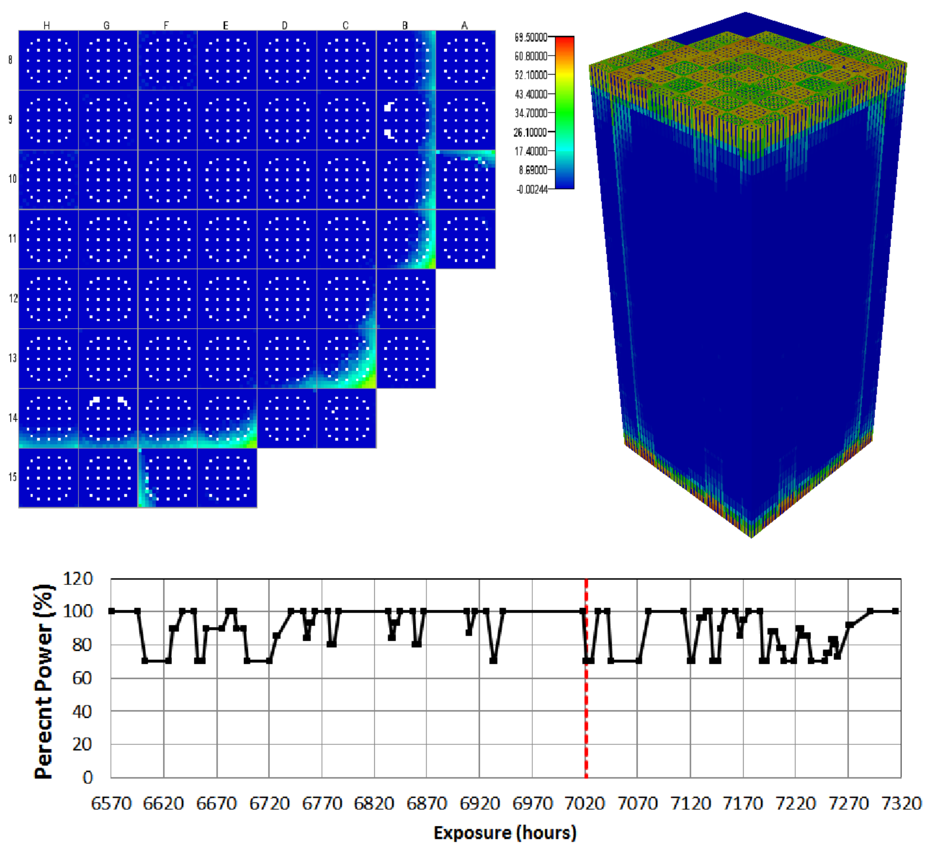
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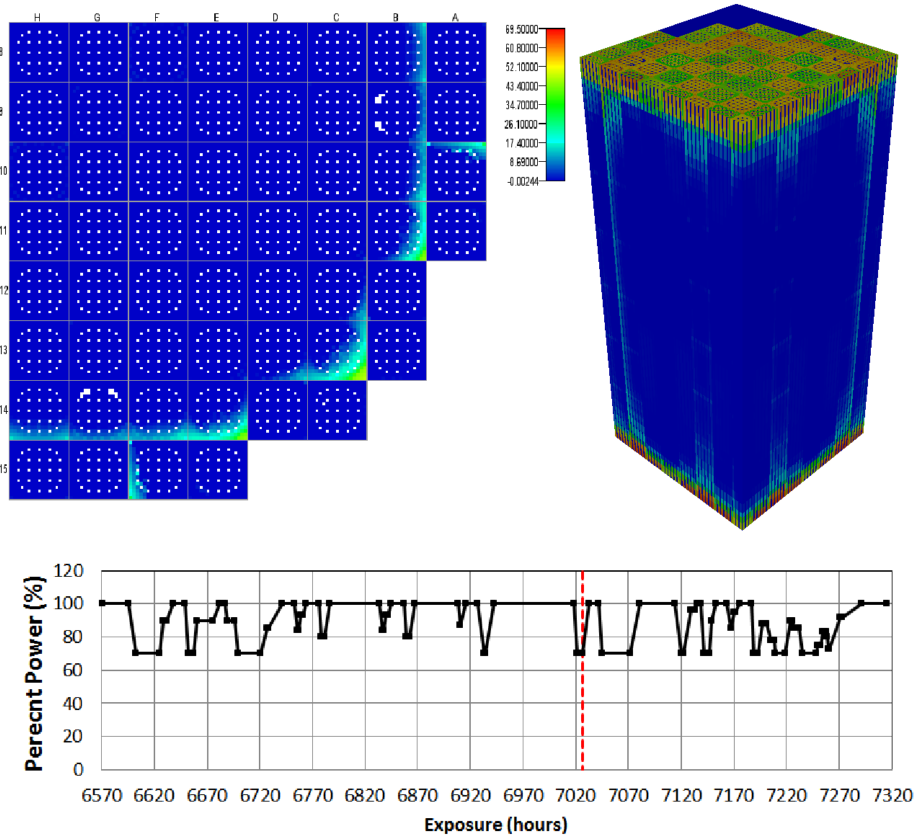
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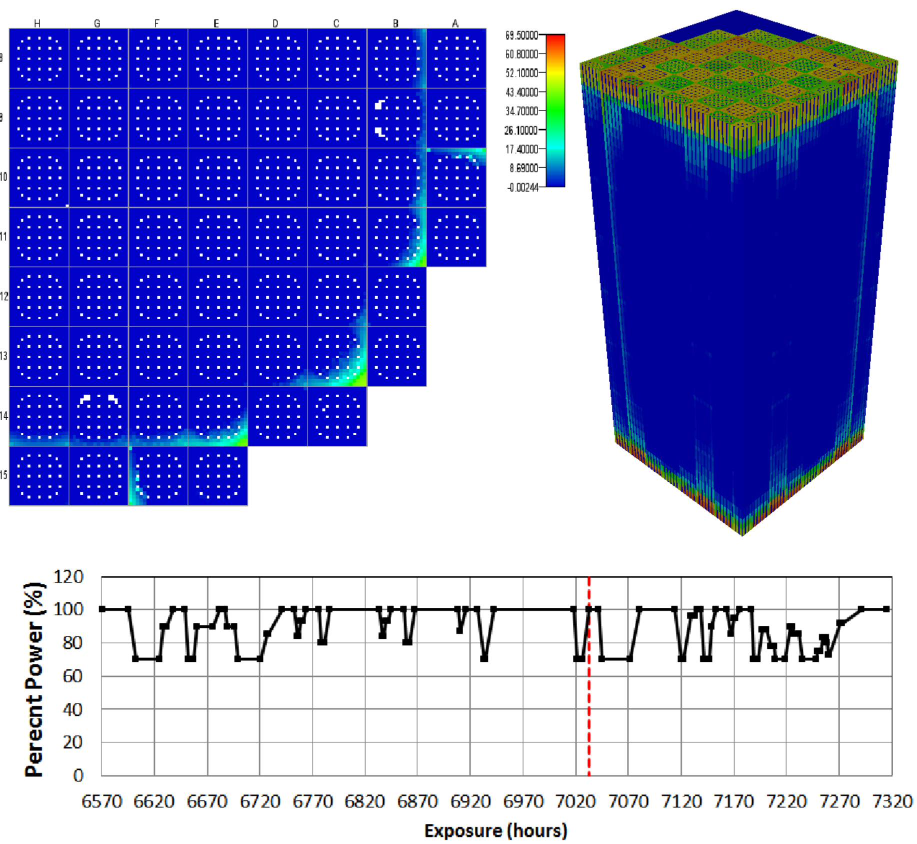
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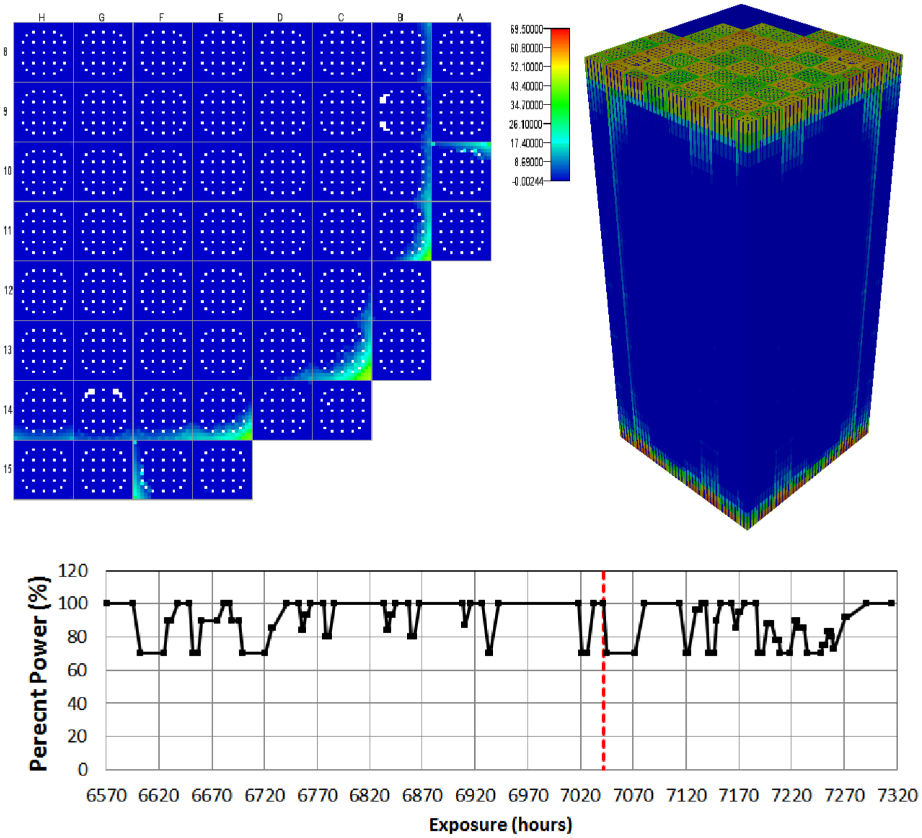
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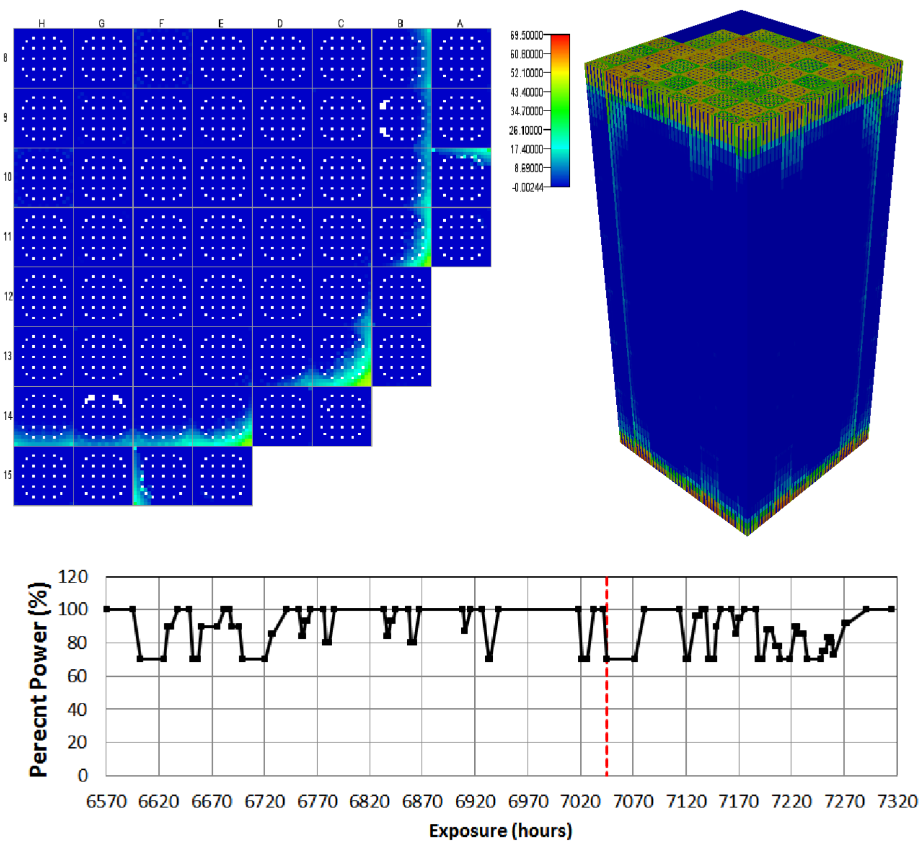
Exposure (hours)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-0.00244
Perecnt Power (%)
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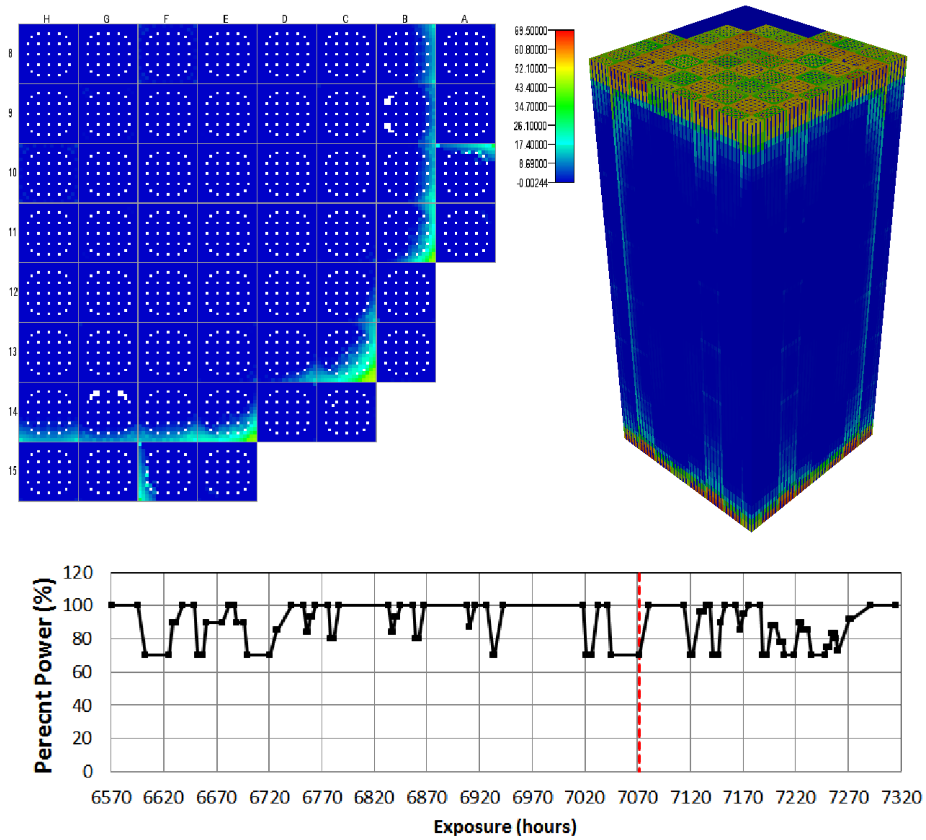
Exposure (hours)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Perecnt Power (%)
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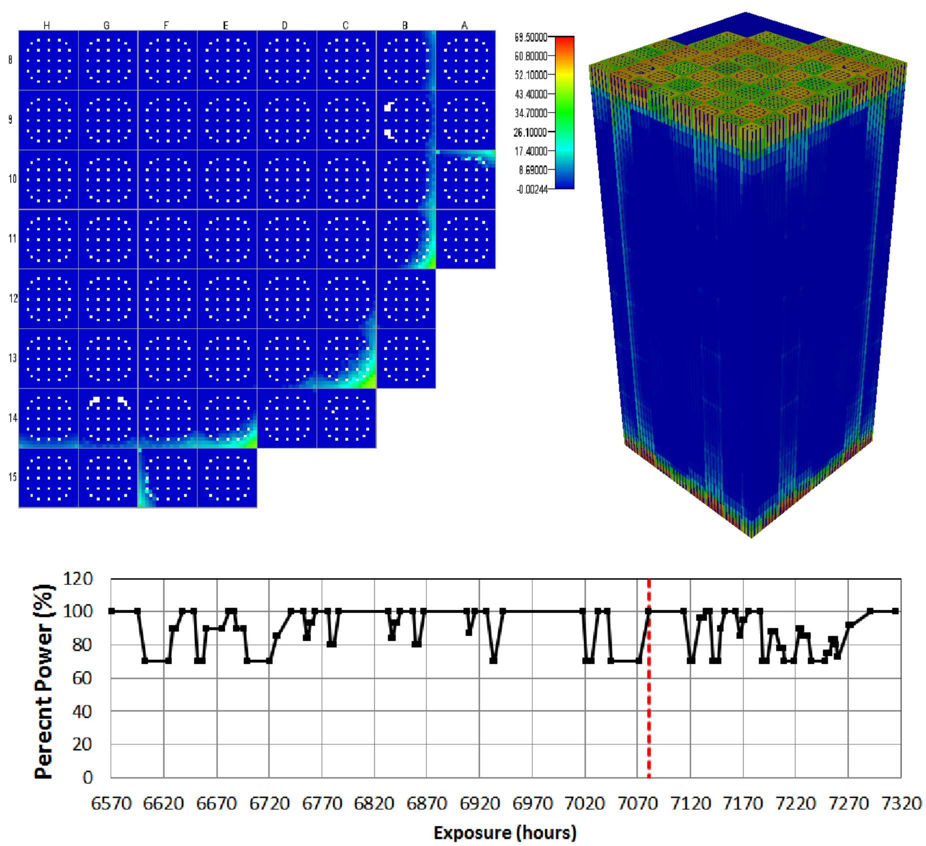
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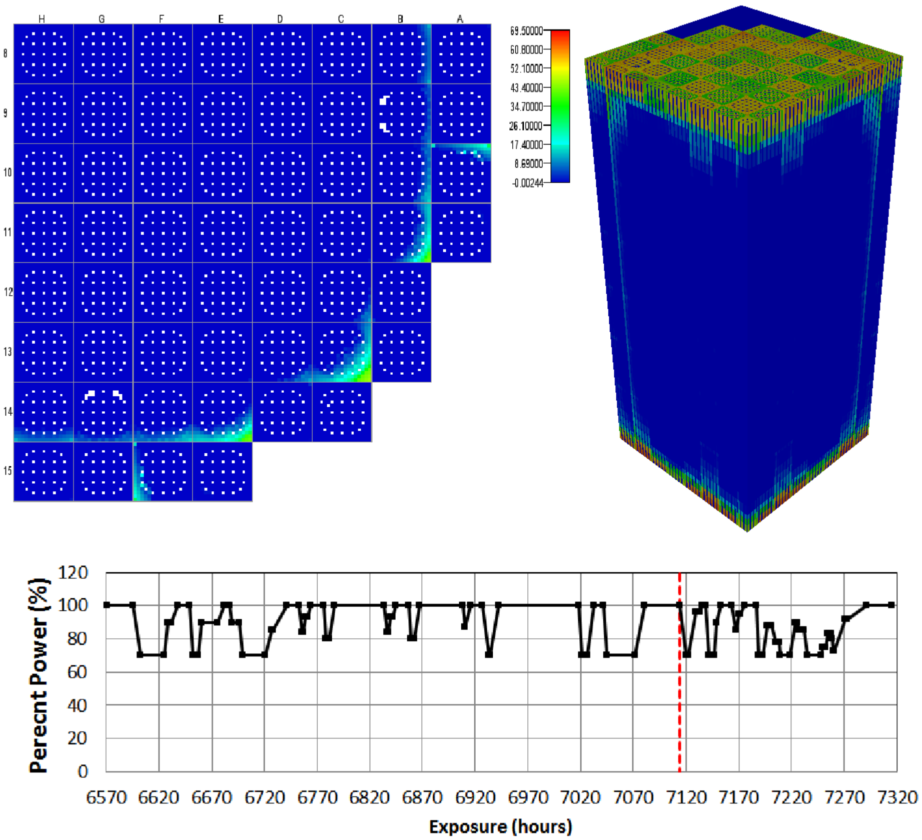
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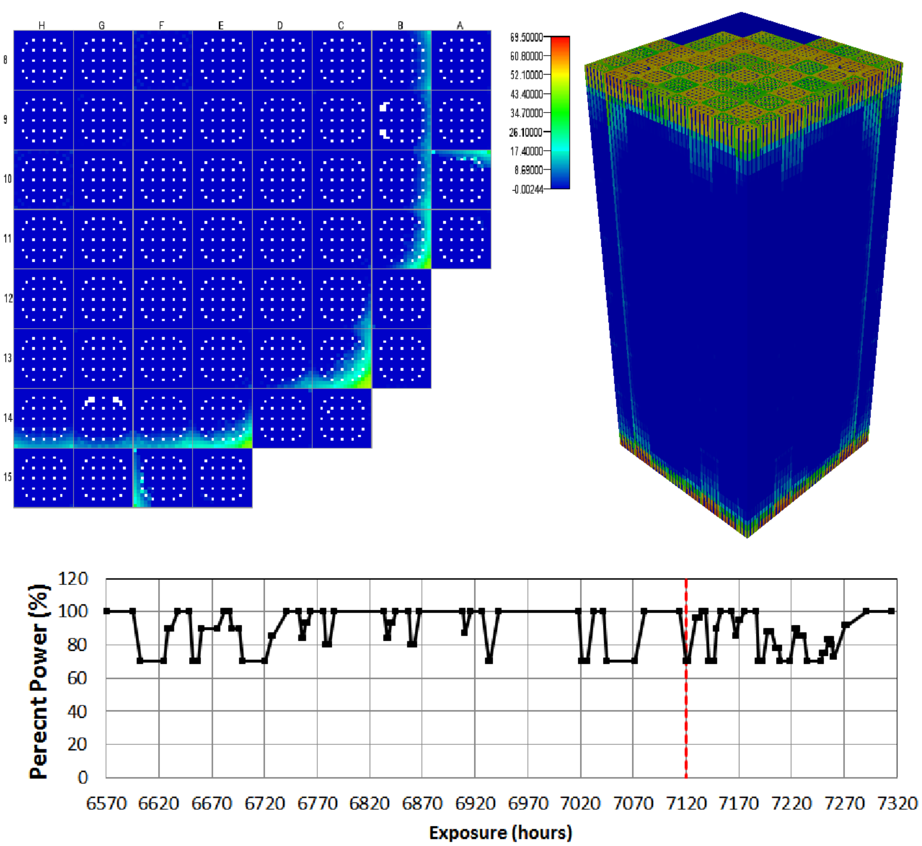
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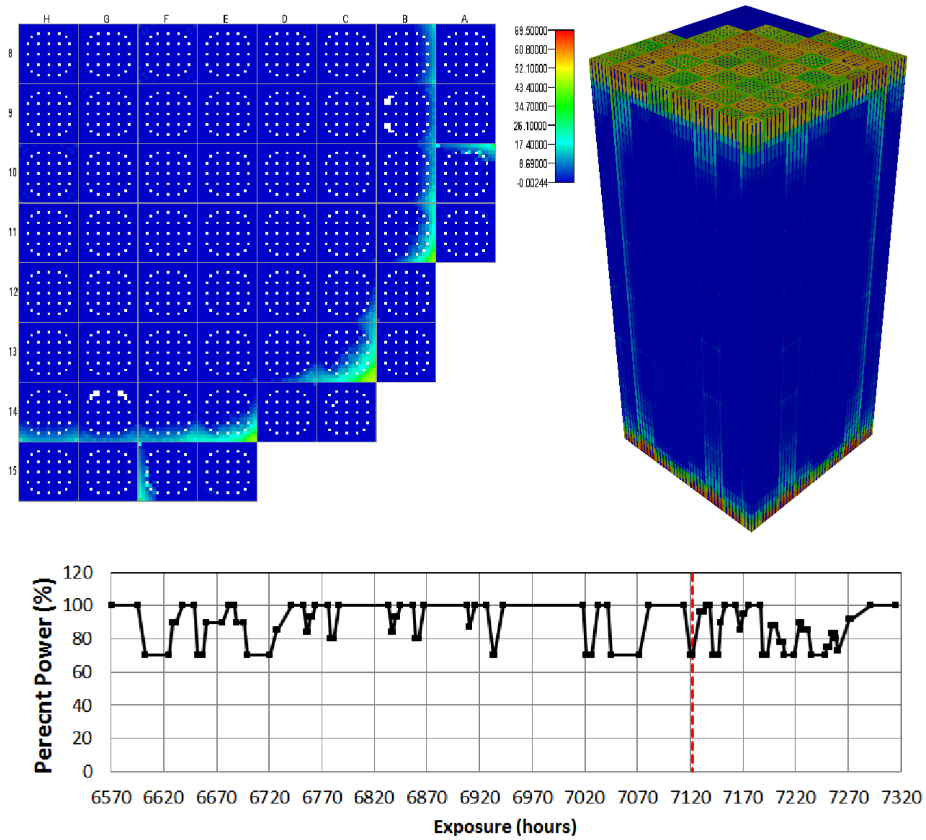
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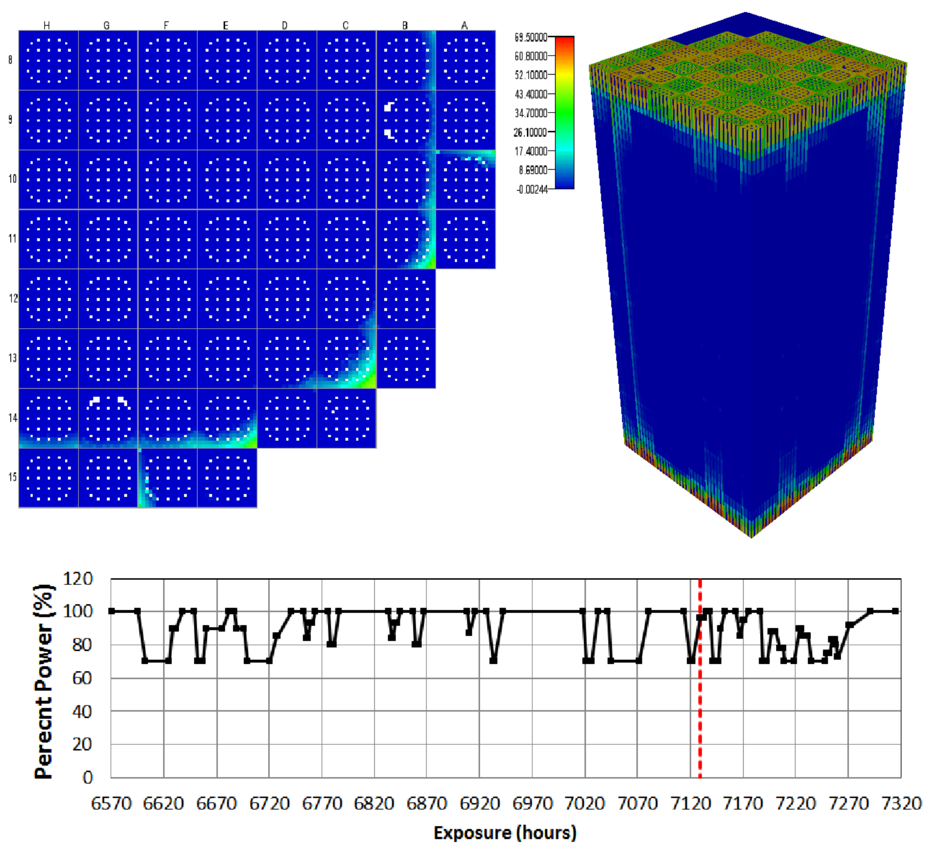
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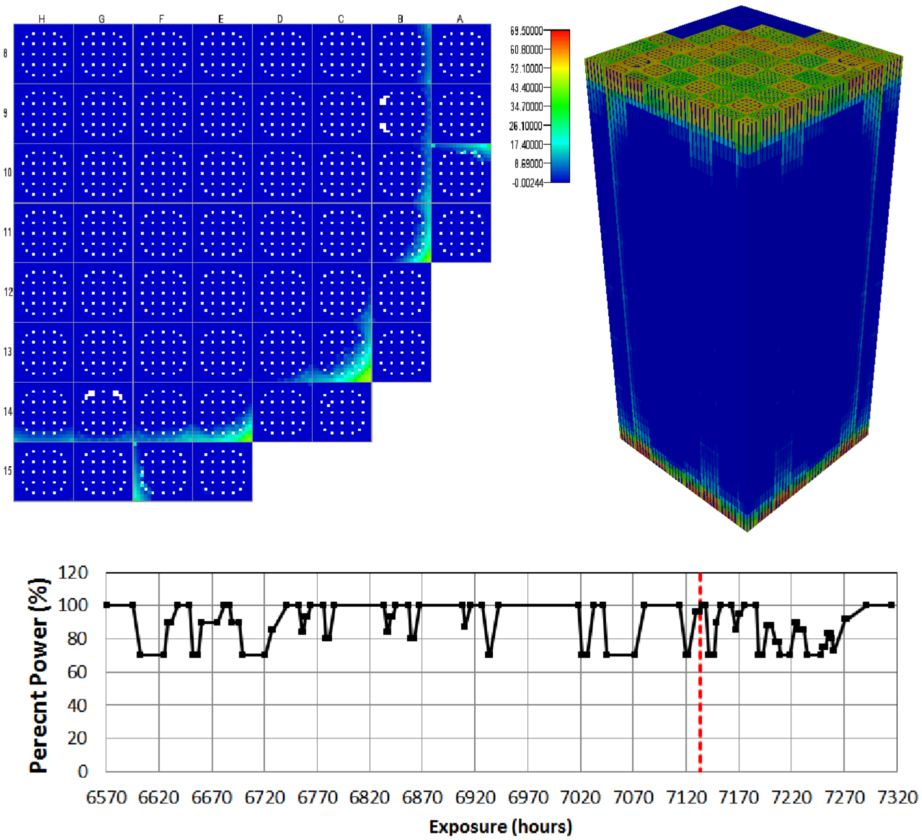
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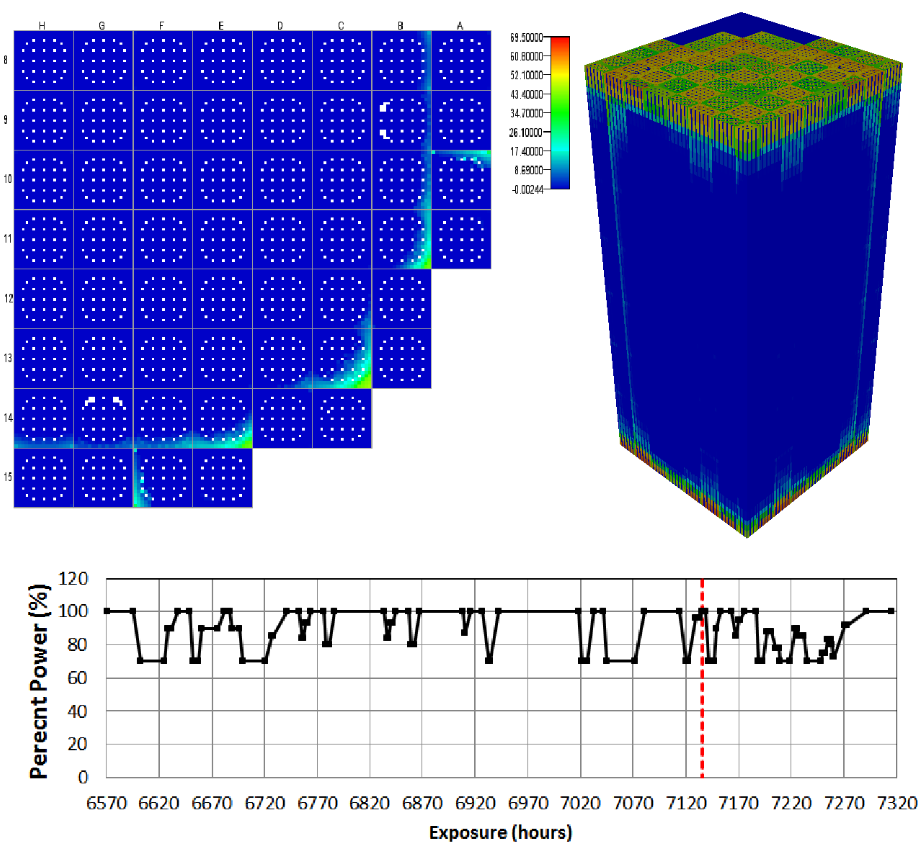
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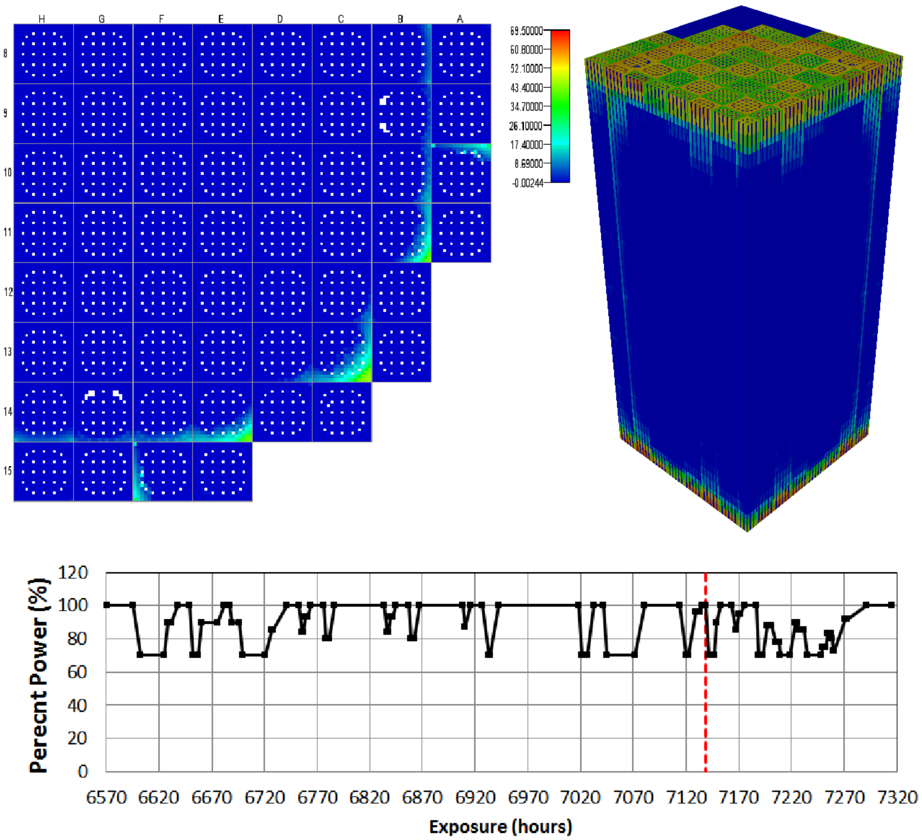
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Perecnt Power (%)
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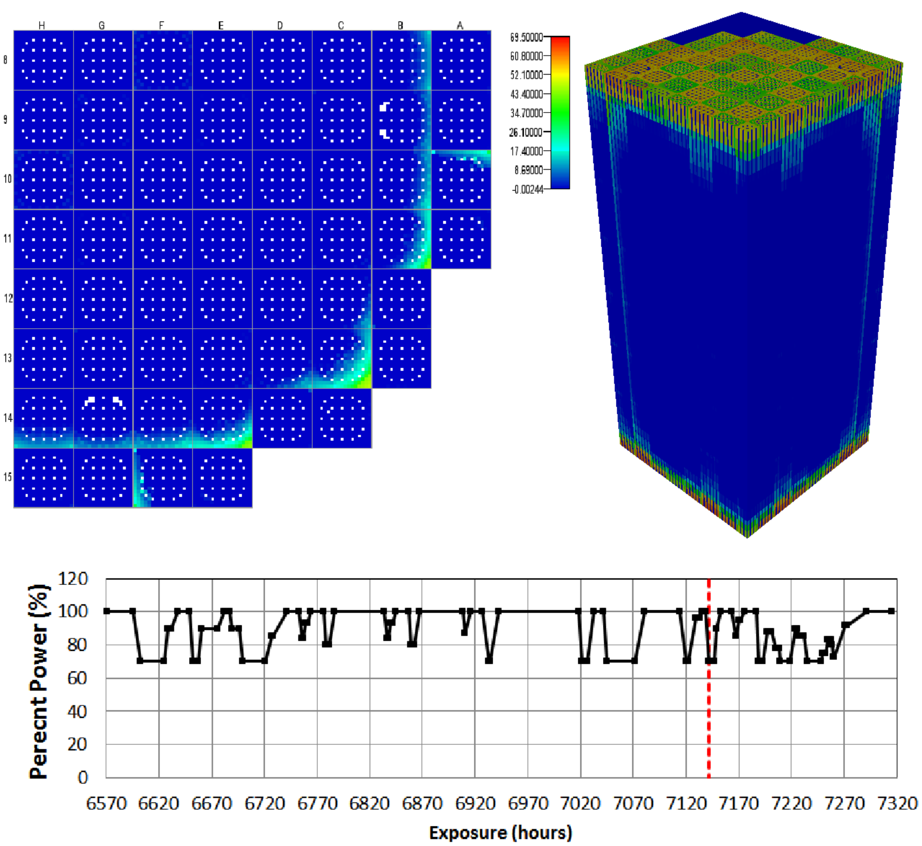
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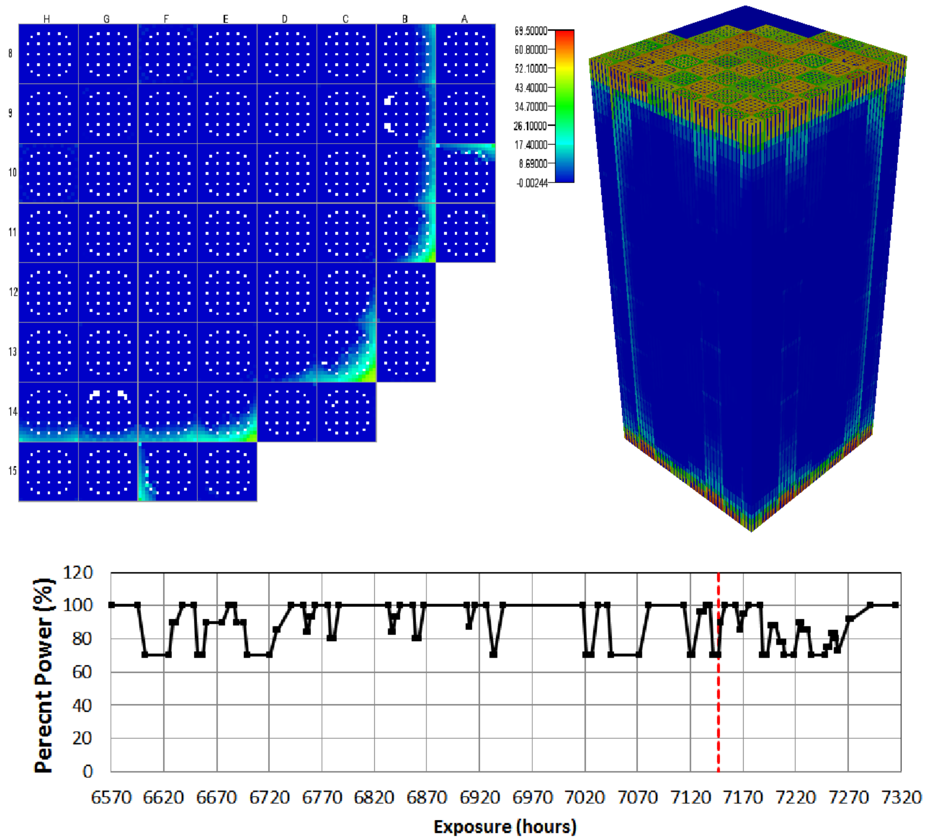
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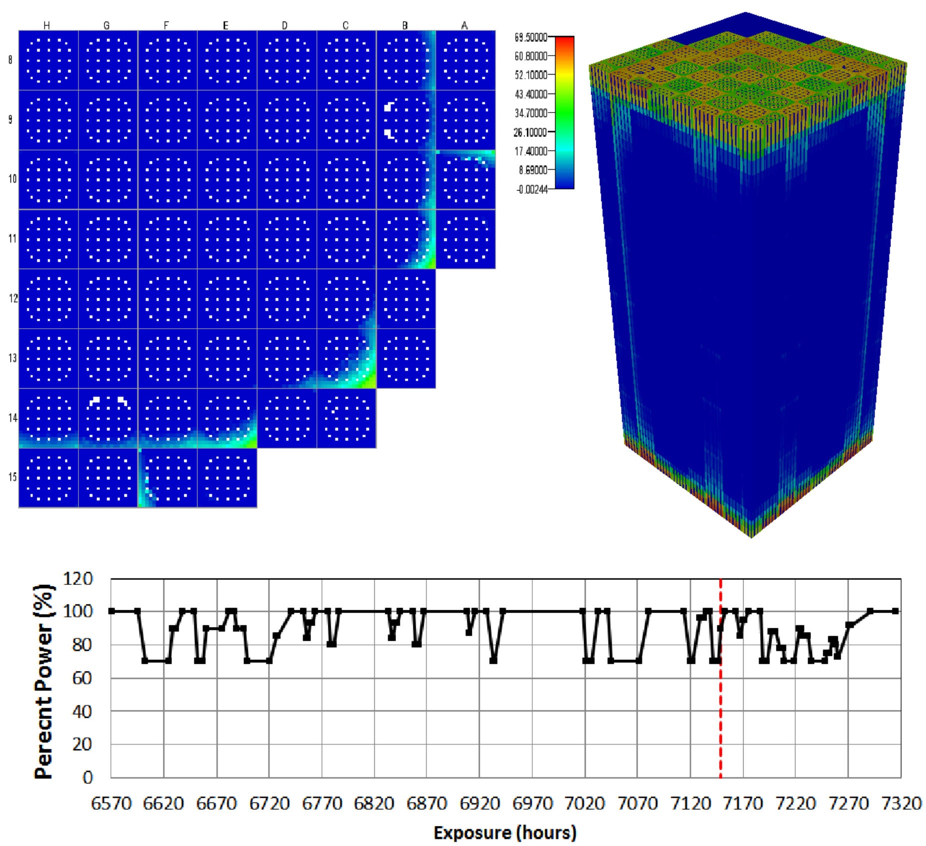
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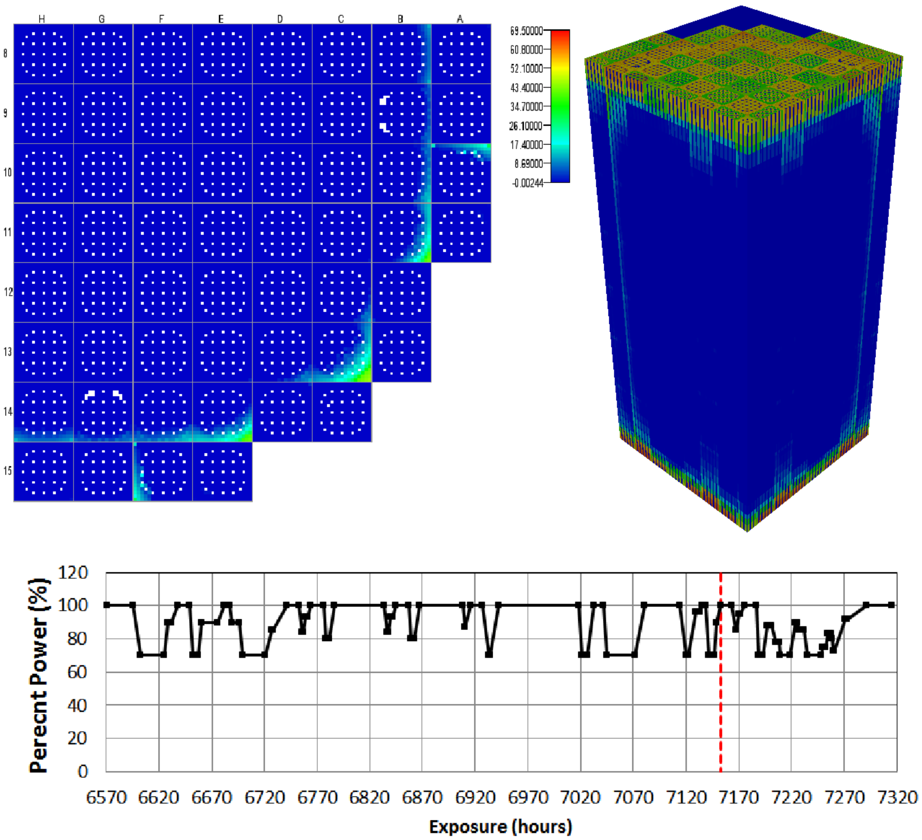
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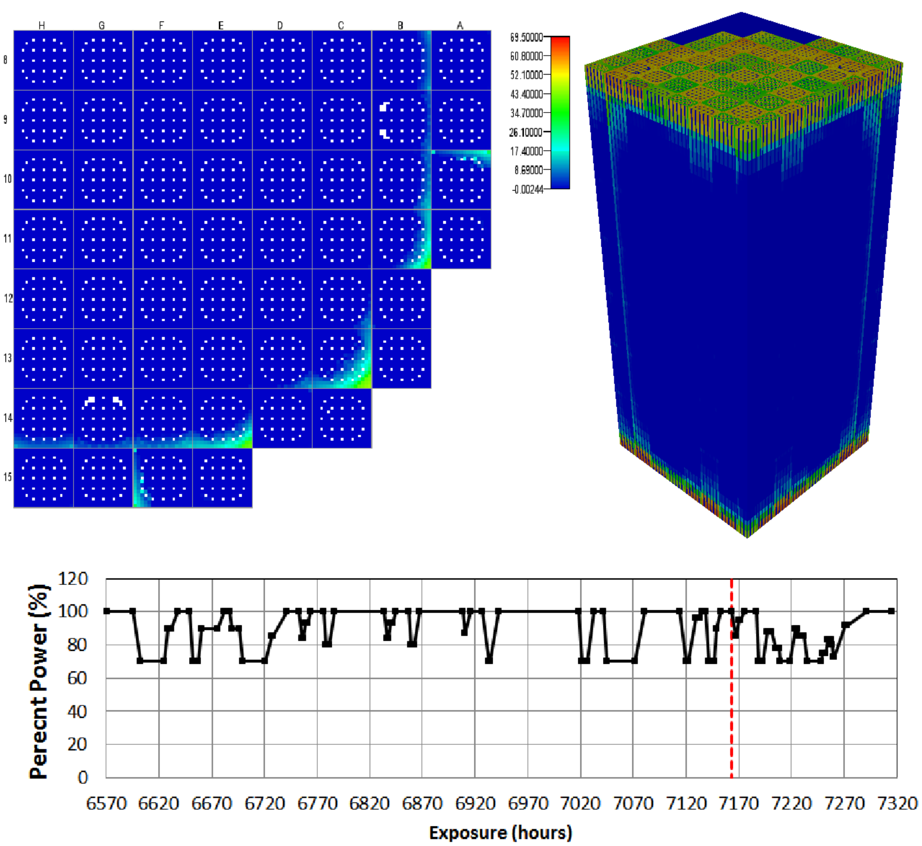
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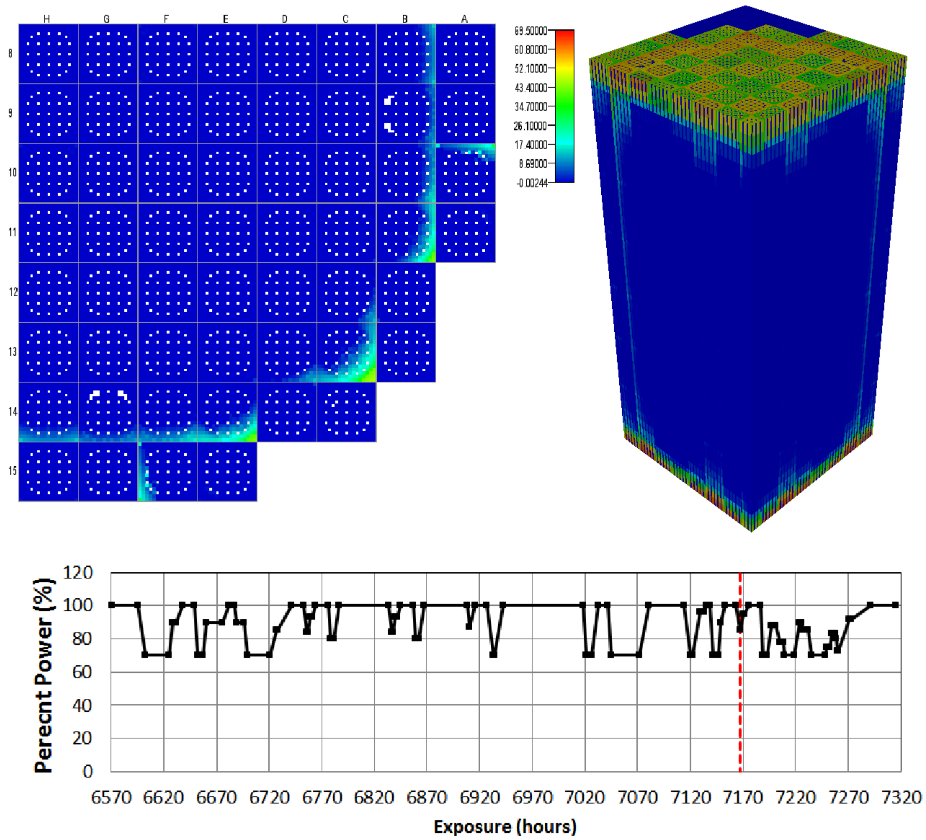
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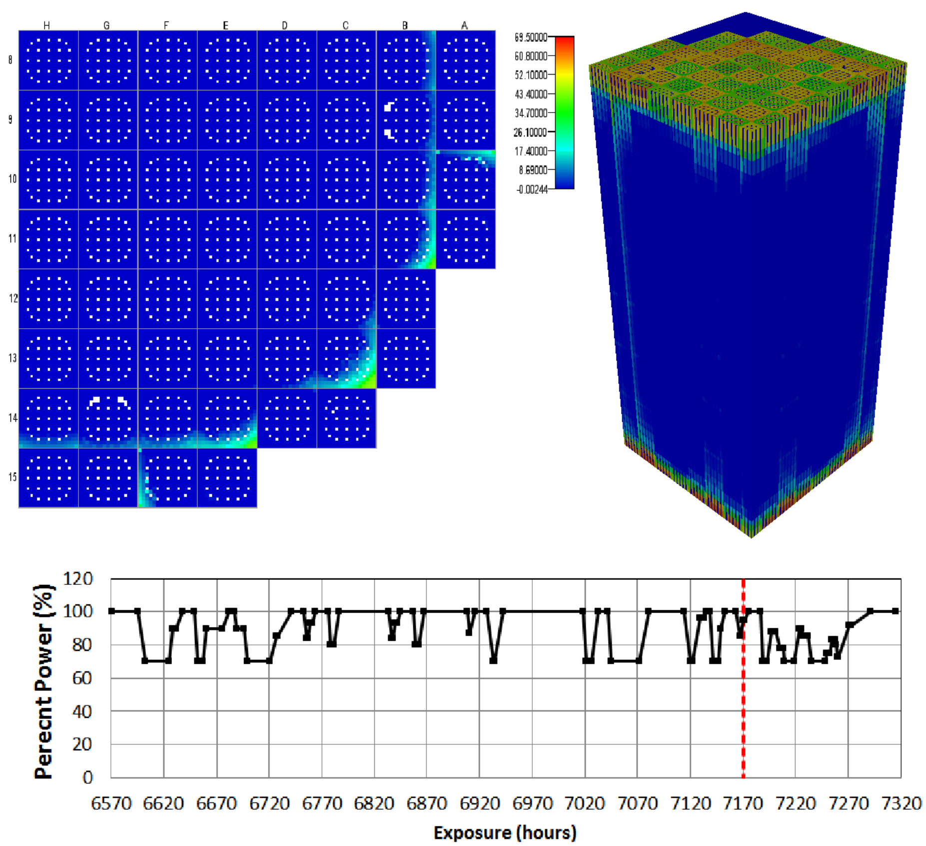
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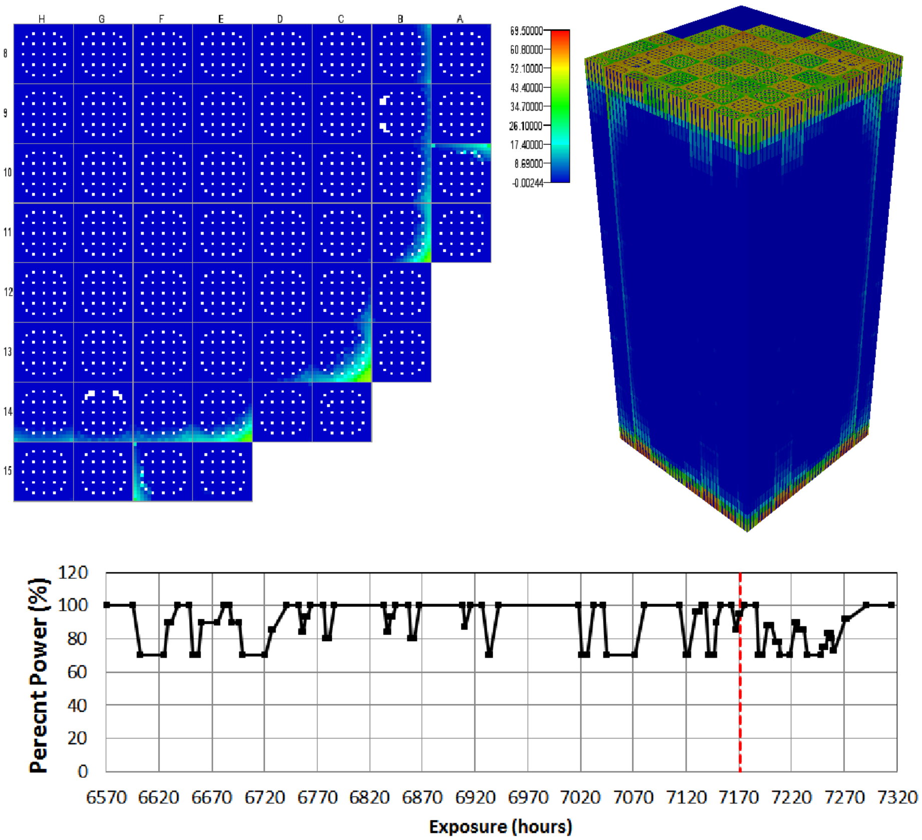
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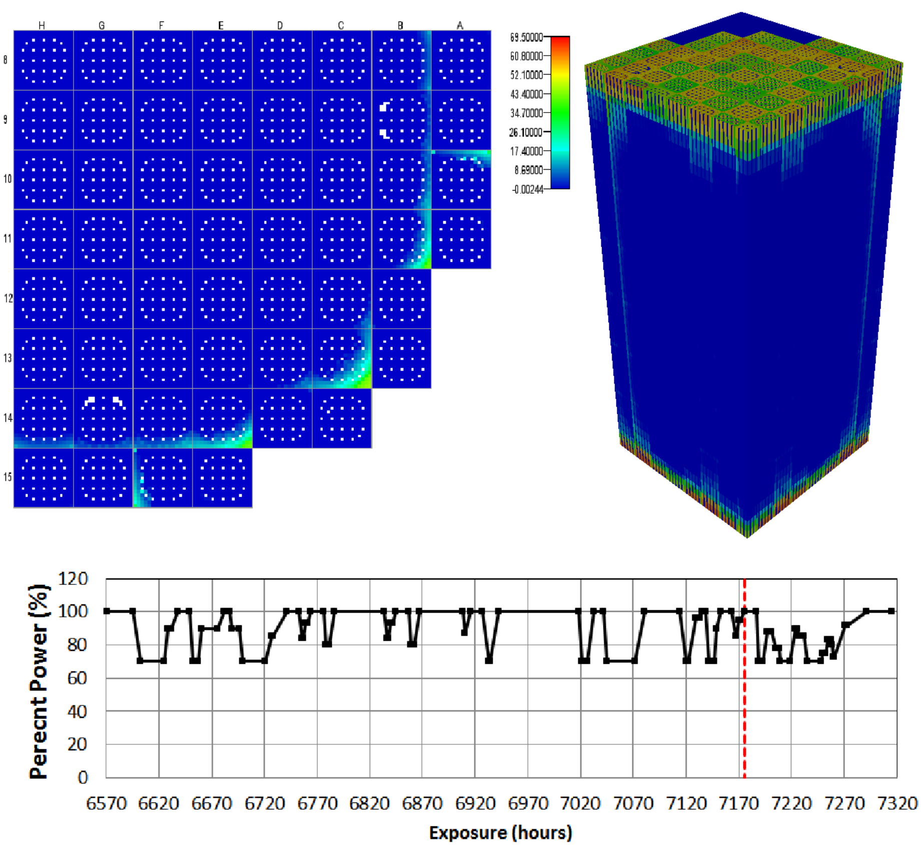
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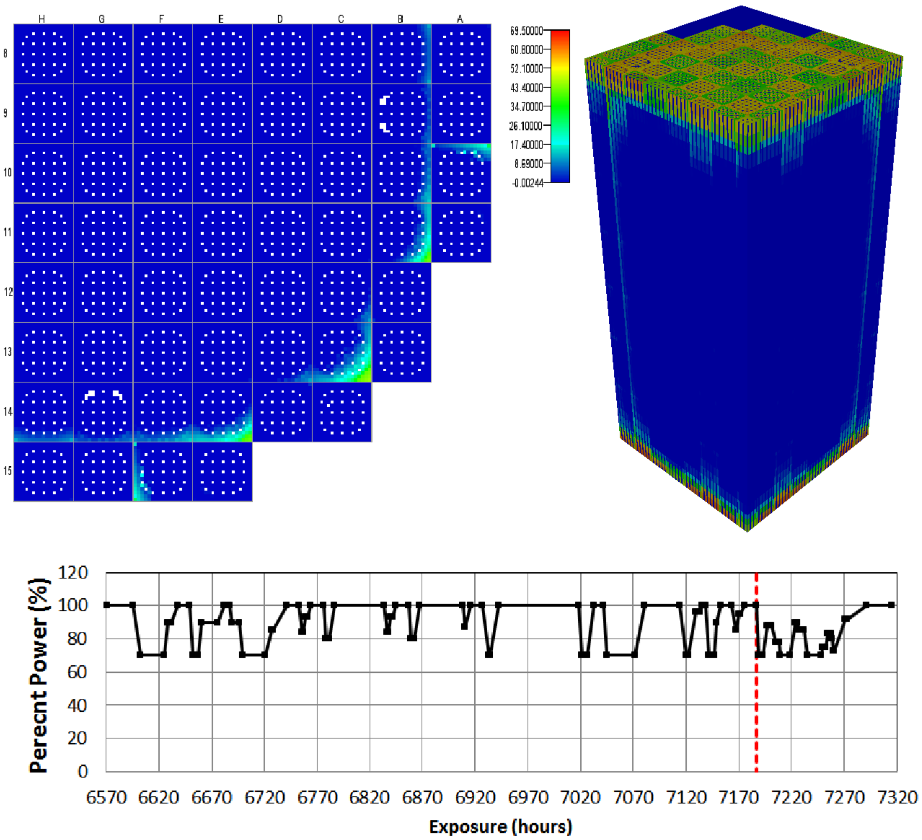
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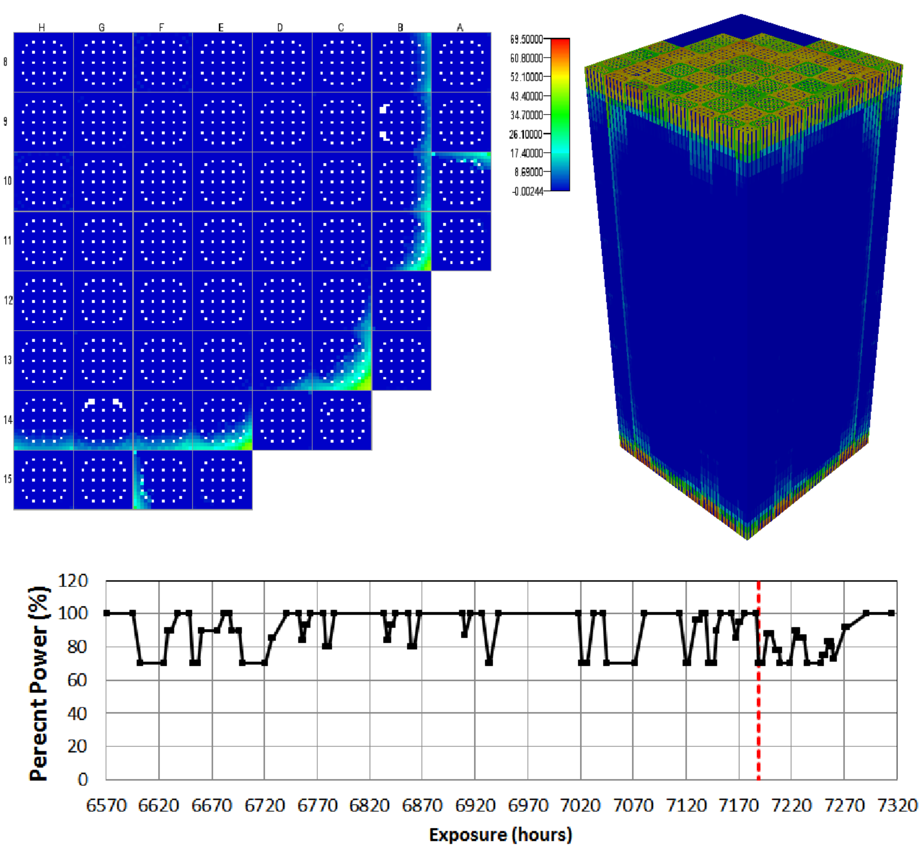
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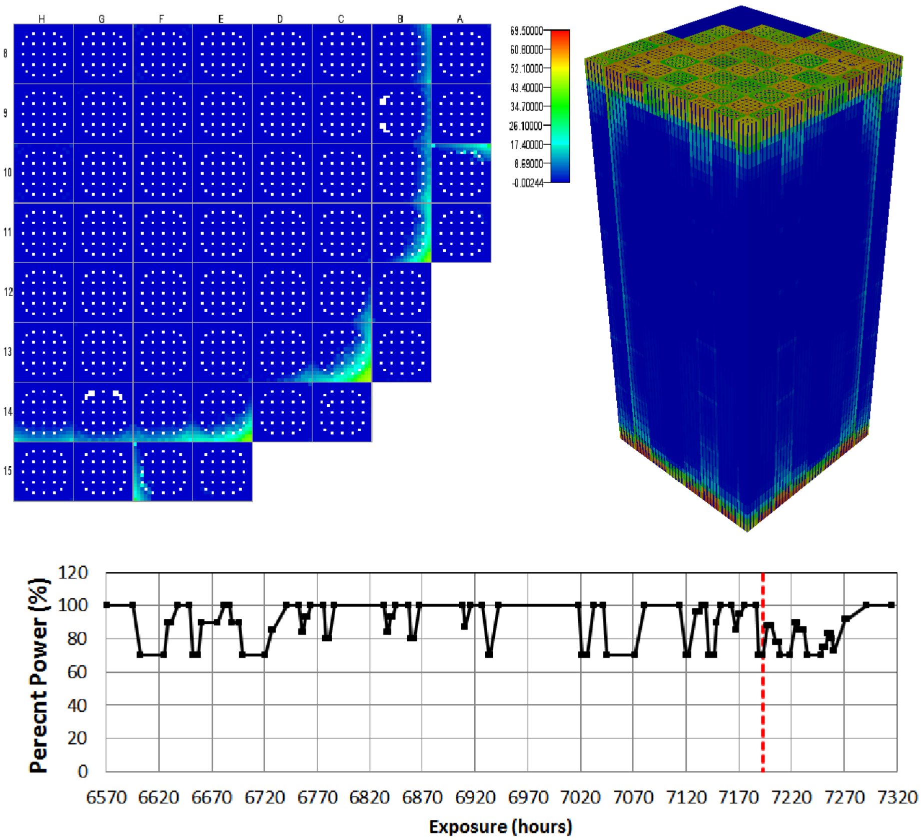
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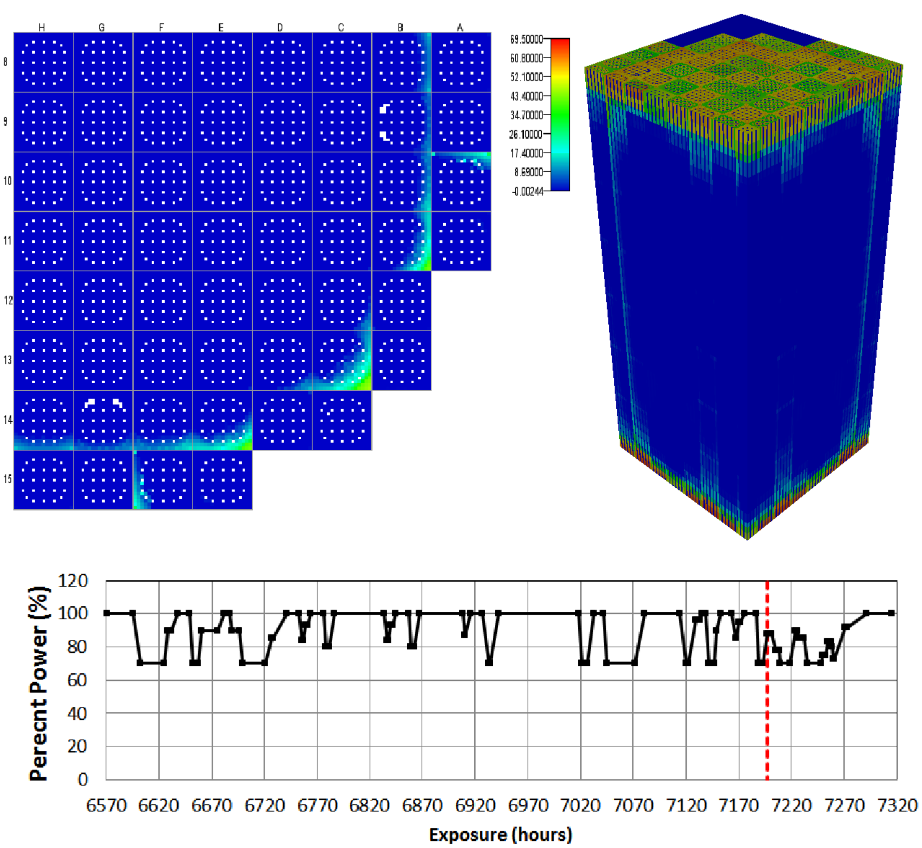
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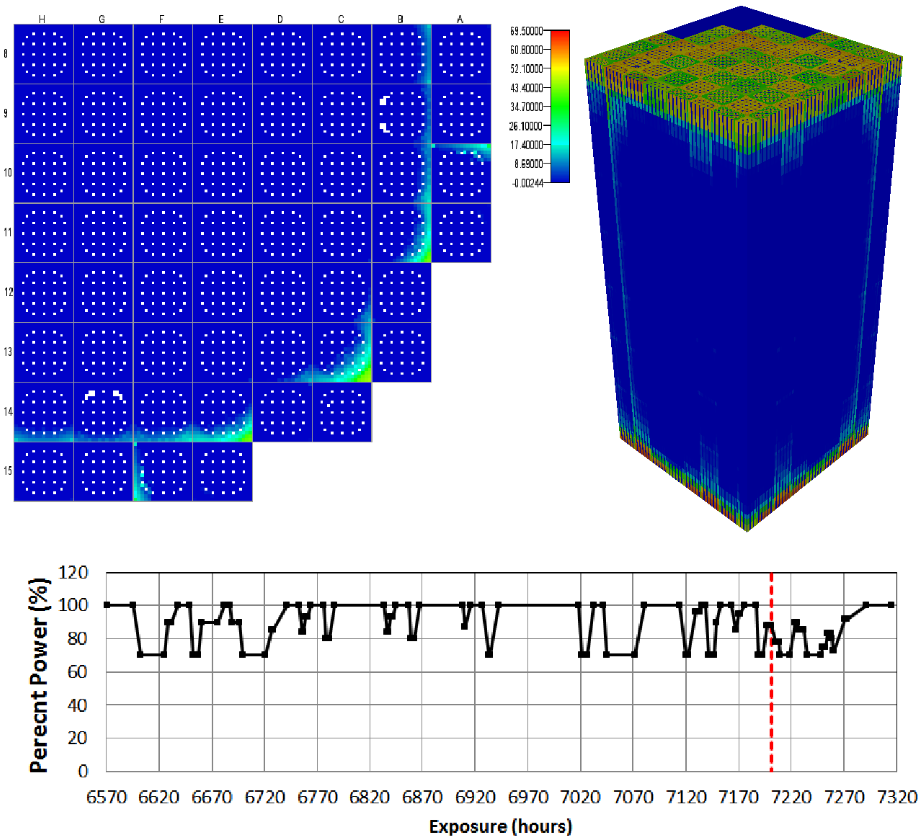
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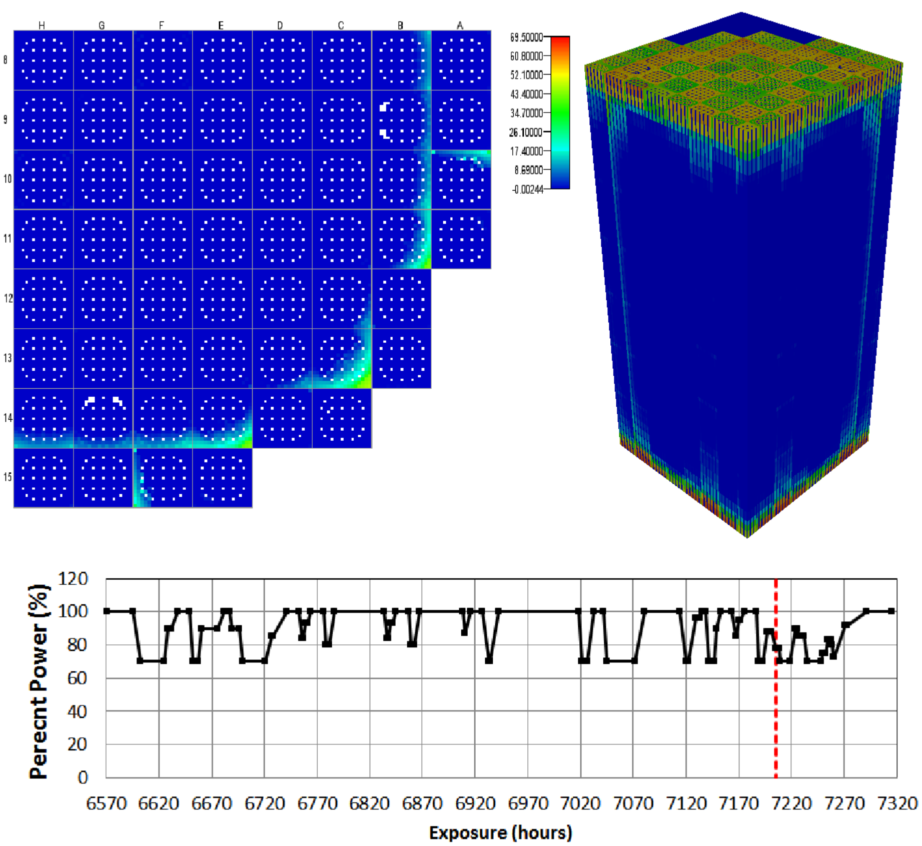
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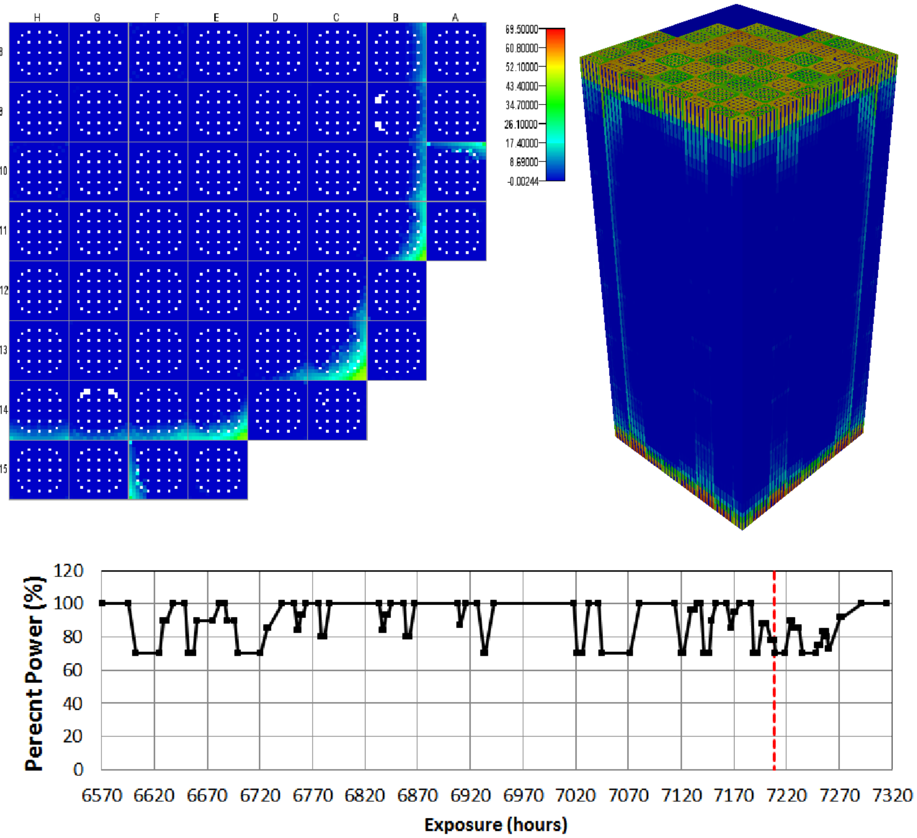
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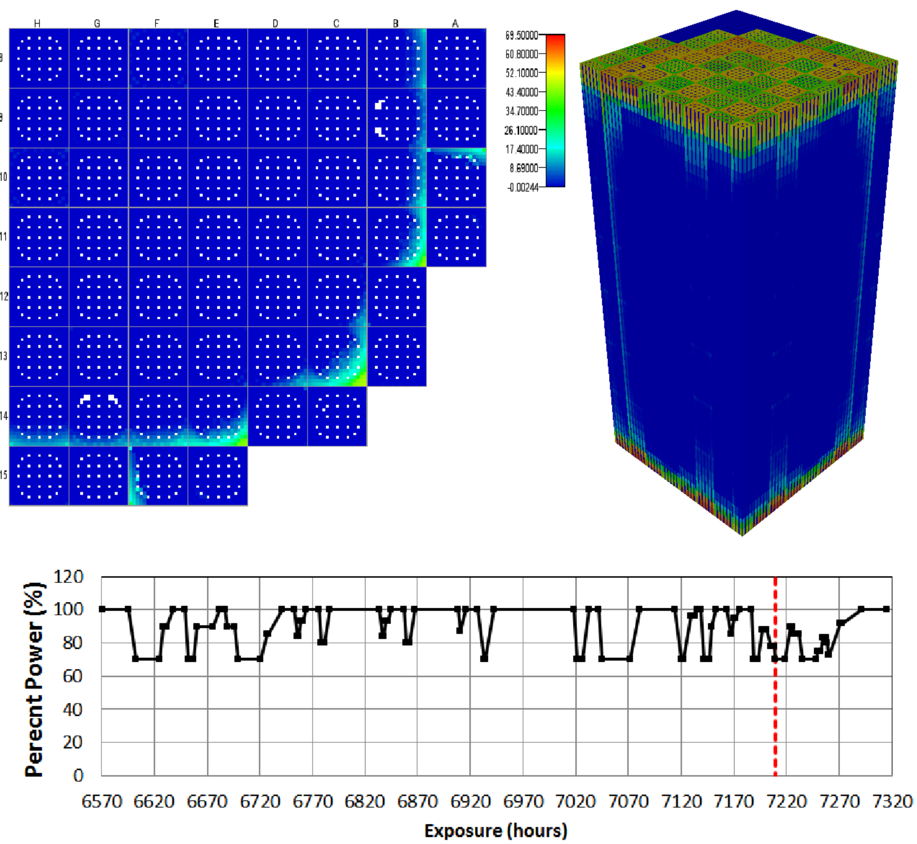
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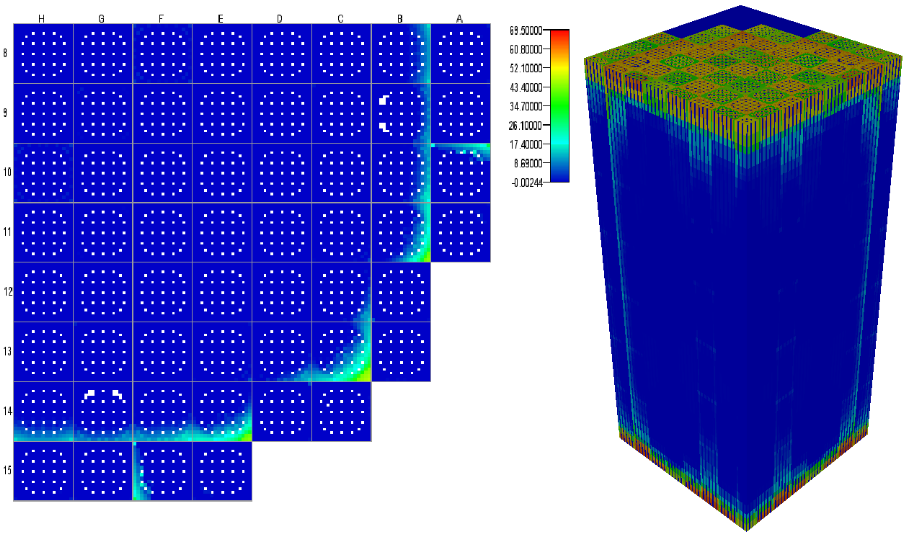

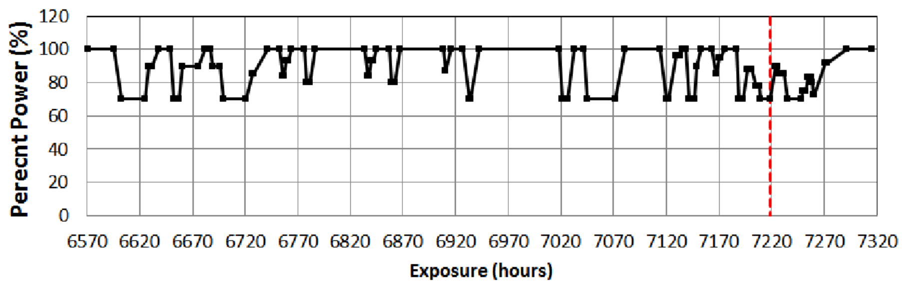
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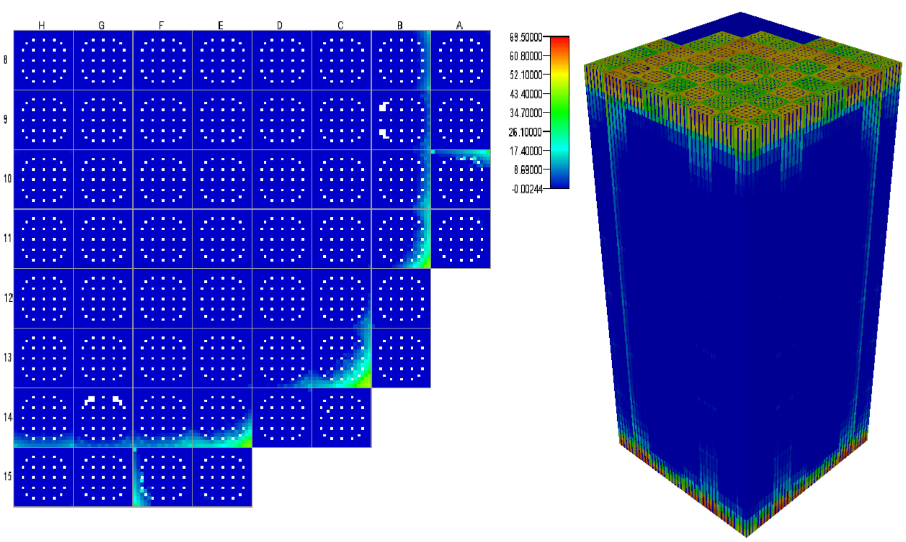

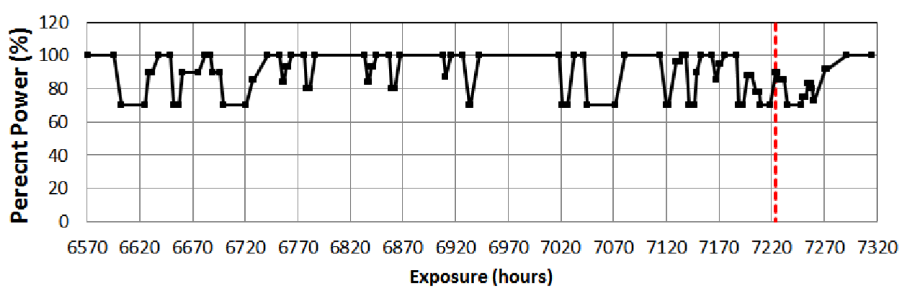
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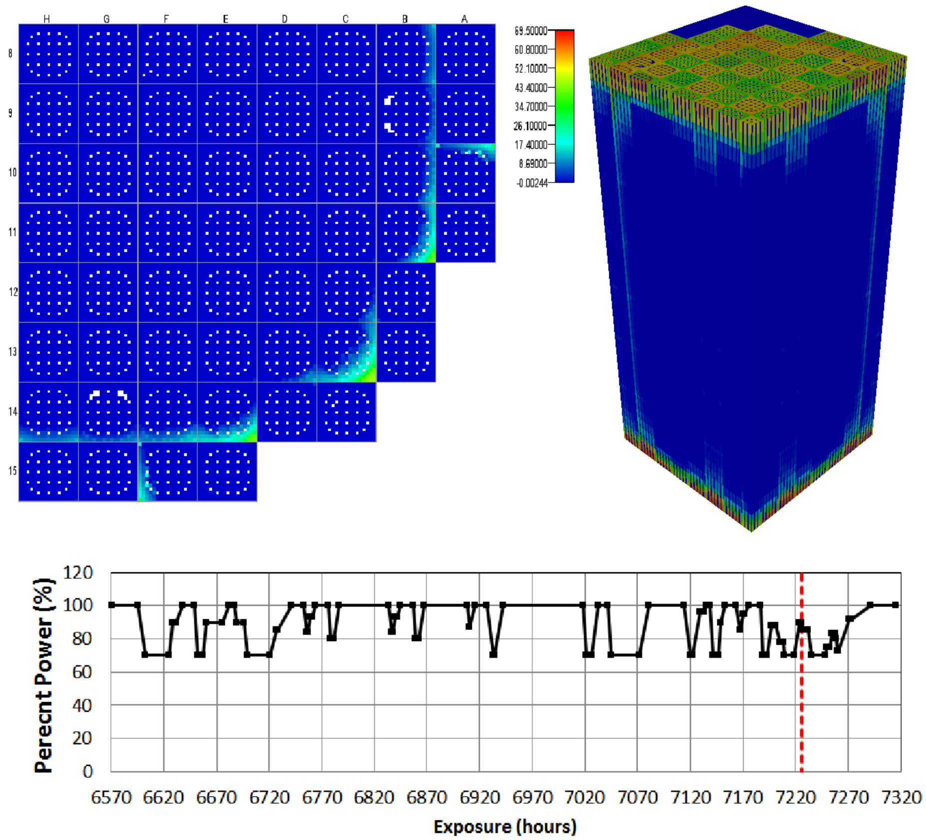
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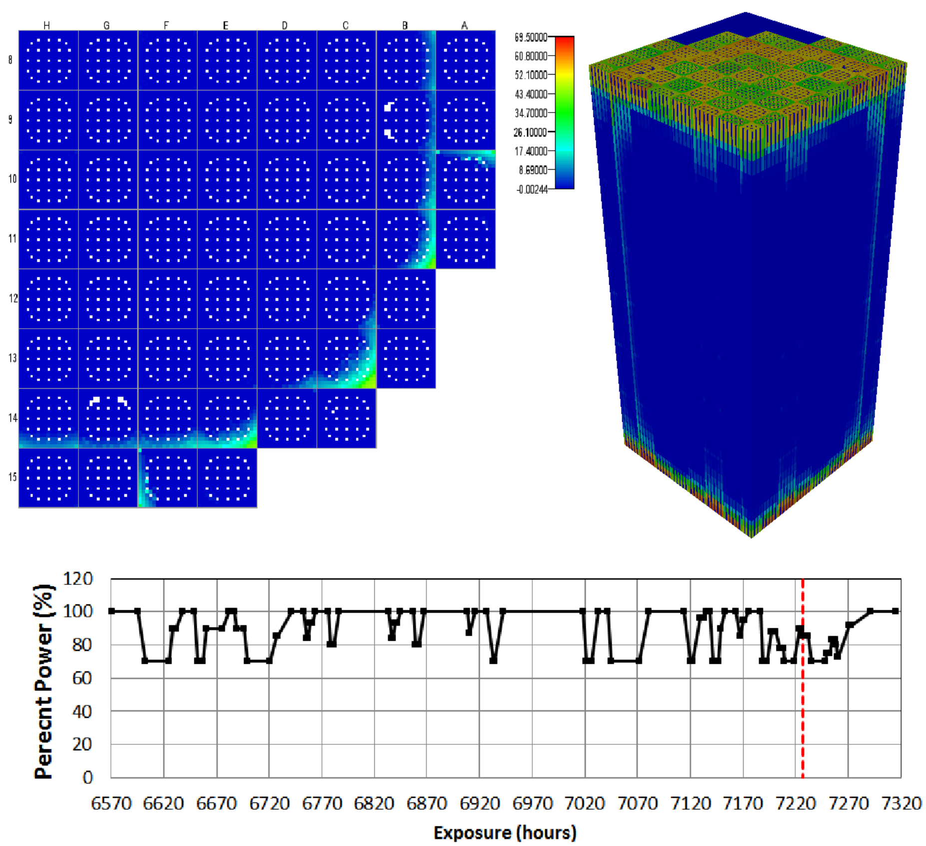
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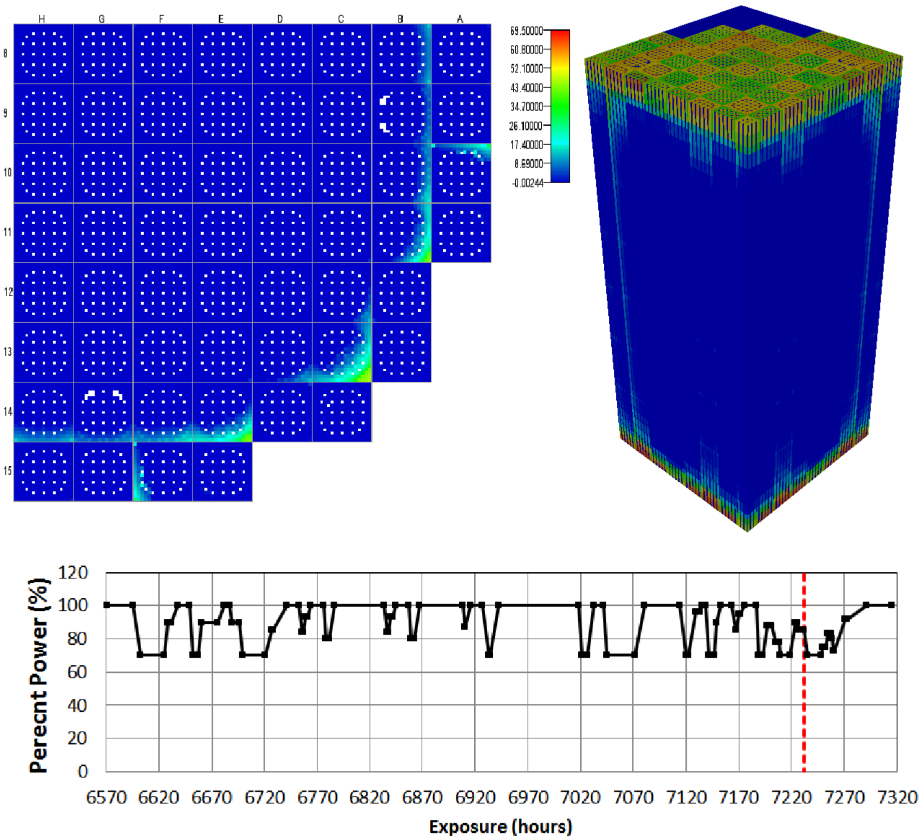
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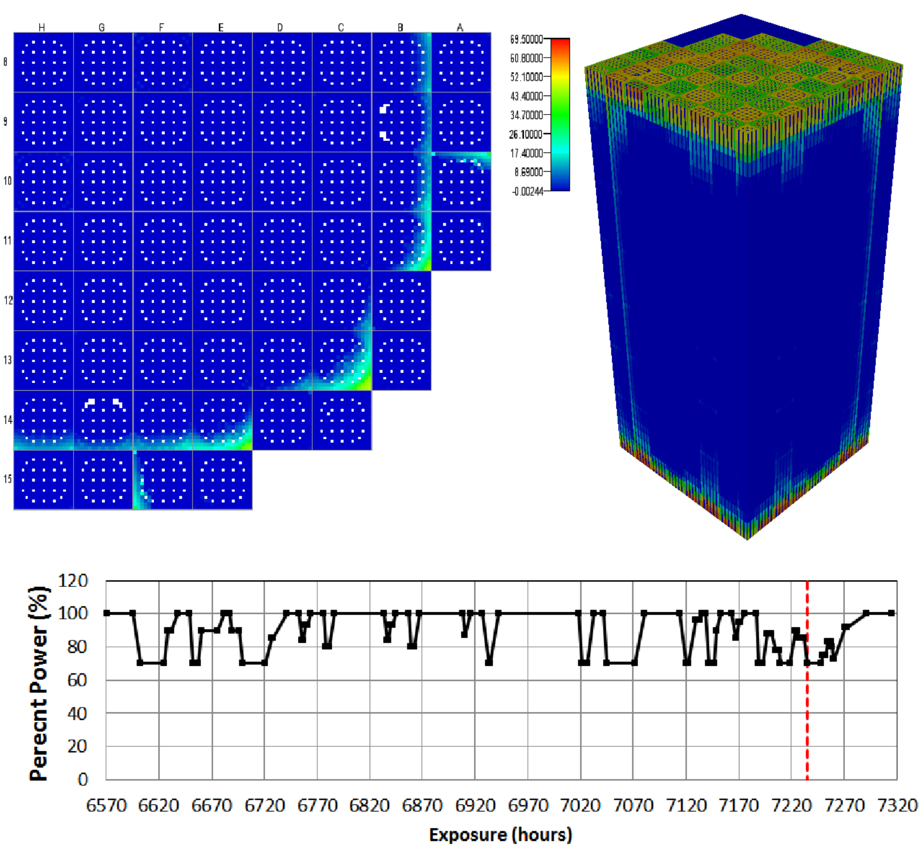
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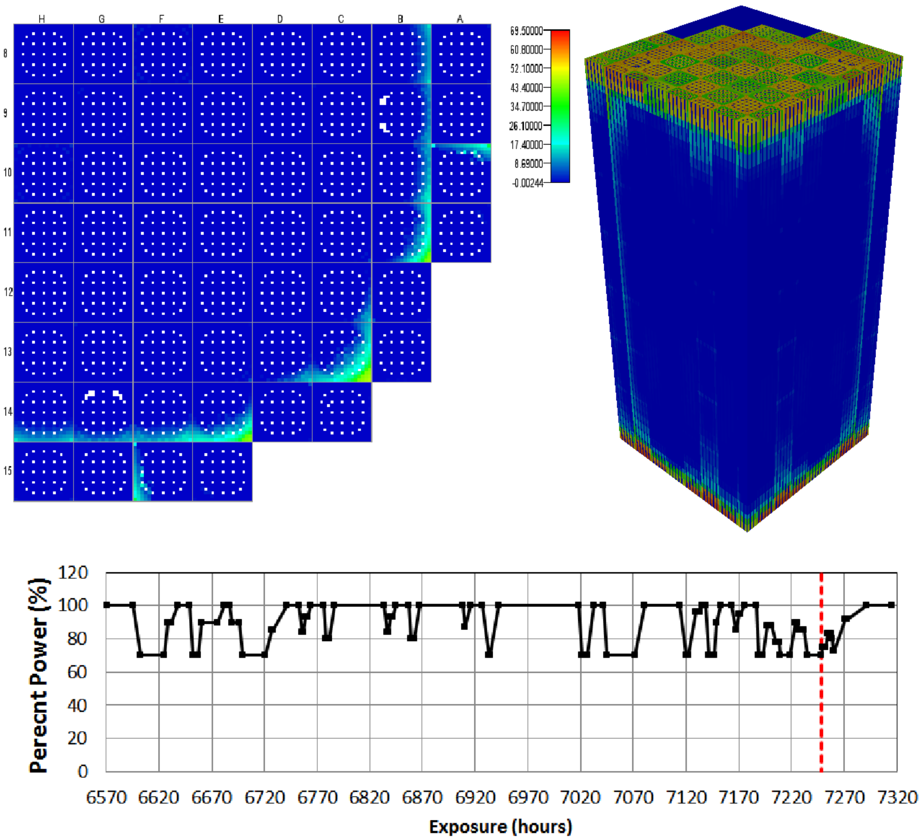
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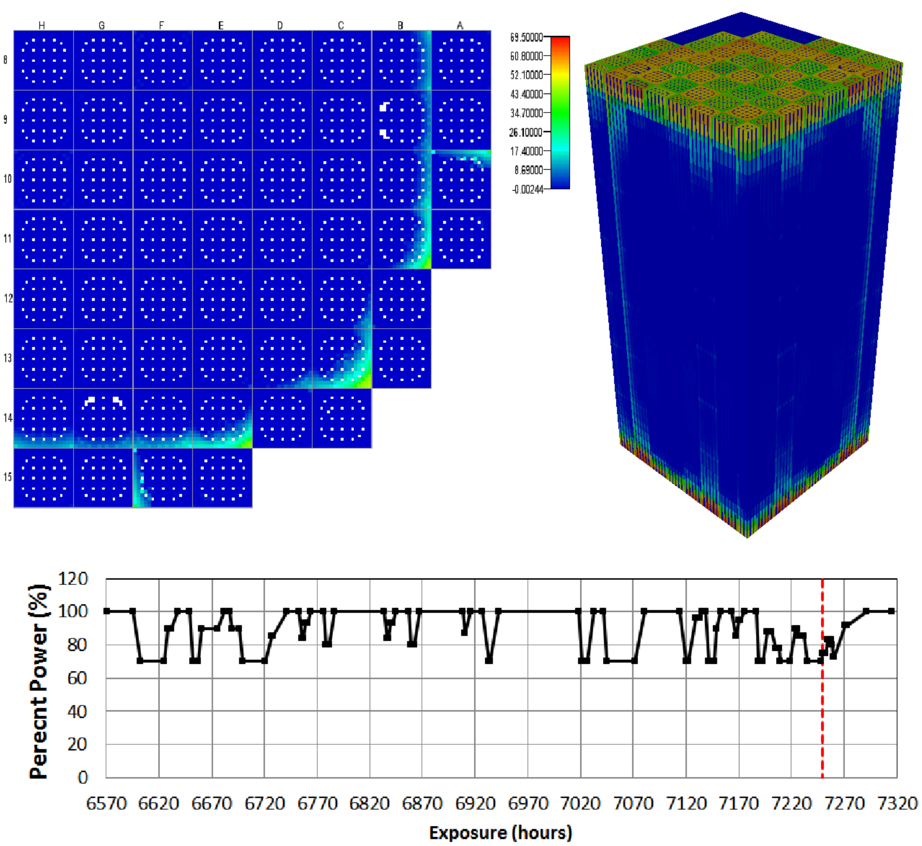
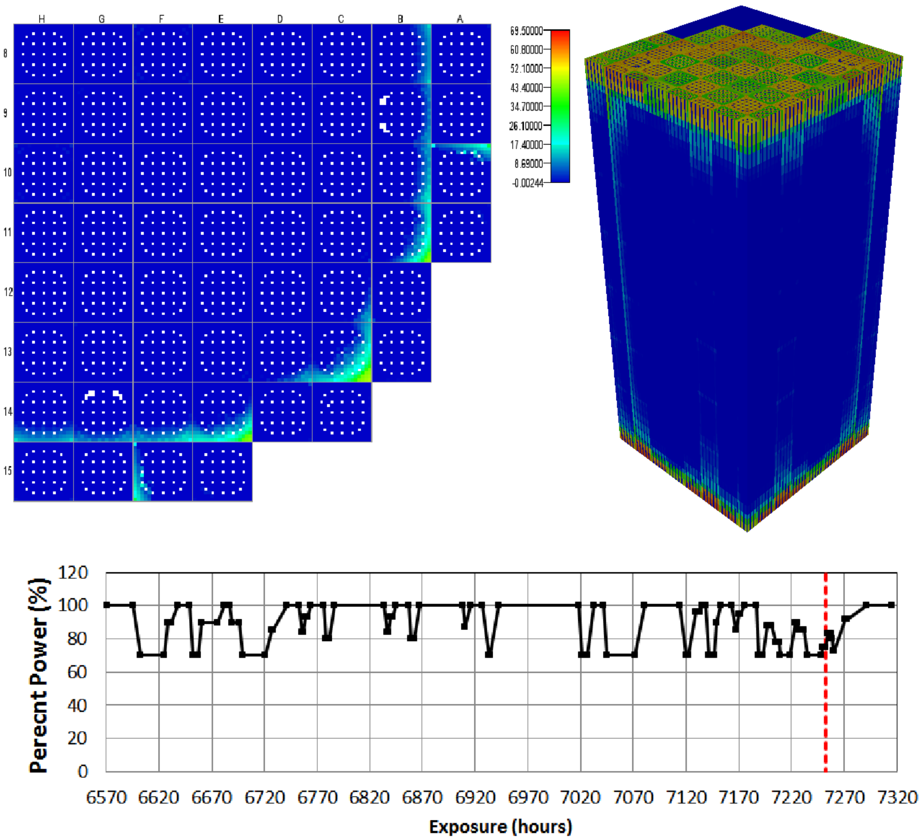
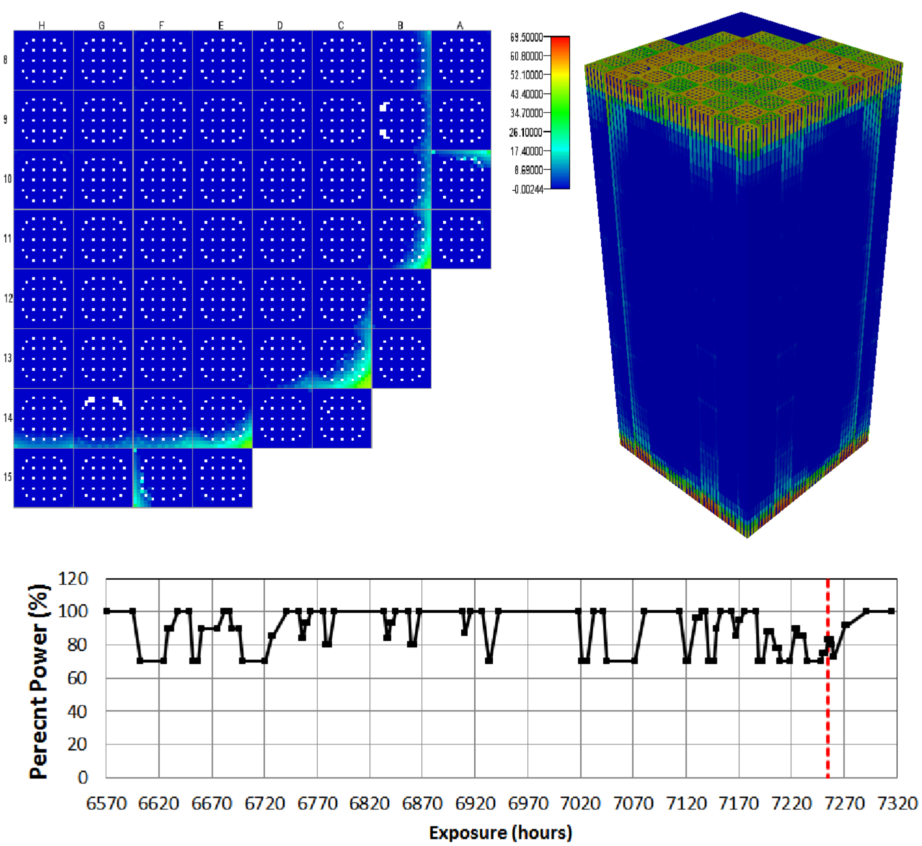
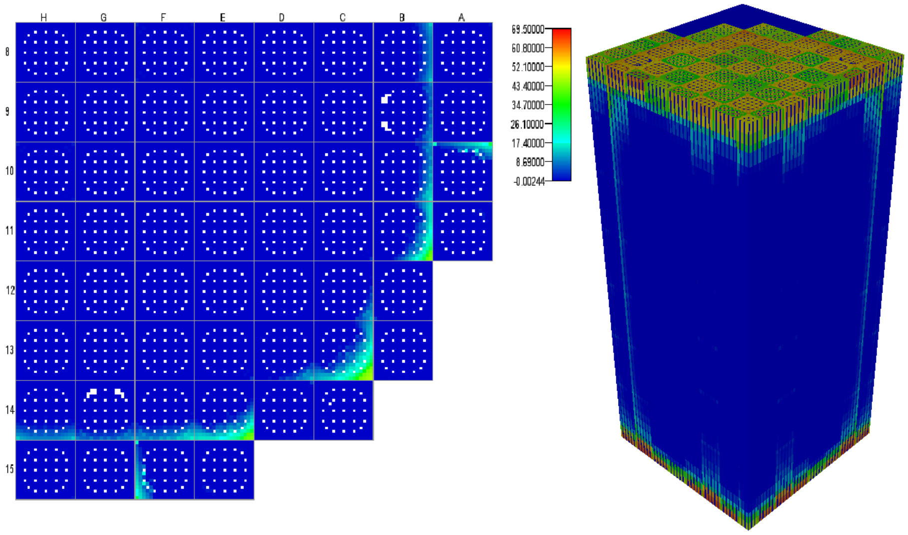
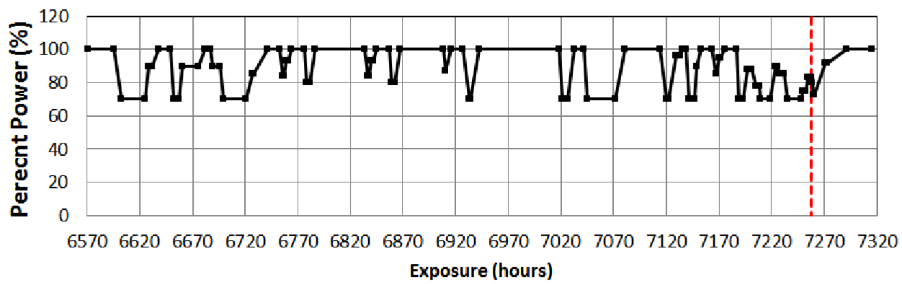
Exposure (hours)

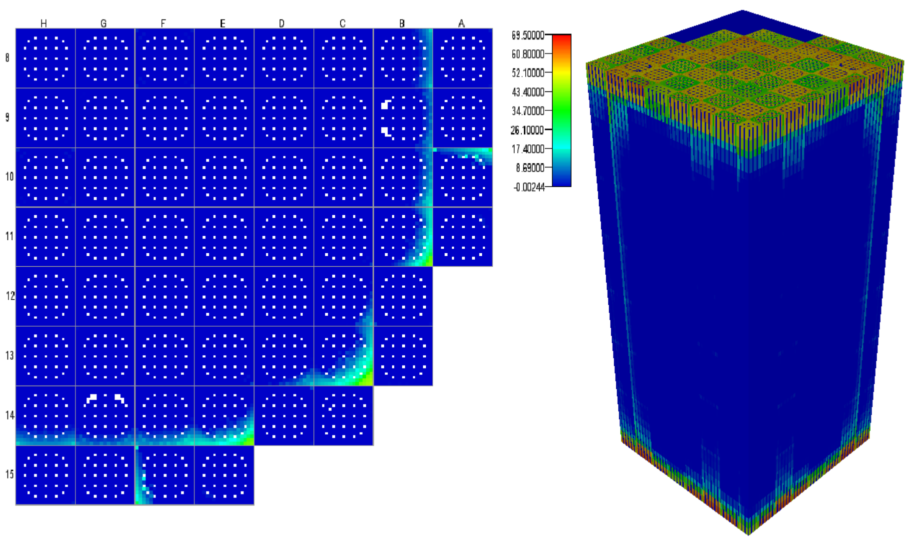

H G F E D C B A
8 9 10 11 12 13 14 15
Perecnt Power (%)
120 100 80 60 40 20 0
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)

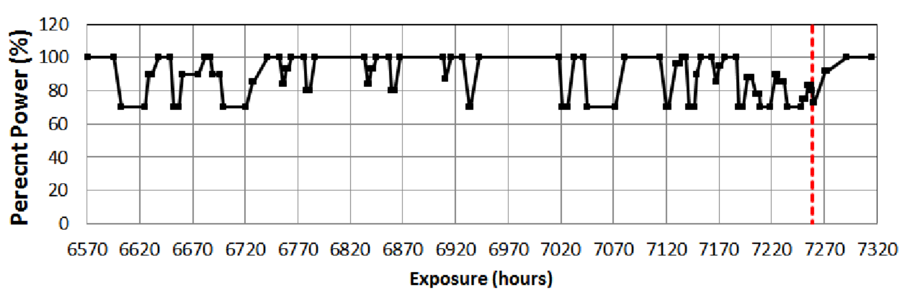

H G F E D C B A
8 9 10 11 12 13 14 15
69.50000
60.80000
52.10000
43.40000
34.70000
26.10000
17.40000
8.68000
-0.00244
120 100 80 60 40 20 0
Perecnt Power (%)
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)

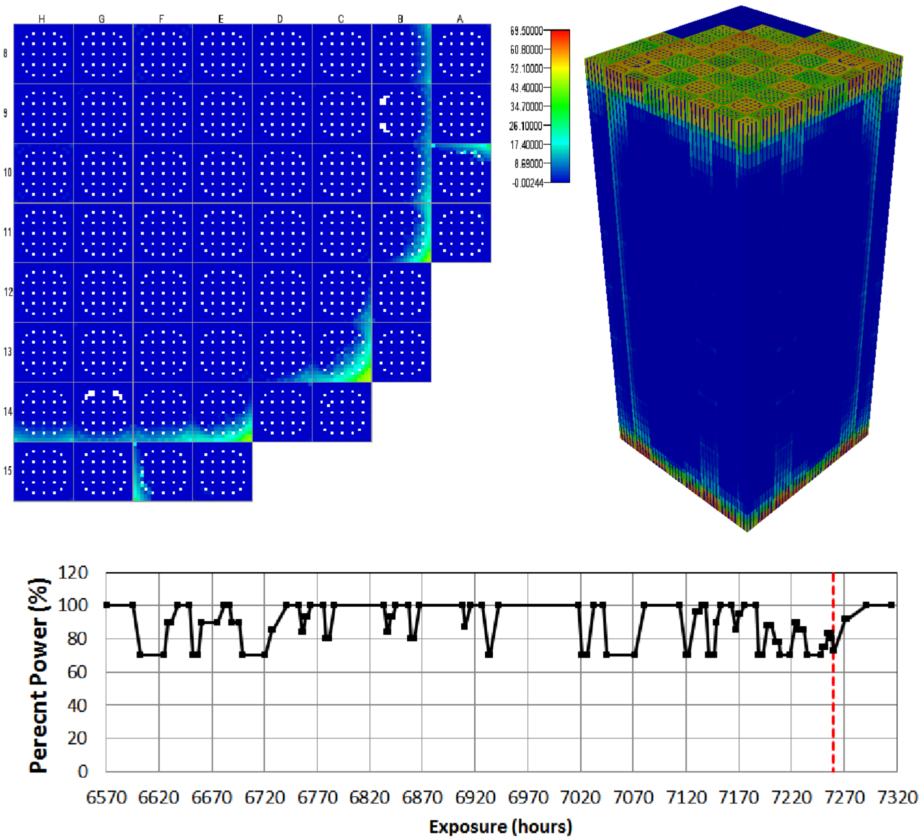

H G F E D C B A
8 9 10 11 12 13 14 15
69.50000
60.80000
52.10000
43.40000
34.70000
26.10000
17.40000
8.68000
-0.00244
120 100 80 60 40 20 0
Perecnt Power (%)
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)

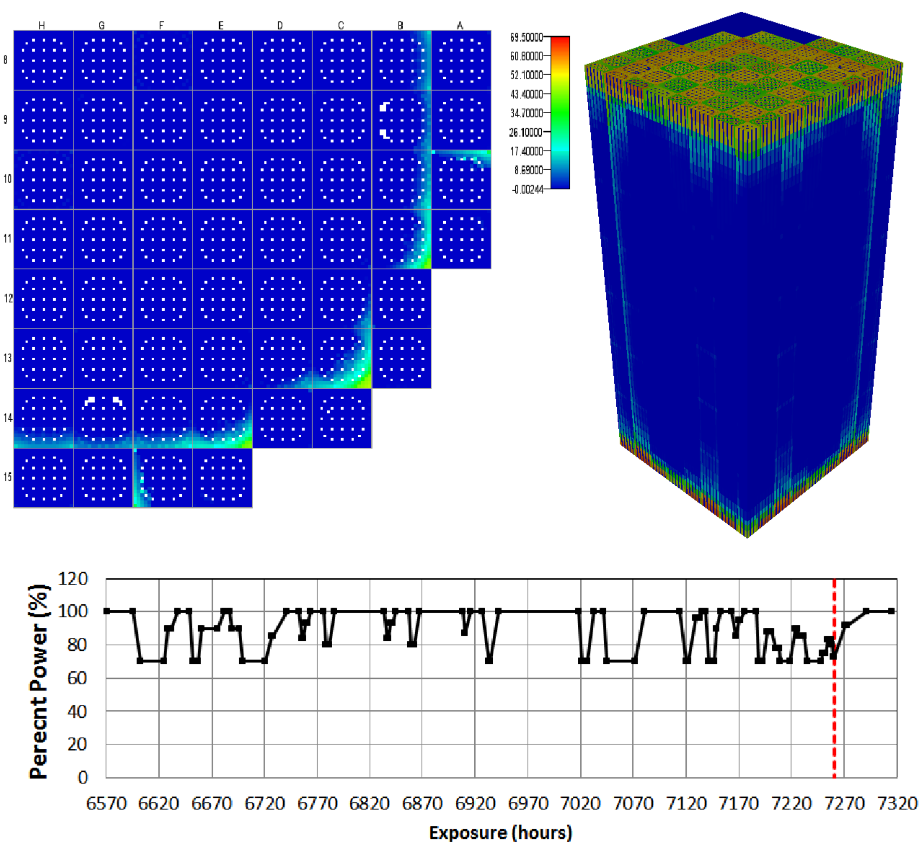

H G F E D C B A
8
9
10
11
12
13
14
15
69.50000
60.80000
52.10000
43.40000
34.70000
26.10000
17.40000
8.68000
-0.00244


Perecnt Power (%)
120
100
80
60
40
20
0
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)


H G F E D C B A
8
9
10
11
12
13
14
15
69.50000
60.80000
52.10000
43.40000
34.70000
26.10000
17.40000
8.68000
-0.00244


Perecnt Power (%)
120
100
80
60
40
20
0
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)


H G F E D C B A
8 9 10 11 12 13 14 15
69.50000
60.80000
52.10000
43.40000
34.70000
26.10000
17.40000
8.68000
-0.00244
Perecnt Power (%)
0 20 40 60 80 100 120
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)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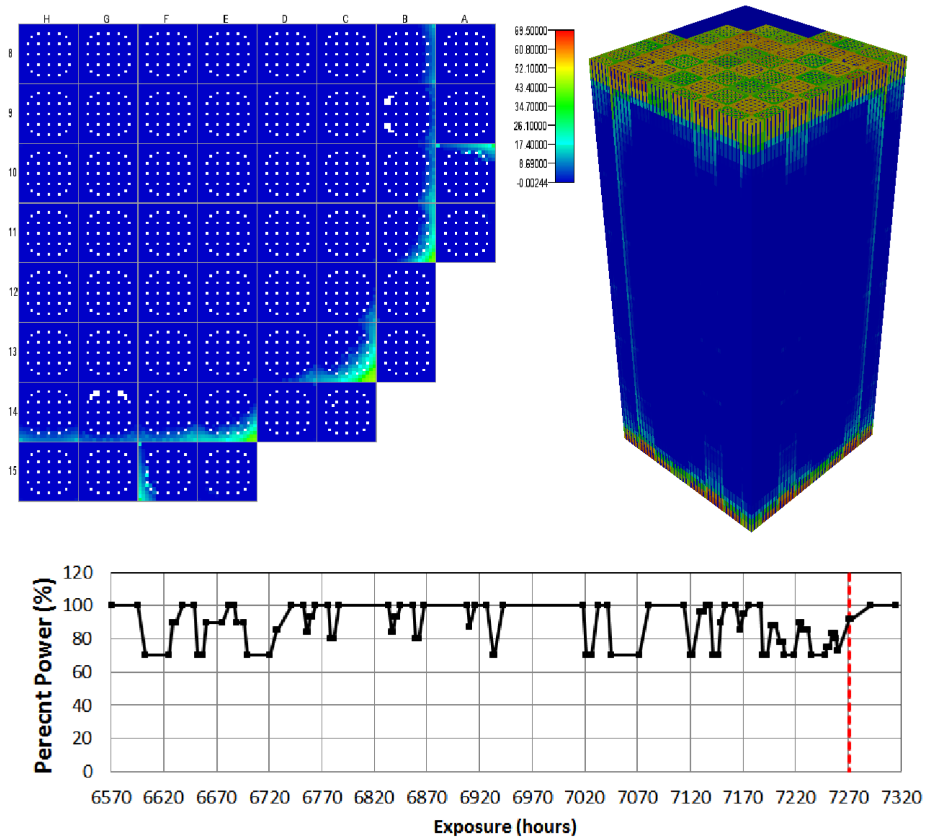
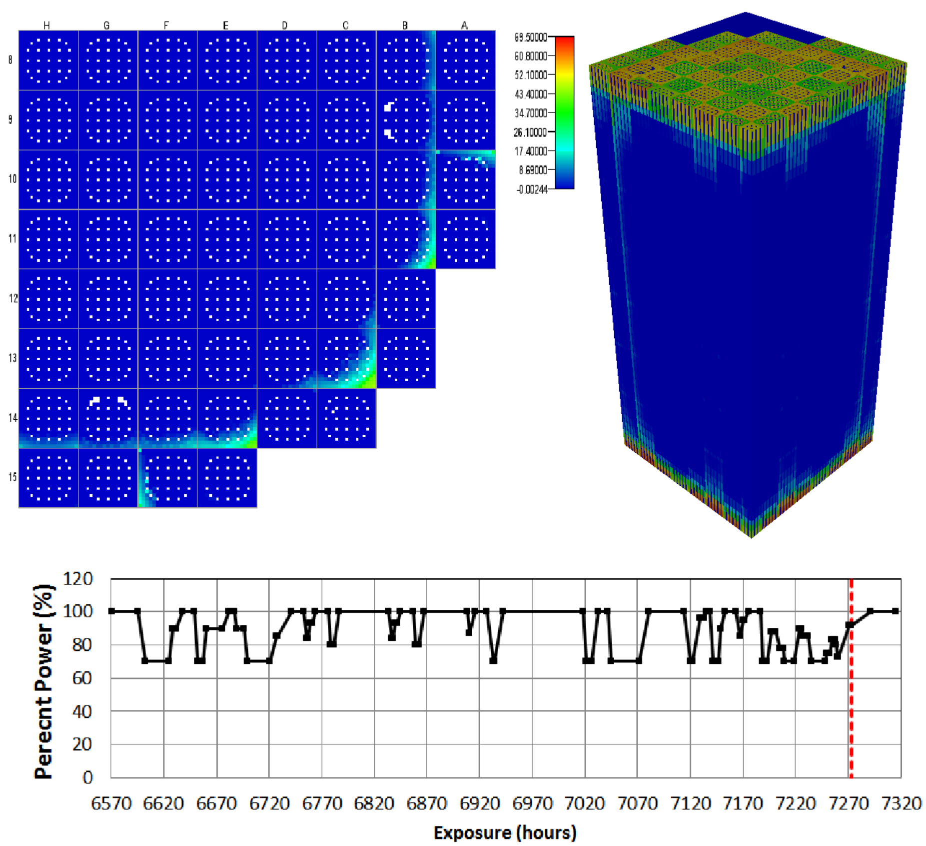
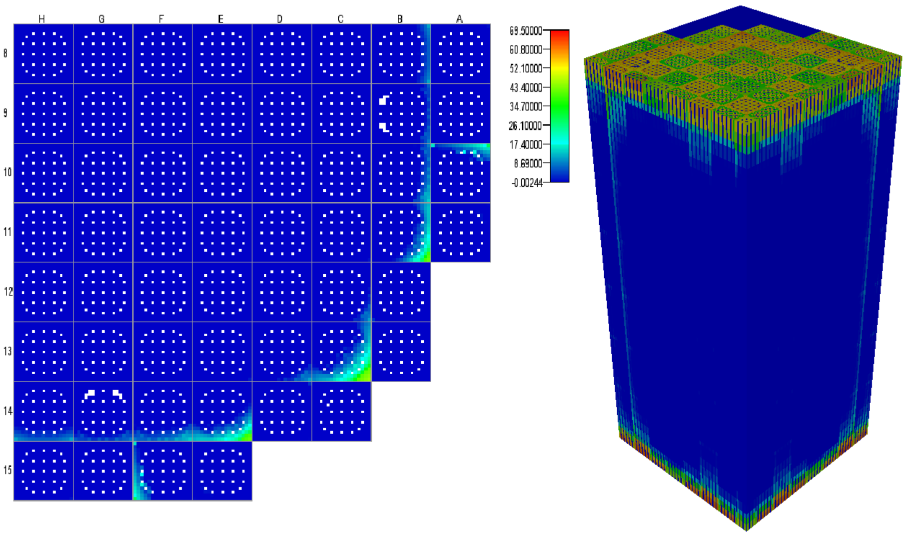
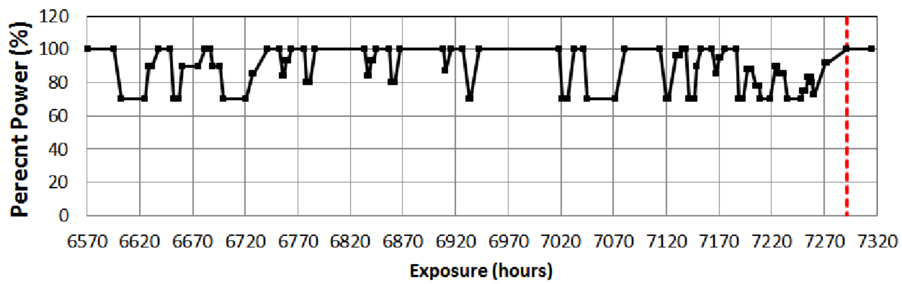
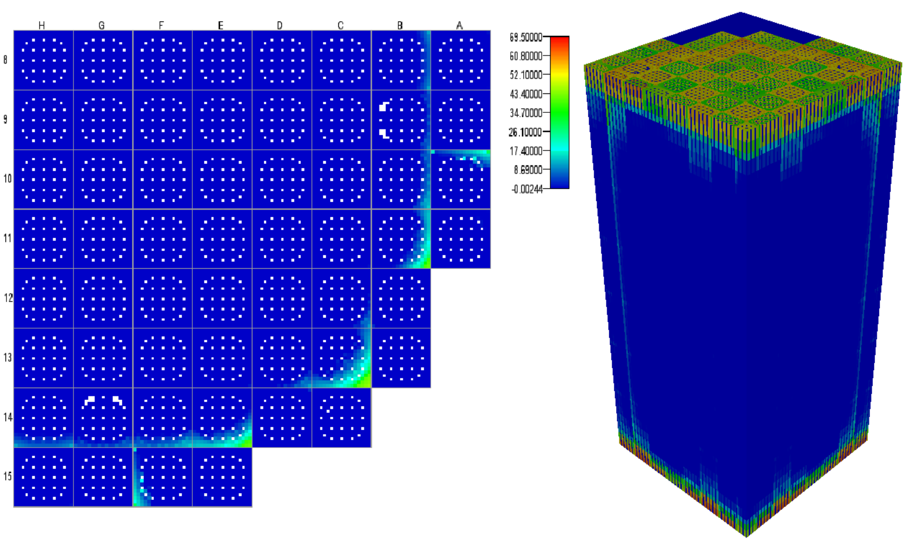
8 9 10 11 12 13 14 15
69.50000
60.80000
52.10000
43.40000
34.70000
26.10000
17.40000
8.68000
-0.00244
Perecnt Power (%)
0 20 40 60 80 100 120
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)

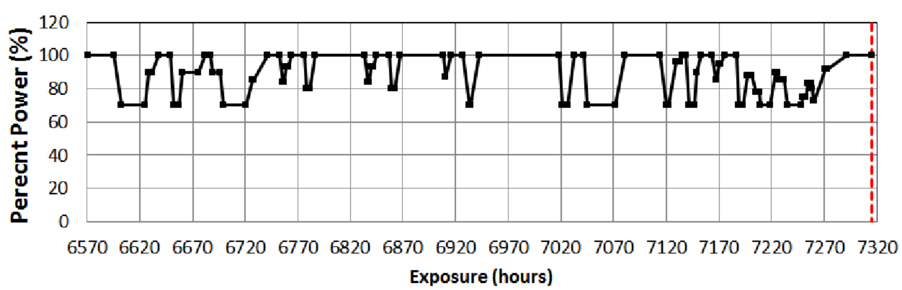

H
G
F
E
D
C
B
A
8
9
10
11
12
13
14
15
Perecnt Power (%)
120
100
80
60
40
20
0
6570
6620
6670
6720
6770
6820
6870
6920
6970
7020
7070
7120
7170
7220
7270
7320
Exposure (hours)


H
G
F
E
D
C
B
A
8
9
10
11
12
13
14
15
Perecnt Power (%)
120
100
80
60
40
20
0
6570
6620
6670
6720
6770
6820
6870
6920
6970
7020
7070
7120
7170
7220
7270
7320
Exposure (hours)

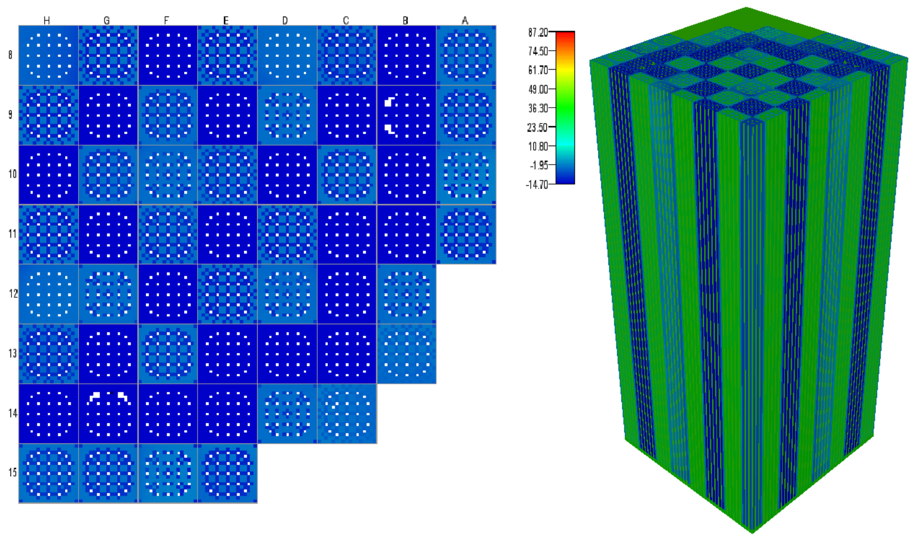

H G F E D C B A
8
9
10
11
12
13
14
15
69.50000
60.80000
52.10000
43.40000
34.70000
26.10000
17.40000
8.68000
-0.00244

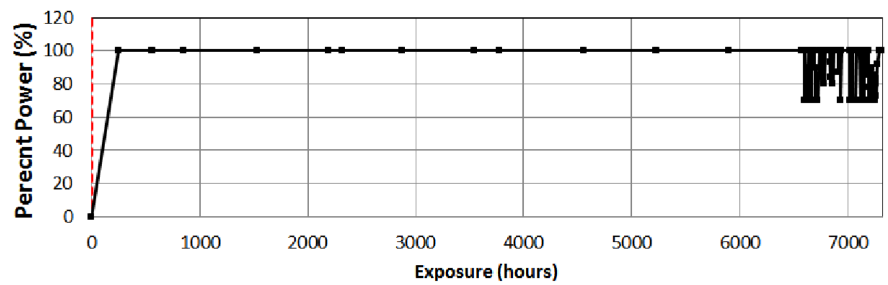

Perecnt Power (%)
0
20
40
60
80
100
120
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)

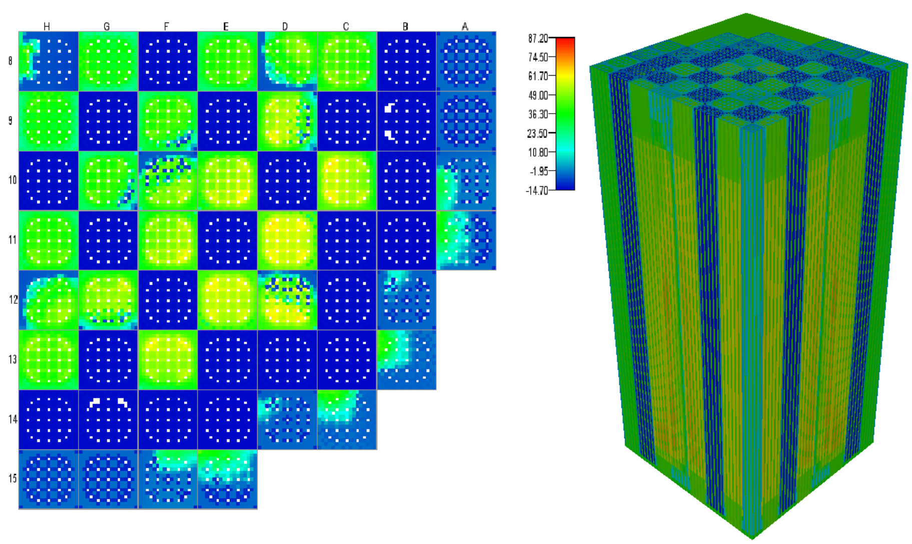

H G F E D C B A
8
9
10
11
12
13
14
15
69.50000
60.80000
52.10000
43.40000
34.70000
26.10000
17.40000
8.68000
-0.00244

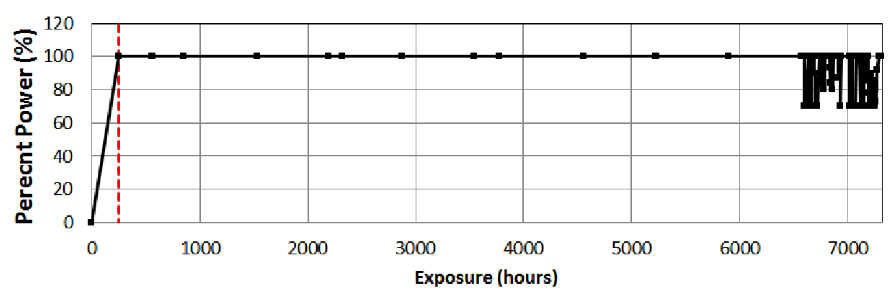

Perecnt Power (%)
0
20
40
60
80
100
120
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)

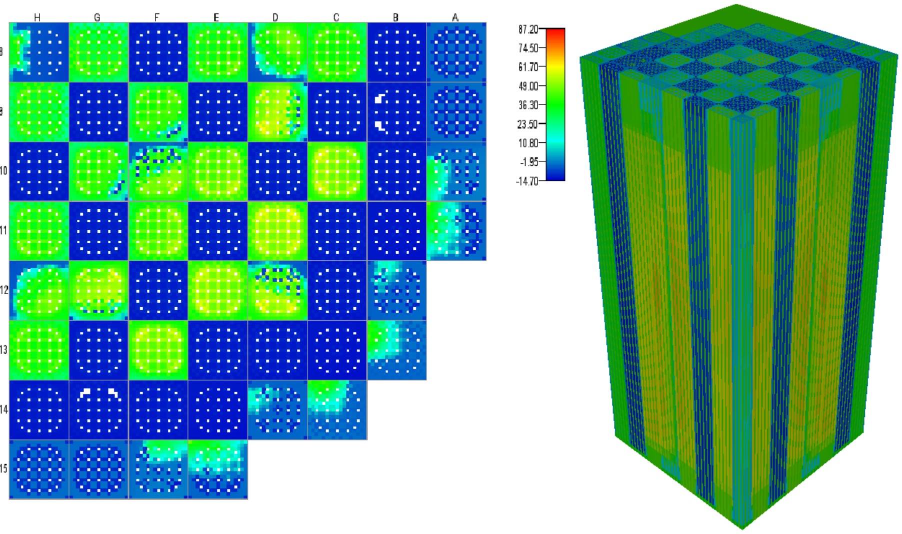
APPENDIX C - QUARTER CORE, MAXIMUM CLAD HOOP STRESS RESULTS

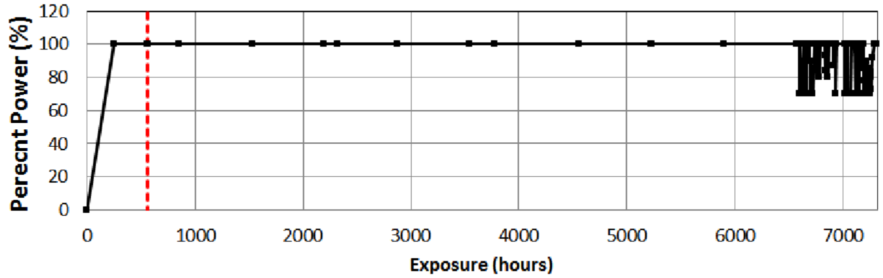




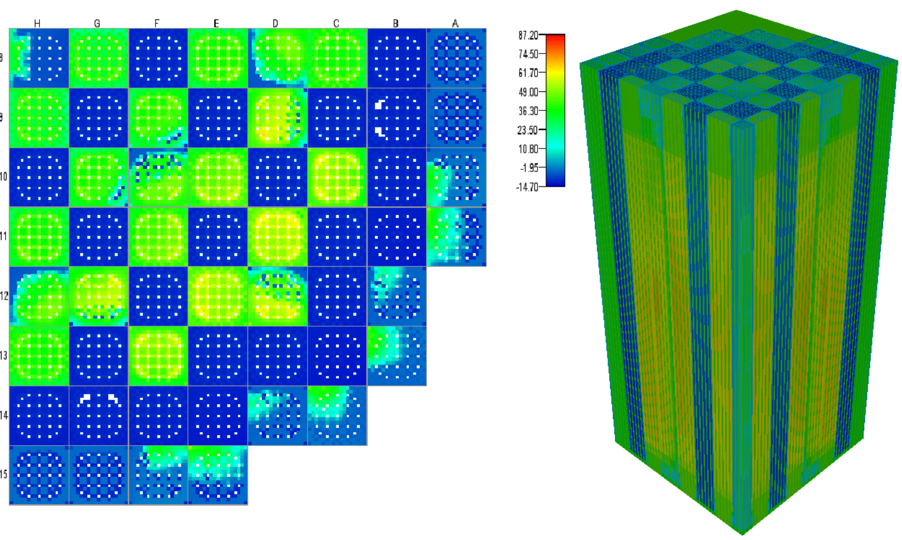


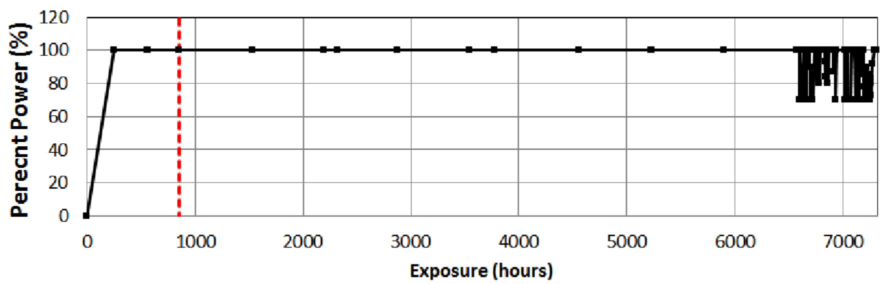




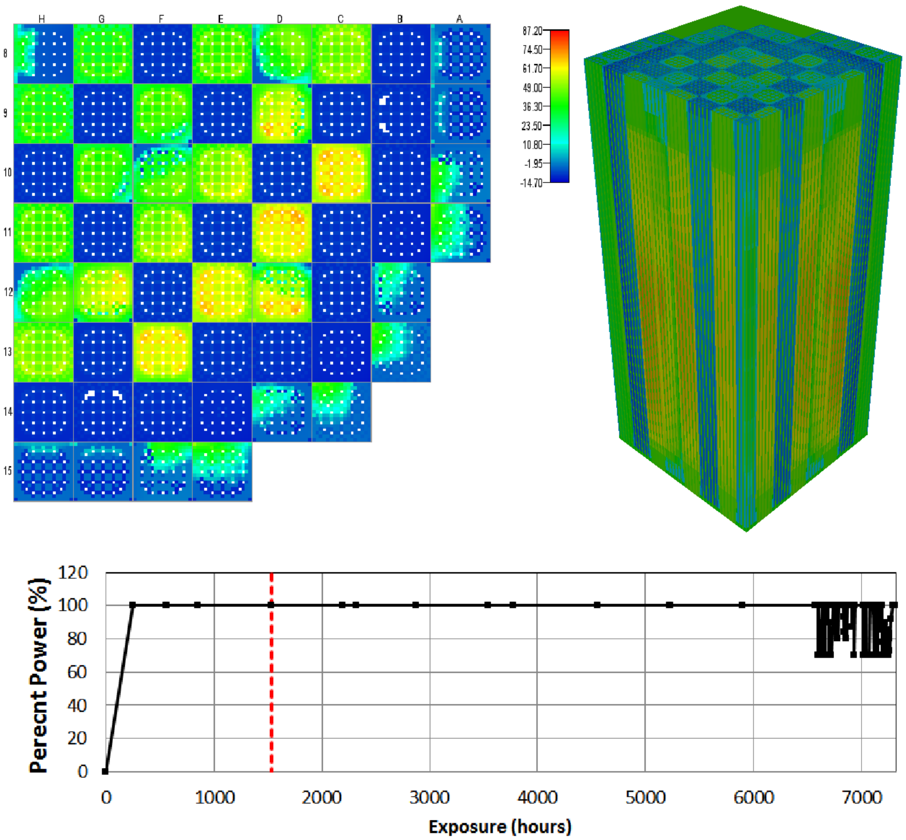


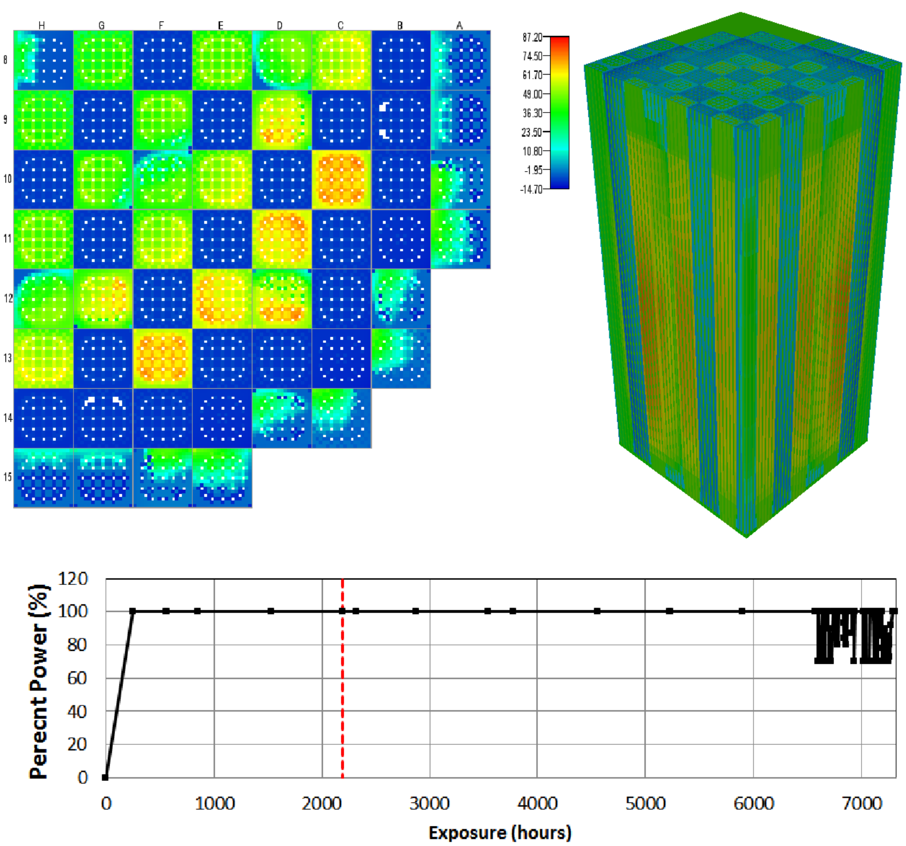
Perecnt Power (%)
120
100
80
60
40
20
0
0
1000
2000
3000
4000
5000
6000
7000
Exposure (hours)

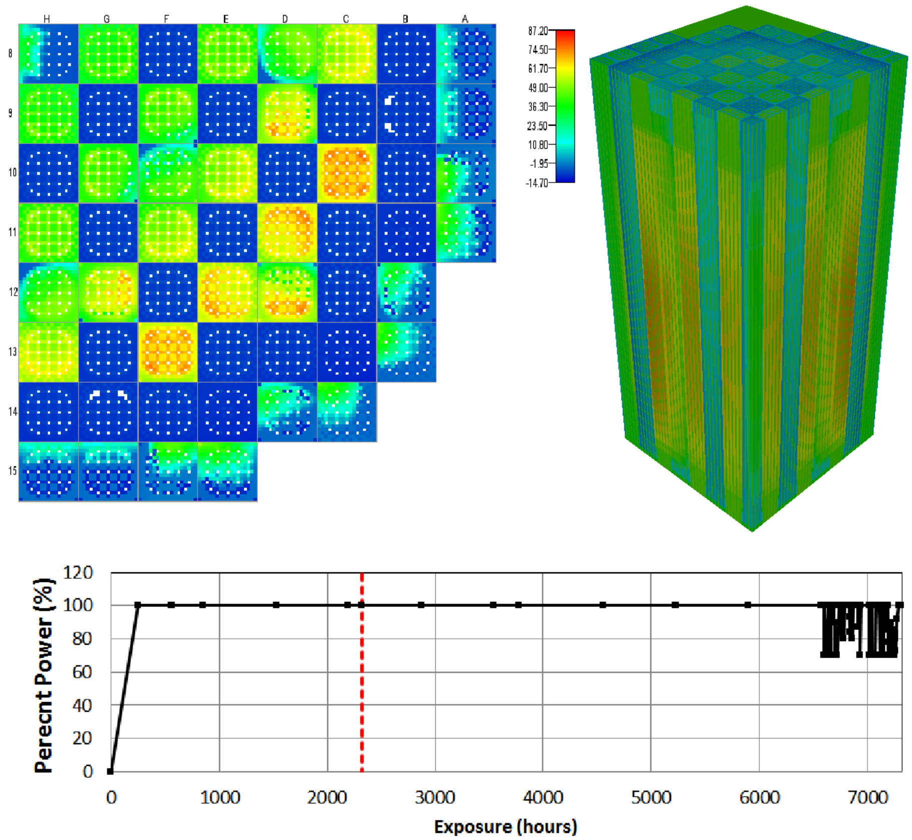


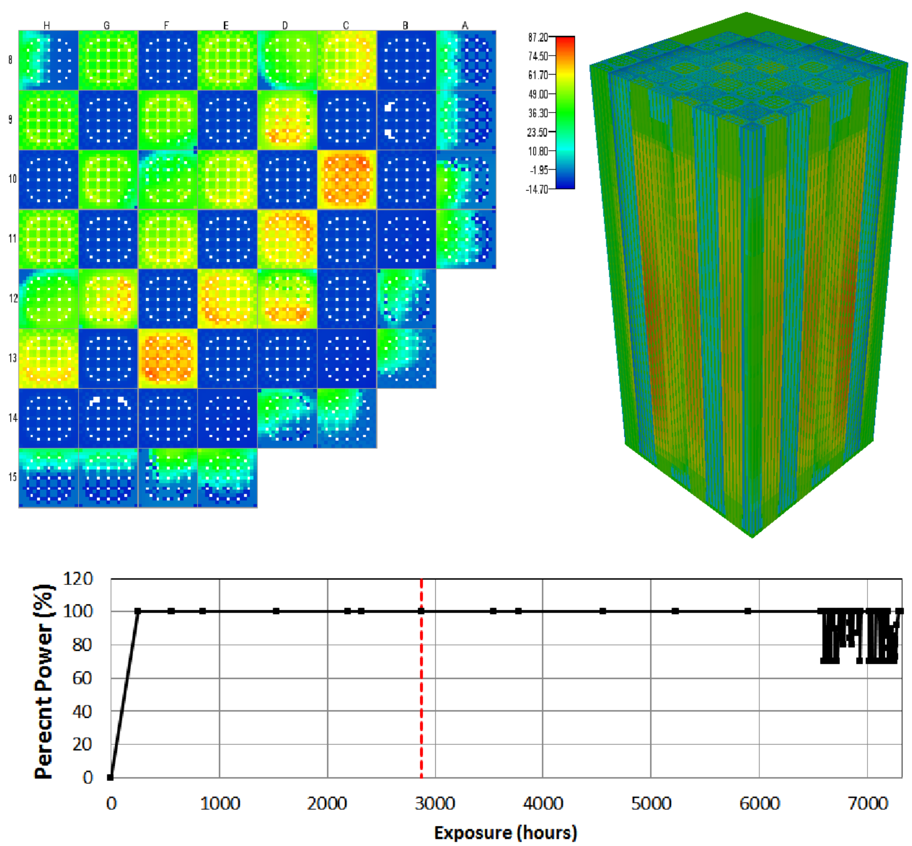


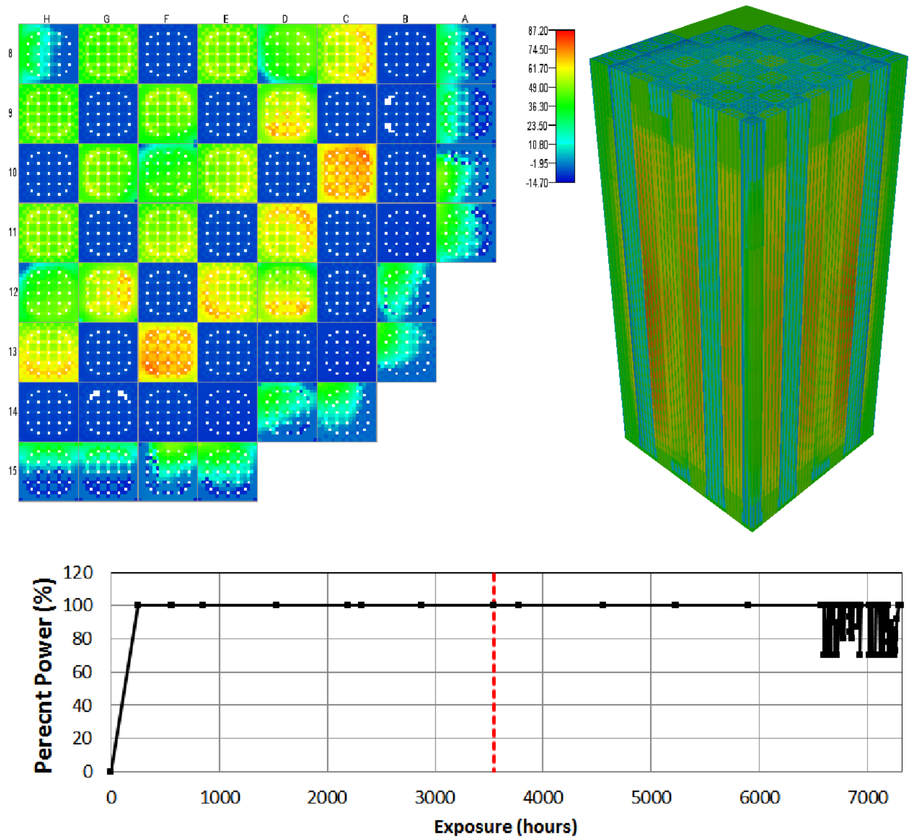
Perecnt Power (%)
120
100
80
60
40
20
0
0
1000
2000
3000
4000
5000
6000
7000
Exposure (hours)

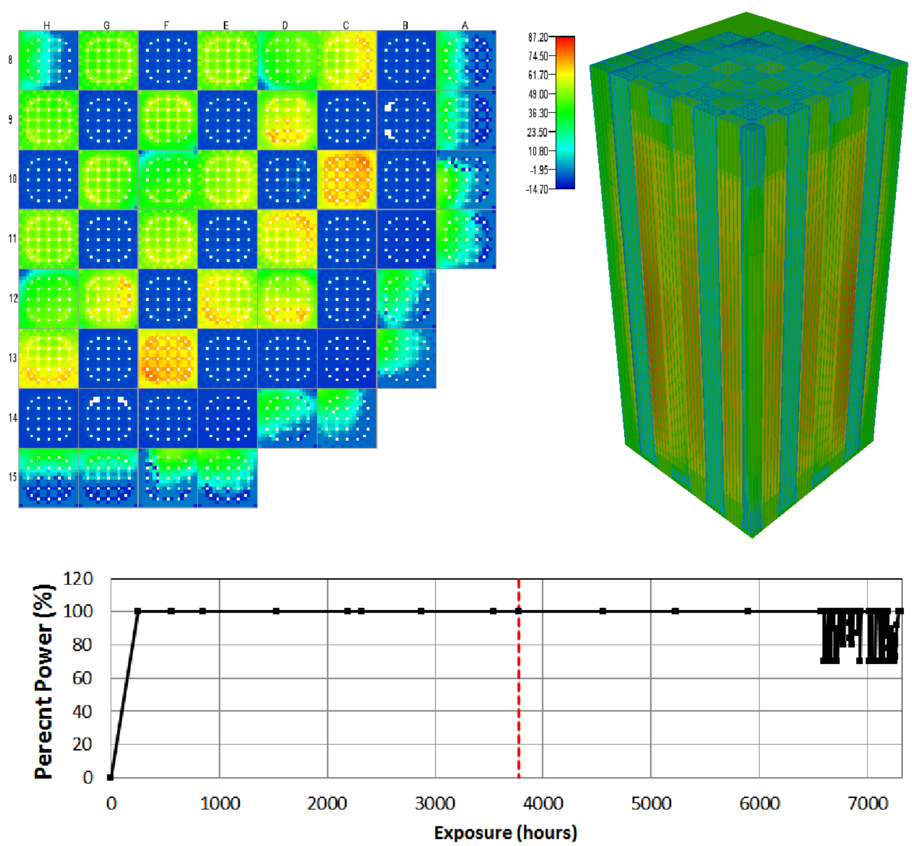

H G F E D C B A
8
9
10
11
12
13
14
15
87.20
74.50
61.70
49.00
36.30
23.50
10.80
-1.95
-14.70
Perecnt Power (%)
120
100
80
60
40
20
0
0
1000
2000
3000
4000
5000
6000
7000
Exposure (hours)

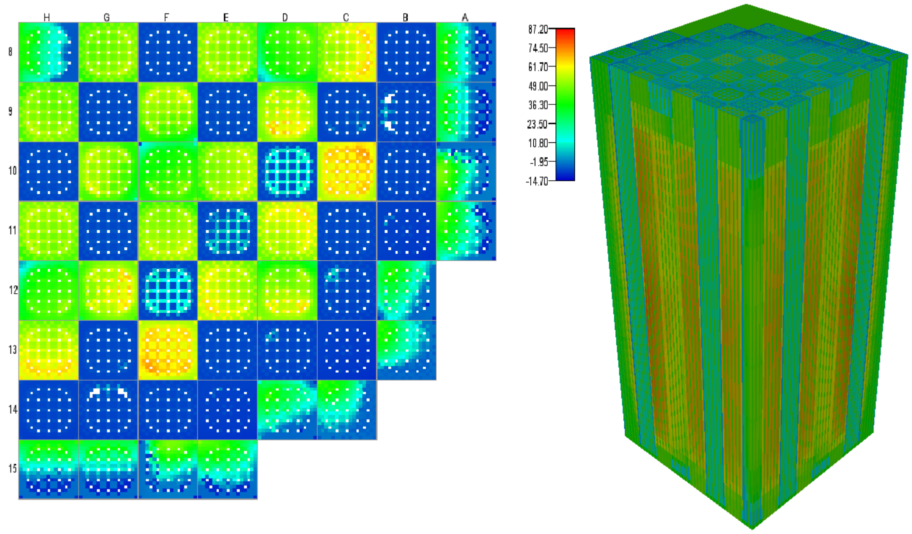

H G F E D C B A
8
9
10
11
12
13
14
15
87.20
74.50
61.70
49.00
36.30
23.50
10.80
-1.95
-14.70
Perecnt Power (%)
120
100
80
60
40
20
0
0
1000
2000
3000
4000
5000
6000
7000
Exposure (hours)

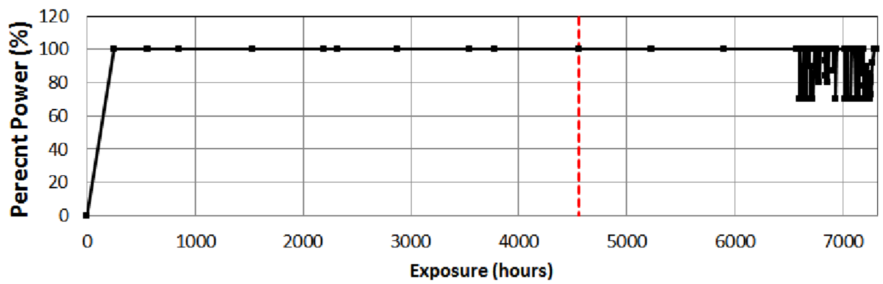

H G F E D C B A
8 9 10 11 12 13 14 15
87.20
74.50
61.70
49.00
36.30
23.50
10.80
-1.95
-14.70
Perecnt Power (%)
0 20 40 60 80 100 120
0 1000 2000 3000 4000 5000 6000 7000
Exposure (hours)

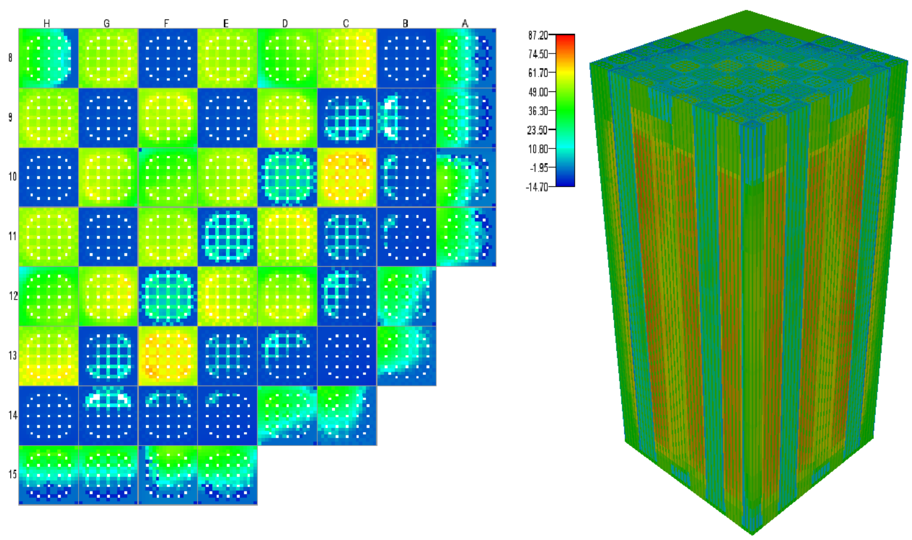

H G F E D C B A
8 9 10 11 12 13 14 15
87.20
74.50
61.70
49.00
36.30
23.50
10.80
-1.95
-14.70
Perecnt Power (%)
0 20 40 60 80 100 120
0 1000 2000 3000 4000 5000 6000 7000
Exposure (hours)

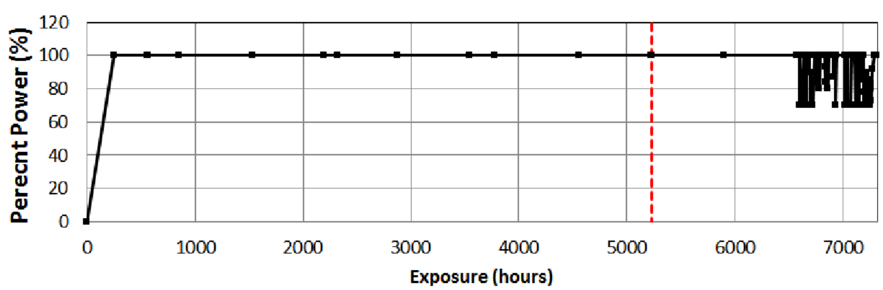

H
G
F
E
D
C
B
A
8
9
10
11
12
13
14
15
87.20
74.50
61.70
49.00
36.30
23.50
10.80
-1.95
-14.70
Perecnt Power (%)
120
100
80
60
40
20
0
0
1000
2000
3000
4000
5000
6000
7000
Exposure (hours)

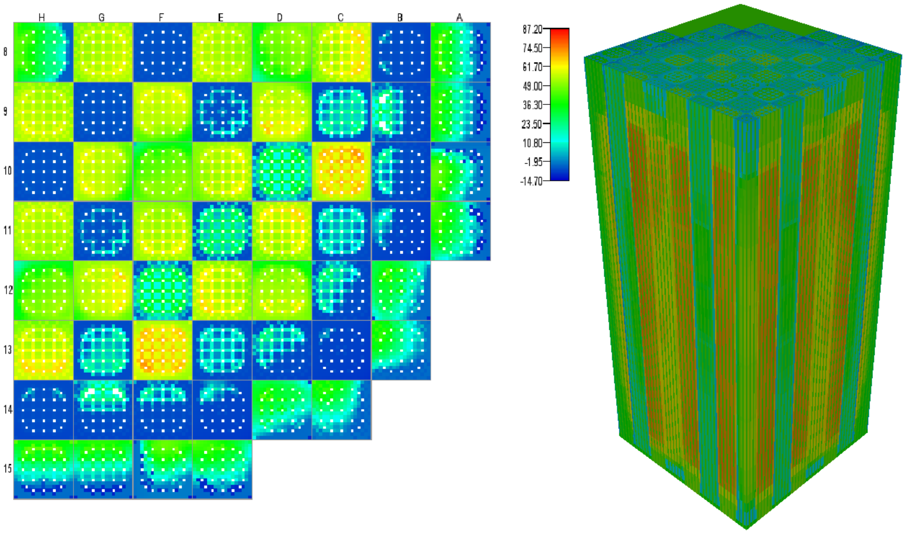

H
G
F
E
D
C
B
A
8
9
10
11
12
13
14
15
87.20
74.50
61.70
49.00
36.30
23.50
10.80
-1.95
-14.70
Perecnt Power (%)
120
100
80
60
40
20
0
0
1000
2000
3000
4000
5000
6000
7000
Exposure (hours)

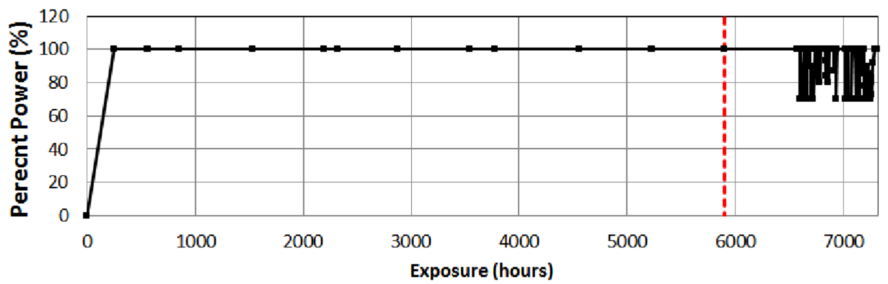

H G F E D C B A
8
9
10
11
12
13
14
15
87.20
74.50
61.70
49.00
36.30
23.50
10.80
-1.95
-14.70

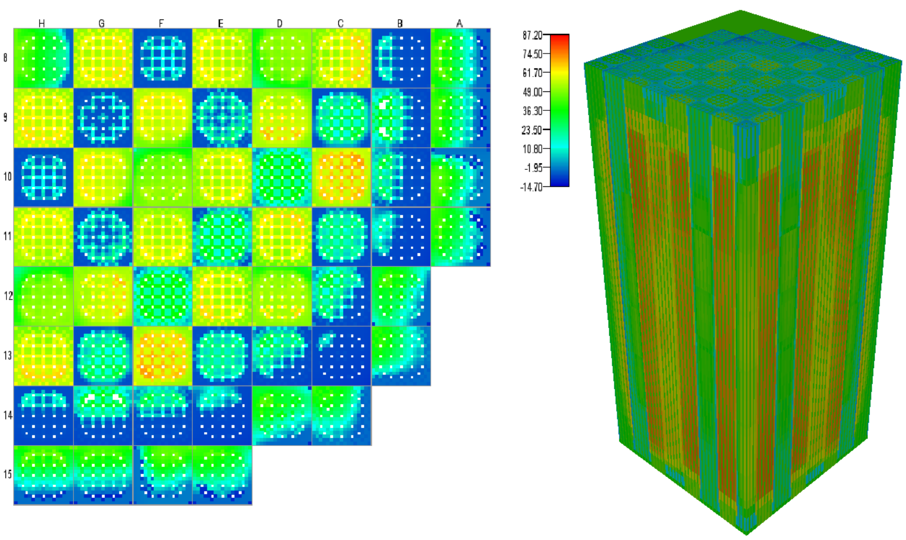

Perecnt Power (%)
120
100
80
60
40
20
0
0
1000
2000
3000
4000
5000
6000
7000
Exposure (hours)

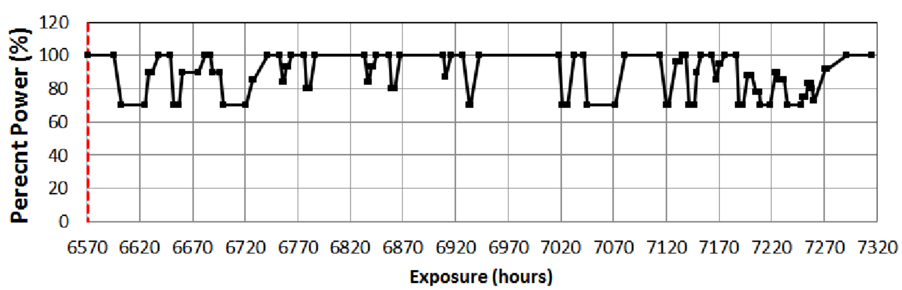

H G F E D C B A
8
9
10
11
12
13
14
15
87.20
74.50
61.70
49.00
36.30
23.50
10.80
-1.95
-14.70

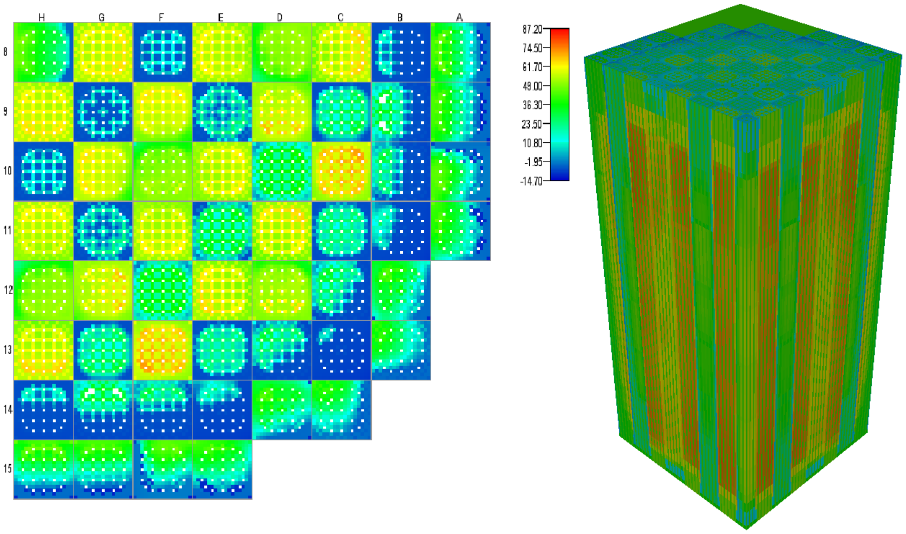

Perecnt Power (%)
120
100
80
60
40
20
0
0
1000
2000
3000
4000
5000
6000
7000
Exposure (hours)

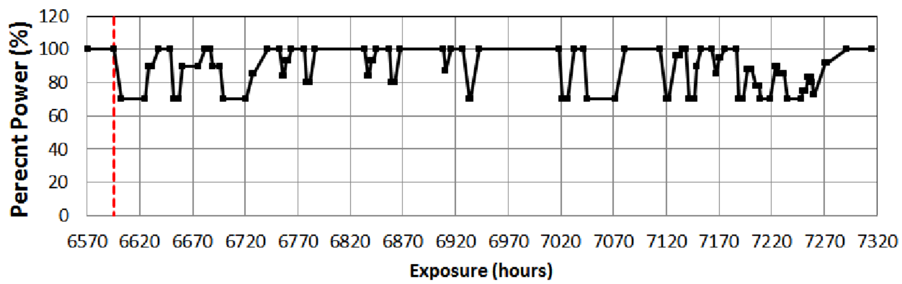

H
G
F
E
D
C
B
A
8
9
10
11
12
13
14
15

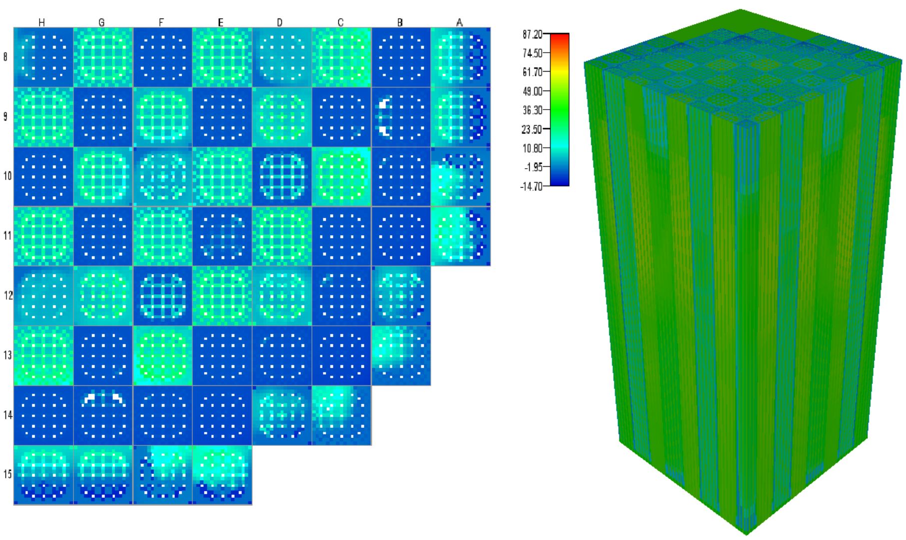

Perecnt Power (%)
120
100
80
60
40
20
0
0
1000
2000
3000
4000
5000
6000
7000
Exposure (hours)

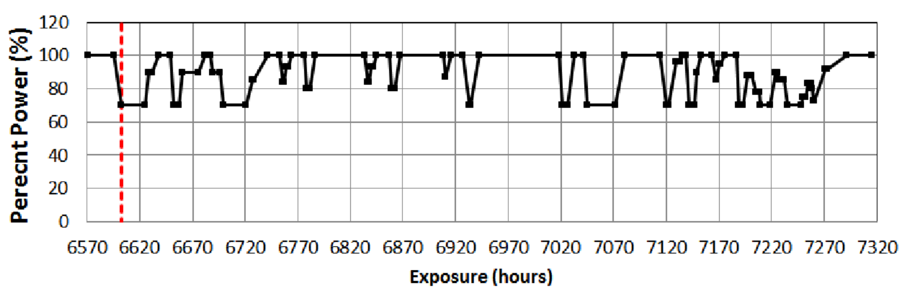

H
G
F
E
D
C
B
A
8
9
10
11
12
13
14
15

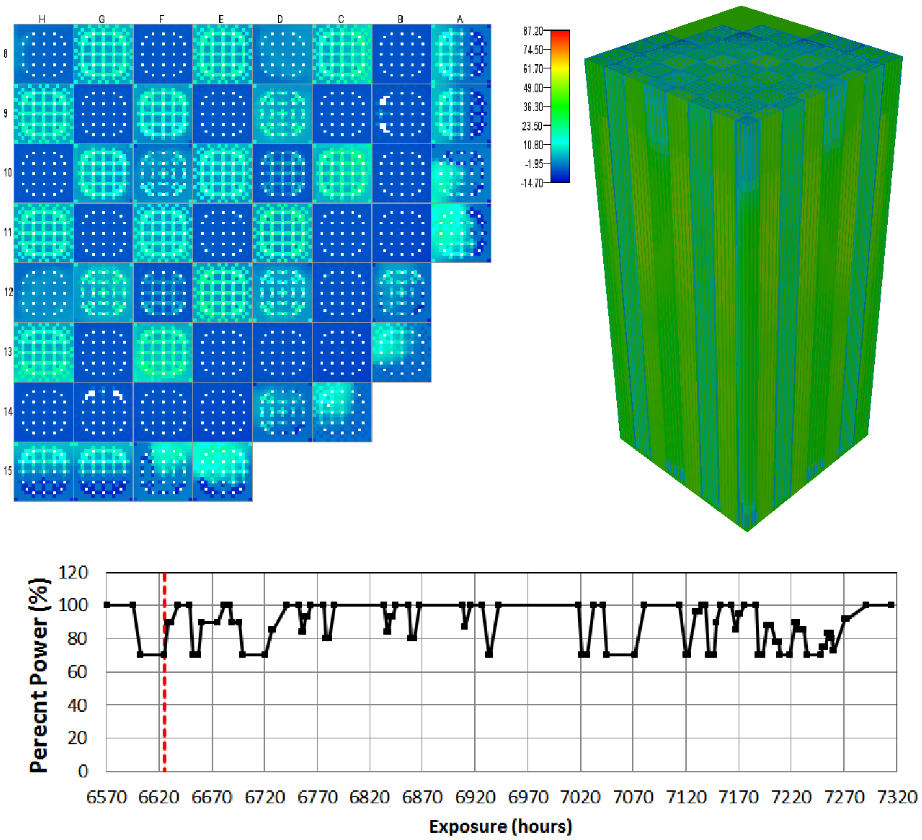

Perecnt Power (%)
120
100
80
60
40
20
0
6570
6620
6670
6720
6770
6820
6870
6920
6970
7020
7070
7120
7170
7220
7270
7320
Exposure (hours)

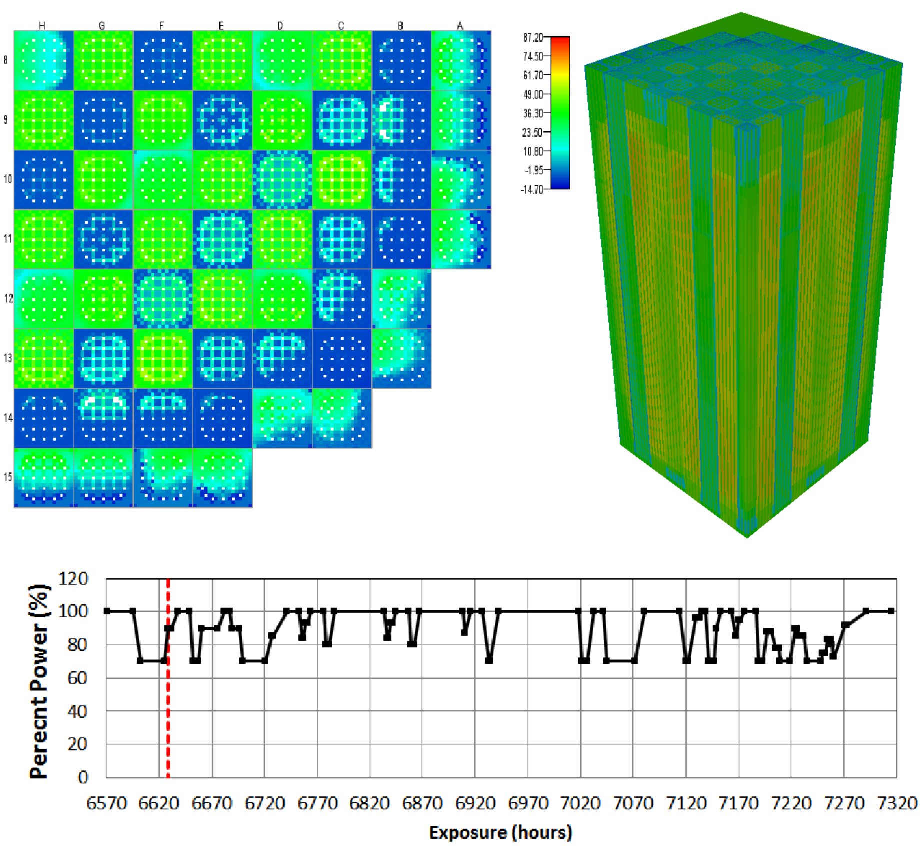

H G F E D C B A
8 9 10 11 12 13 14 15
87.20 74.50 61.70 49.00 36.30 23.50 10.80 -1.95 -14.70

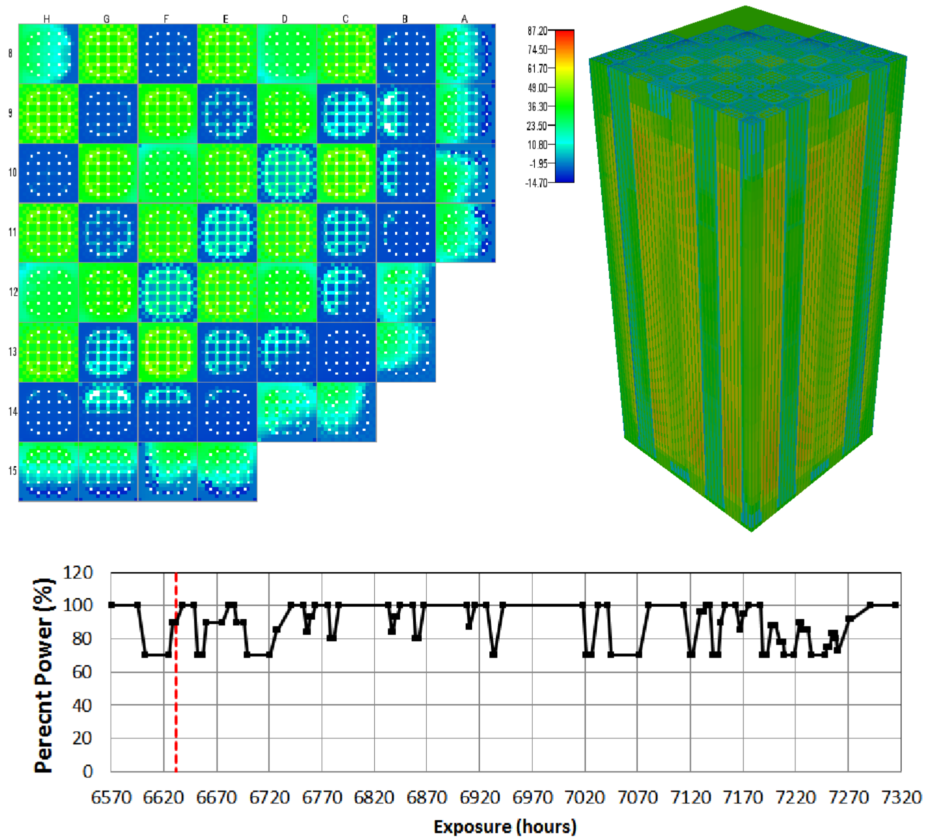

Perecnt Power (%)
120 100 80 60 40 20 0
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)

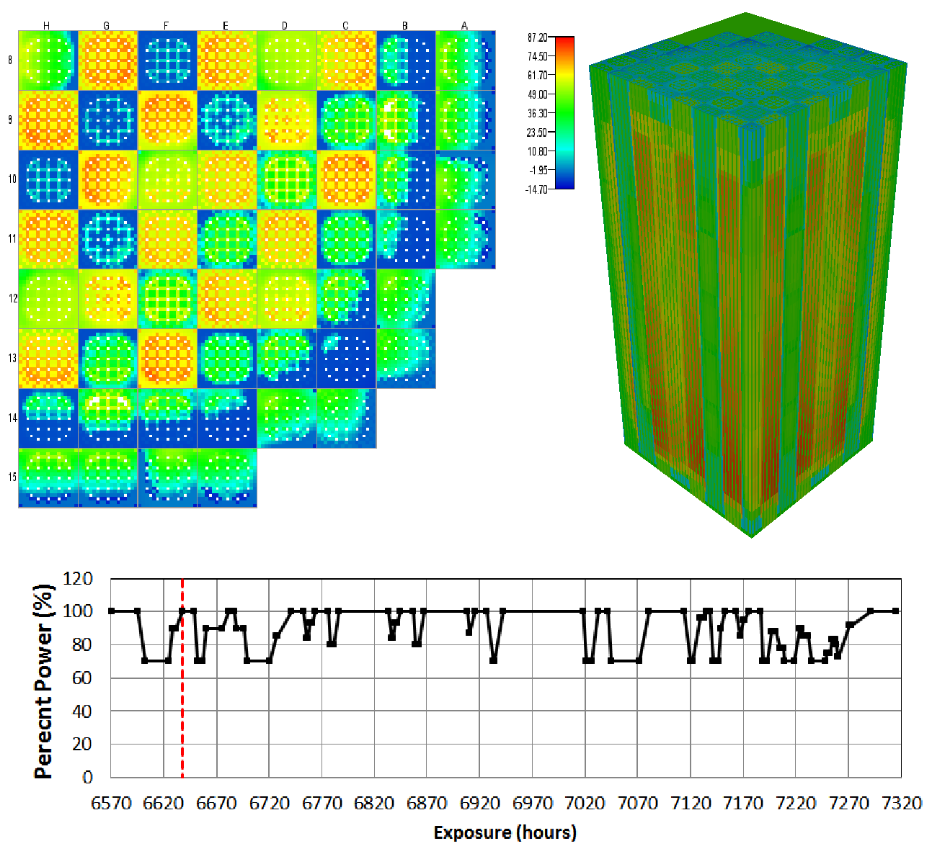

H G F E D C B A
8 9 10 11 12 13 14 15
87.20 74.50 61.70 49.00 36.30 23.50 10.80 -1.95 -14.70


Perecnt Power (%)
120 100 80 60 40 20 0
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)


H
G
F
E
D
C
B
A
8
9
10
11
12
13
14
15
87.20
74.50
61.70
49.00
36.30
23.50
10.80
-1.95
-14.70
Perecnt Power (%)
Exposure (hours)


H
G
F
E
D
C
B
A
8
9
10
11
12
13
14
15
87.20
74.50
61.70
49.00
36.30
23.50
10.80
-1.95
-14.70
Perecnt Power (%)
Exposure (hours)


H G F E D C B A
8 9 10 11 12 13 14 15
87.20 74.50 61.70 49.00 36.30 23.50 10.80 -1.95 -14.70
Perecnt Power (%)
120 100 80 60 40 20 0
6570 6620 6670 6720 6770 6820 6870 6920 6970 7020 7070 7120 7170 7220 7270 7320
Exposure (hours)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Perecnt Power (%)
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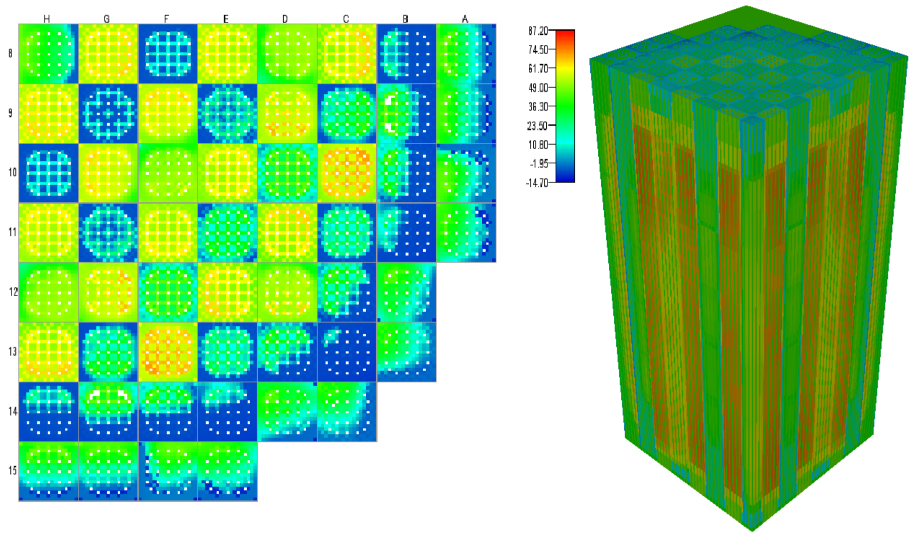
Exposure (hours)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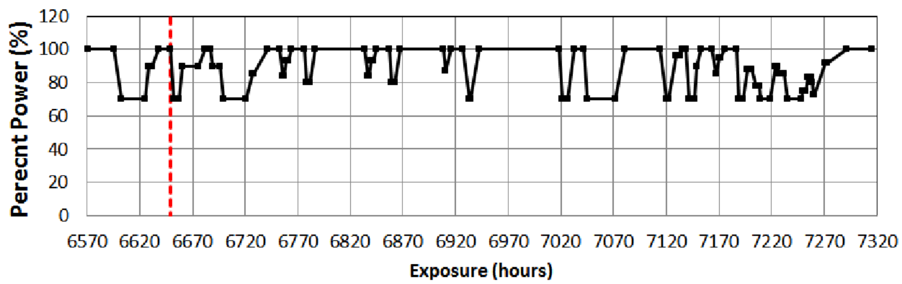
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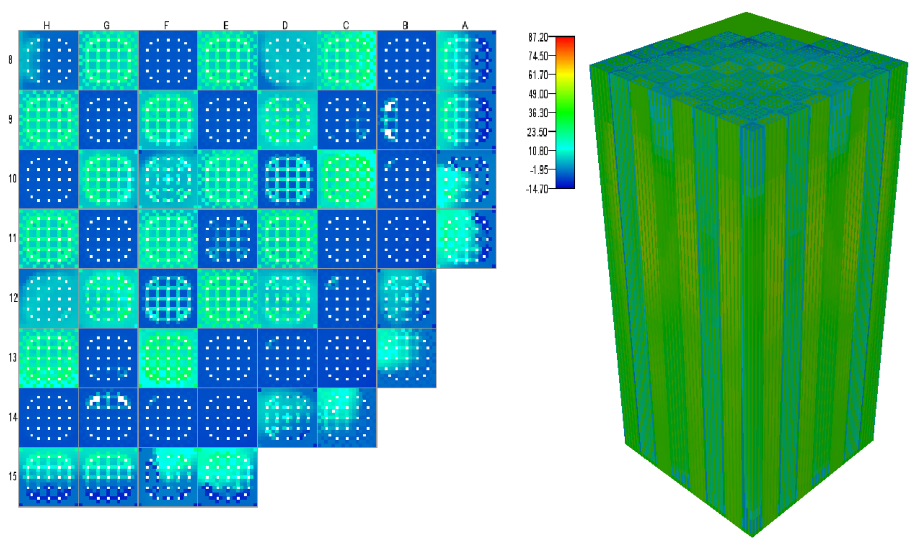
Exposure (hours)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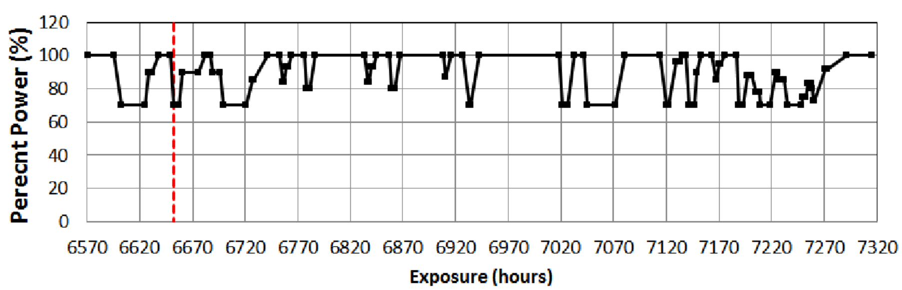
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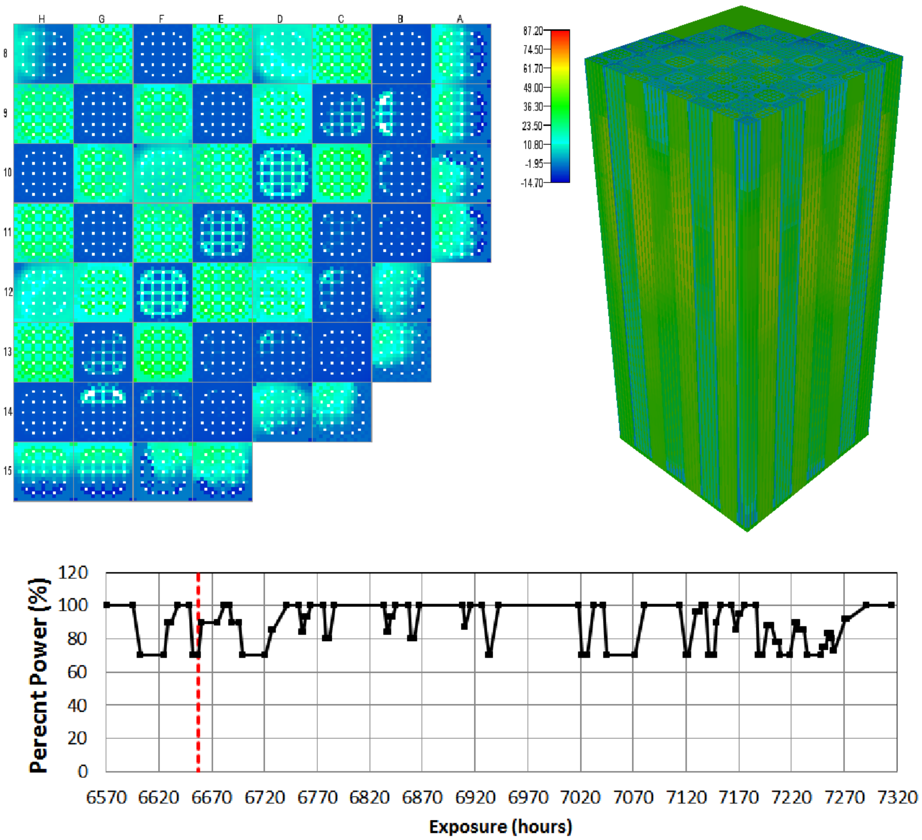
Exposure (hours)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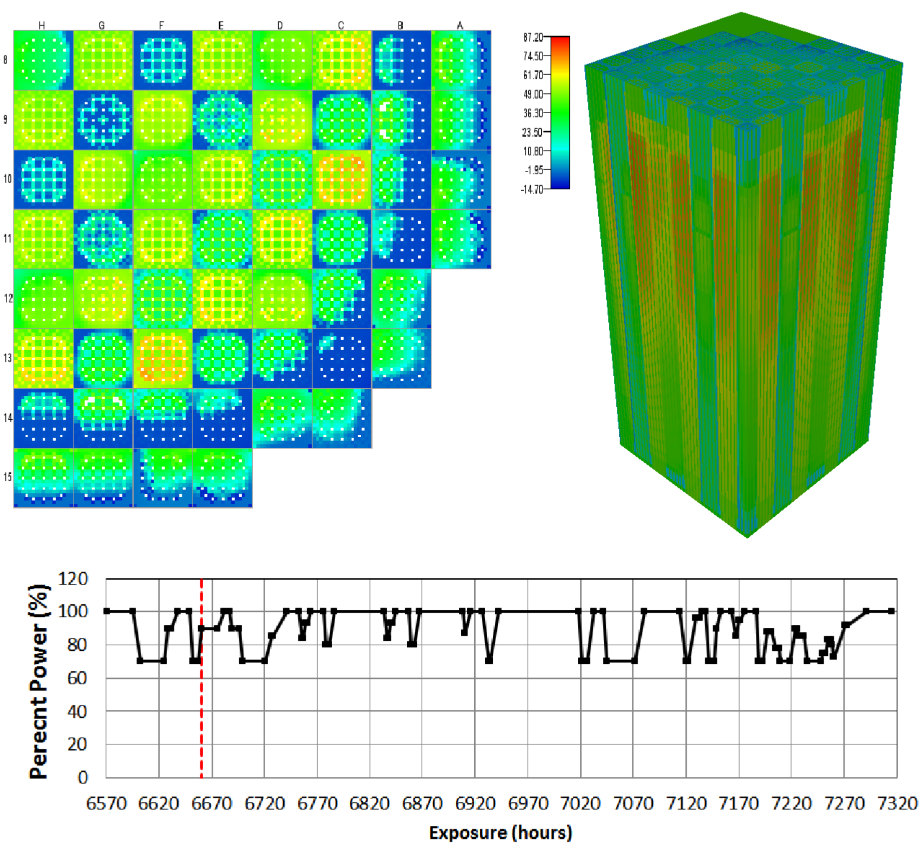
Exposure (hours)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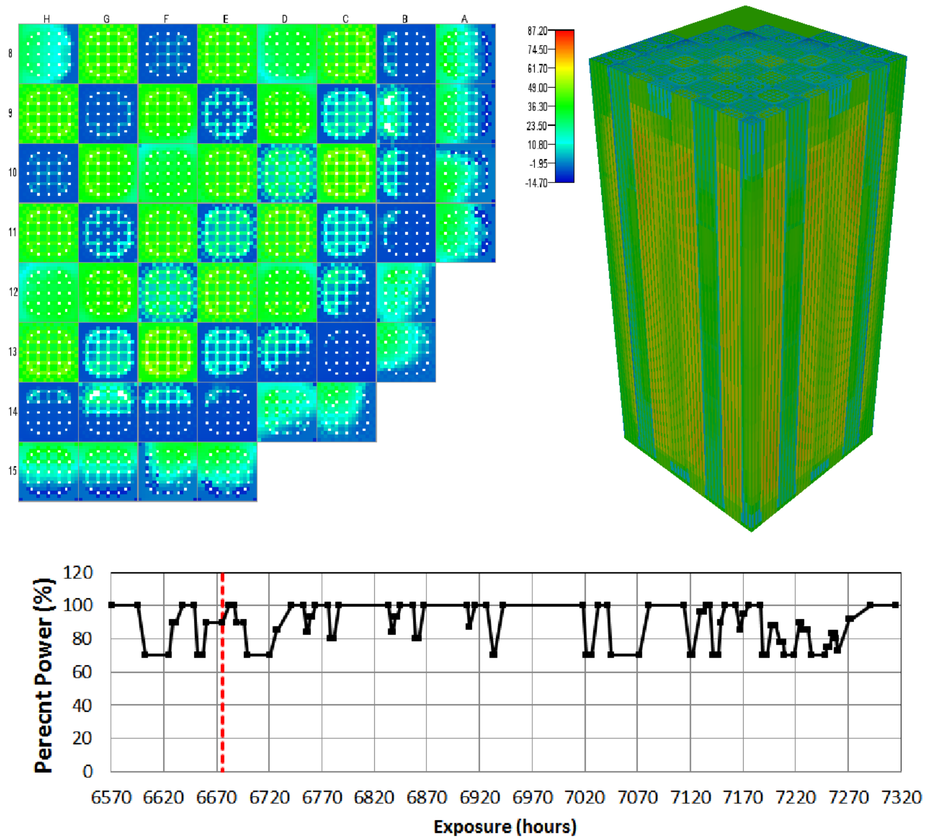
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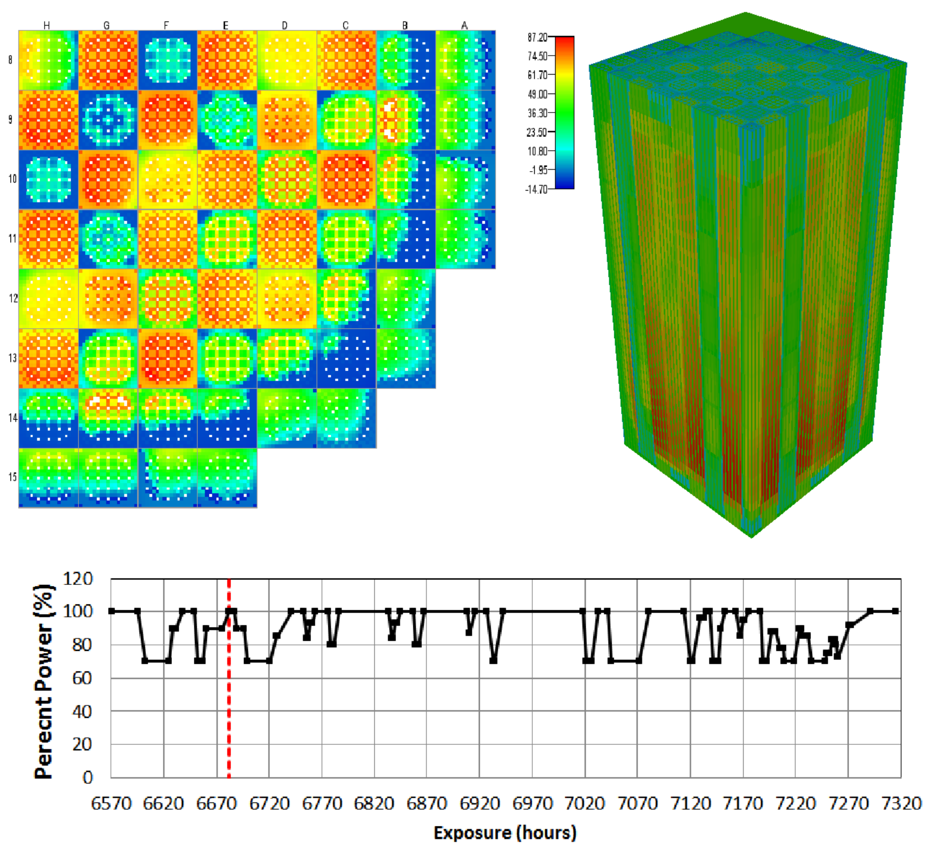
Exposure (hours)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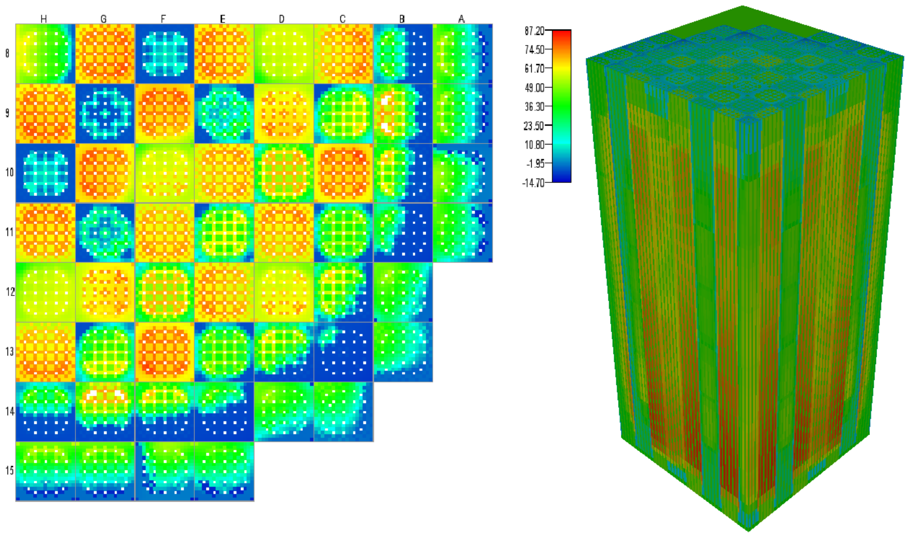
Exposure (hours)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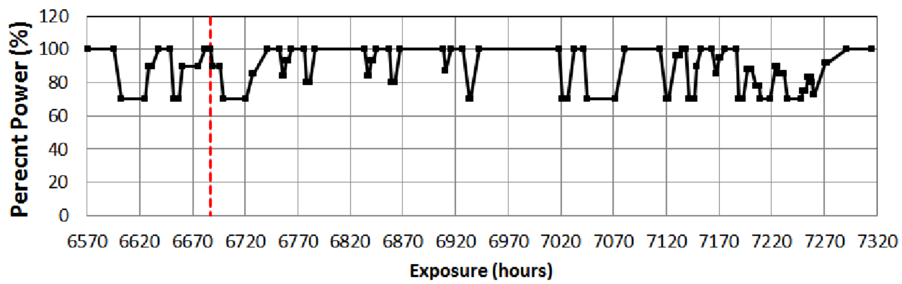
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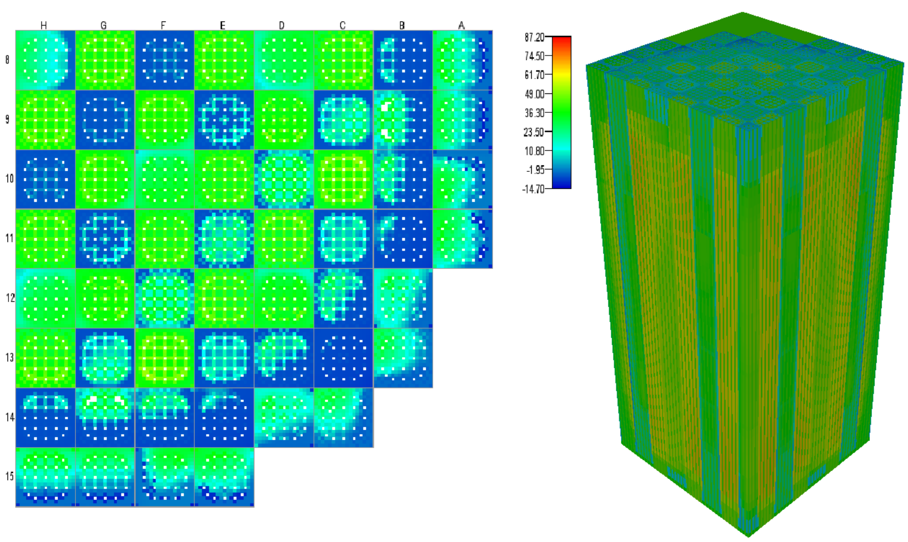
Exposure (hours)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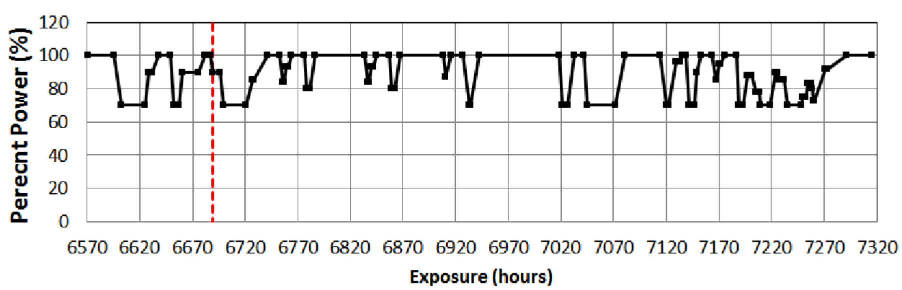
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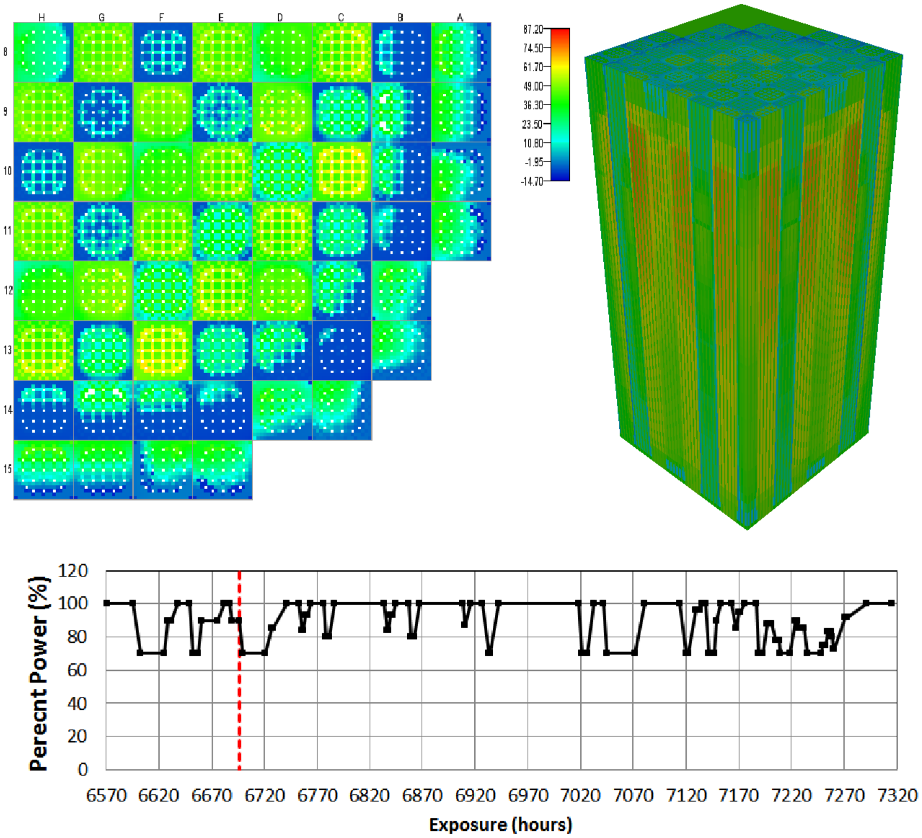
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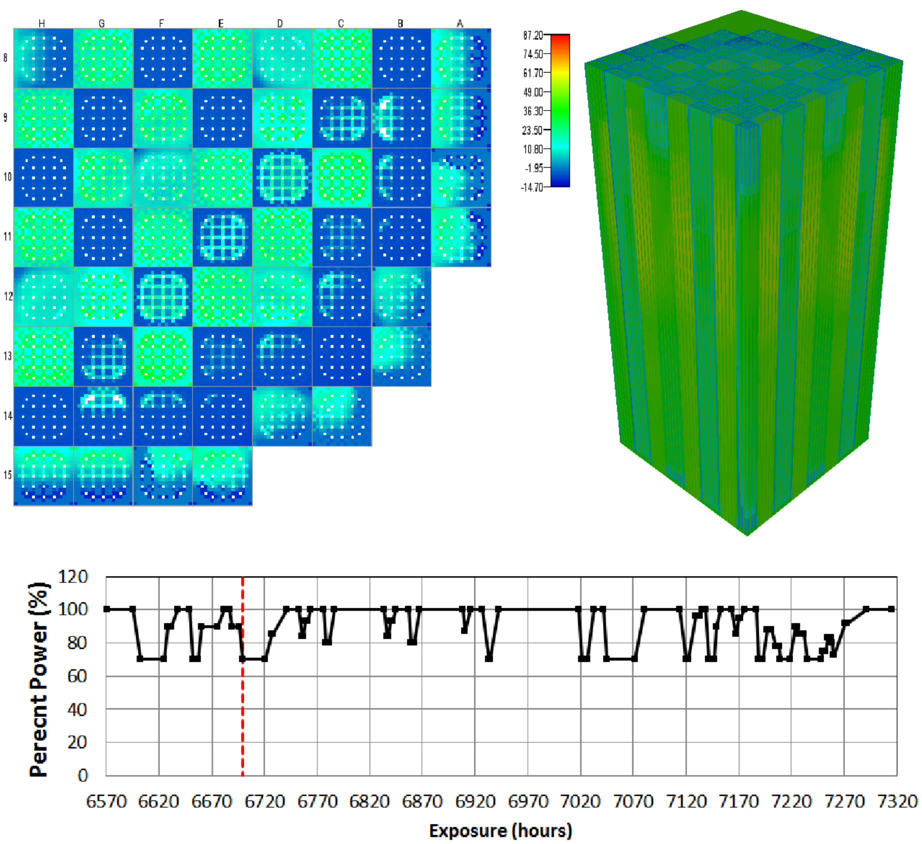
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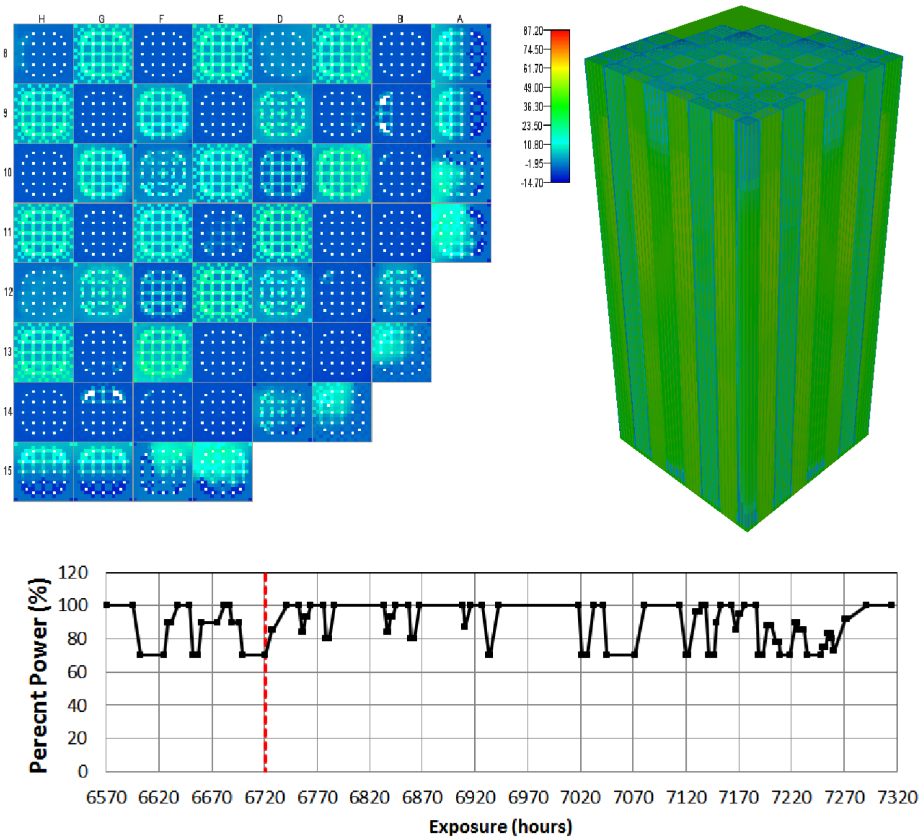
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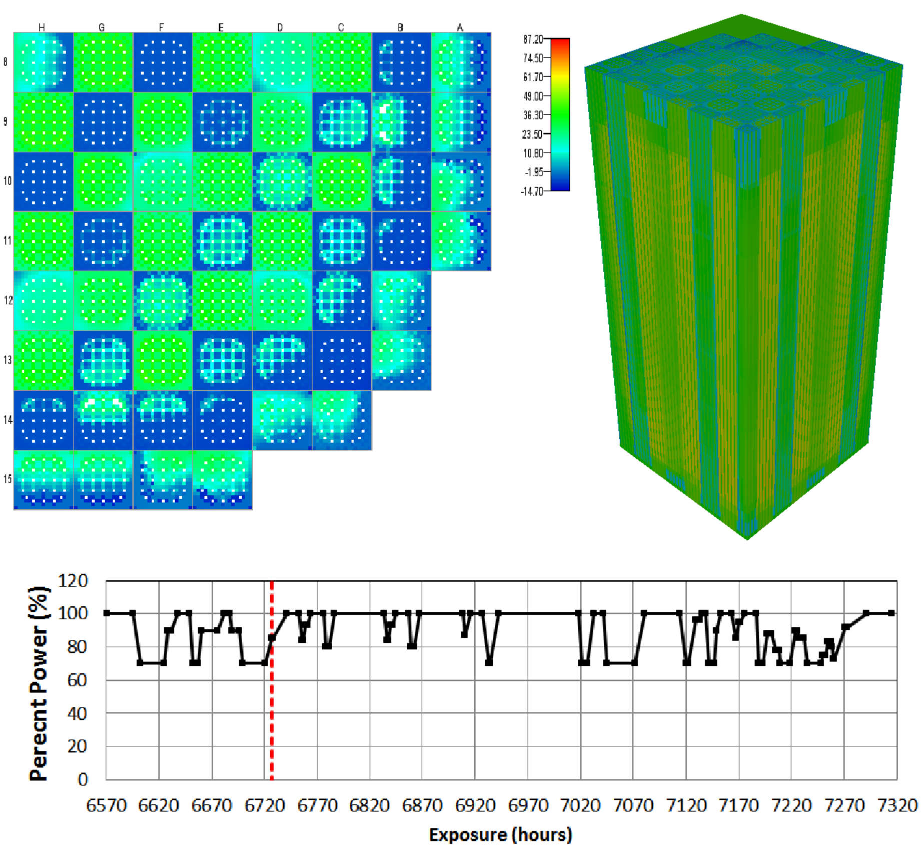
Exposure (hours)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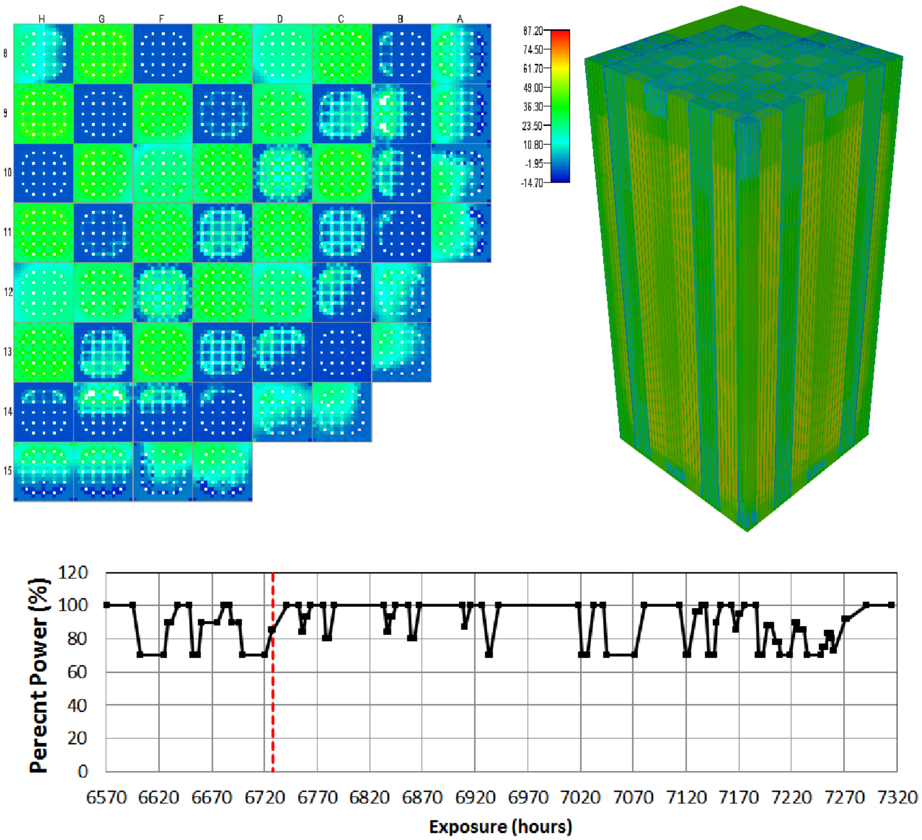
Exposure (hours)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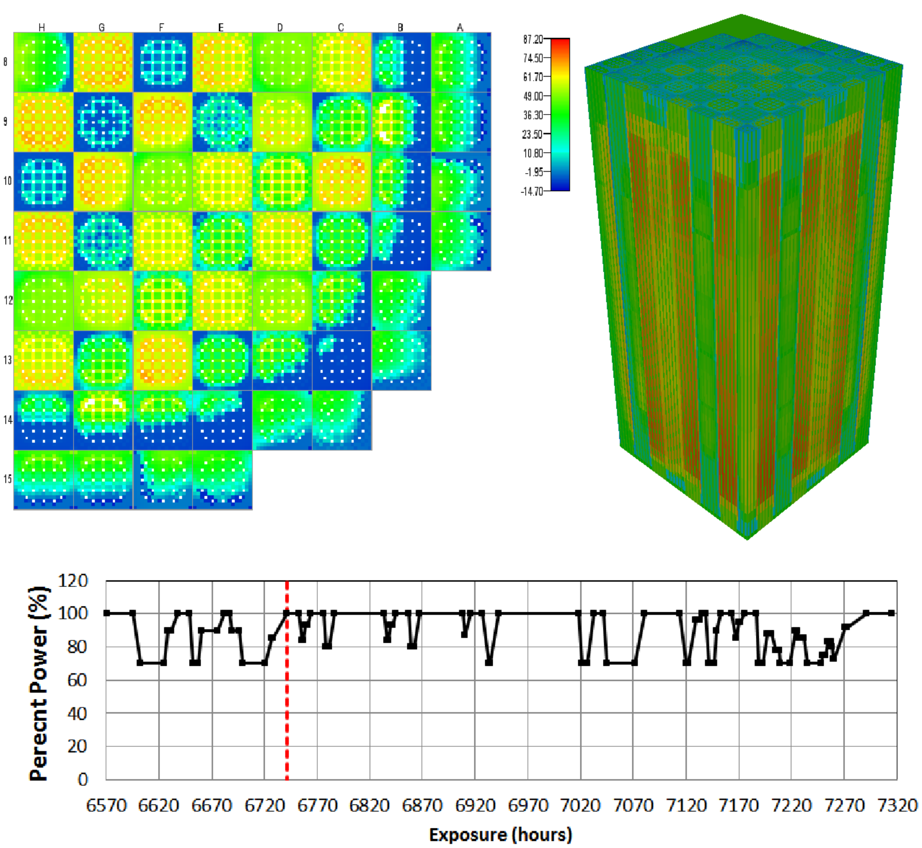
Exposure (hours)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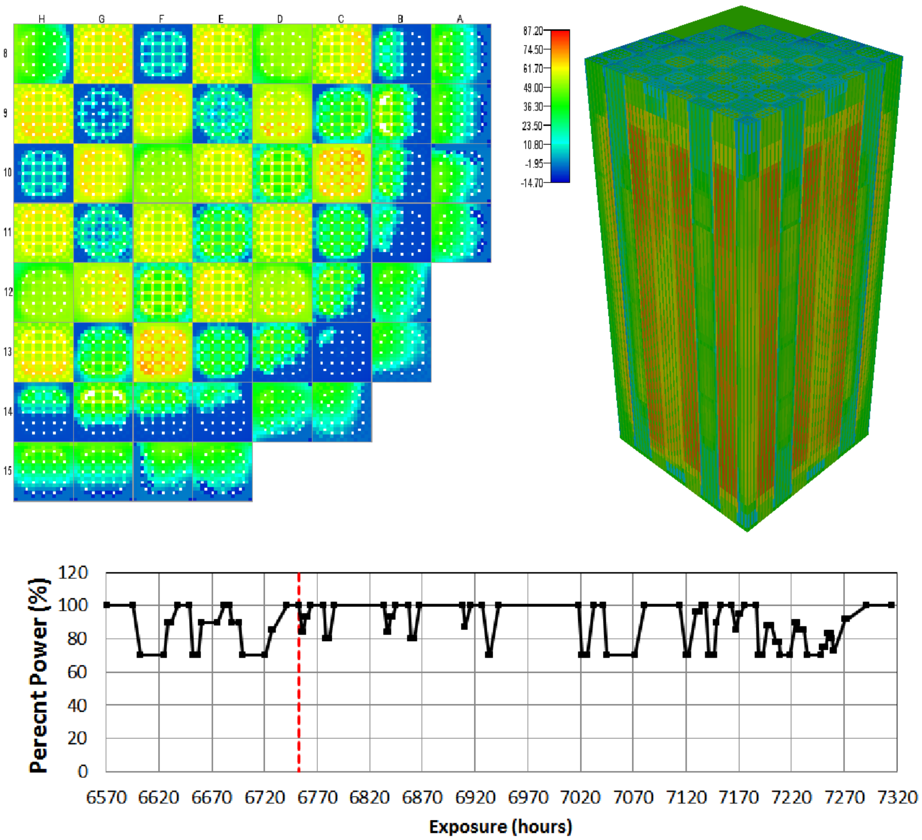
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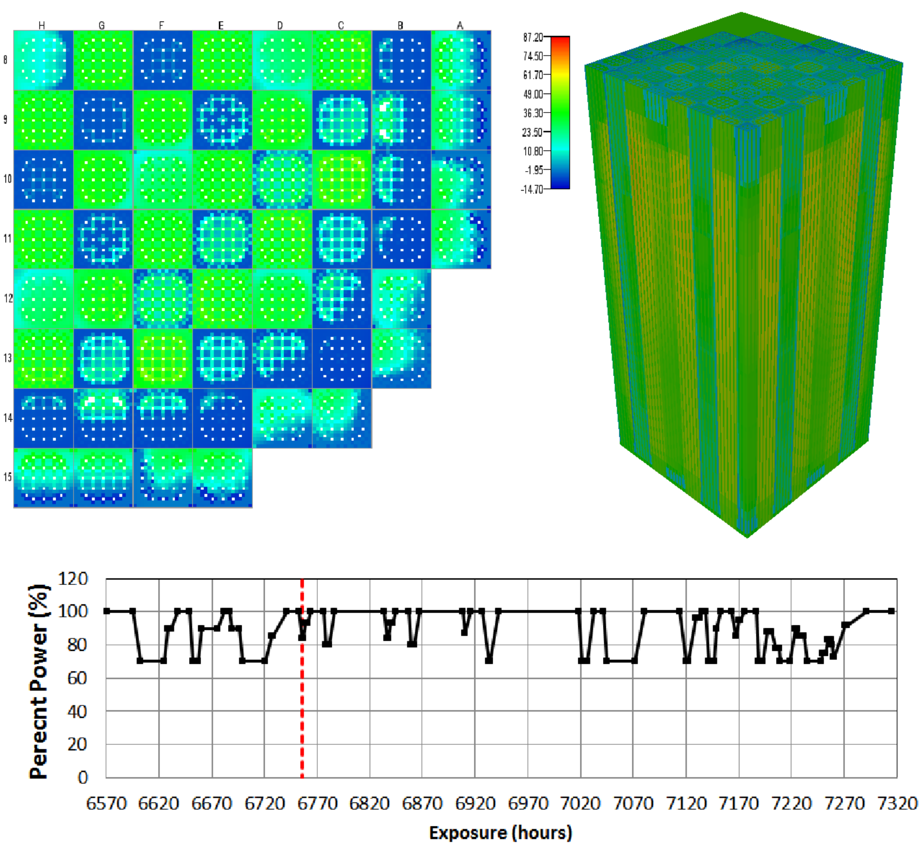
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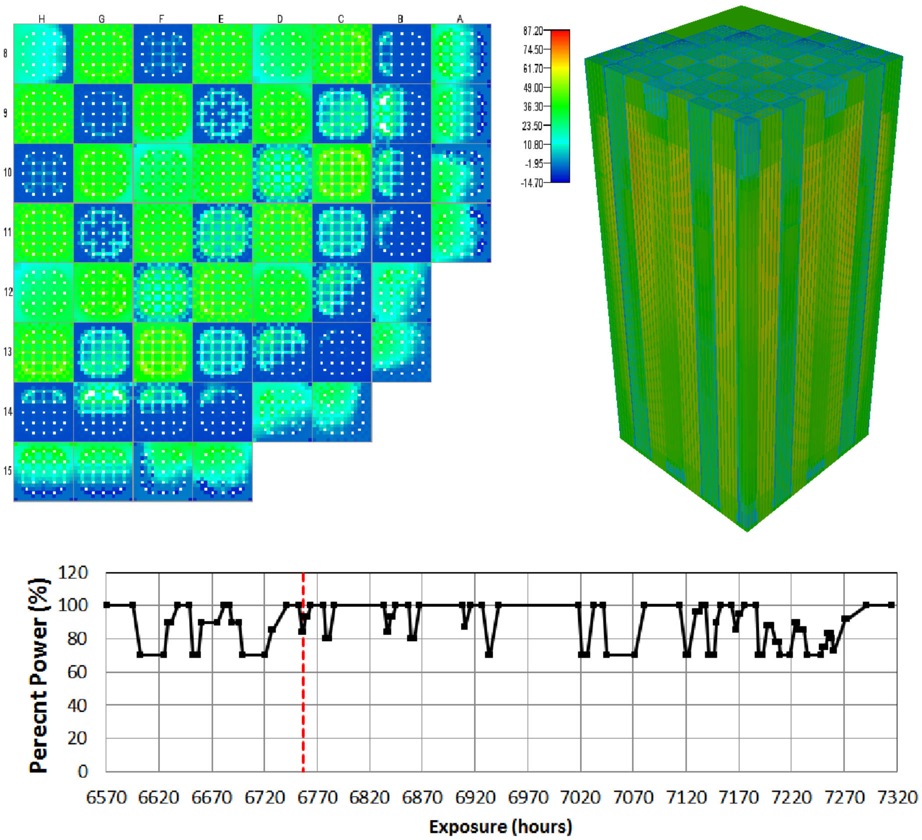
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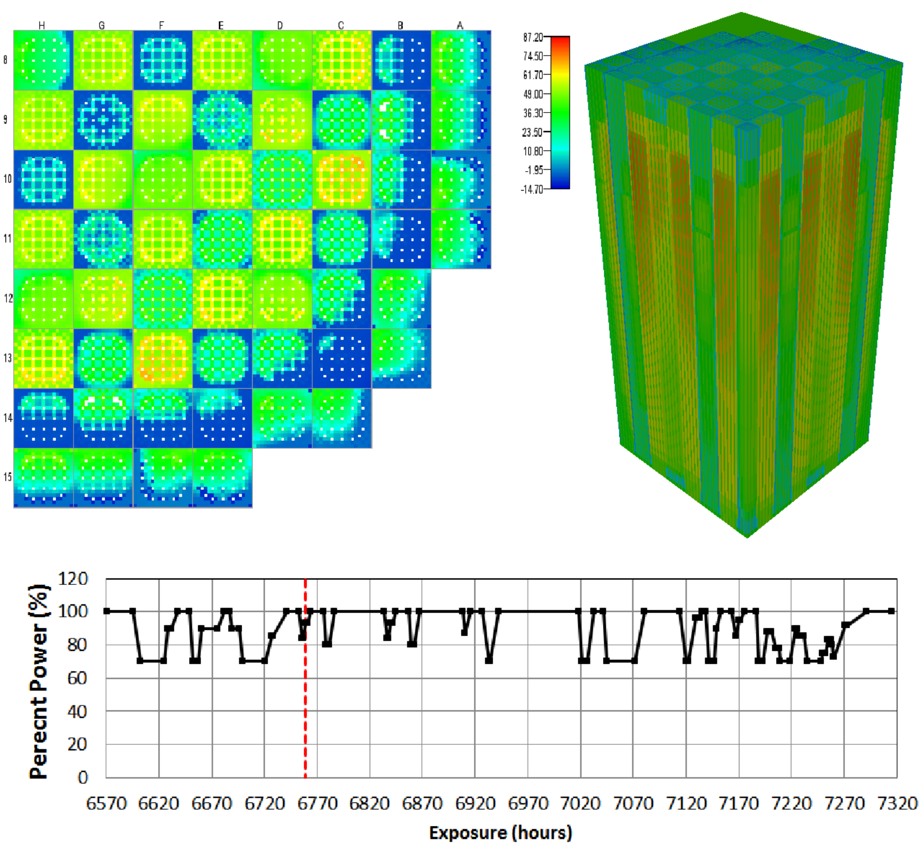
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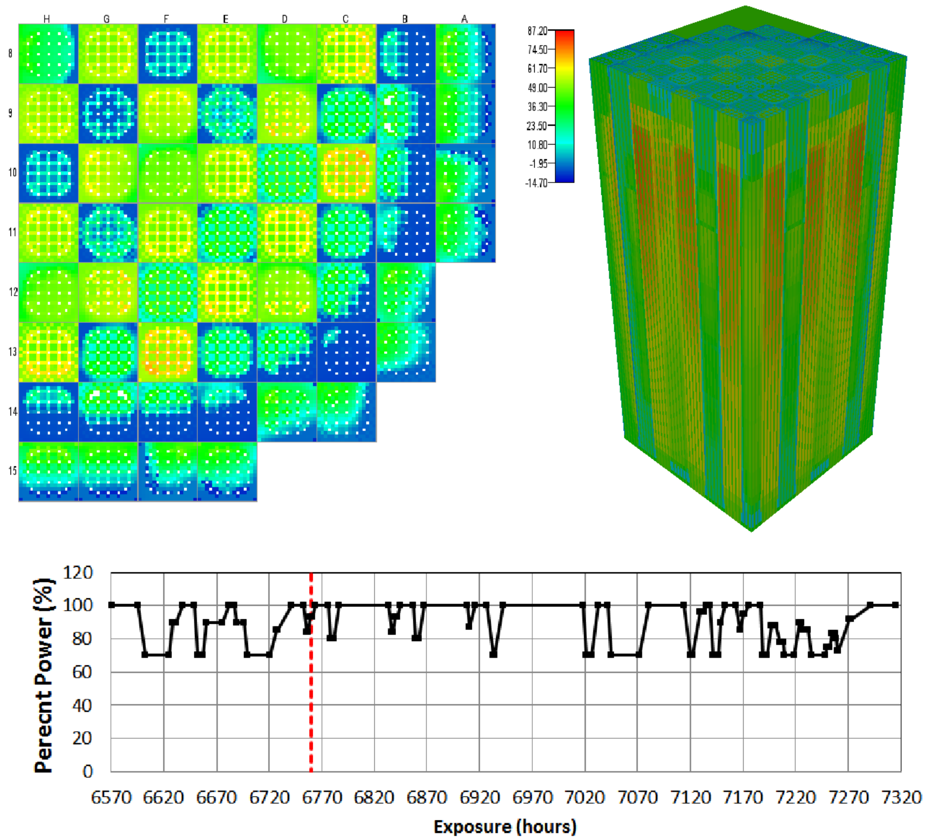
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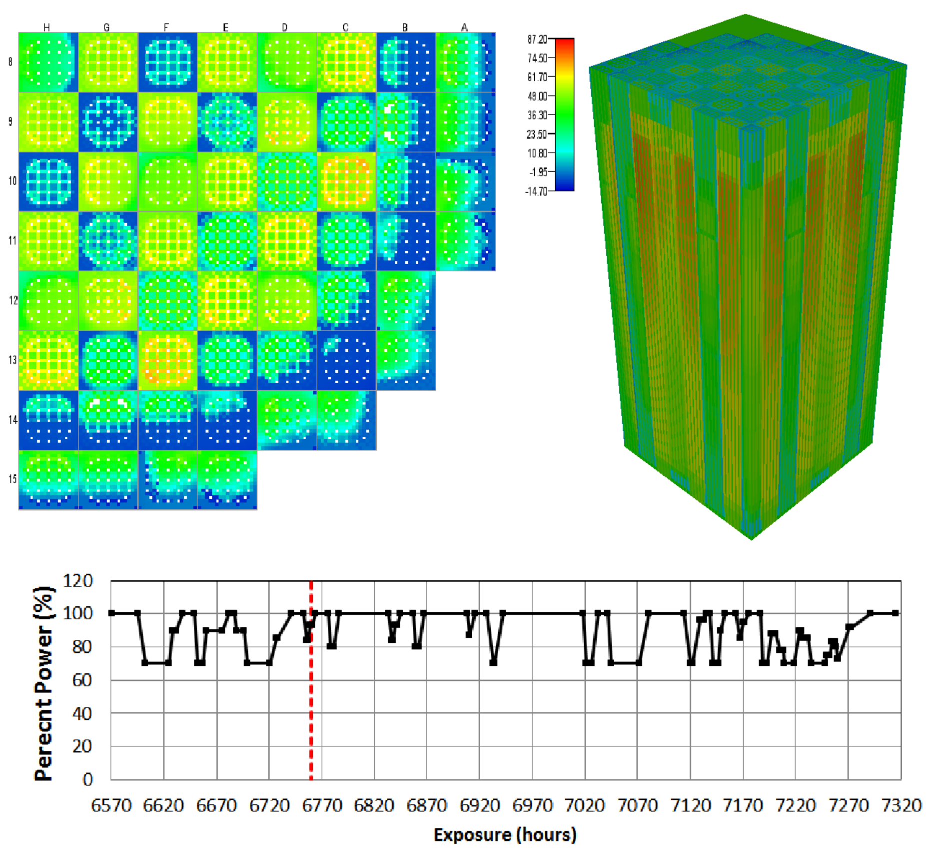
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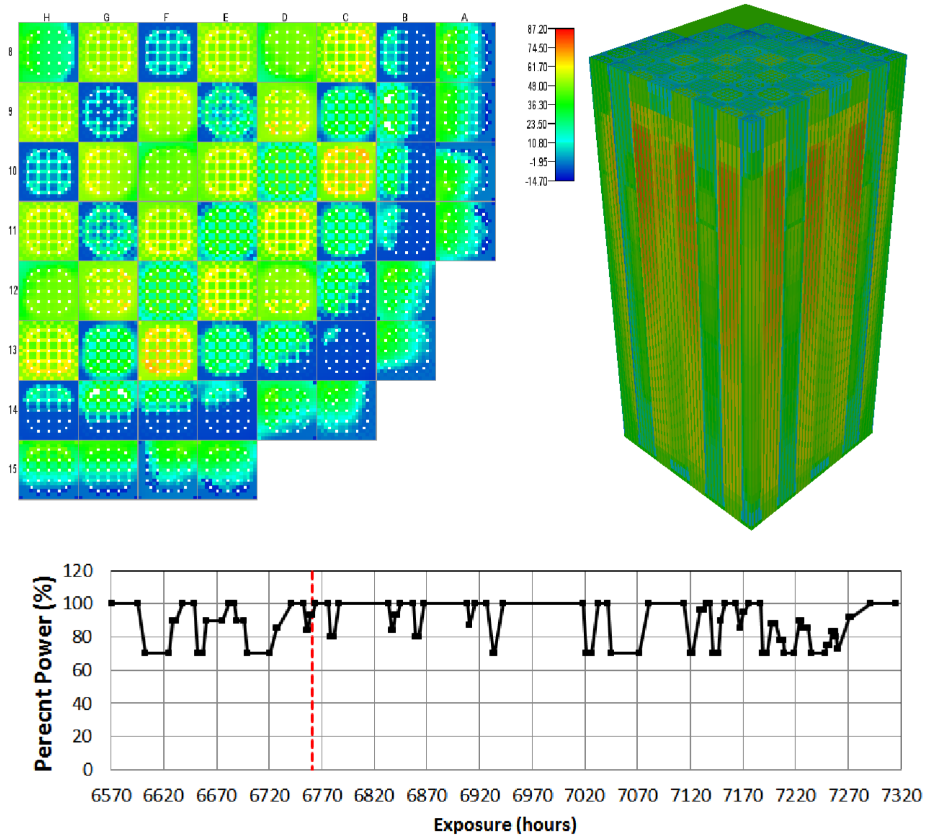
Exposure (hours)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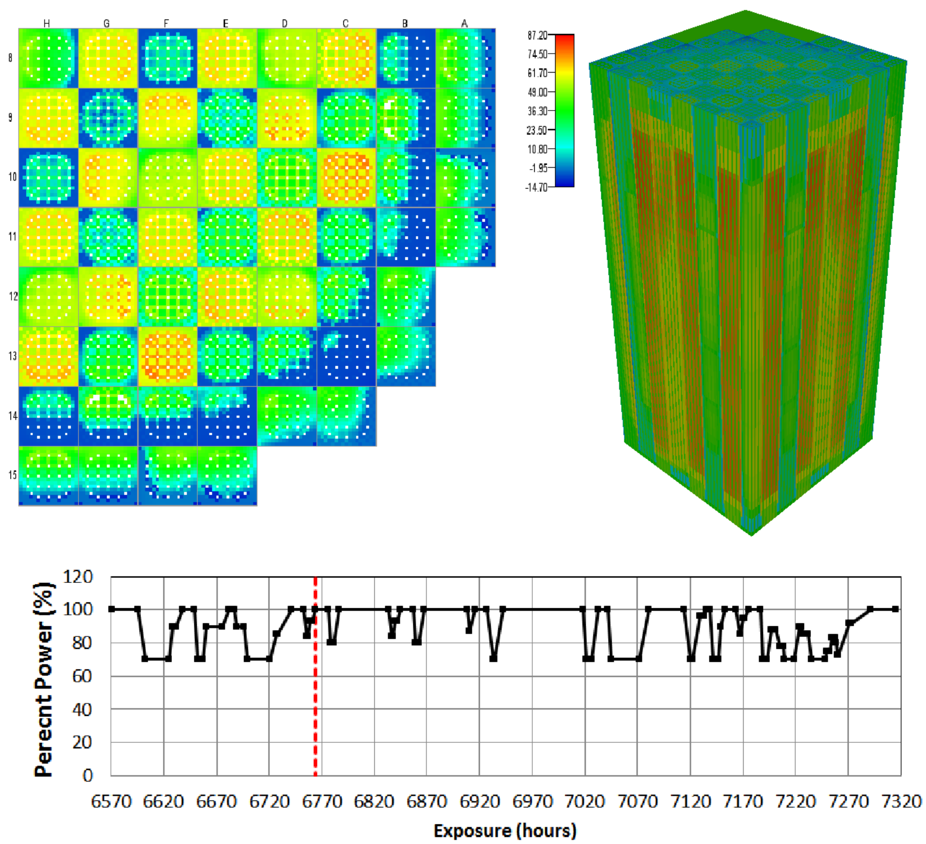
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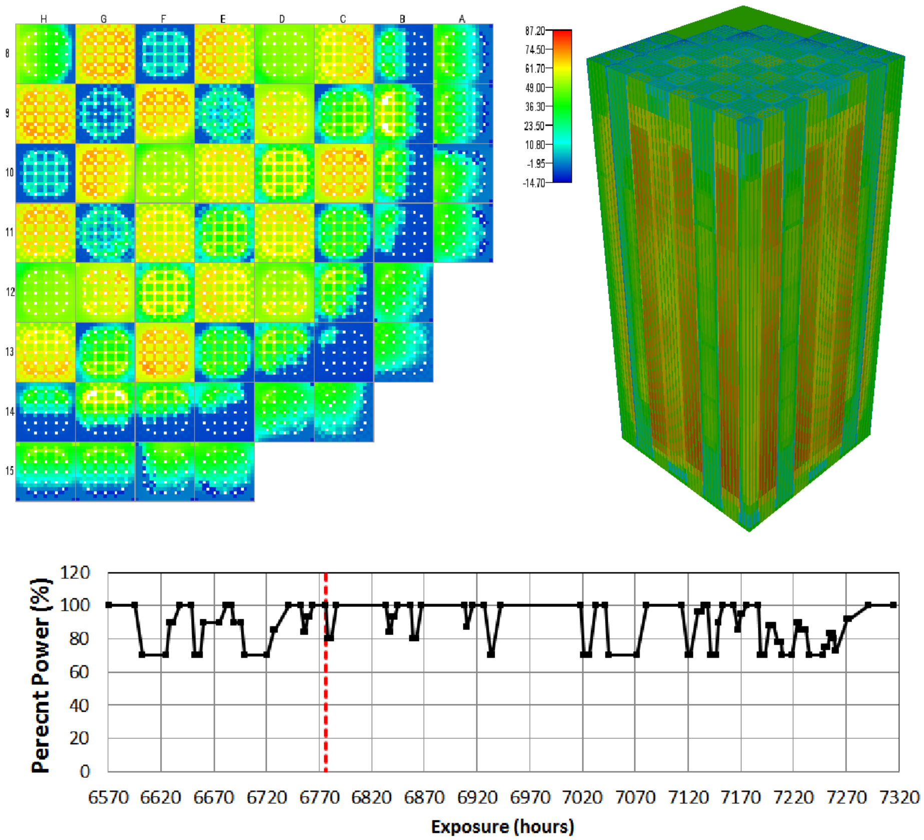
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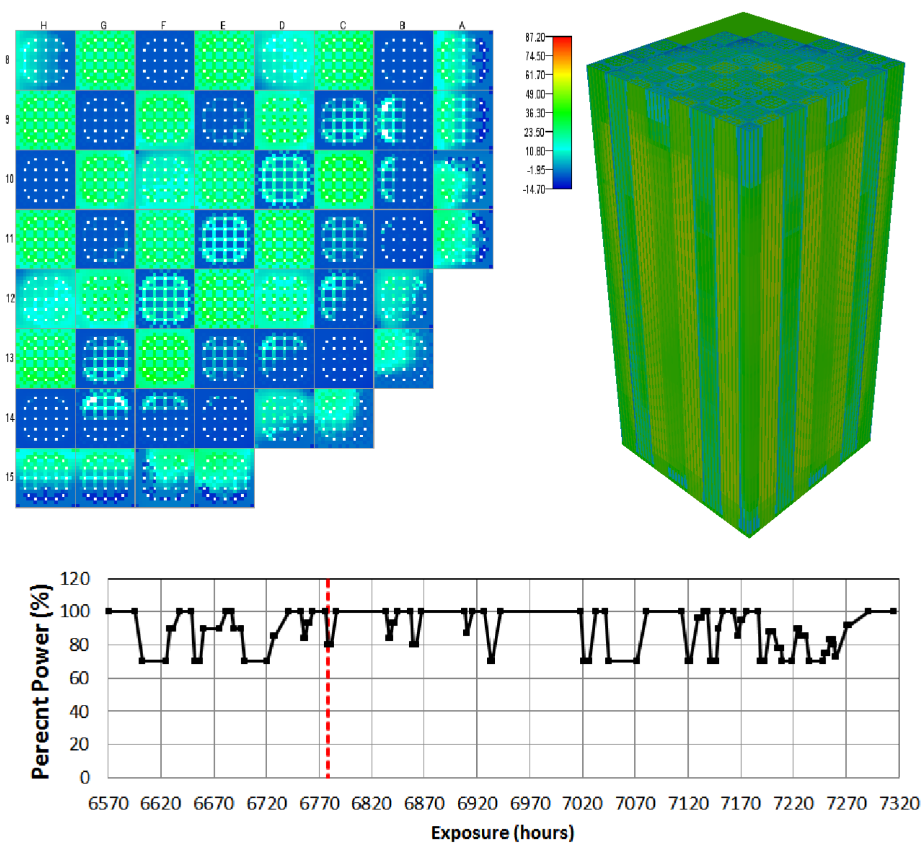
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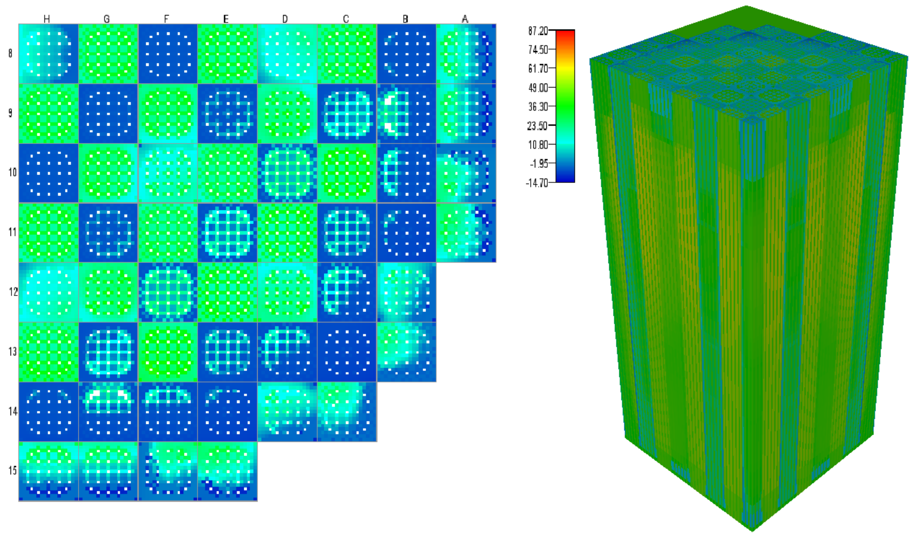
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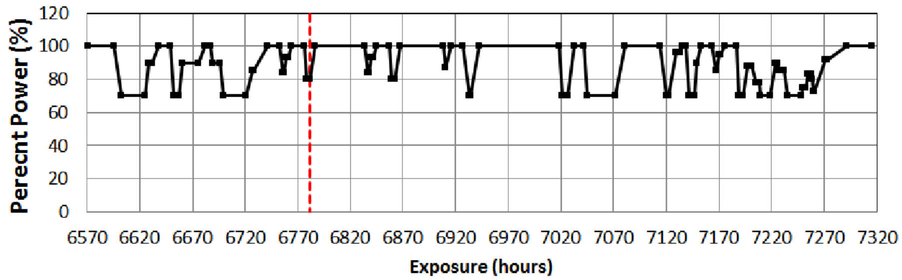
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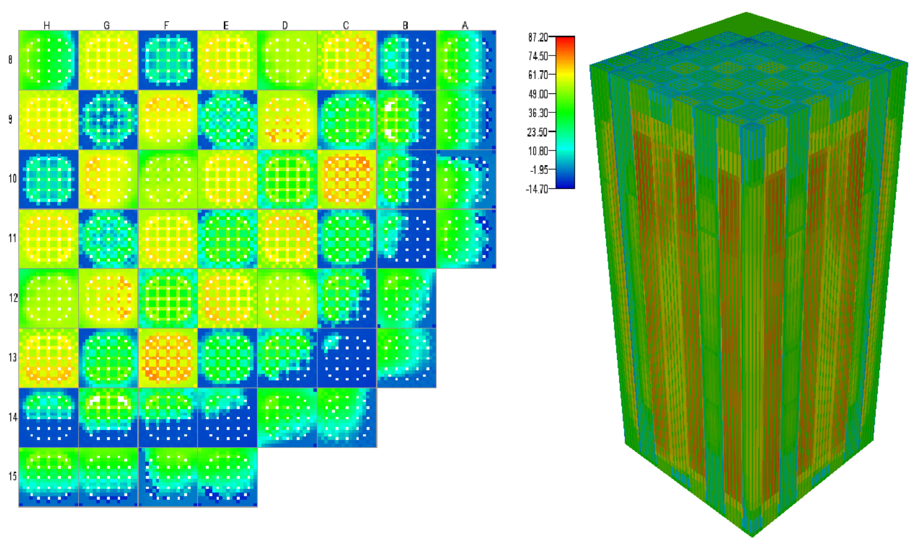
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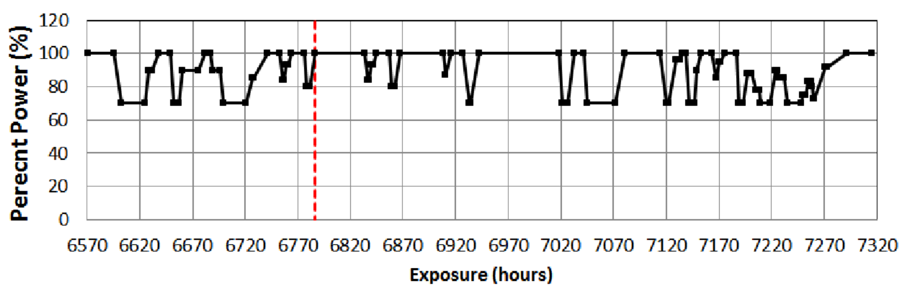
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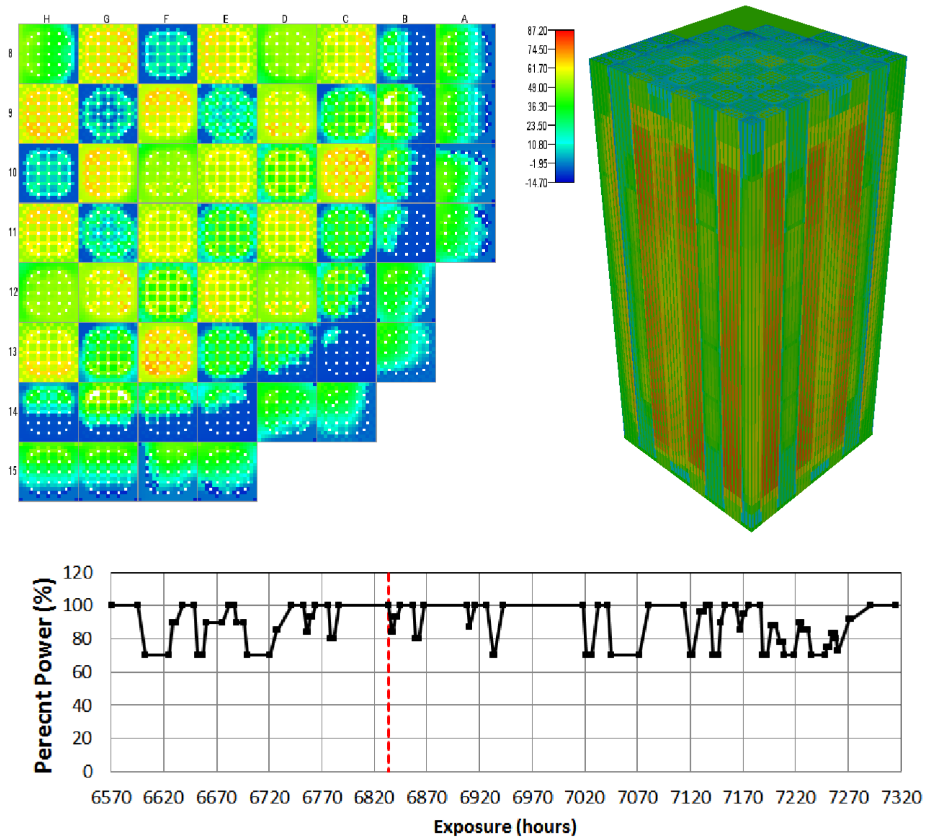
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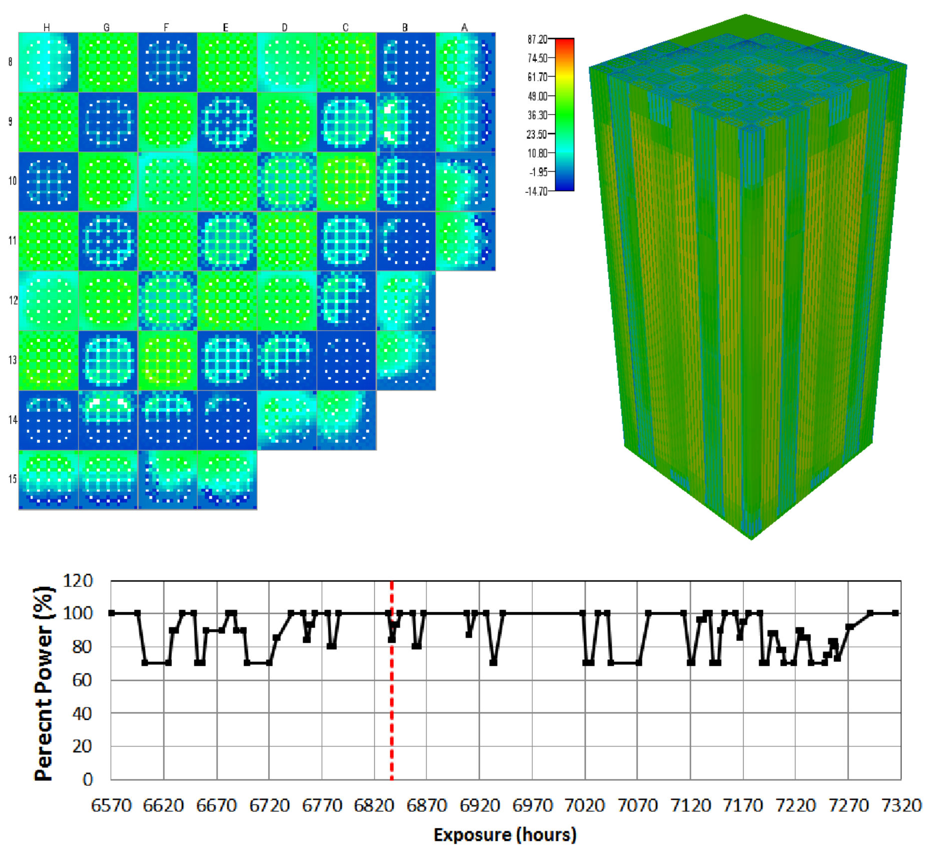
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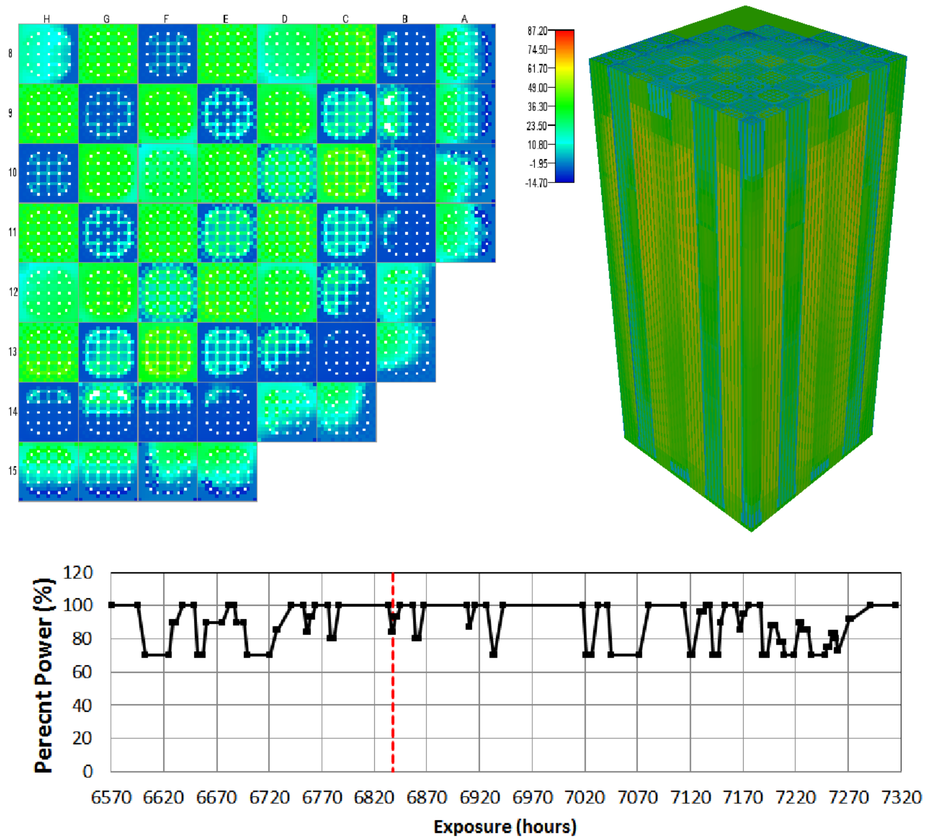
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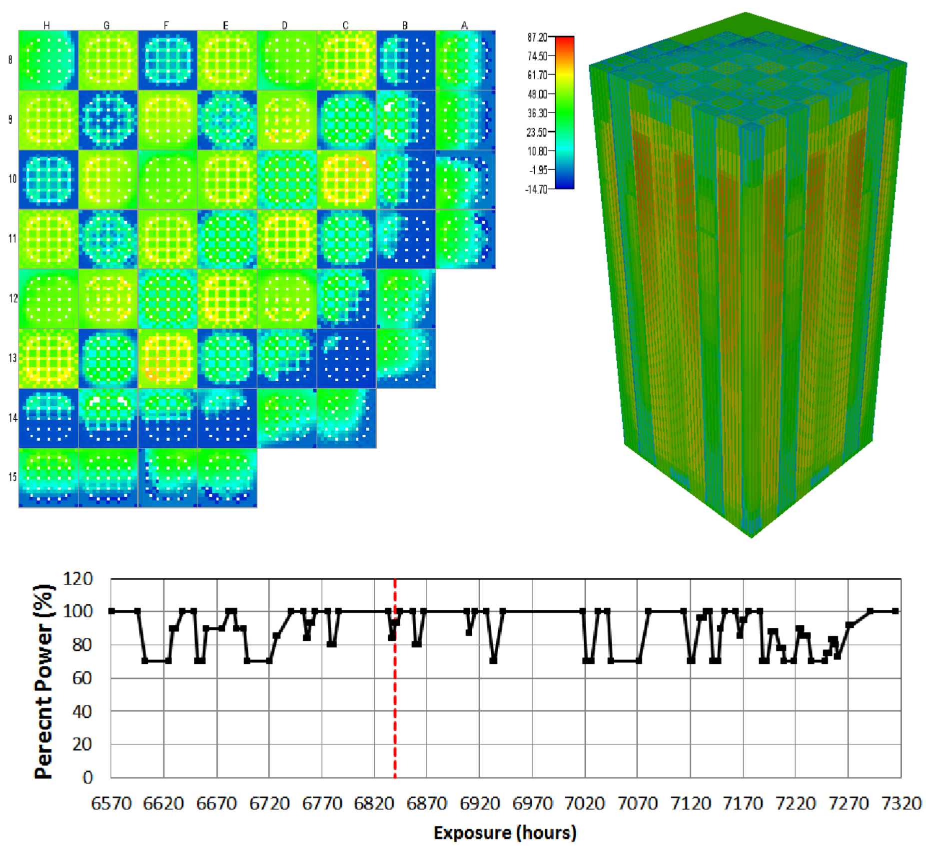
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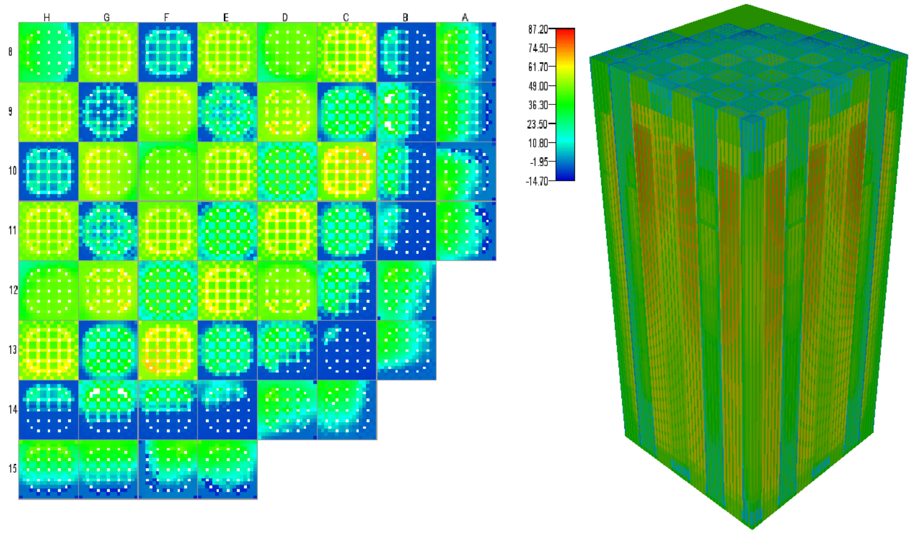
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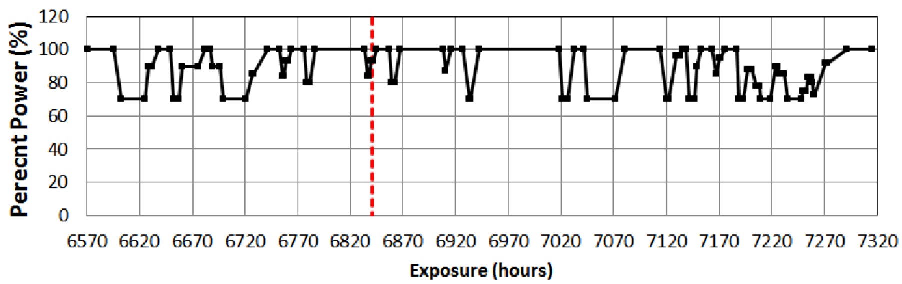
Perecnt Power (%)
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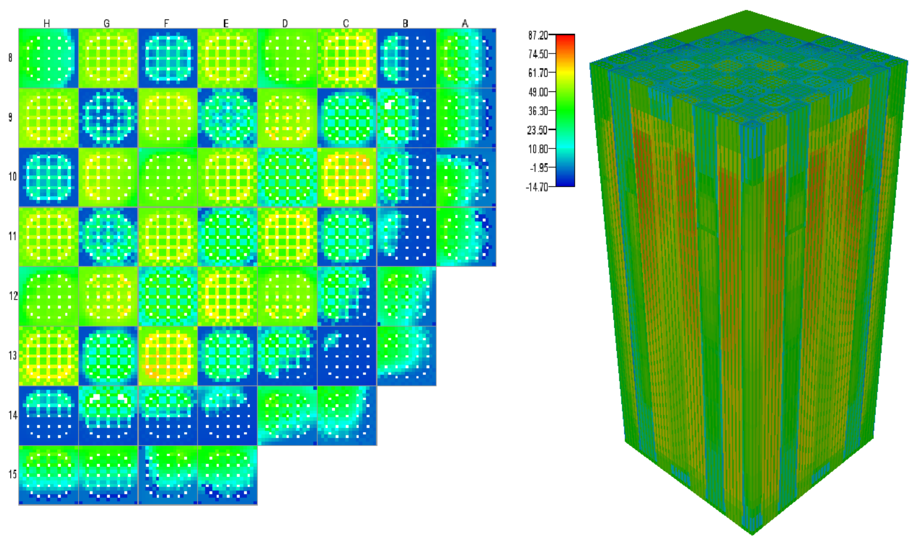
Exposure (hours)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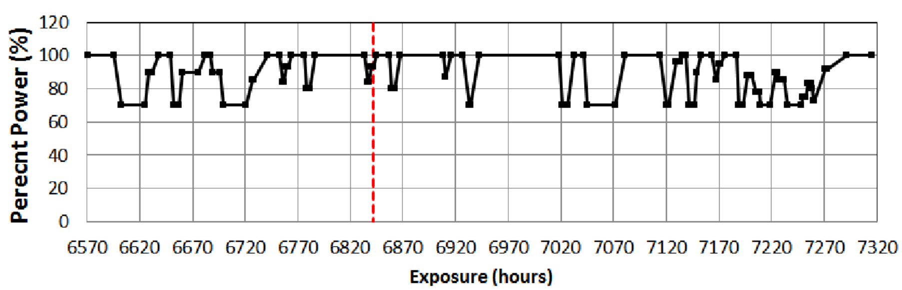
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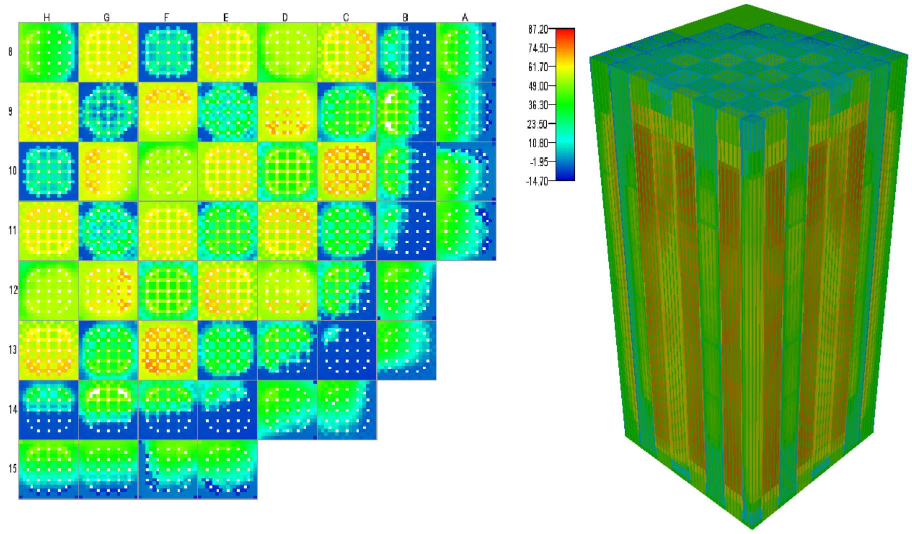
Exposure (hours)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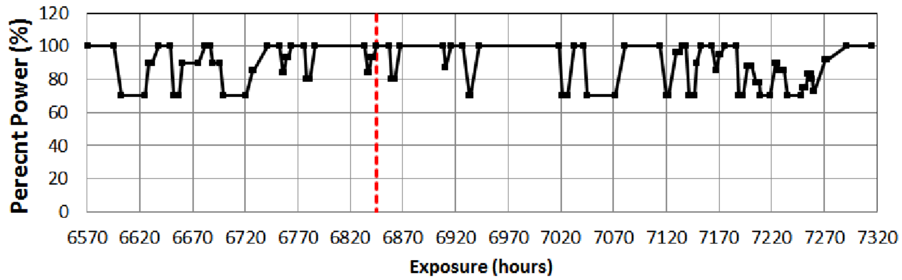
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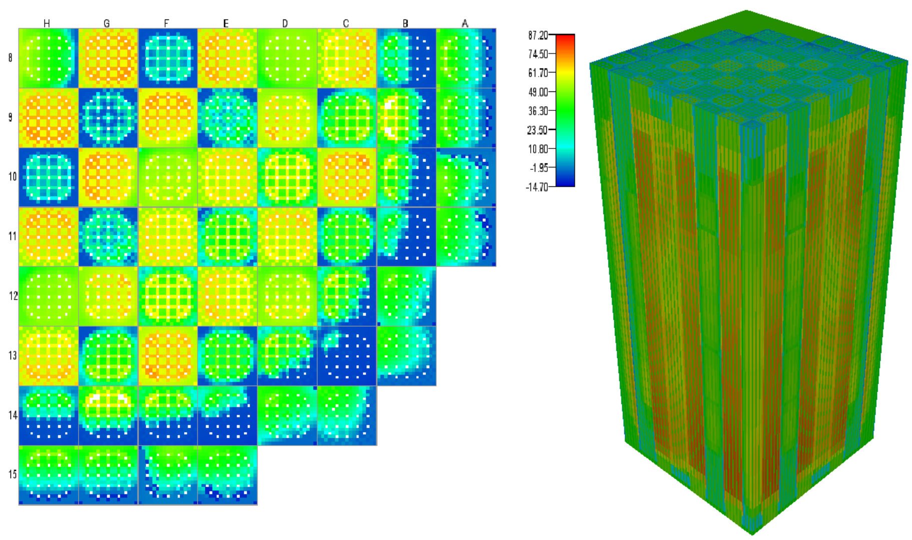
Exposure (hours)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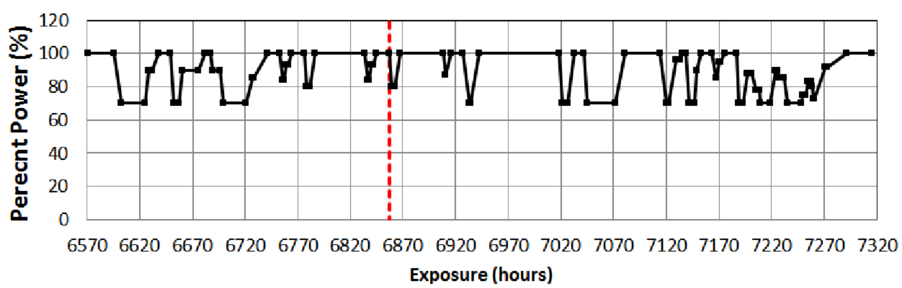
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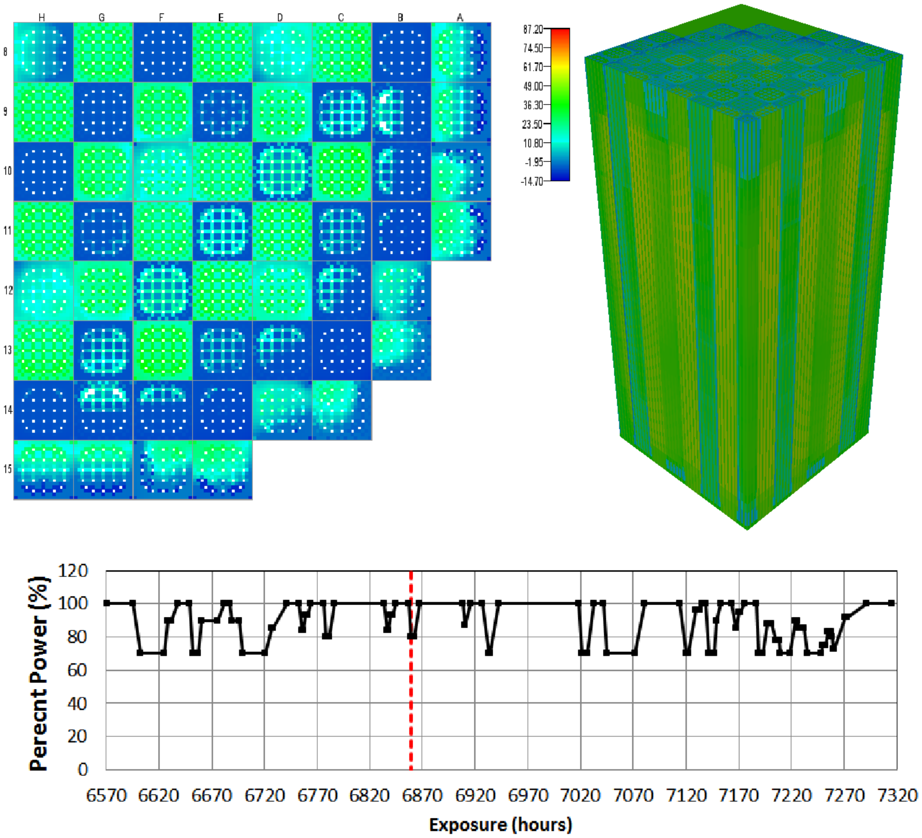
Exposure (hours)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Perecnt Power (%)
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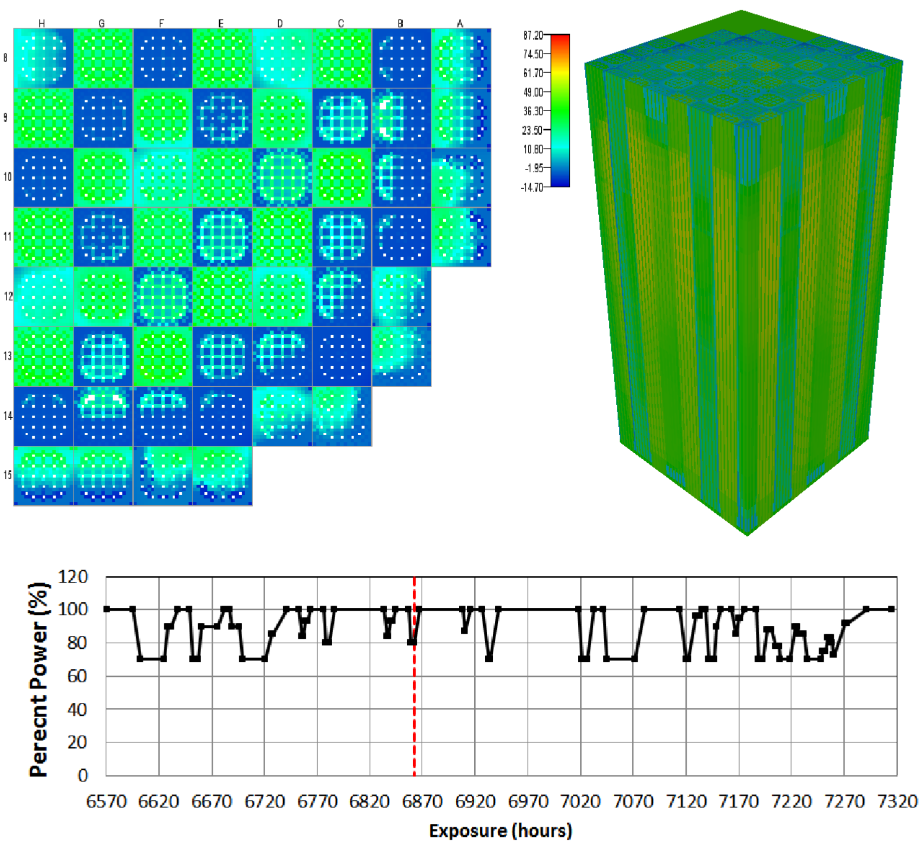
Exposure (hours)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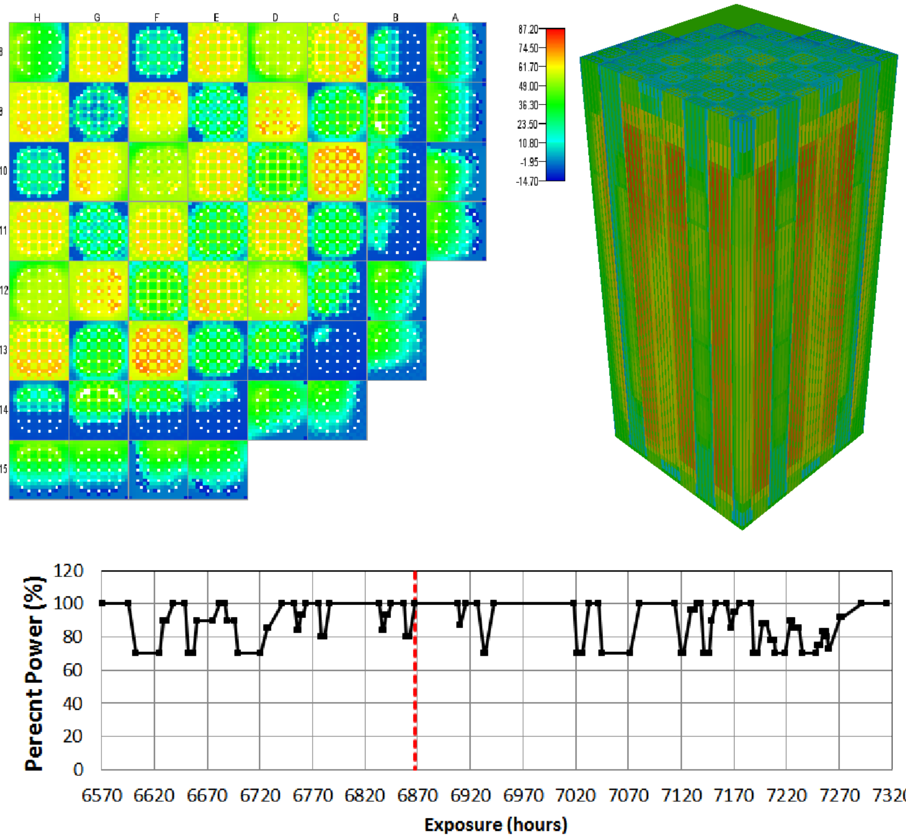
Exposure (hours)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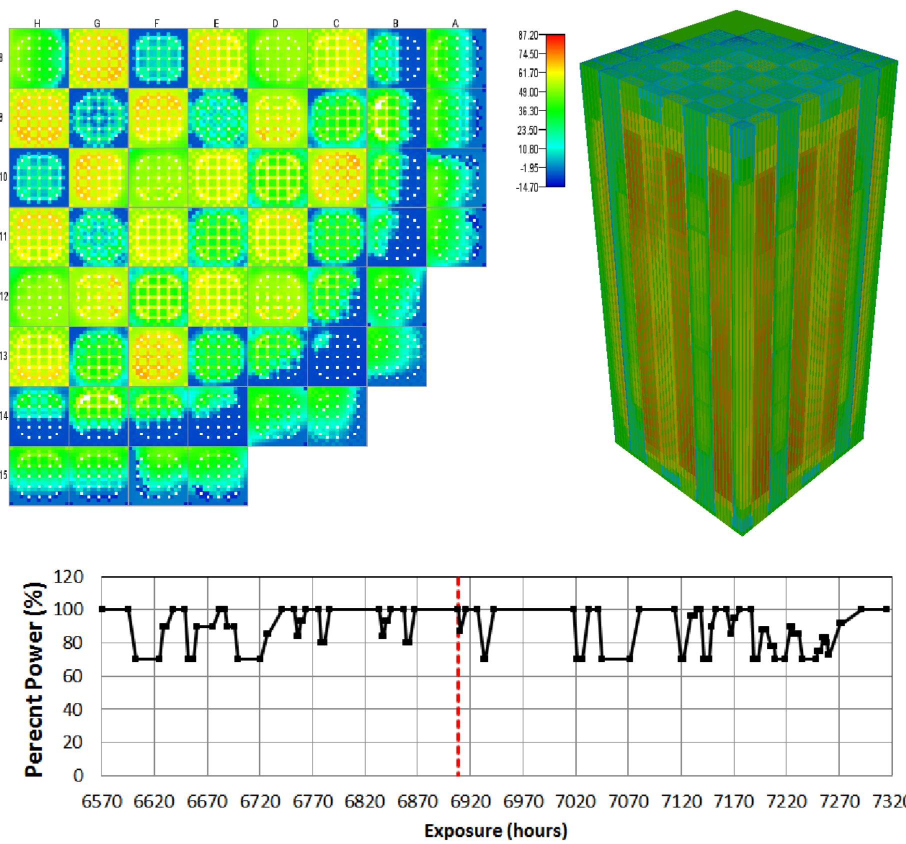
Exposure (hours)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Perecnt Power (%)
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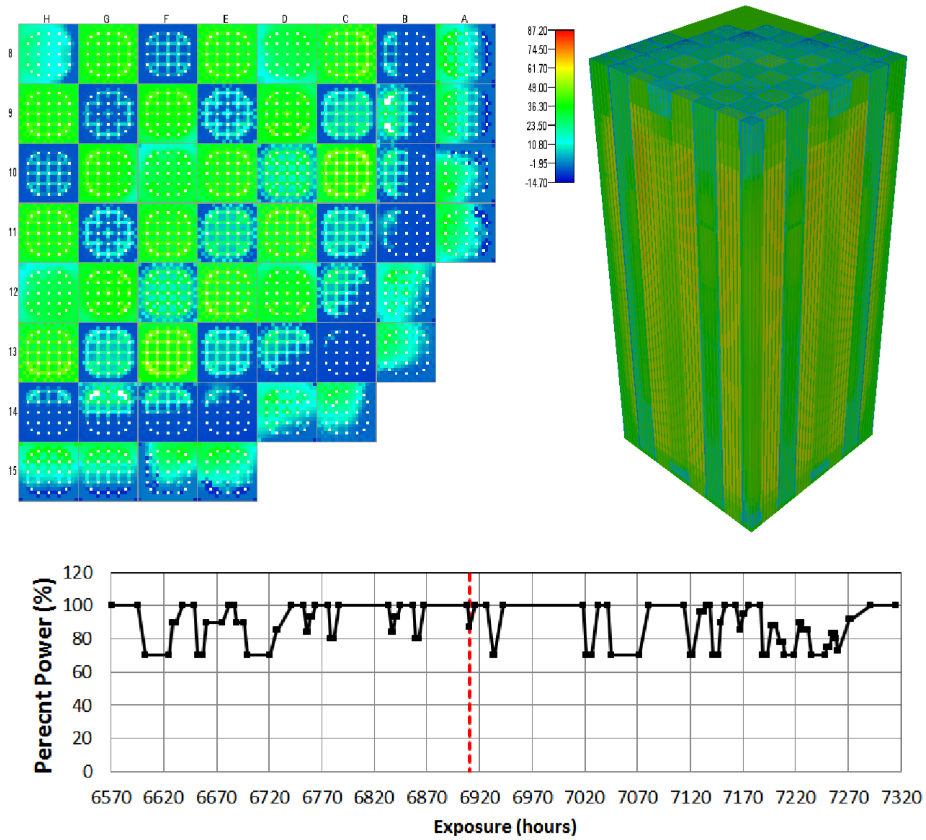
Exposure (hours)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Perecnt Power (%)
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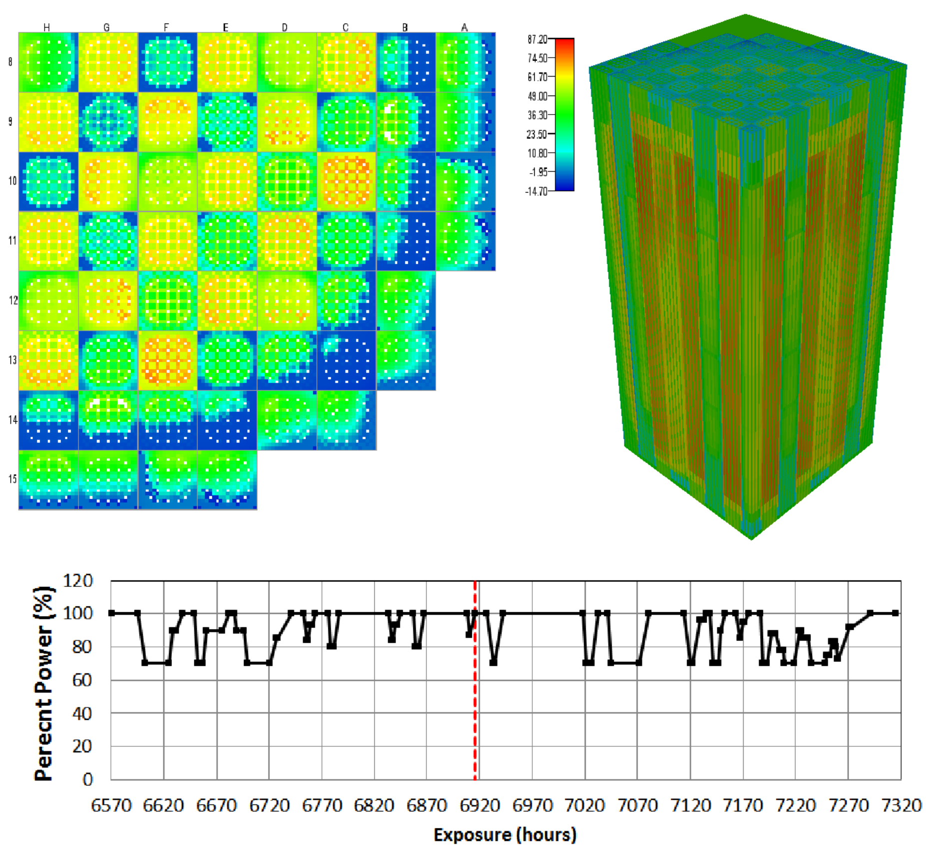
Exposure (hours)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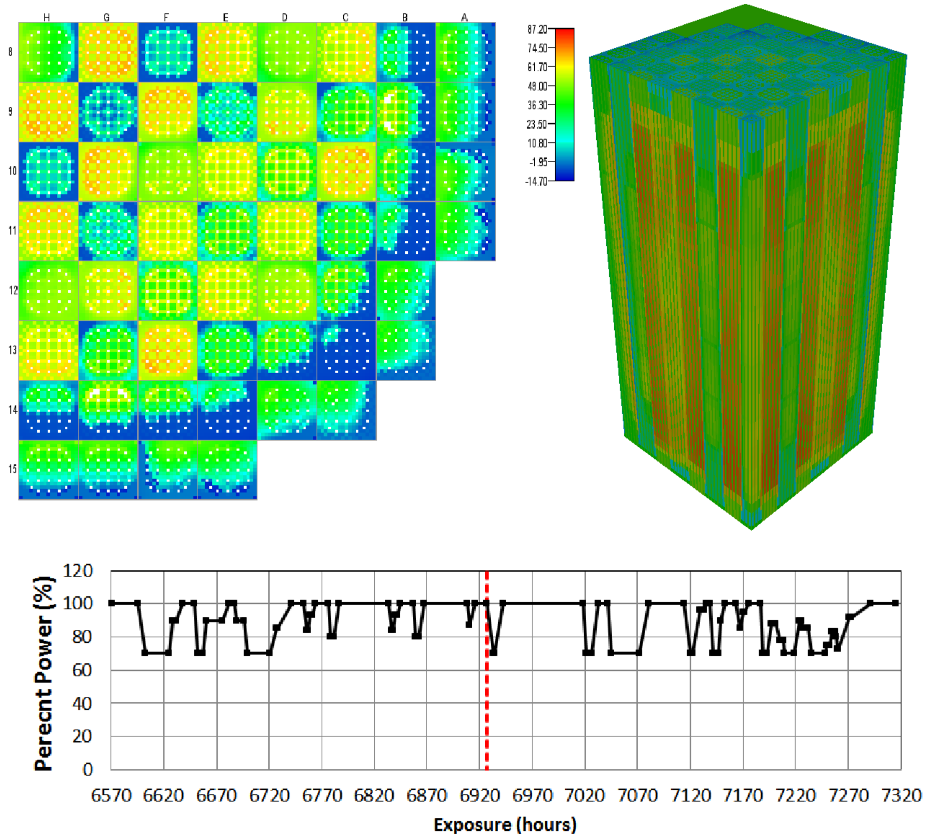
Exposure (hours)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Perecnt Power (%)
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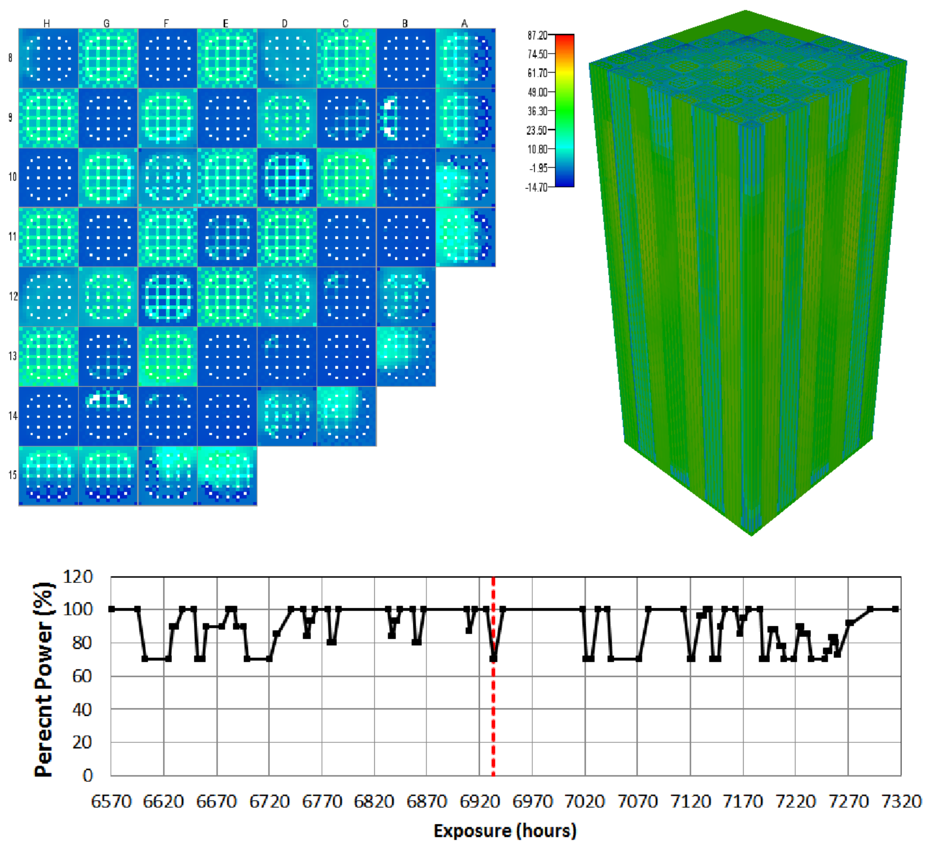
Exposure (hours)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Perecnt Power (%)
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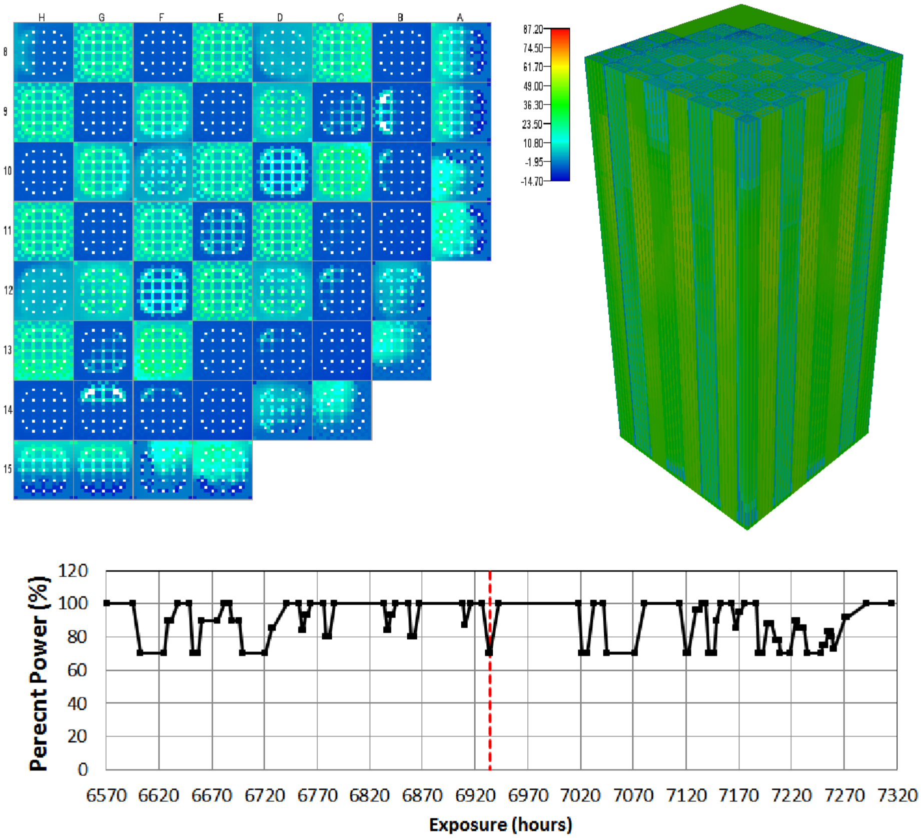
Exposure (hours)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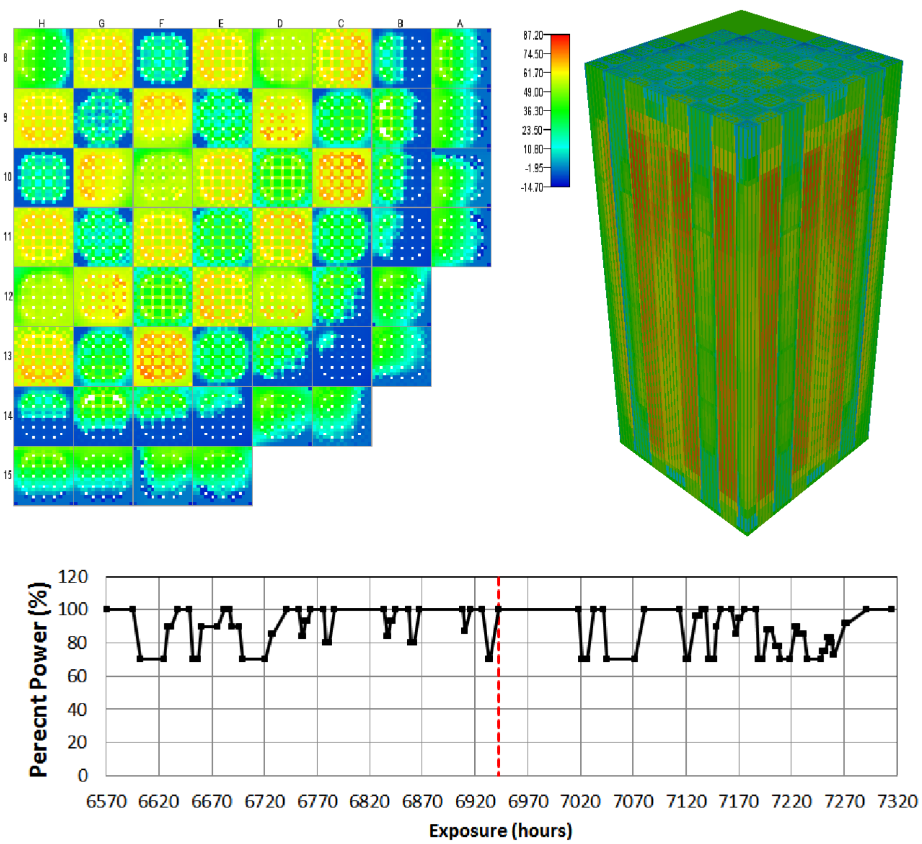
Exposure (hours)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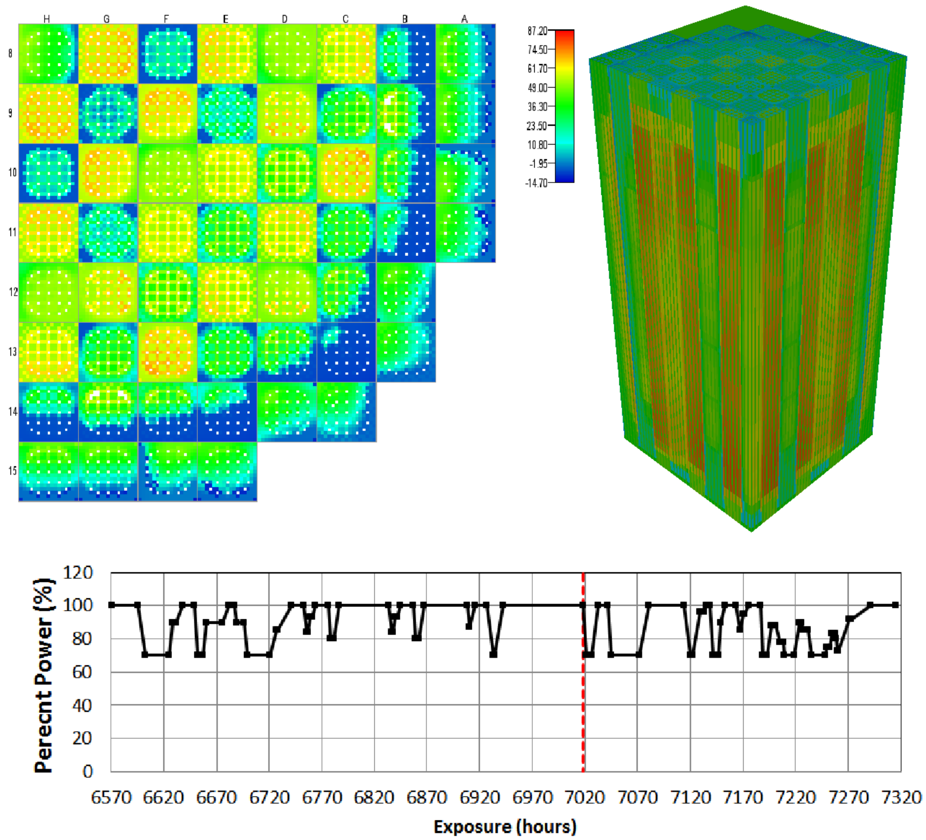
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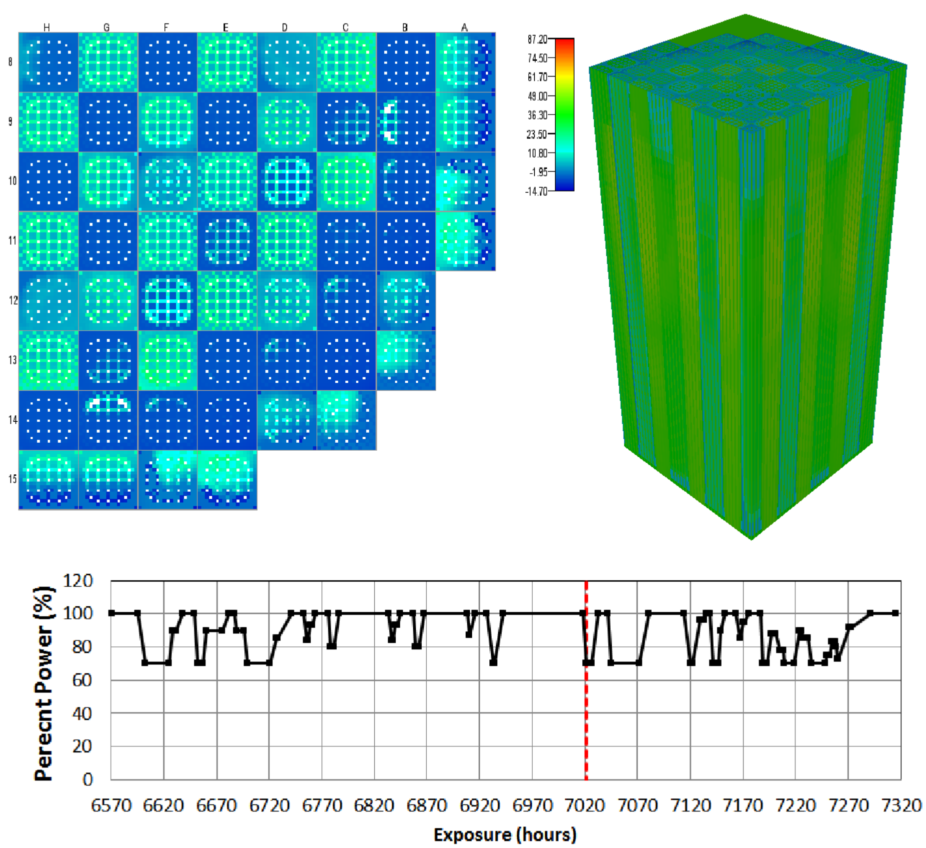
Exposure (hours)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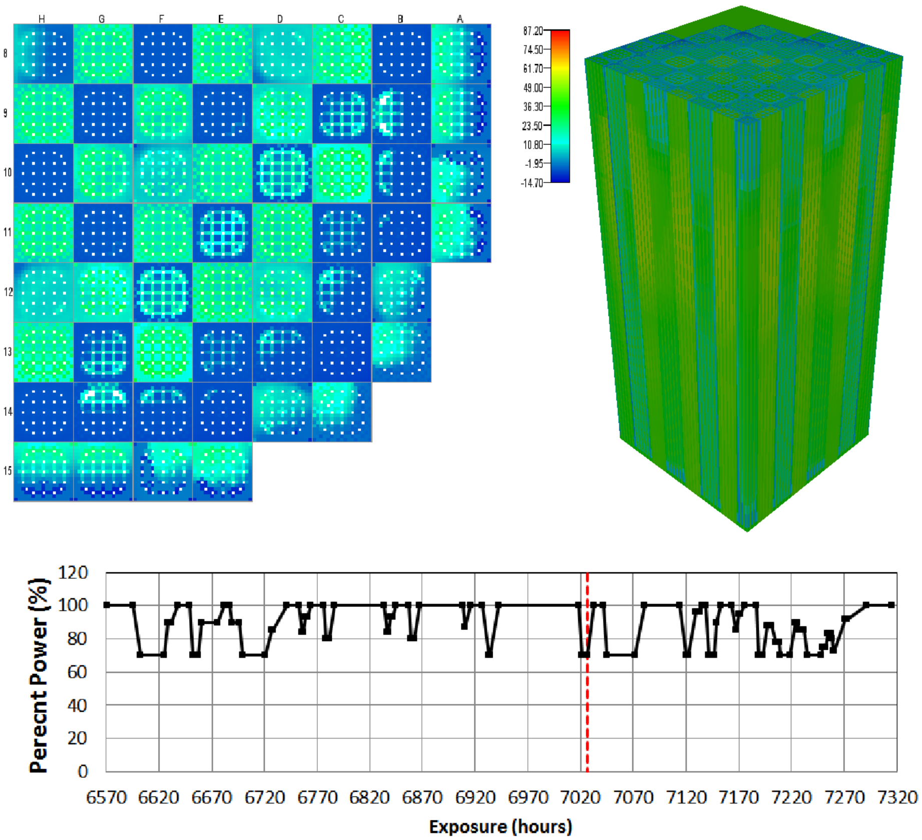
Exposure (hours)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Perecnt Power (%)
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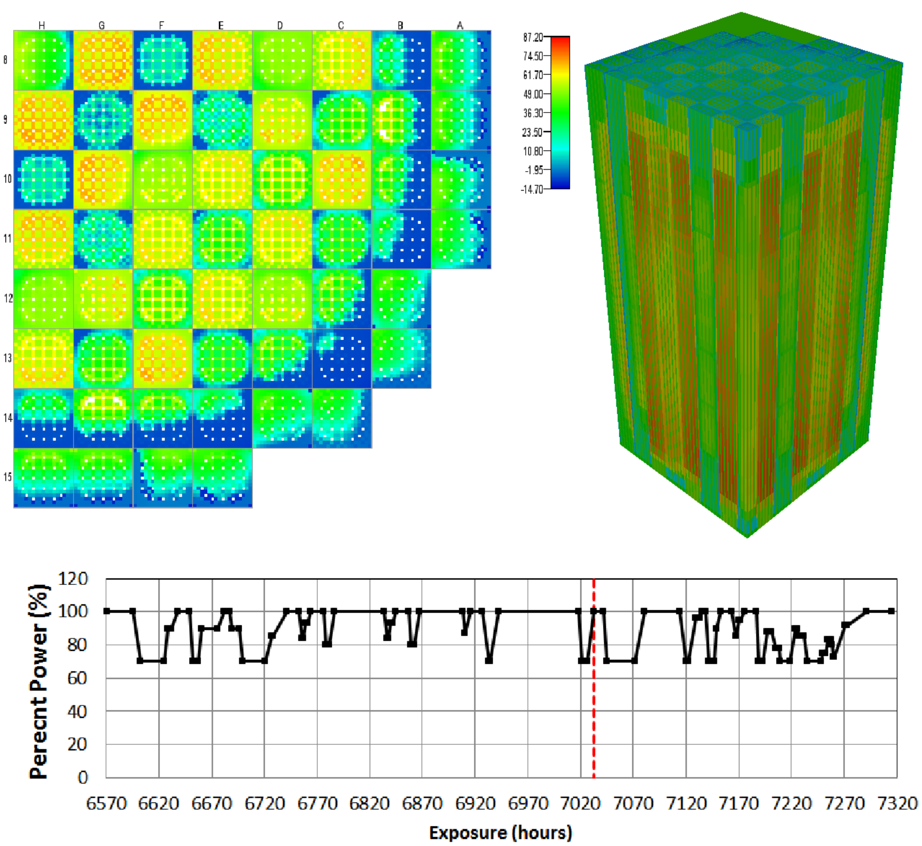
Exposure (hours)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Perecnt Power (%)
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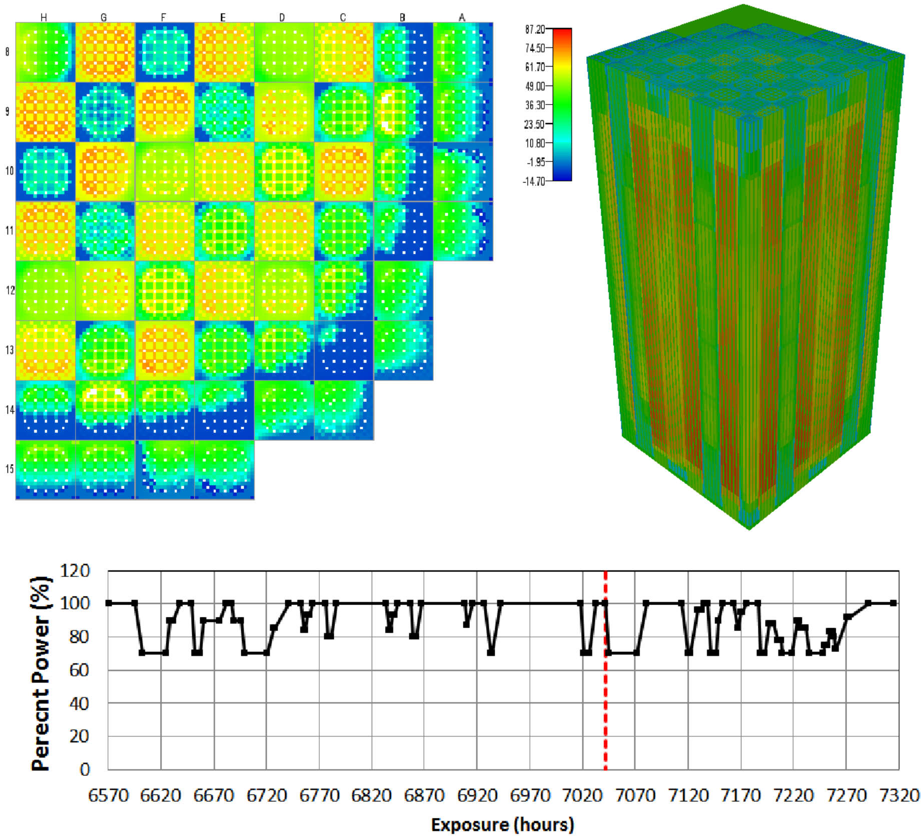
Exposure (hours)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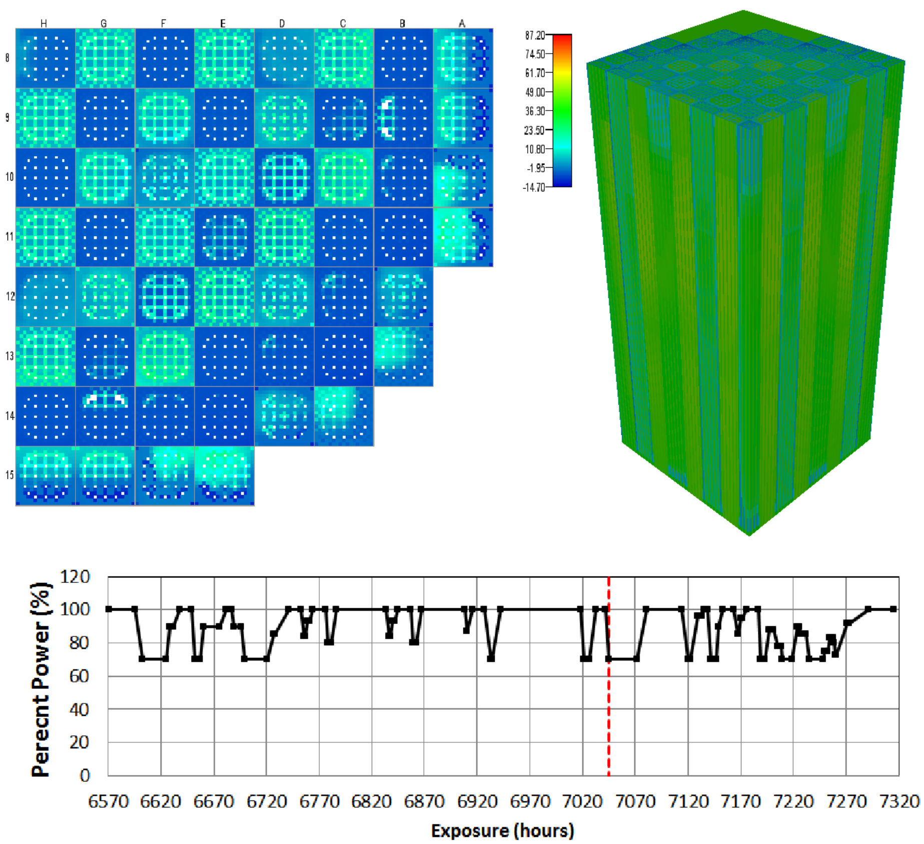
Exposure (hours)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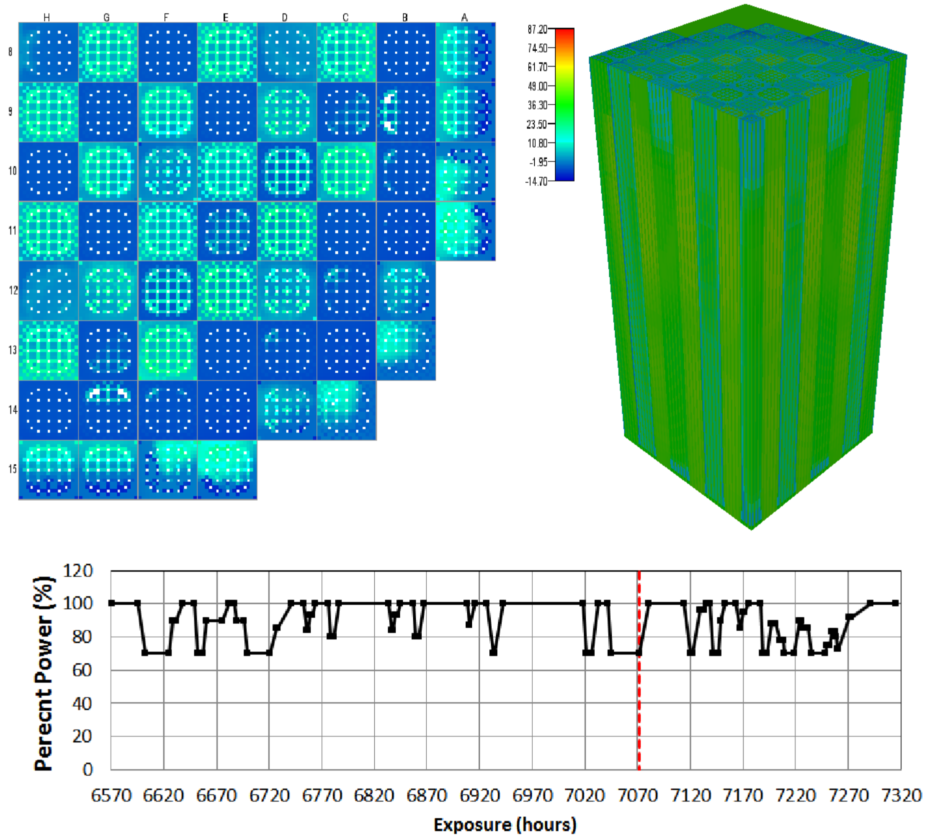
Exposure (hours)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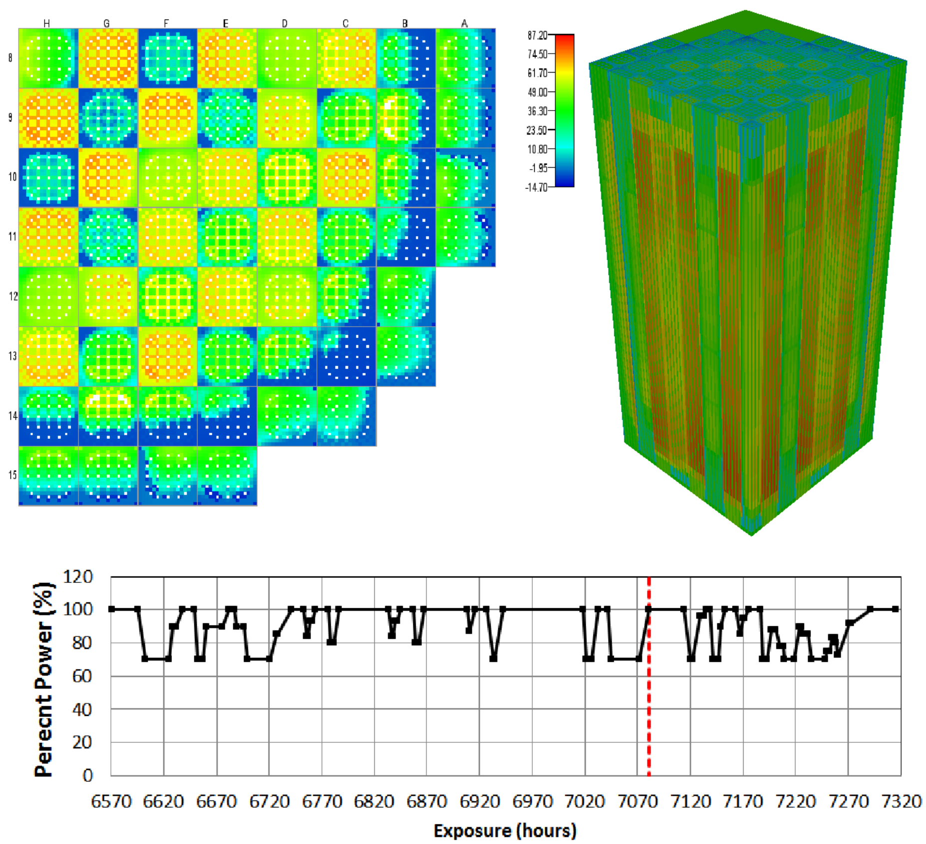
Exposure (hours)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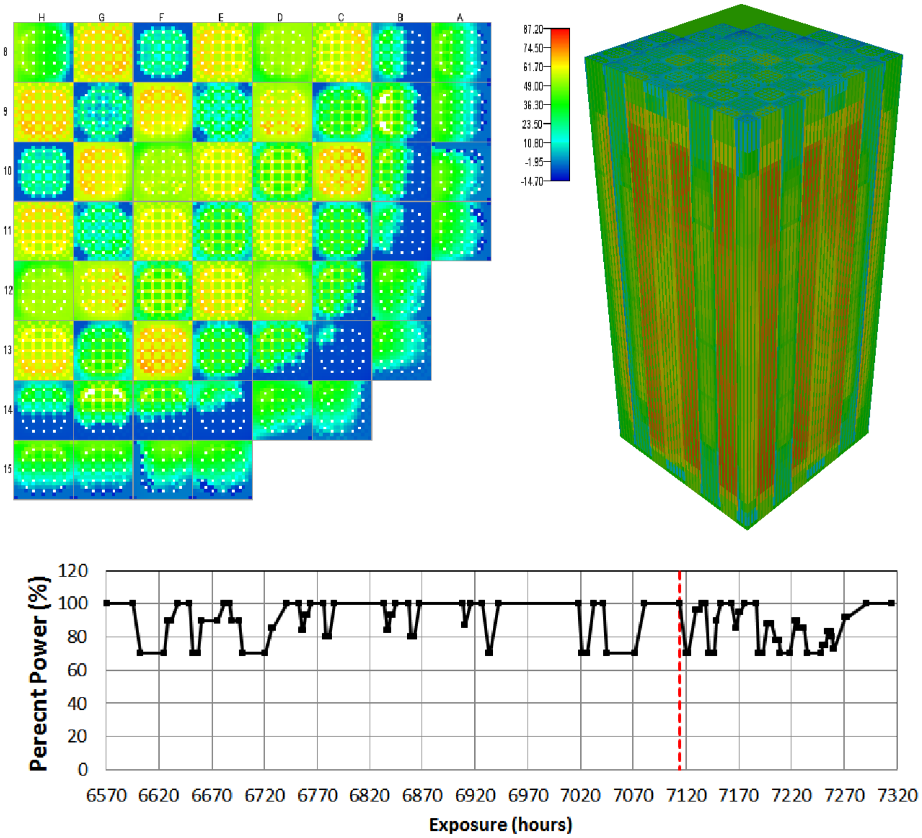
Exposure (hours)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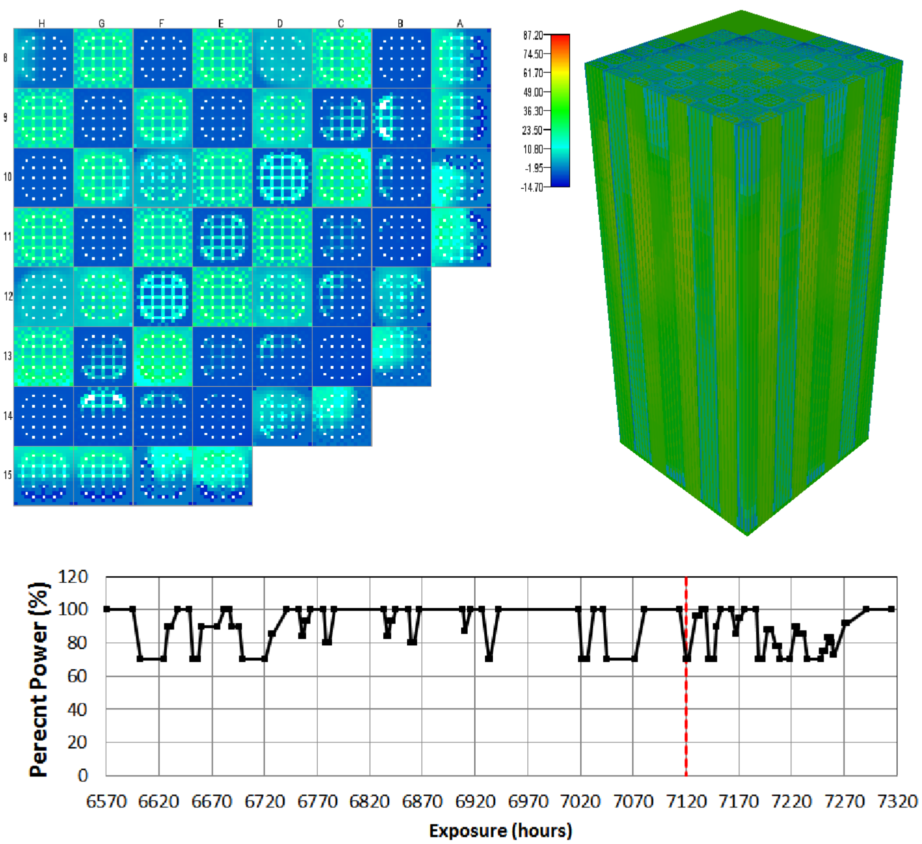
Exposure (hours)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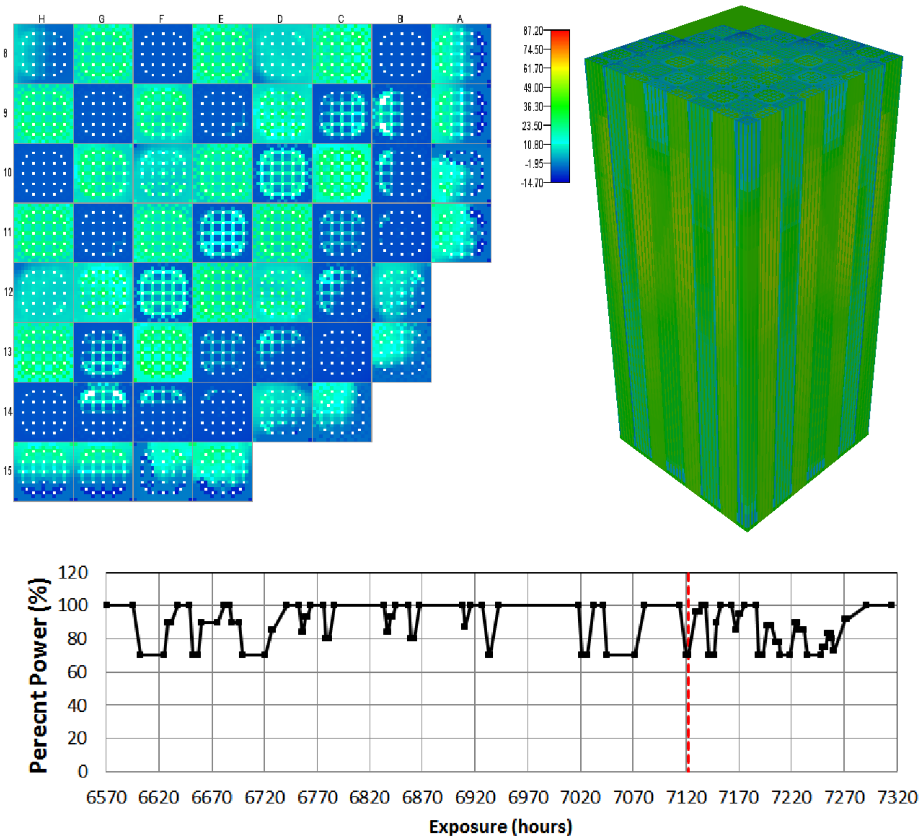
Exposure (hours)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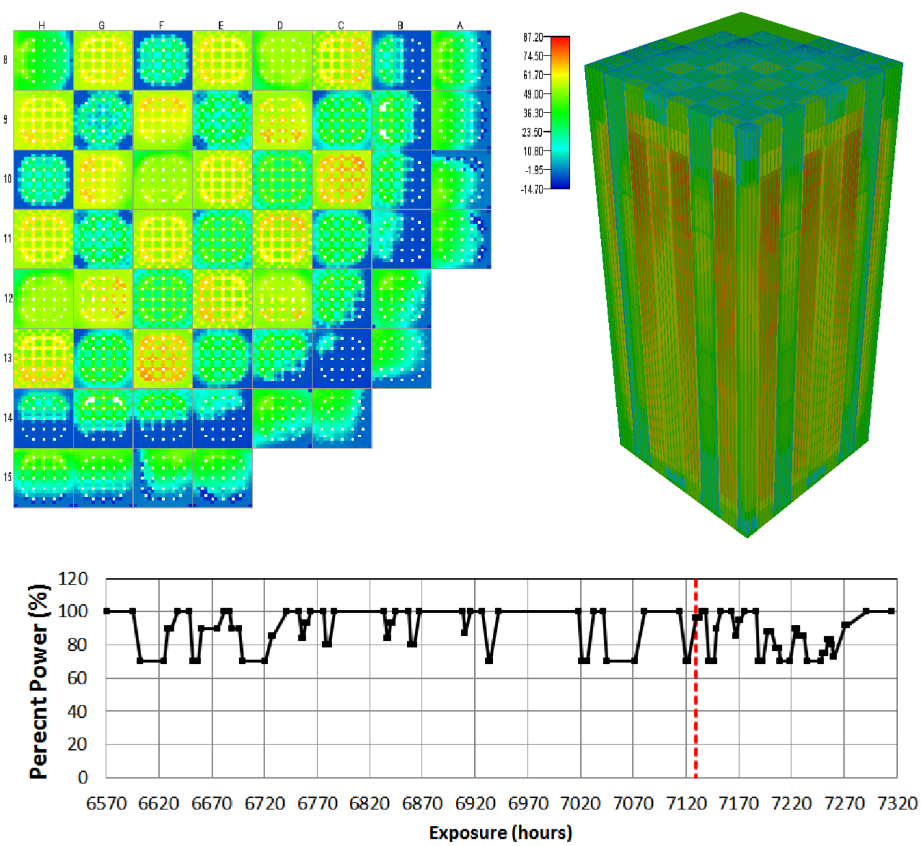
Exposure (hours)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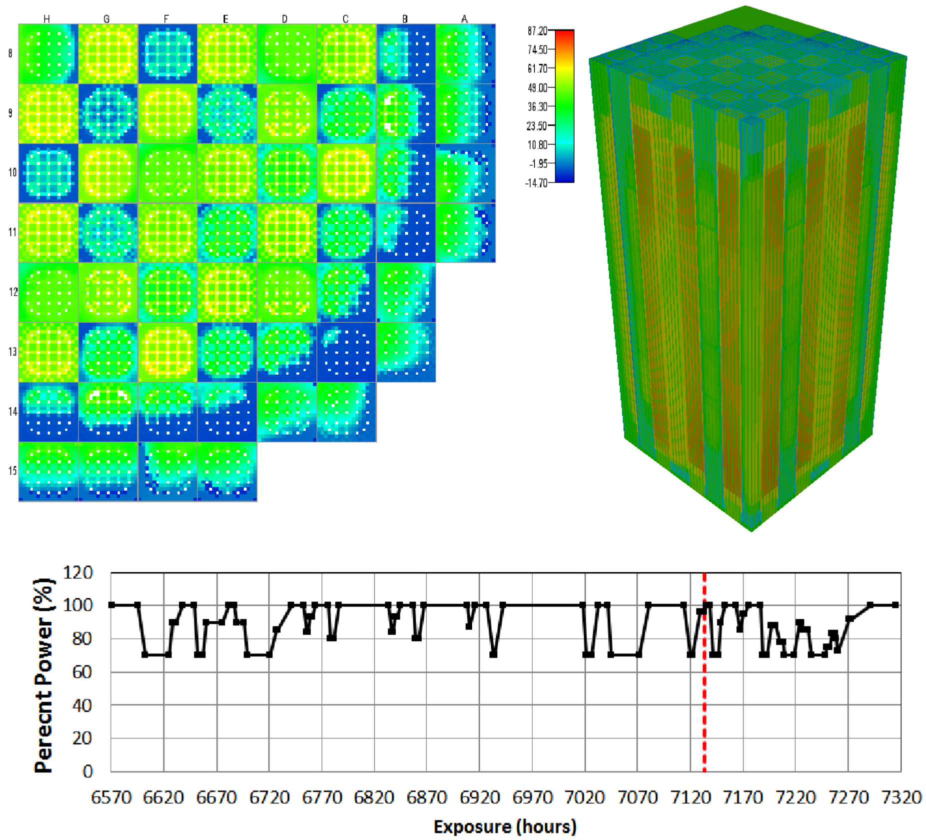
Exposure (hours)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Perecnt Power (%)
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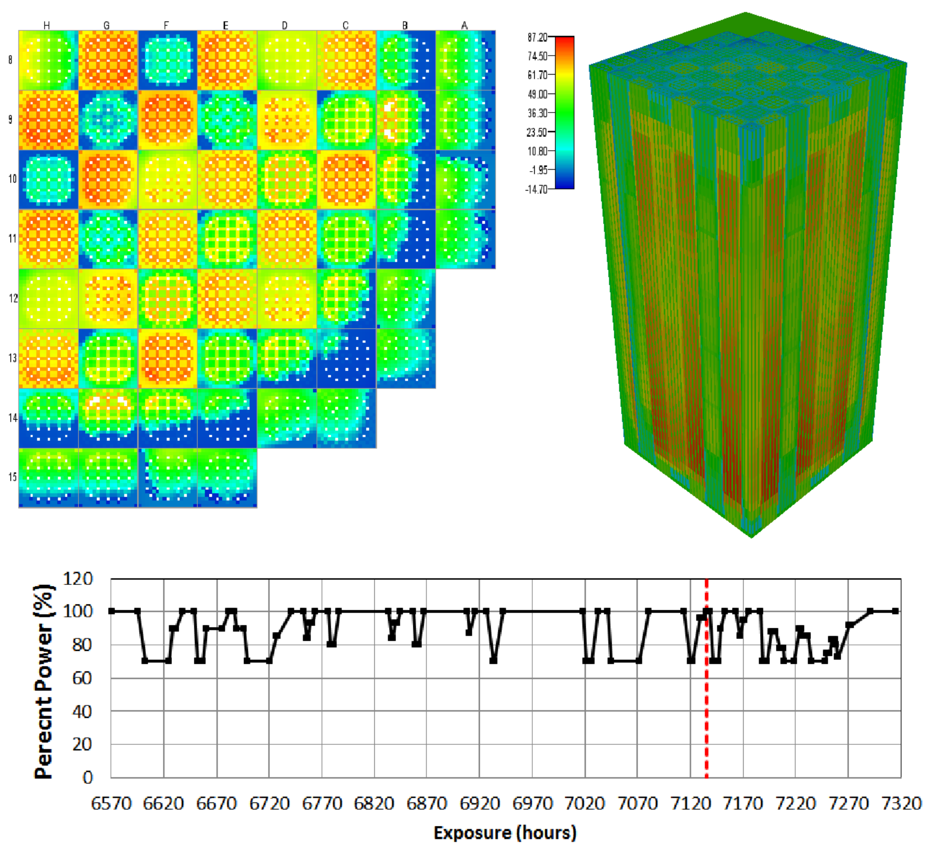
Exposure (hours)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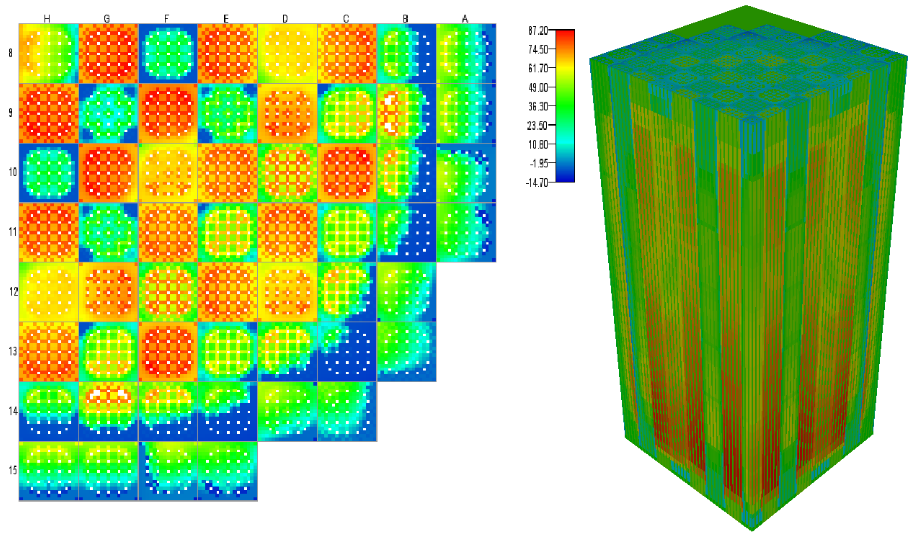
Exposure (hours)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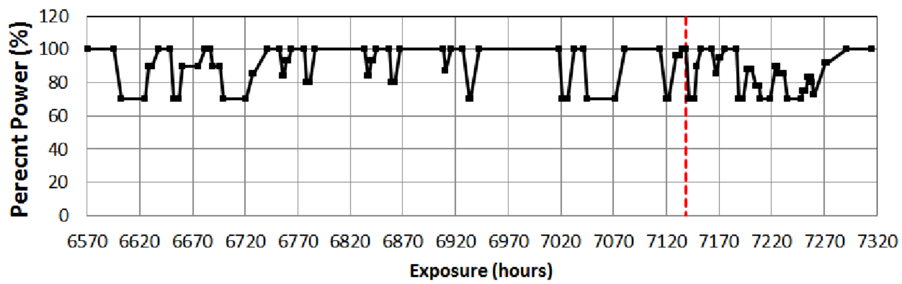
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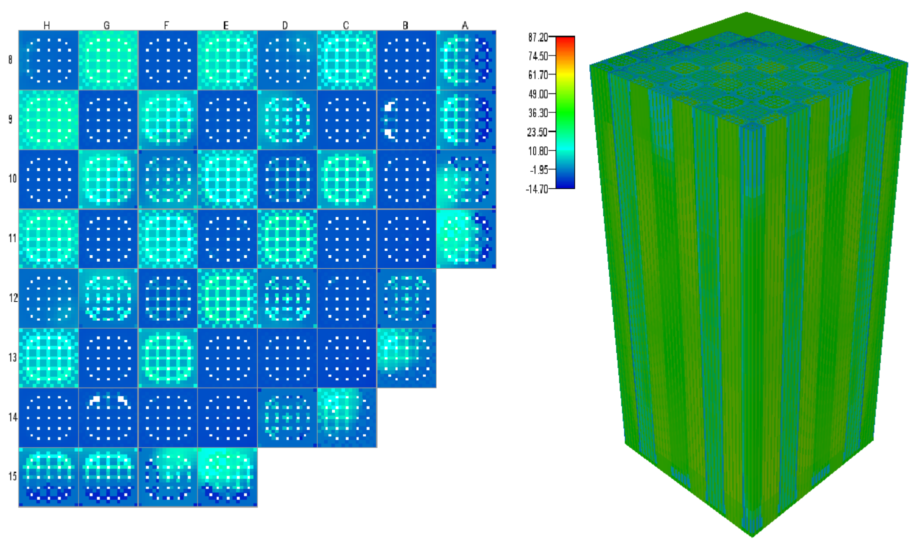
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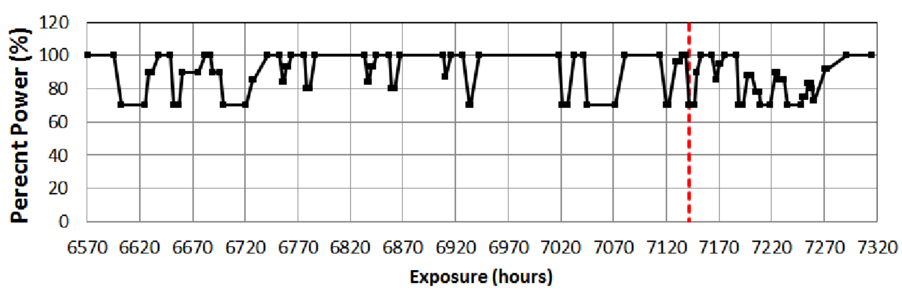
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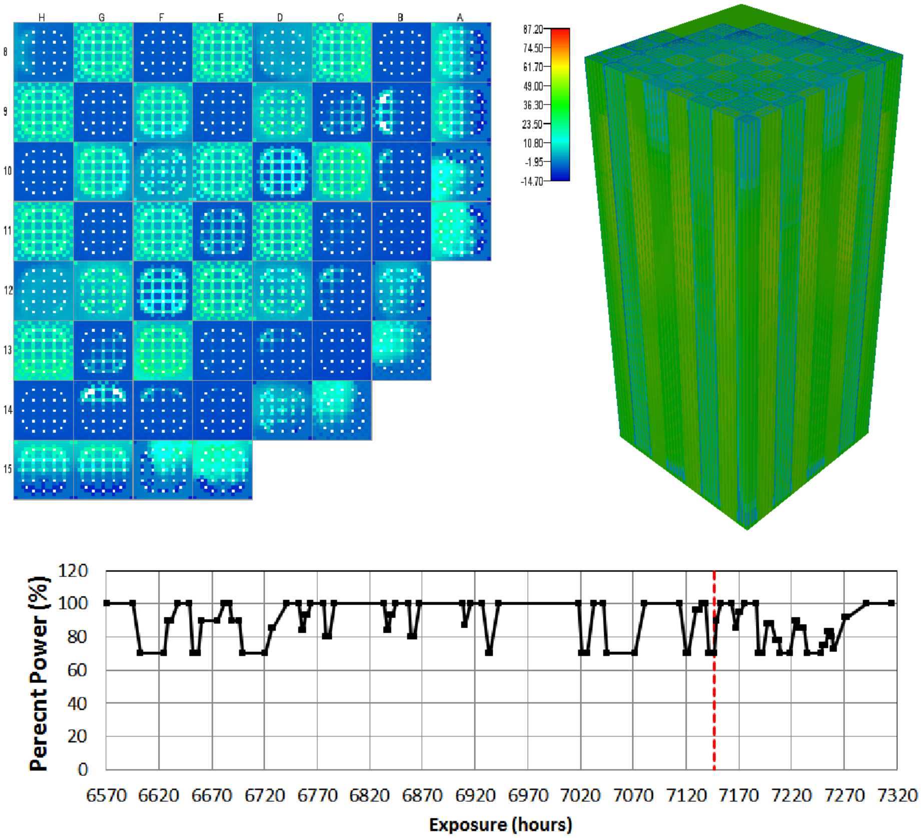
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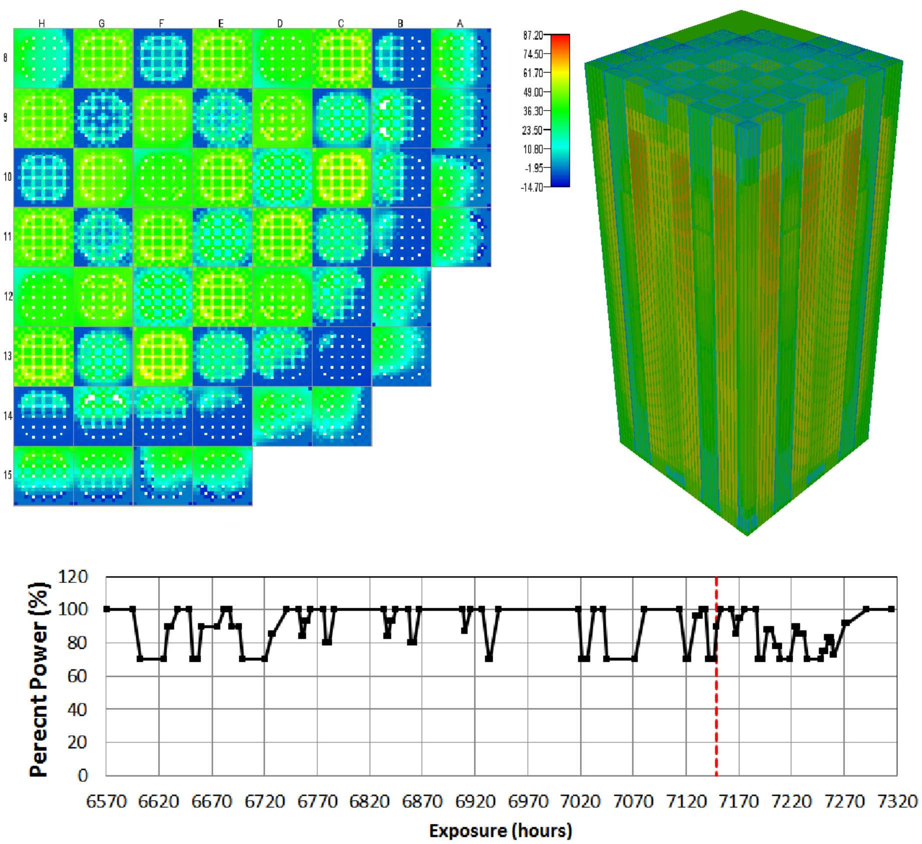
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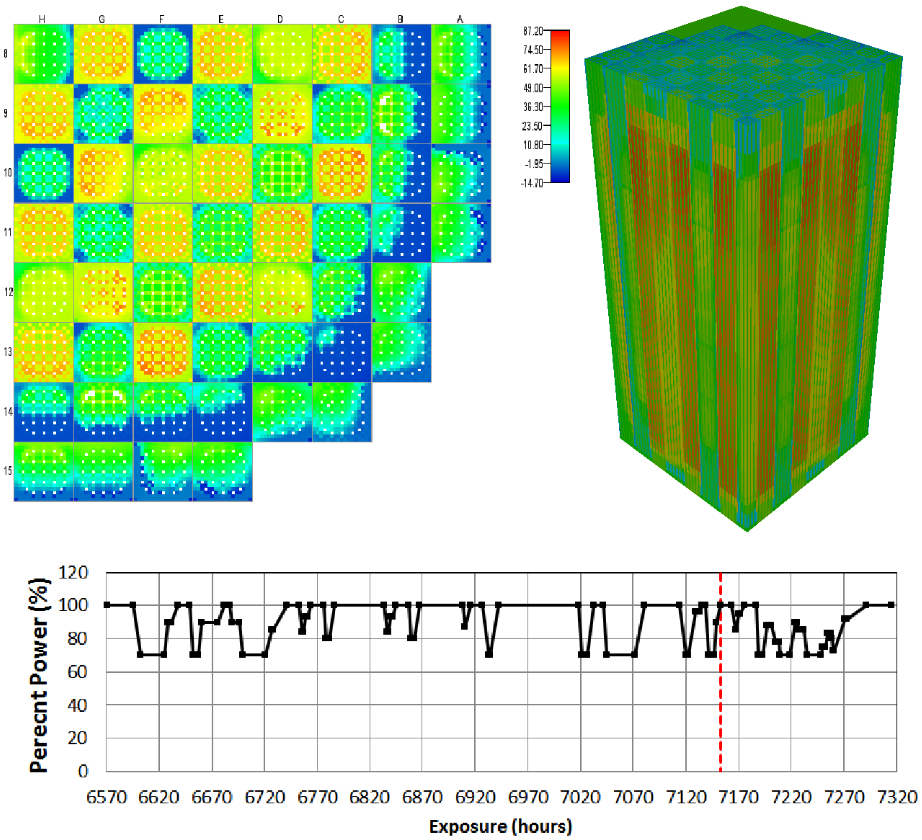
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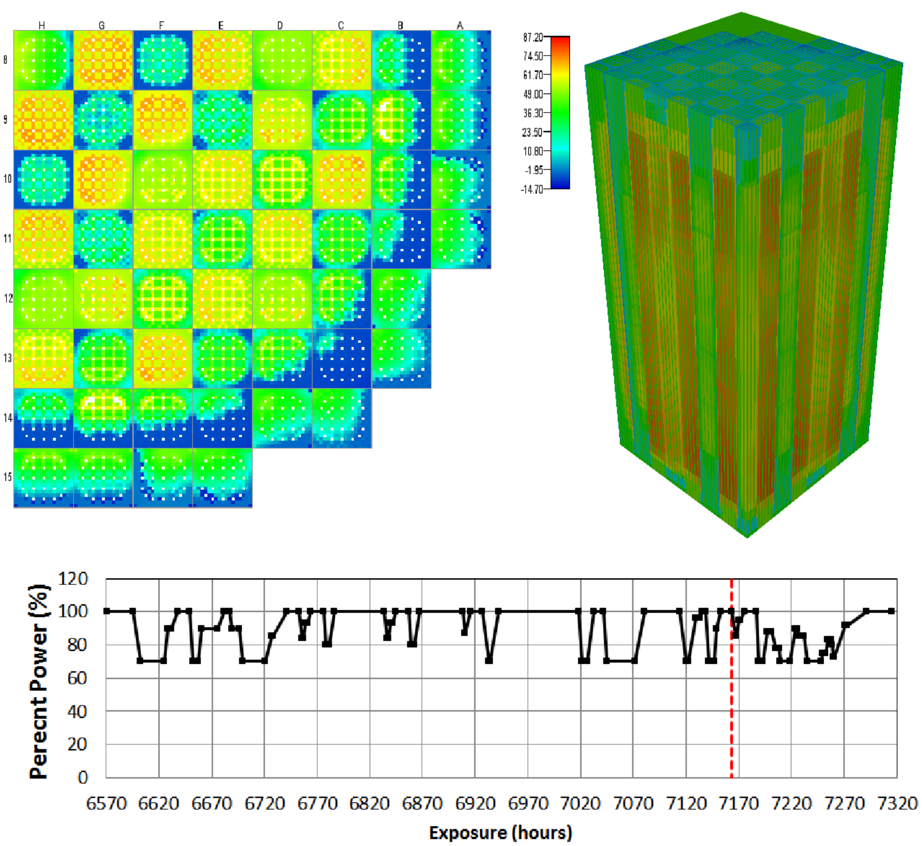
Exposure (hours)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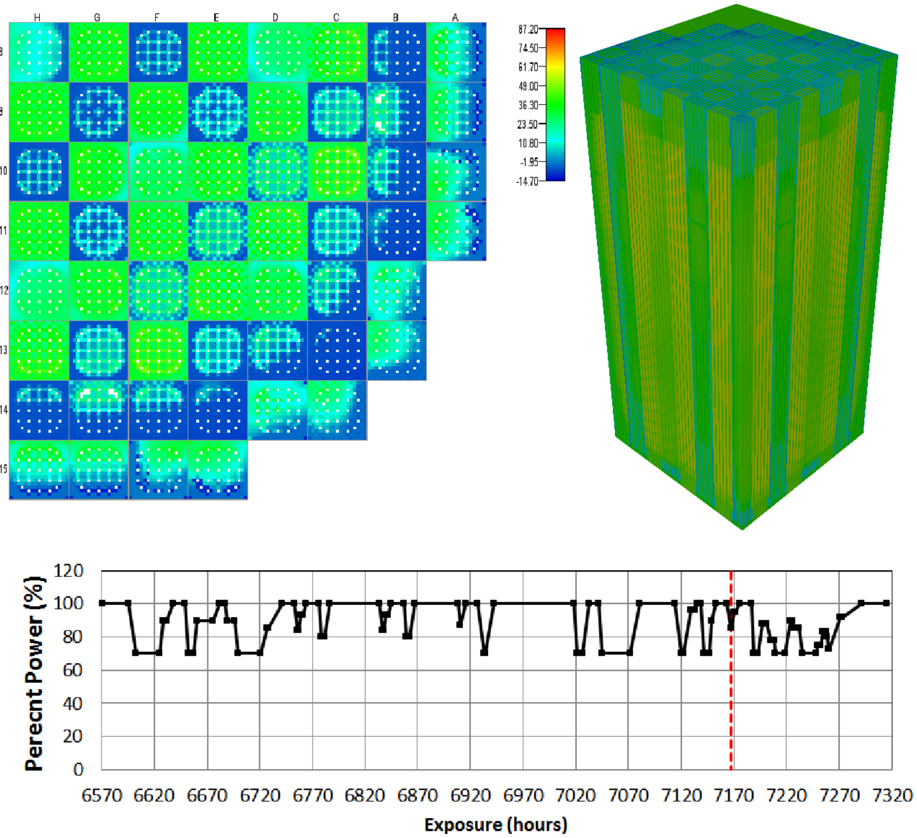
Exposure (hours)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Perecnt Power (%)
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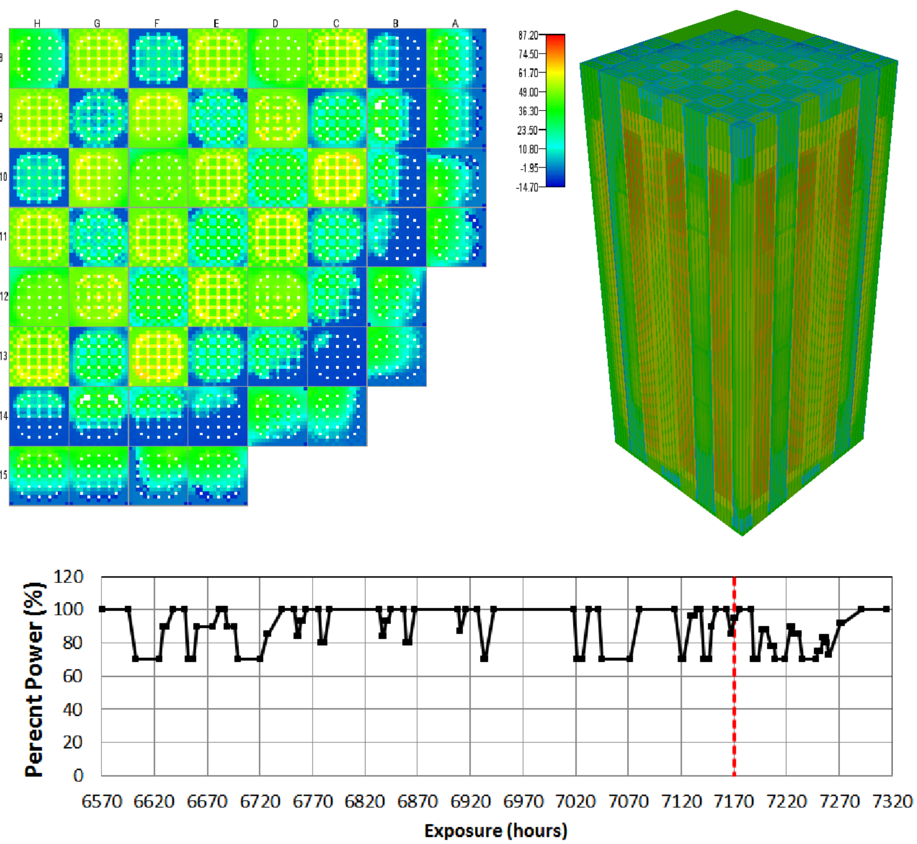
Exposure (hours)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23.50
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120
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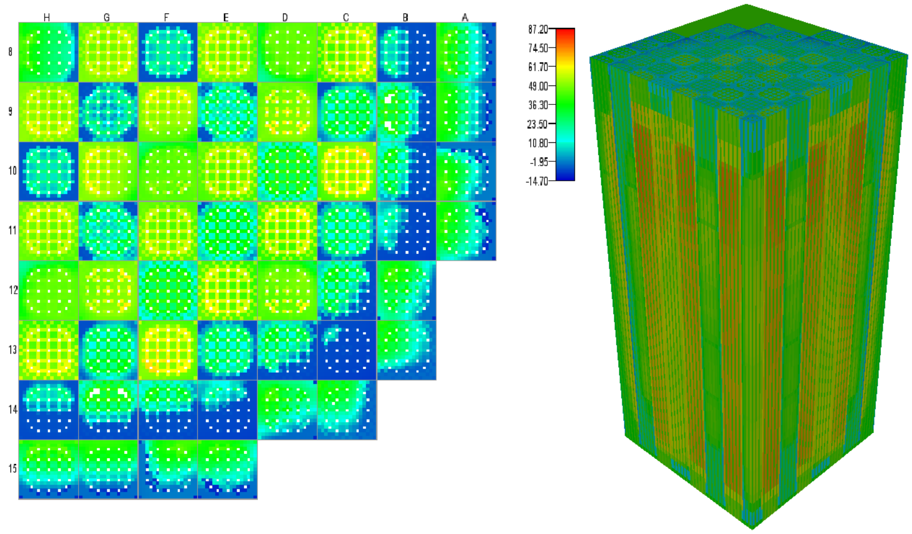
Exposure (hours)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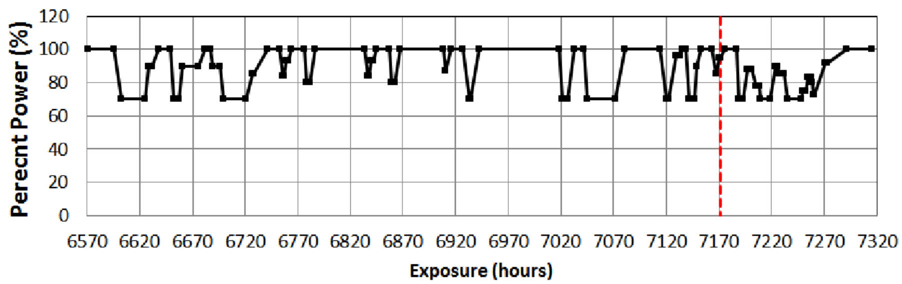
Perecnt Power (%)
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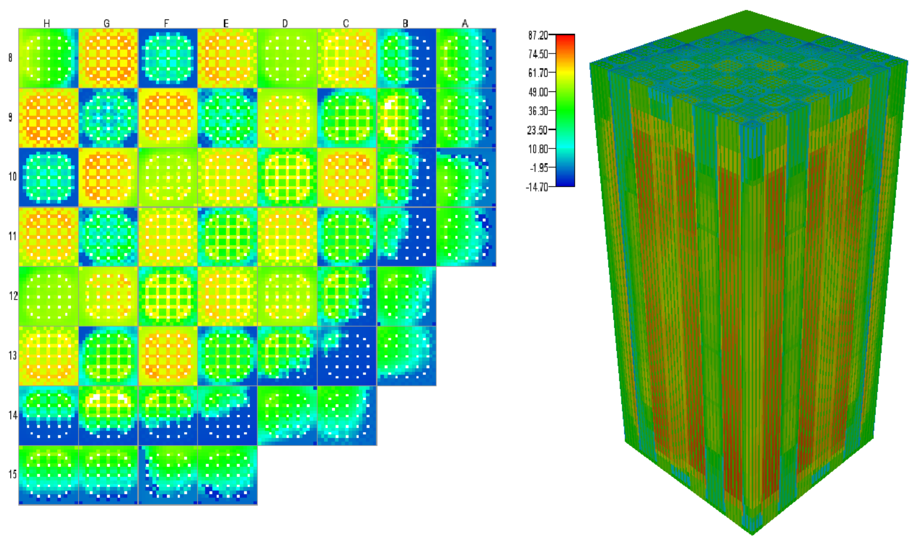
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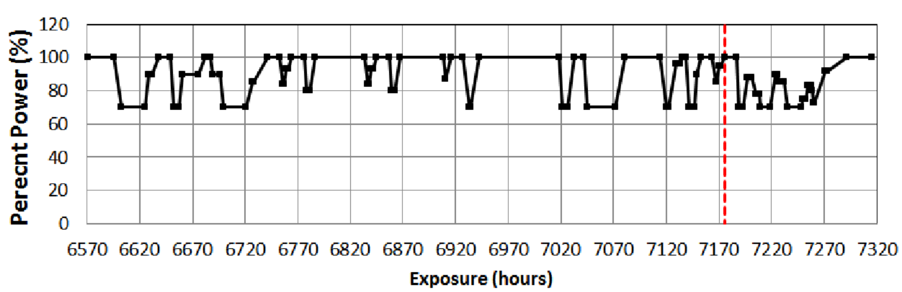
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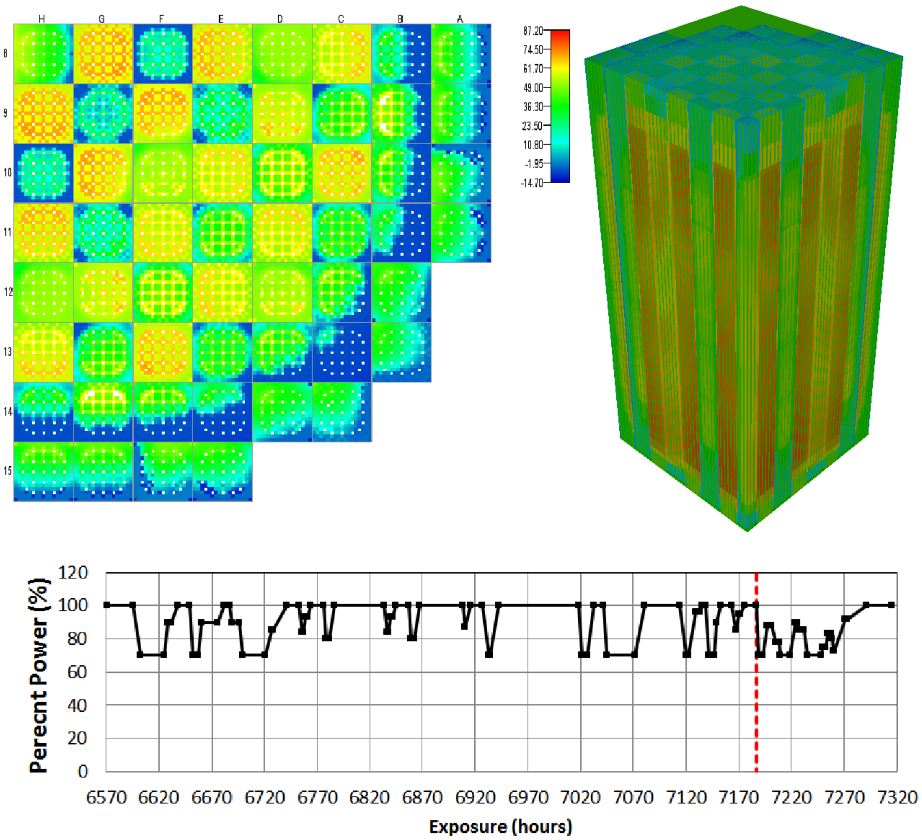
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Perecnt Power (%)
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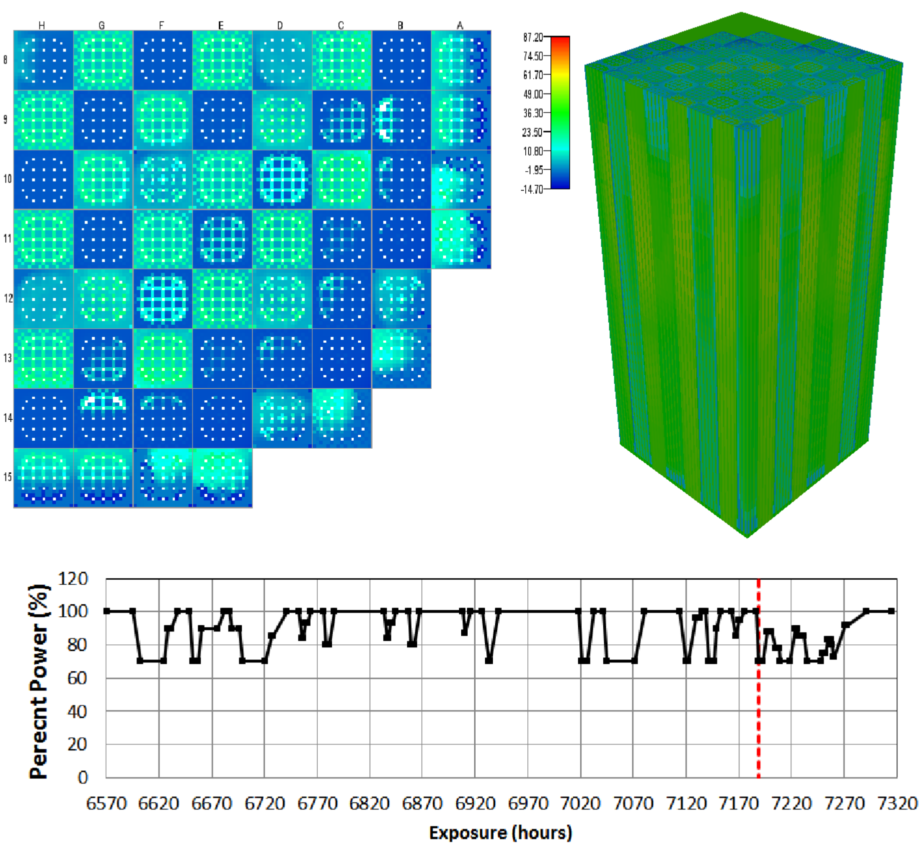
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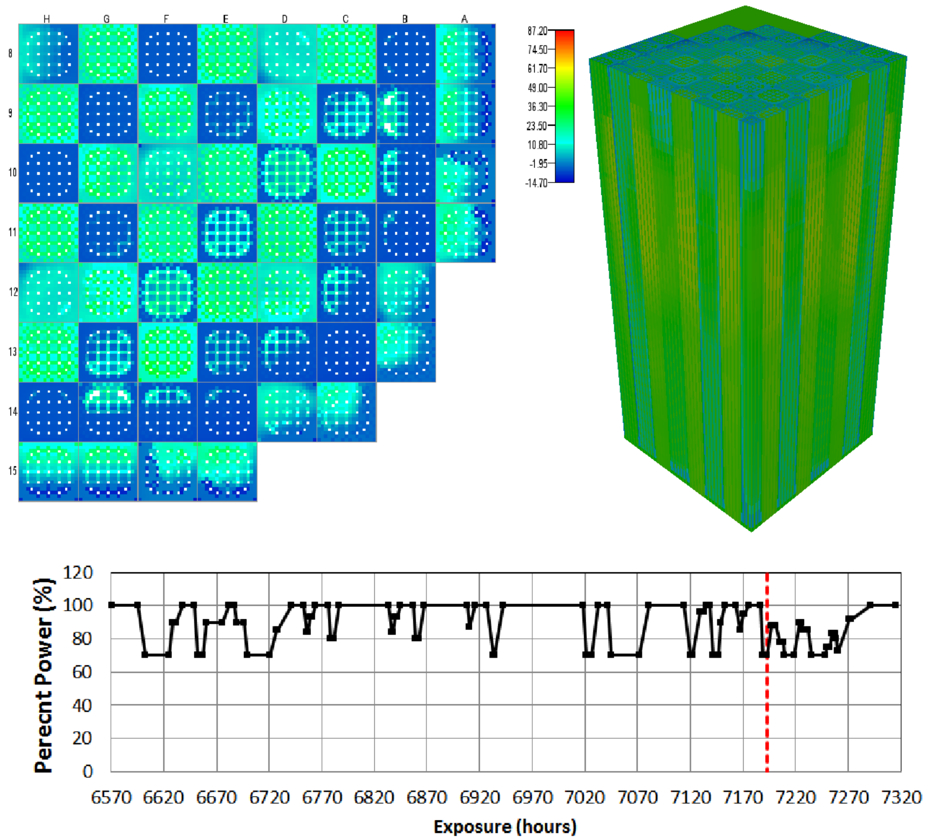
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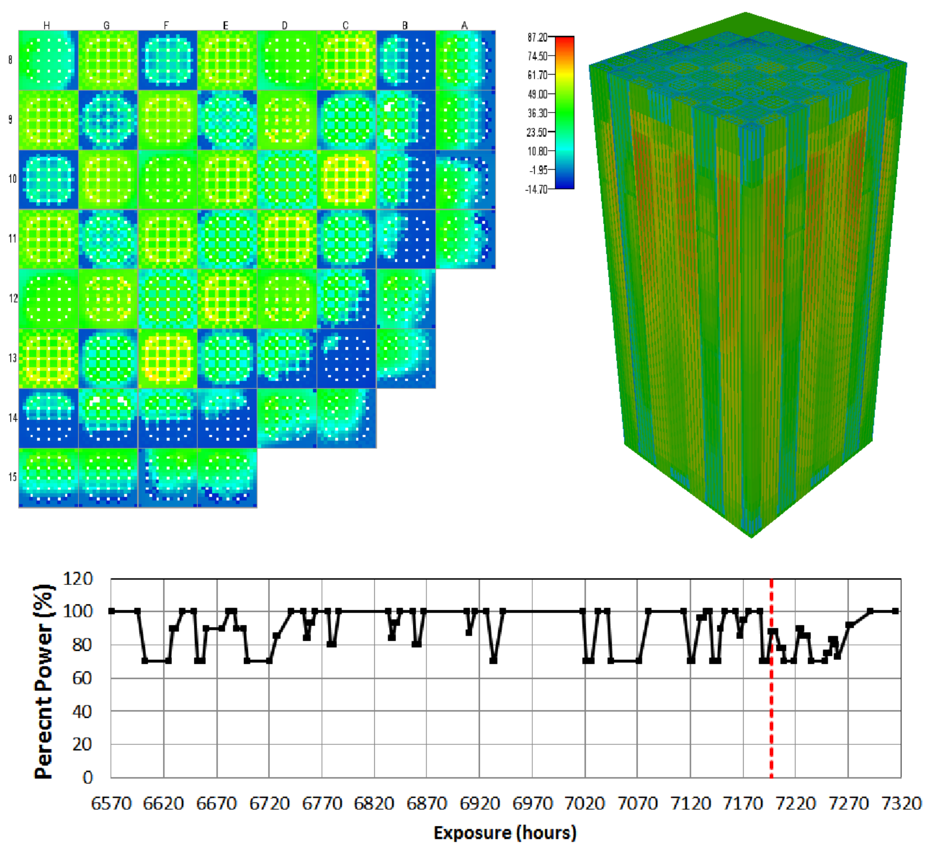
Exposure (hours)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Perecnt Power (%)
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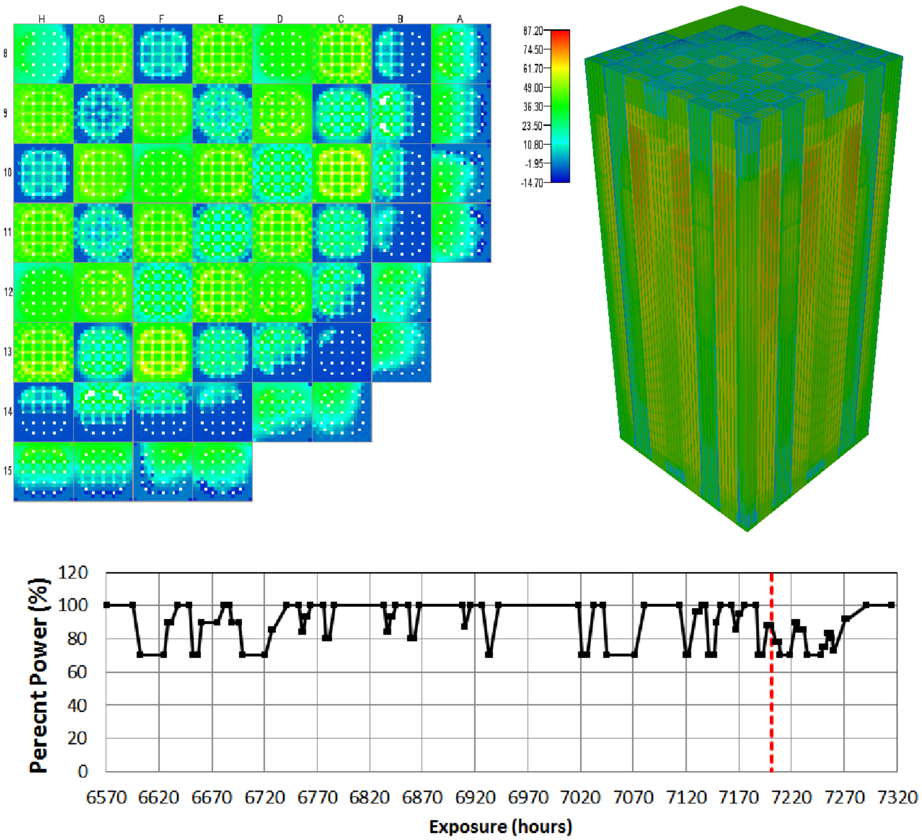
Exposure (hours)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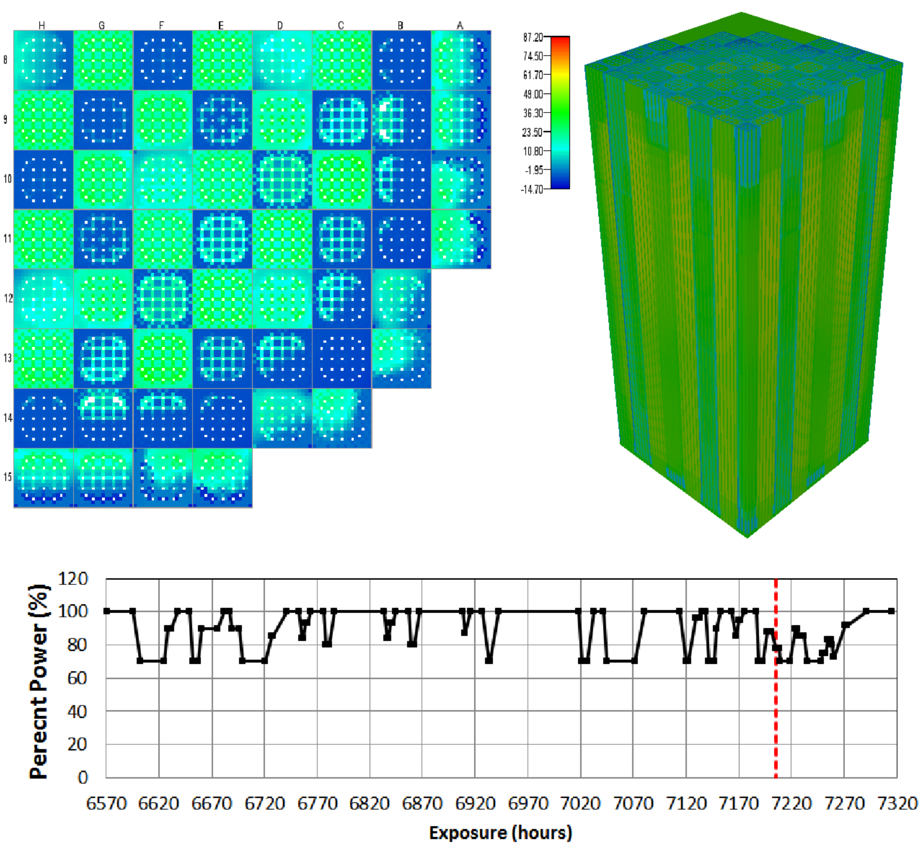
Exposure (hours)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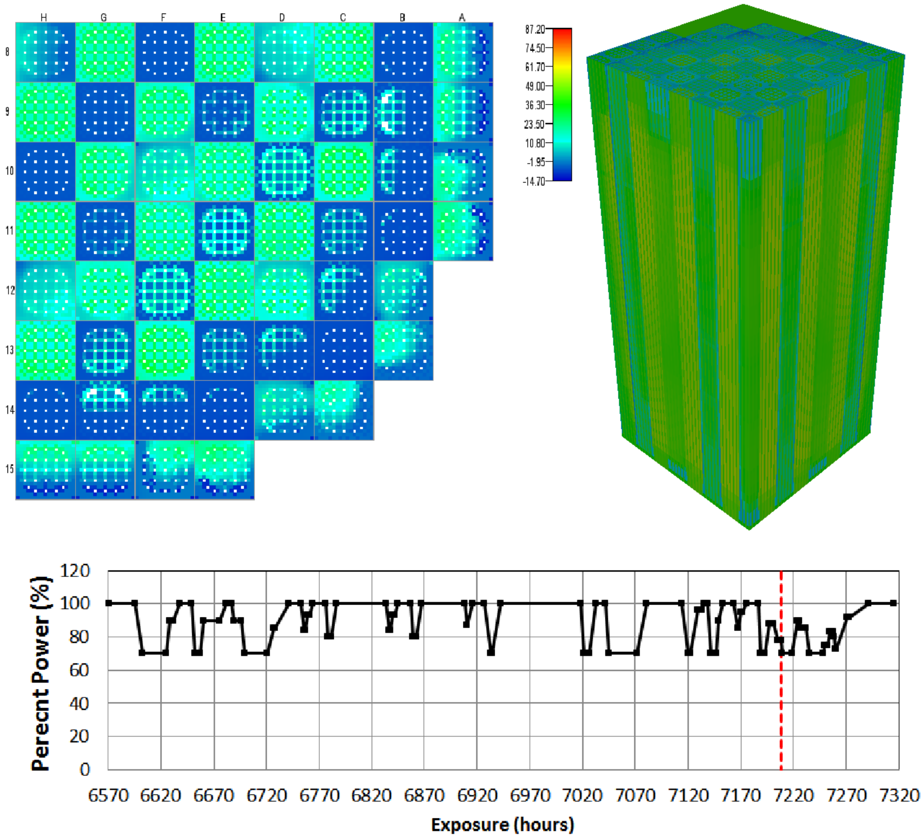
Exposure (hours)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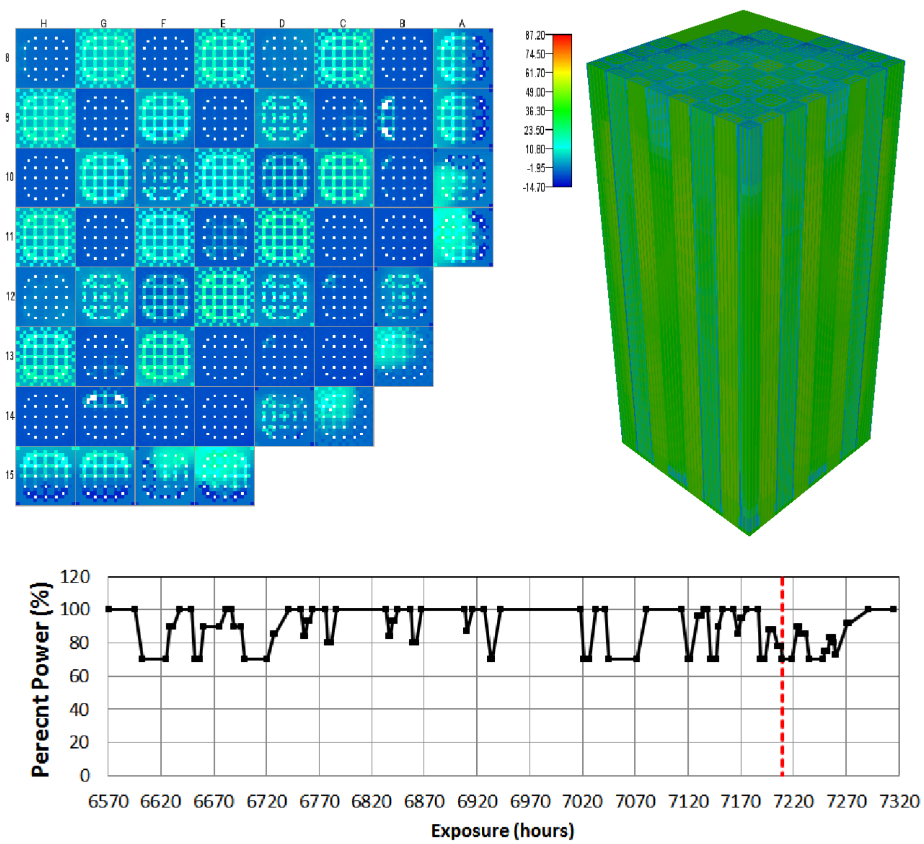
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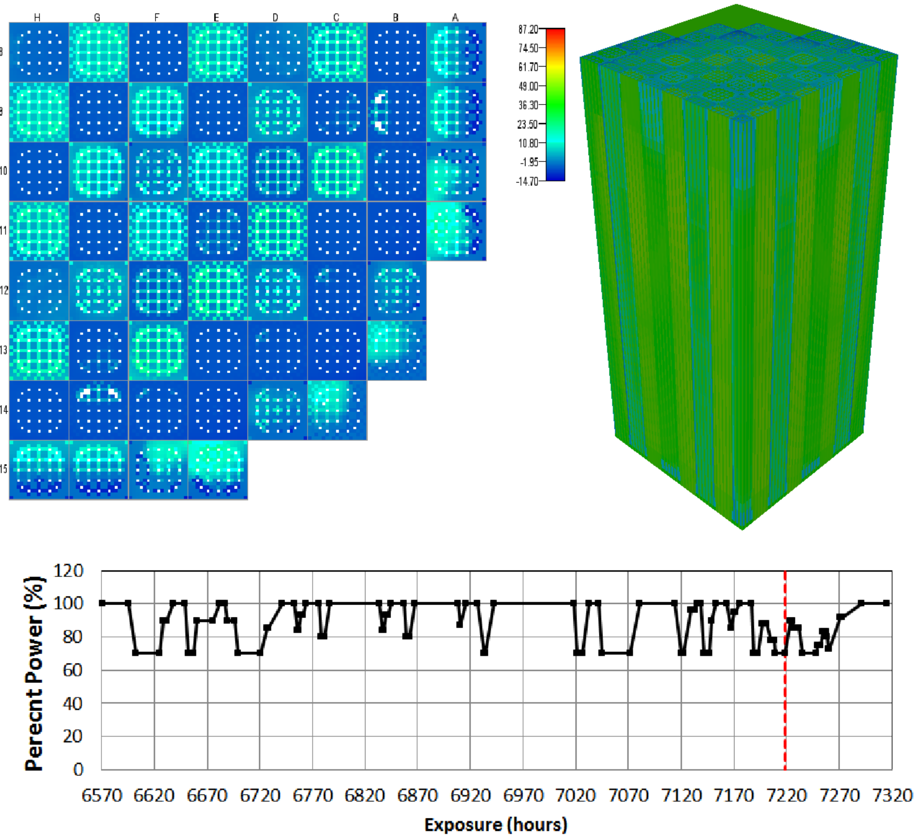
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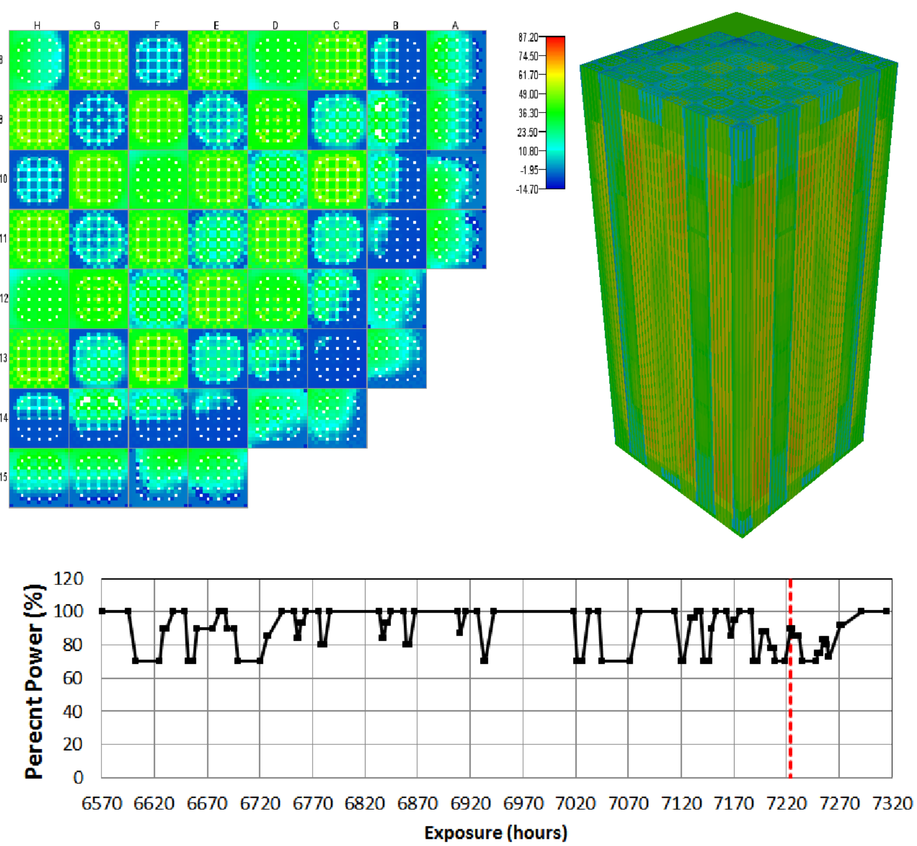
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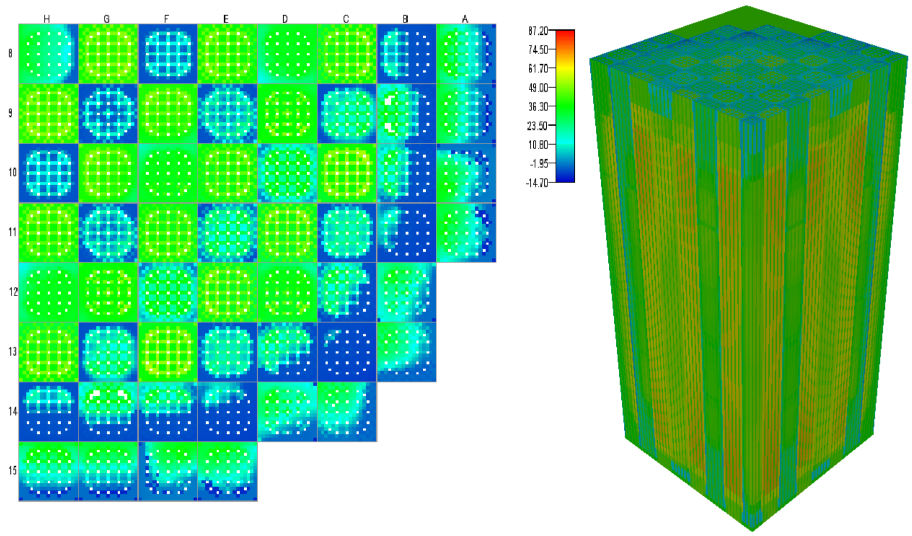
Exposure (hours)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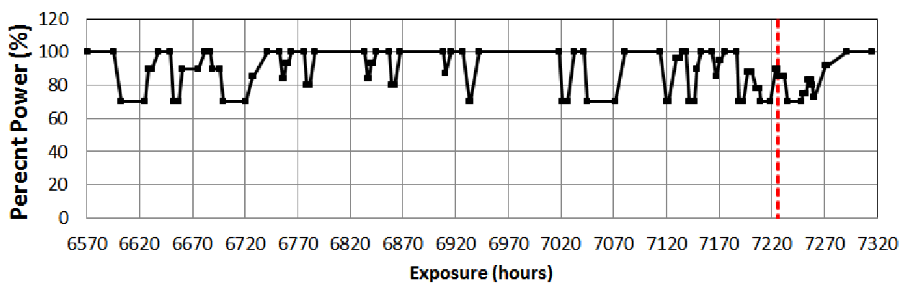
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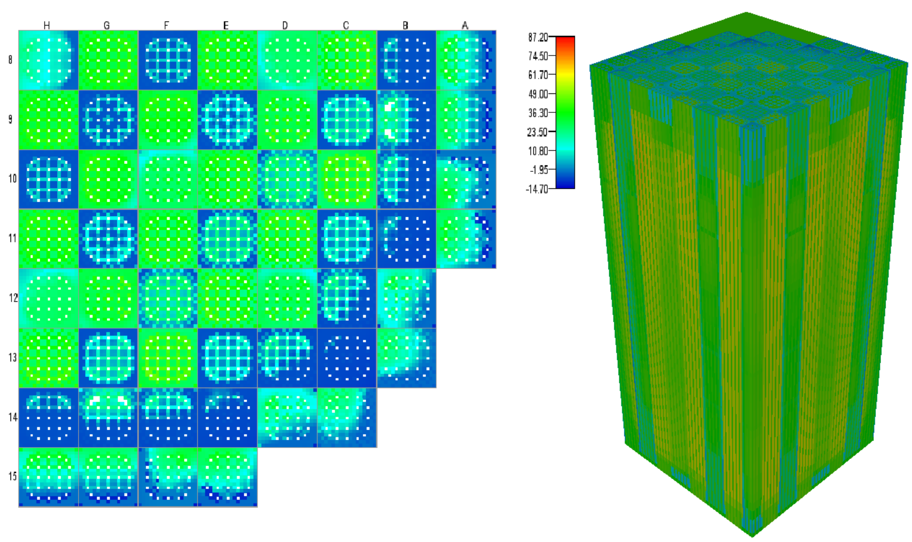
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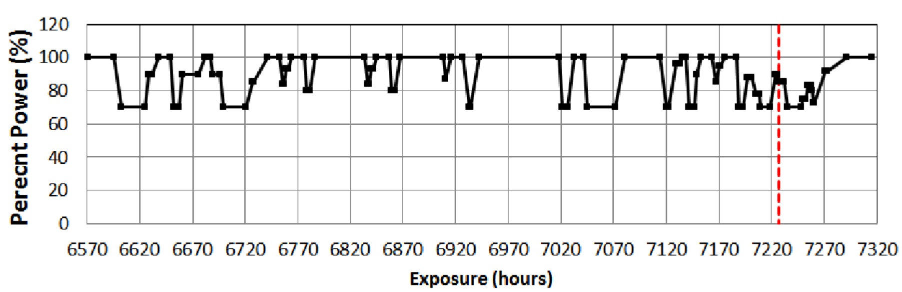
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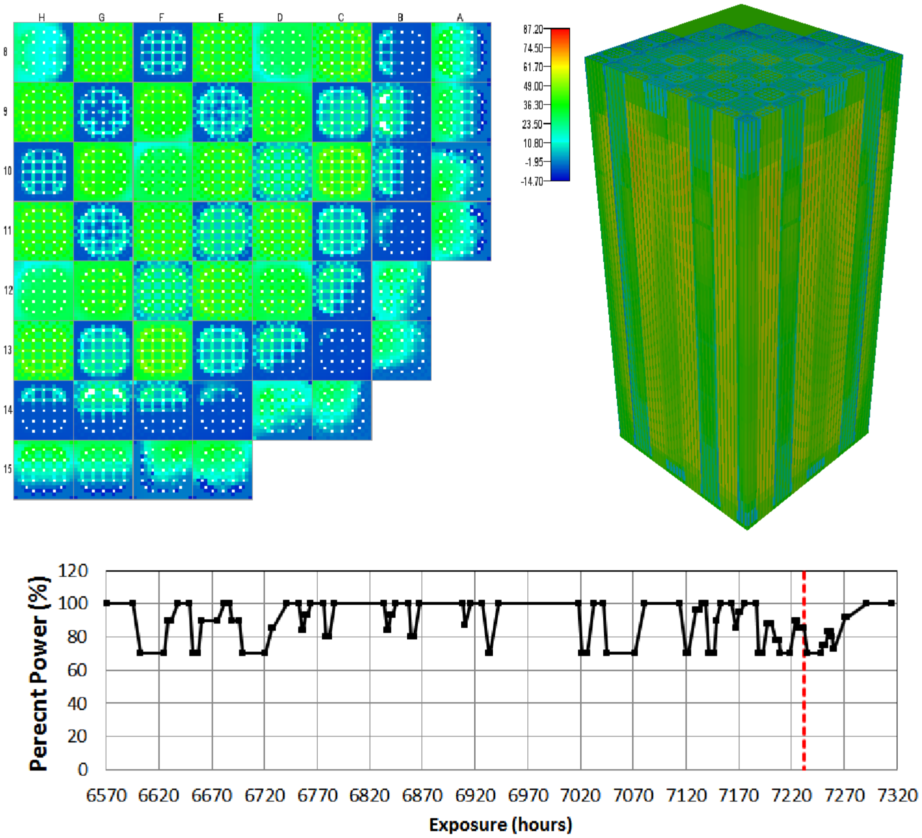
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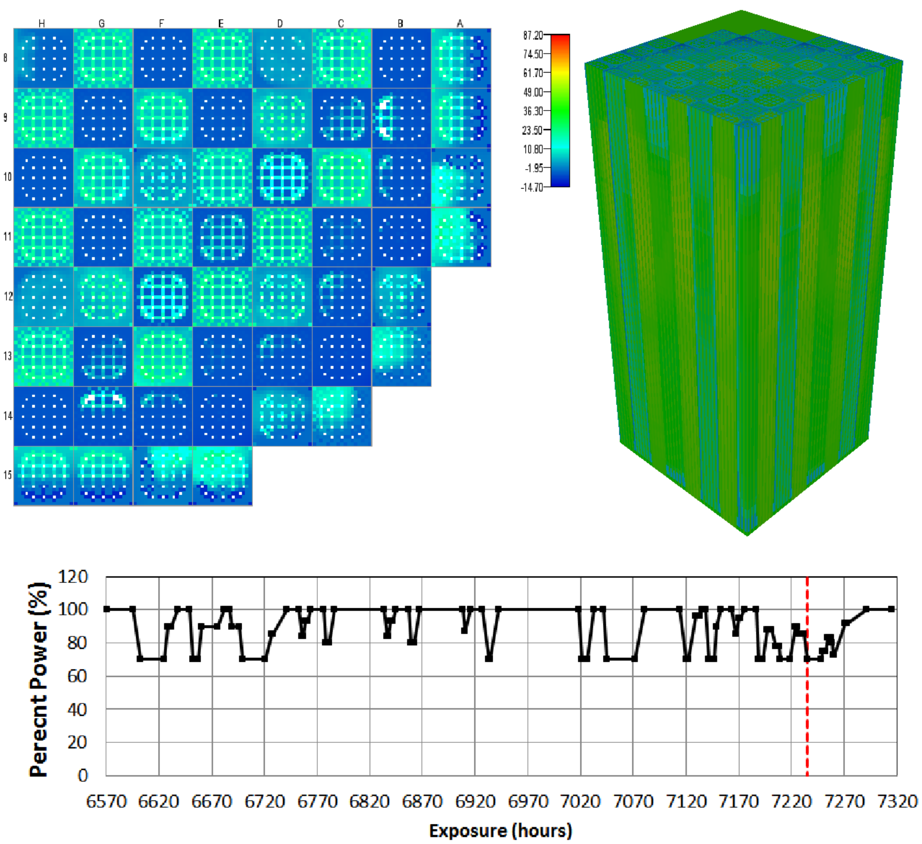
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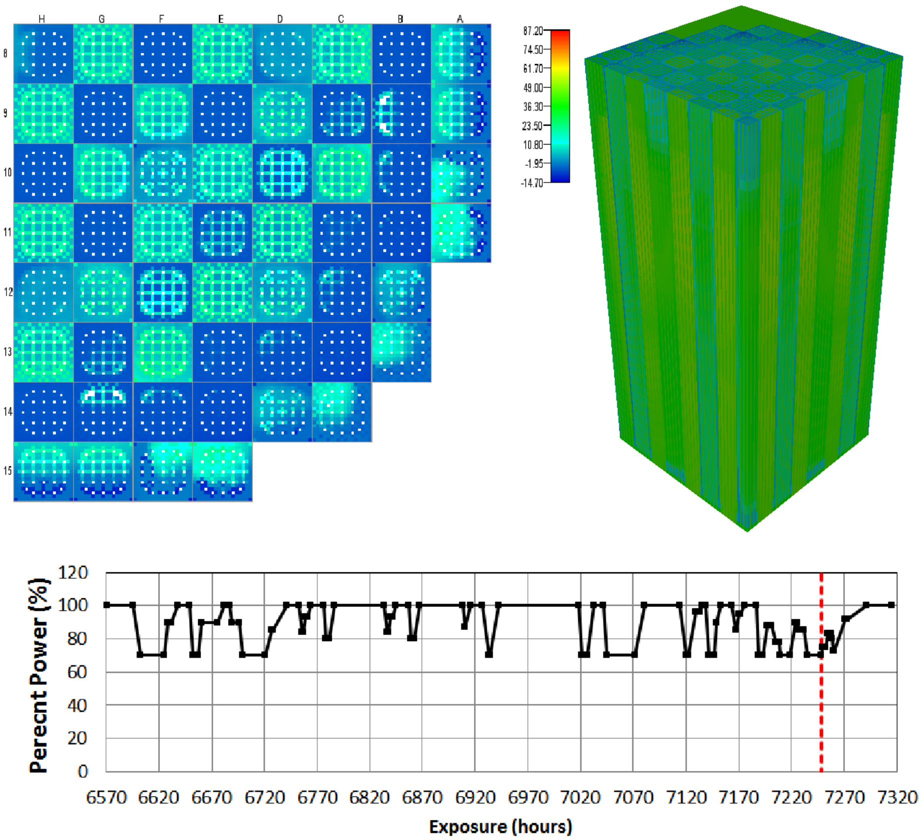
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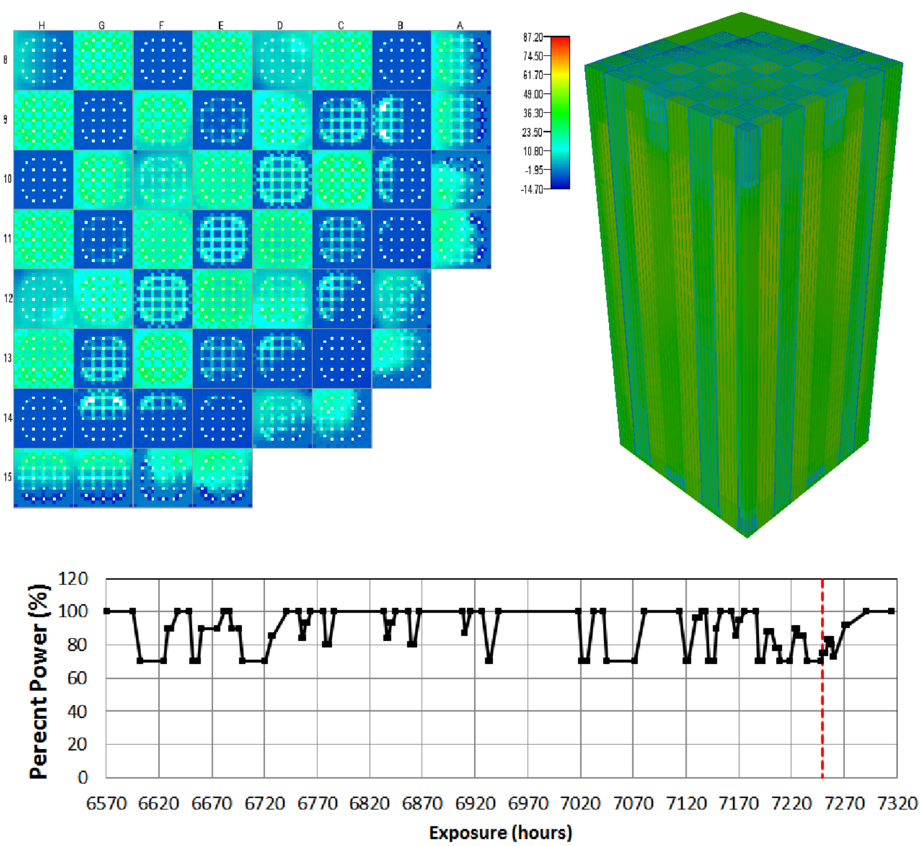
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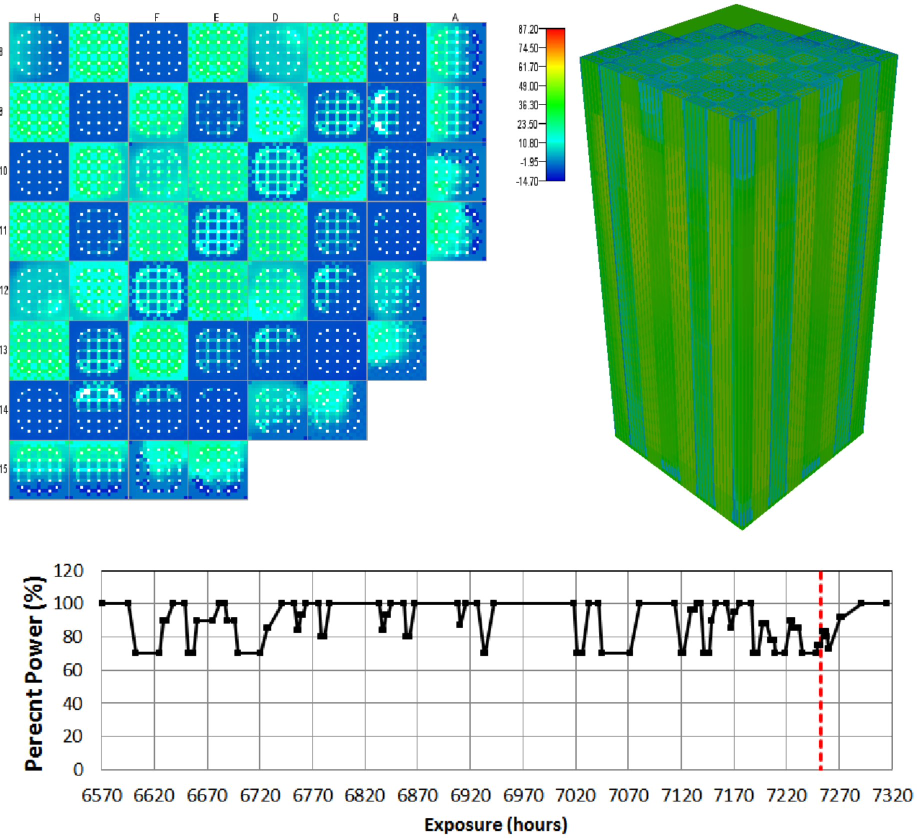
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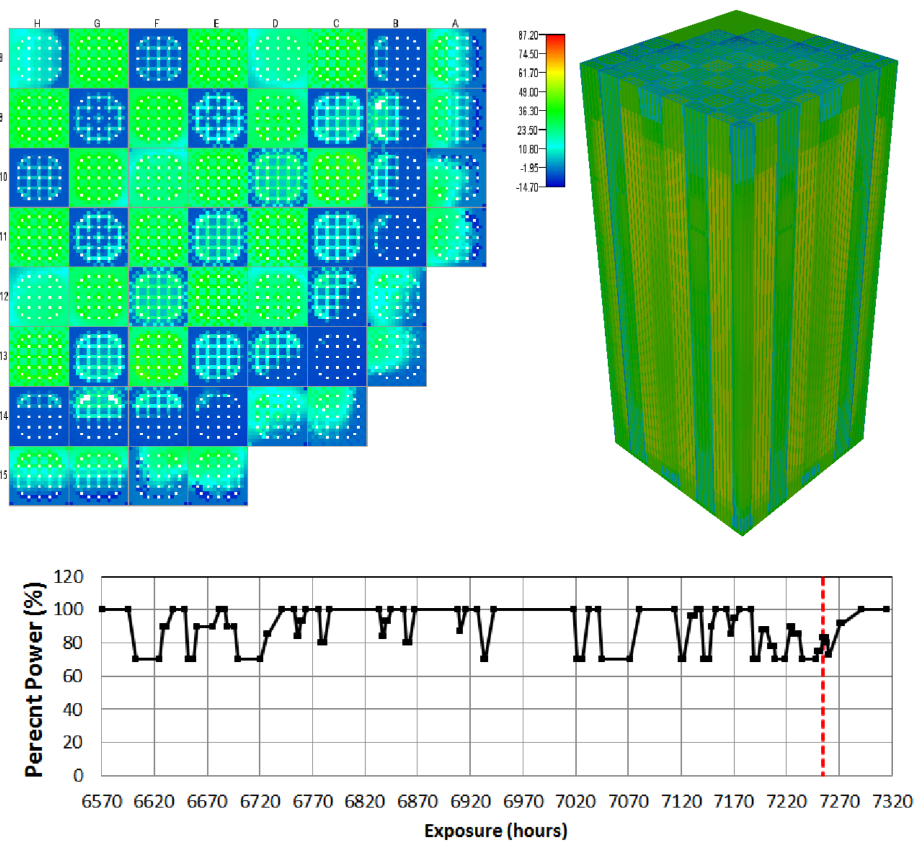
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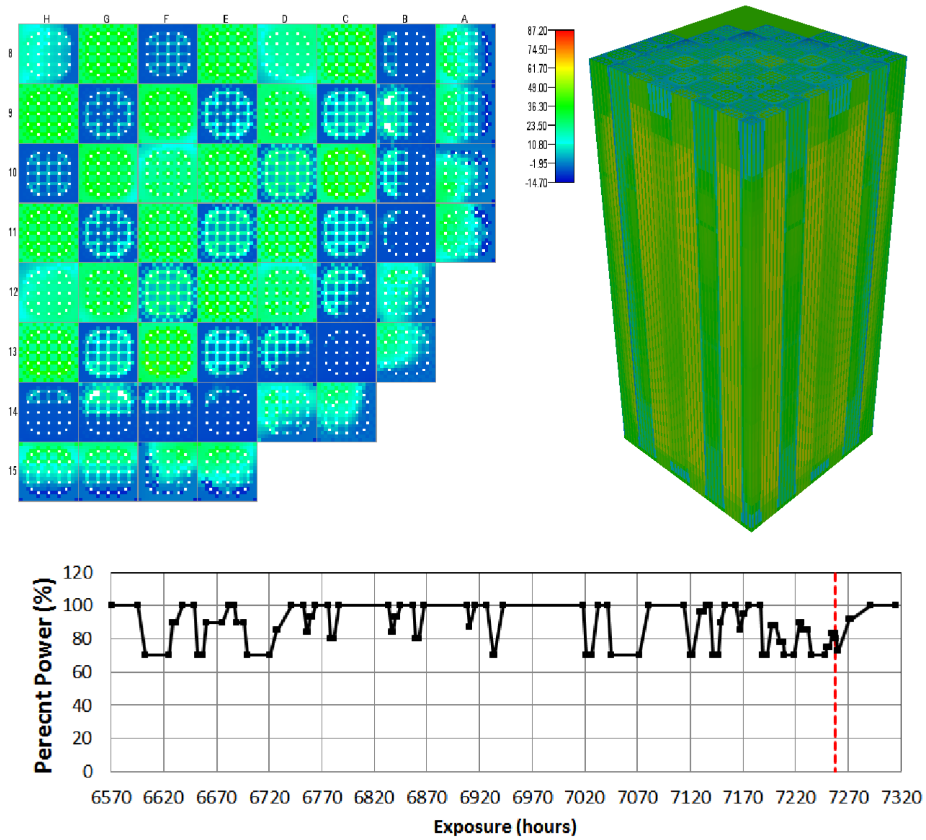
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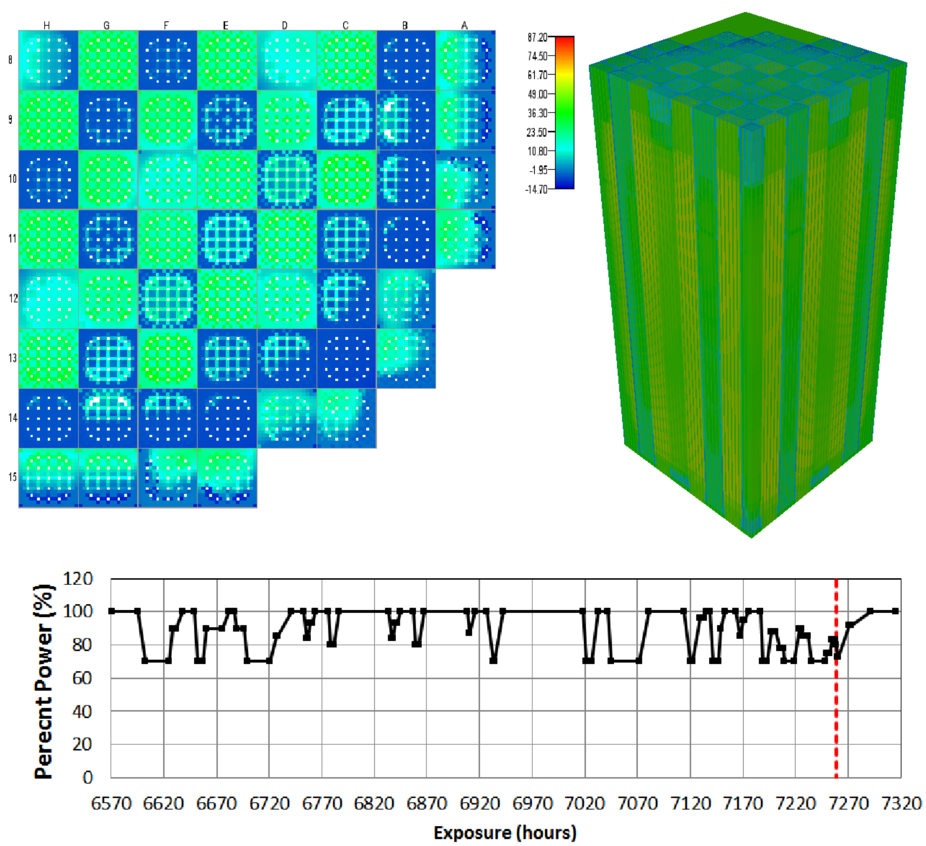
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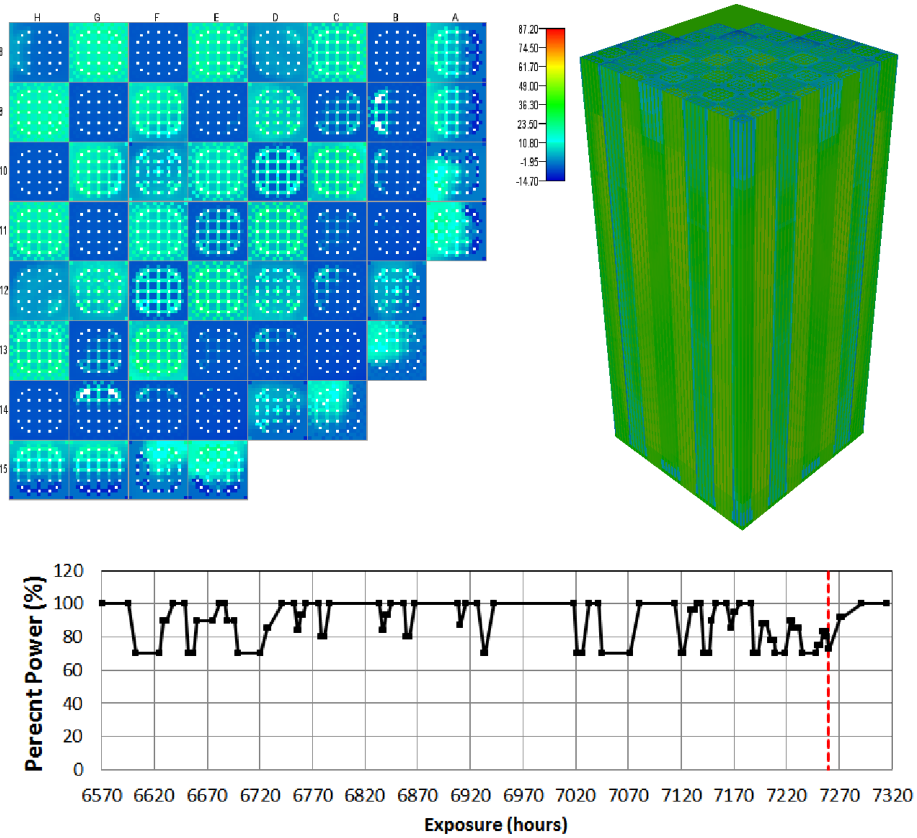
Exposure (hours)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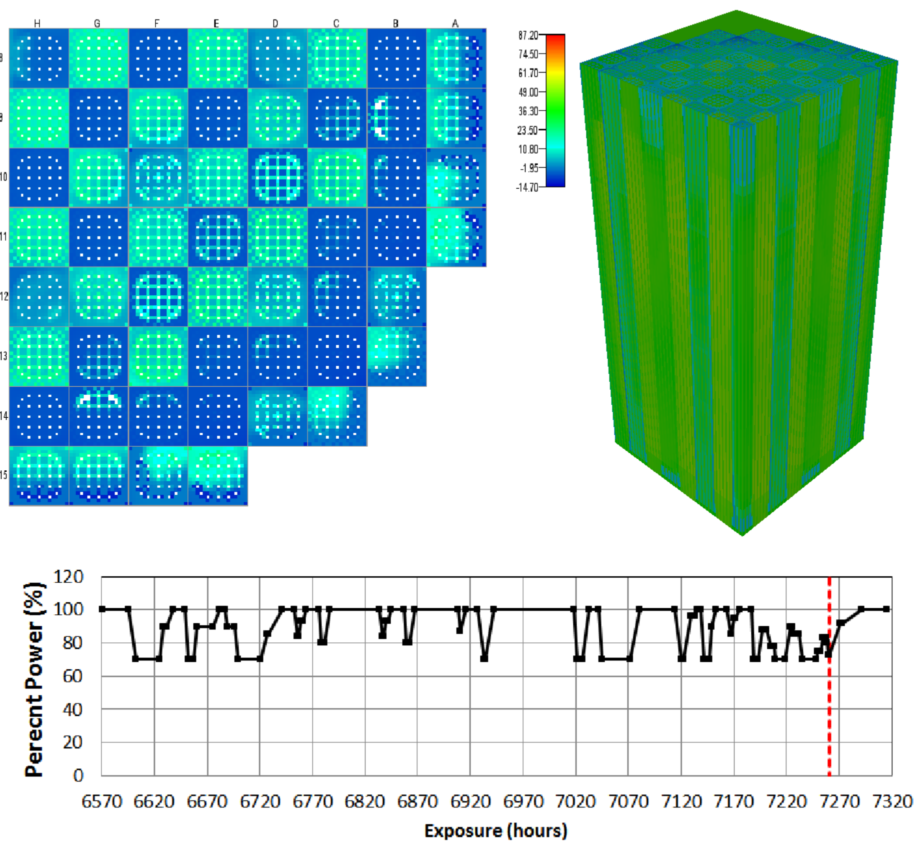
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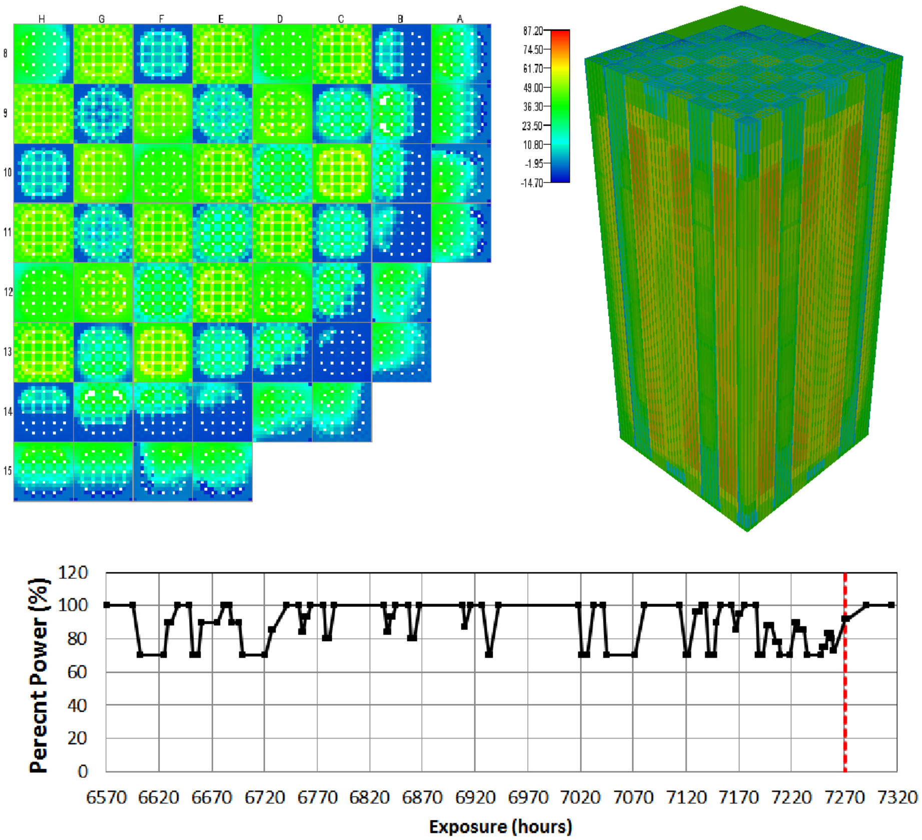
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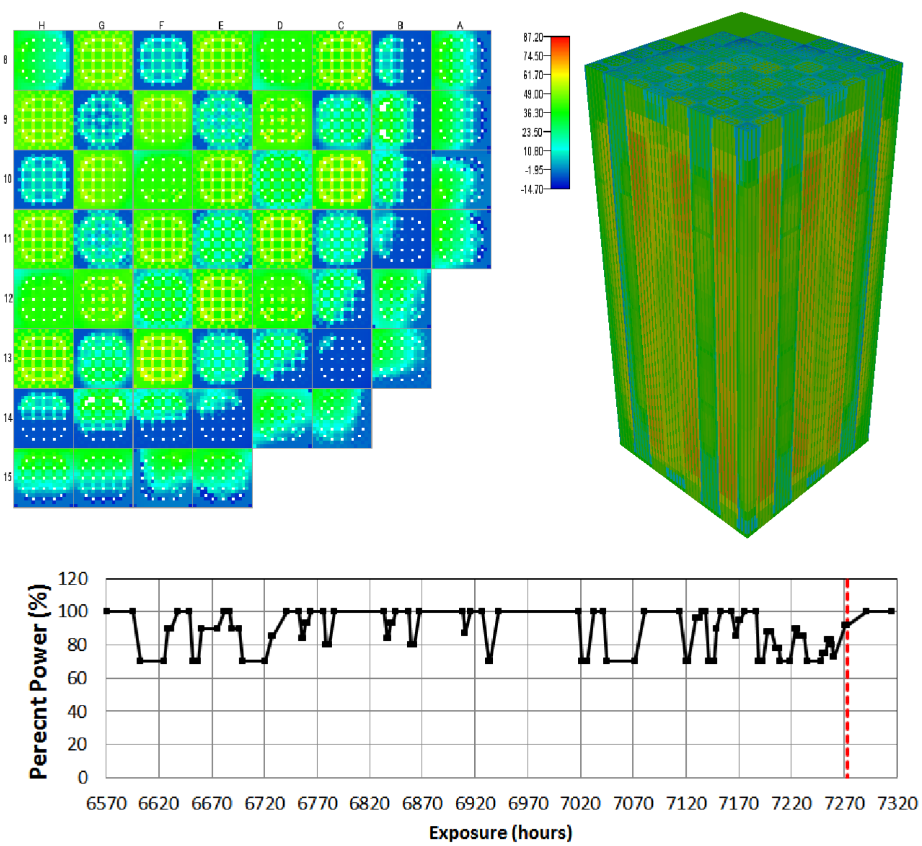
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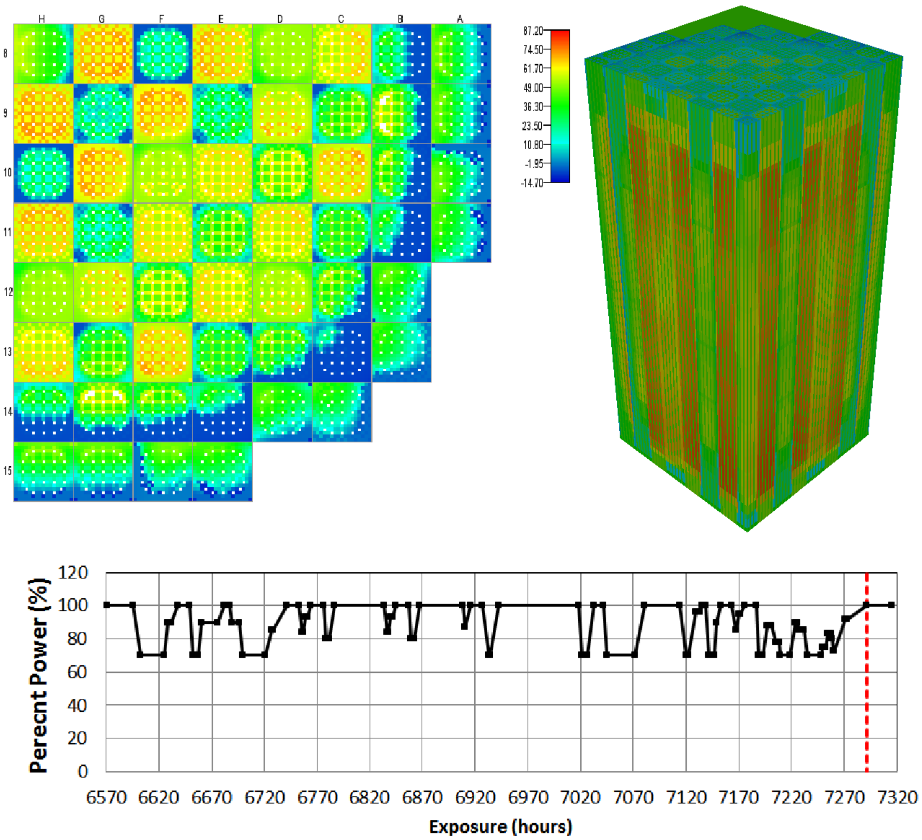
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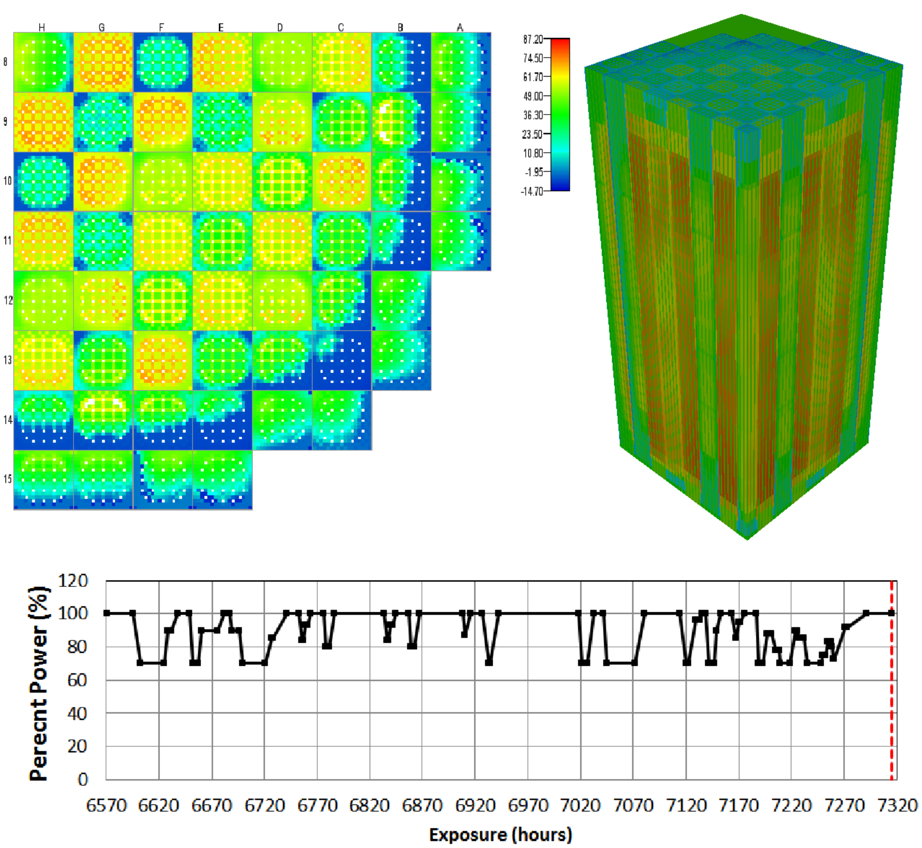
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