Power uprates
and plant life extension

CASL-U-2011-0075-000-a

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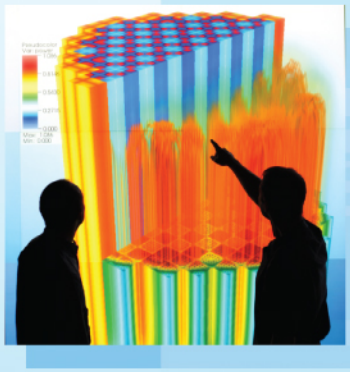


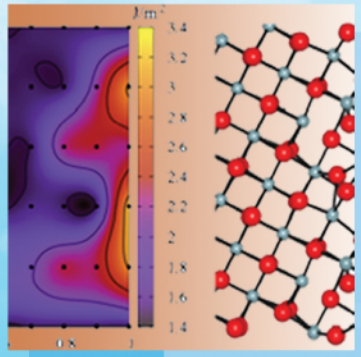
Engineering design
and analysis

L3:RTM.P2.01

Milestone Presentation: Full-core 3D MOC Transport (2D/1D, Pin-resolved) Capability with T-H Coupling

Science-enabling
high performance
computing

Thomas Downar, RTM/University of Michigan
Brendan Kochunas, RTM/University of Michigan
Robert Brewster, CD-adapco
Emilio Baglietto, THM/CD-adapco



Fundamental science

June 30, 2011

Plant operational data

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

RTM.P2.01: Full-core 3D MOC transport (2D/1D, pin-resolved) capability with T-H coupling

Prof. Thomas Downar, RTM/University of Michigan

Brendan Kochunas, RTM/University of Michigan

Robert Brewster, THM/CD-adapco

Emilio Baglietto, THM/CD-adapco

CASL-U-2011-0075-000-a

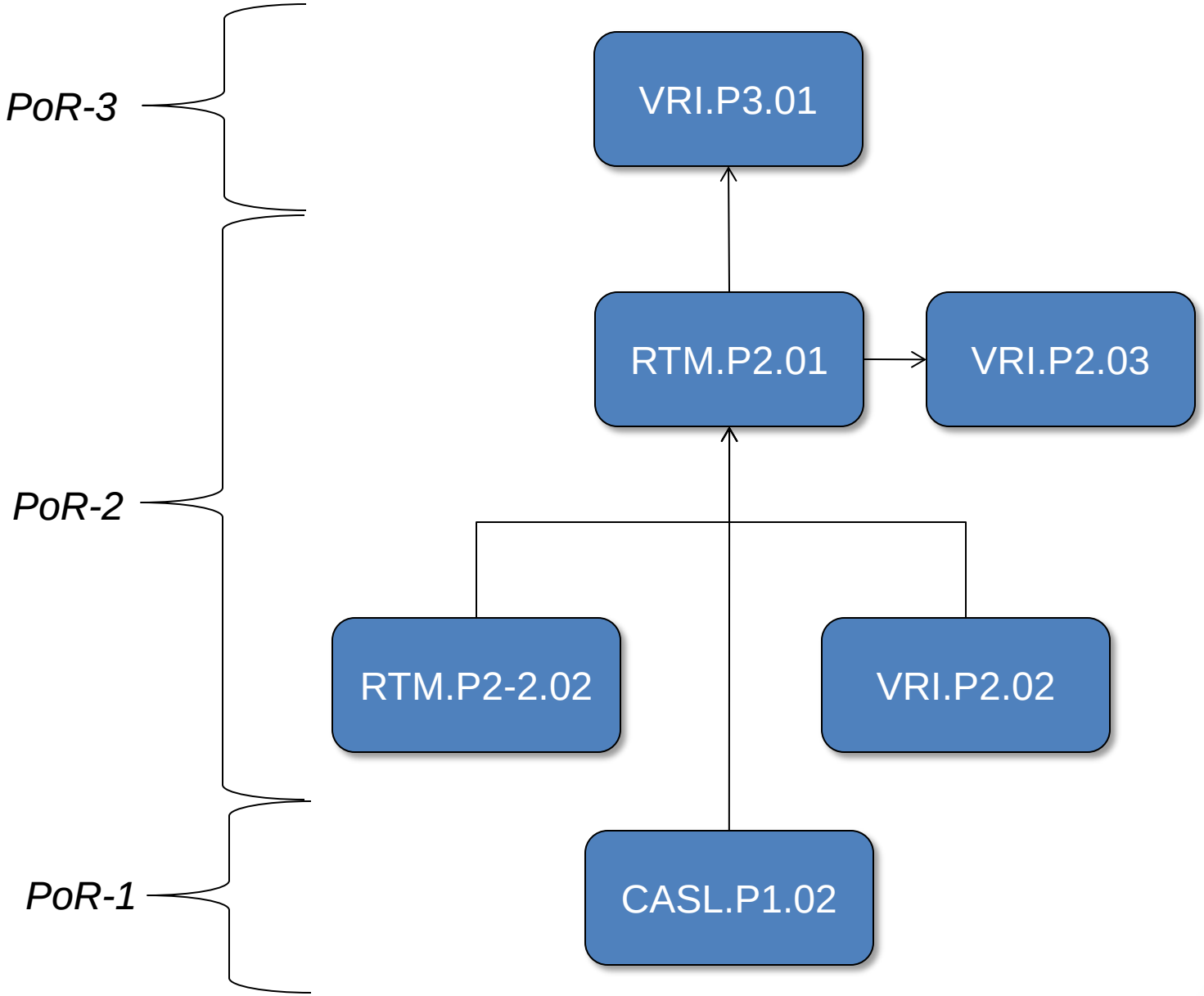
Milestone Execution Responsibility & Personnel

- Prof. Tom Downar (UMich) is point of contact and managed overall execution of milestone.
- Brendan Kochunas (UMich) was primarily responsible for developing the core design, running the coupled calculation, and preparing results.
- Dr. Robert Brewster (CD-adapco) was responsible for supplying CFD models and technical support to Brendan as needed.
- Dr. Emilio Baglietto (CD-adapco) was responsible for managing activities within CD-adapco to insure the necessary support was provided and also gave expert feedback on results

Milestone Description

- Specific: objective is the delivery of the capability to perform a 3D, full-core transport (2D MOC + 1D nodal diffusion) calculation with single phase T/H coupling. The fuel pins will be resolved radially, azimuthally, and axially.
- Measurable: Comparisons to coupled models using low-order T/H feedback begin to quantify feedback effects
- Attainable: DeCART/STAR-CCM+ coupling has been demonstrated previously on single assembly problems.
- Relevant: Demonstration of extended capability to perform large scale high-fidelity coupled calculations; a key CASL goal.
- Timely: Significant capability demonstrated after just one year. Full-core transport/CFD has not been previously demonstrated.

Milestone Linkages



Milestone Execution Plan and Technical Approach

- Model Specification (3/1 – 5/1)
  - Geometry defined by existing CFD mesh
  - Core inlet T/H conditions also provided by CD-adapco
  - Leveraged a significant amount of pre-existing work.
  - Specifications of neutronic core design developed from scratch
  - Estimated effort: 0.5 man-month and 0.5 grad-student-month
- Core Design (3/1 – 4/1)
  - Developed assembly designs and enrichments
  - Developed core design based on assemblies
  - Estimated effort: 0.5 grad-student-month
- Model Setup (5/16 – 6/10)
  - Insure consistency between geometry of STAR-CCM+ and DeCART
  - Debug mesh mapping and solution transfer
  - Estimated effort: 0.5 man-month and 0.5 grad-student-month

Milestone Execution Plan and Technical Approach

- Code Modifications (3/1 – 6/10)
  - To complete previous activities required several code modifications to STAR-CCM+ coupling interface and DeCART.
  - Estimated effort: 1.5 grad-student-month
- Perform Coupled Calculations (6/11 – 6/25)
  - Estimated effort: 0.5 grad-student month
  - CPU Hours: ~15,000
- Analyze Results and Write Report (6/21 – 6/28)
  - Estimated effort: 0.5 man-month and 0.25 grad-student-month
- Oversight/Guidance/Feedback/Management
  - Estimated effort: 1 man-month

Total Effort

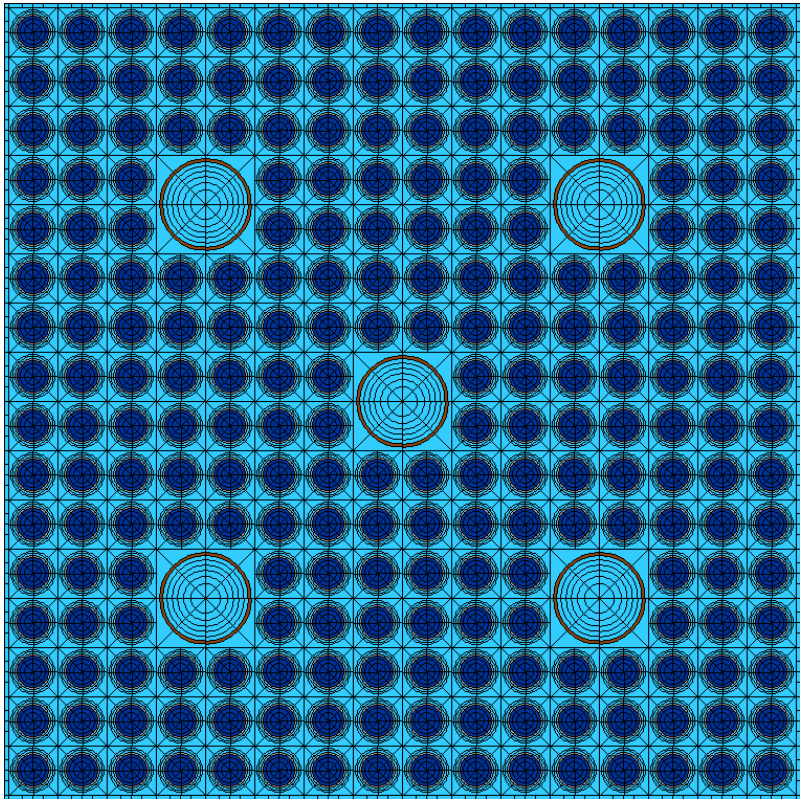
- Man-months: 2
- Grad-student-month: 3.75

- Estimated costs (include institution overhead)
  - Man-month ~$25K (Lab employee ~= $300K/year)
  - Grad-student-month ~$6K (UMich Grad student ~= $72K/year)
  - $/CPU-Hour = ????

- Total estimated cost ~$72K

Problem Description (cont.)

- Low enrichment assembly simulates twice-burned fuel

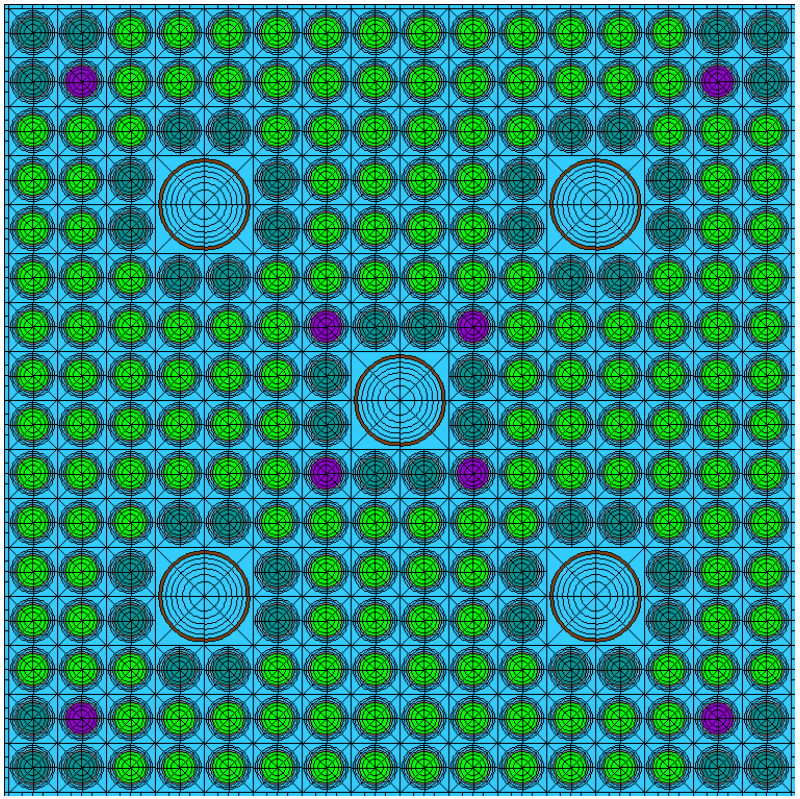


1.40%wt U-235 (236)

Assembly Type A

Problem Description (cont.)

- Middle enrichment
- Lower enriched pins around guide tubes suppress peaking
- Gadolinia rods for suppressing excess reactivity



2.37%wt U-235 (52)

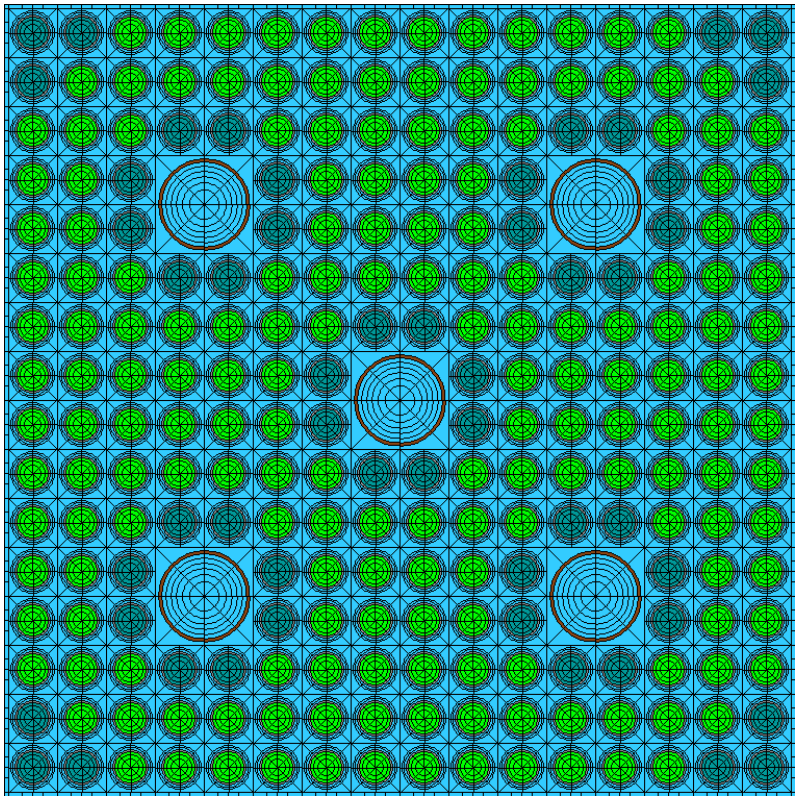
2.87%wt U-235 (176)

2.87%wt U-235 (8)
6.00%wt Gd_2O_3

Assembly Type B1

Problem Description (cont.)

- Same as Type B1 except there are no gadolinia rods.



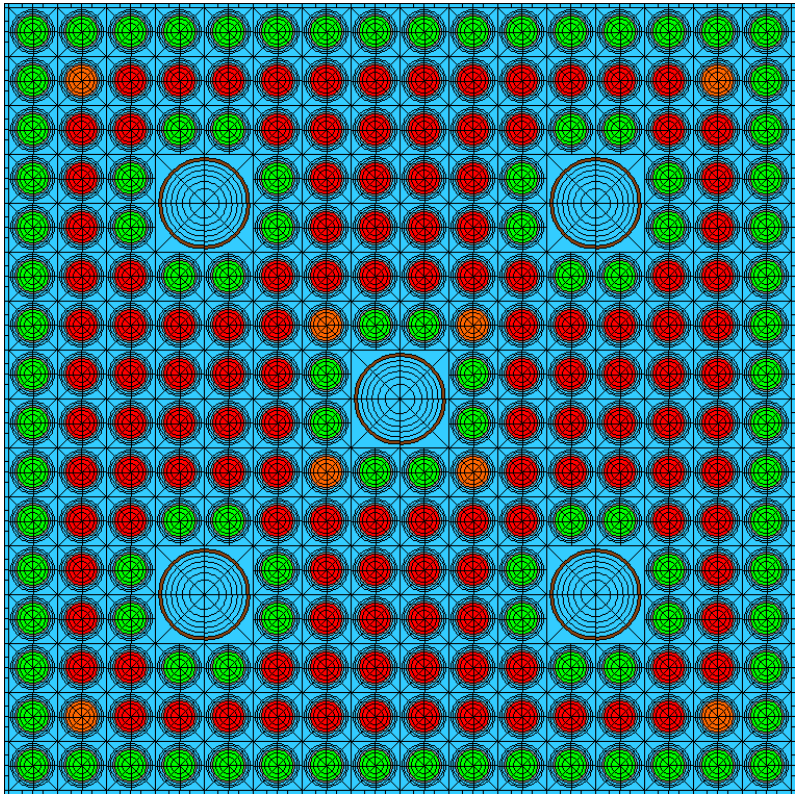
2.37%wt U-235 (52)

2.87%wt U-235 (176)

Assembly Type B2

Problem Description (cont.)

- High enriched assembly typical of fresh fuel.
- Lower enrichmed pins reduce peaking
- Gadolinia rods suppress excess reactivity



2.87%wt U-235 (100)

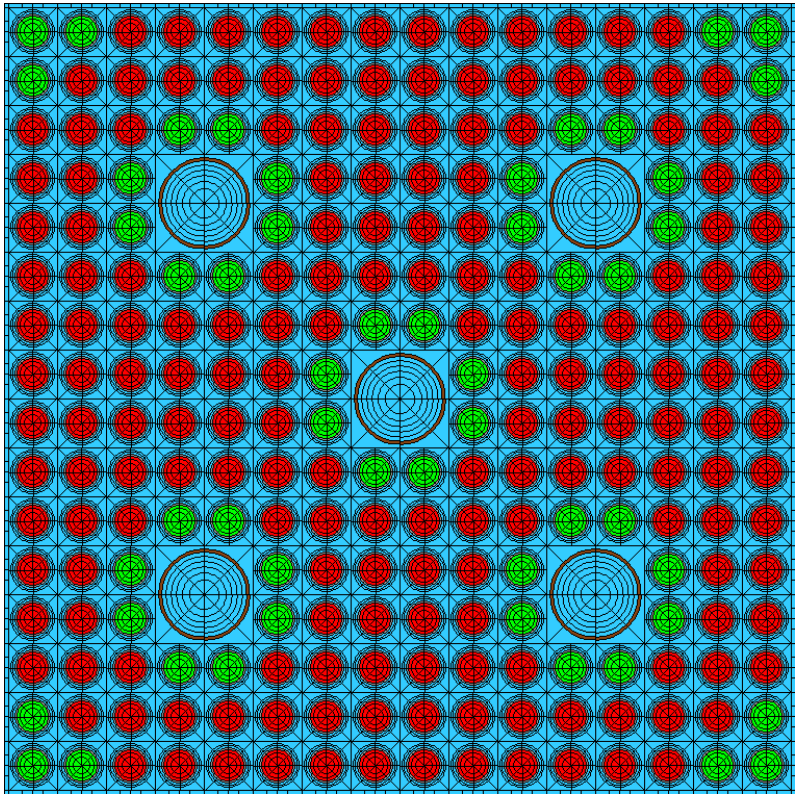
3.37%wt U-235 (128)

3.37%wt U-235 (8)
6.00%wt Gd_2O_3

Assembly Type C1

Problem Description (cont.)

- Same as Type C1 except no gadolinia rods
- High power assembly



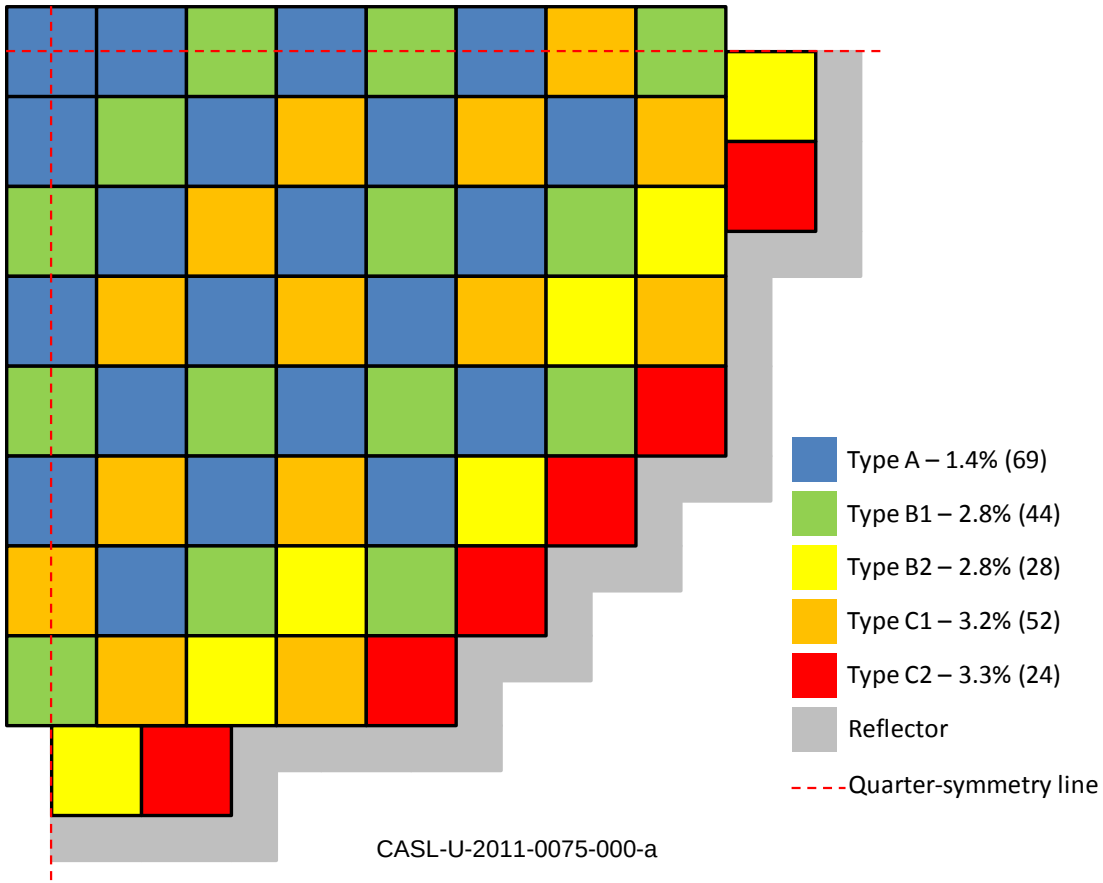
2.87%wt U-235 (100)

3.37%wt U-235 (128)

Assembly Type C2

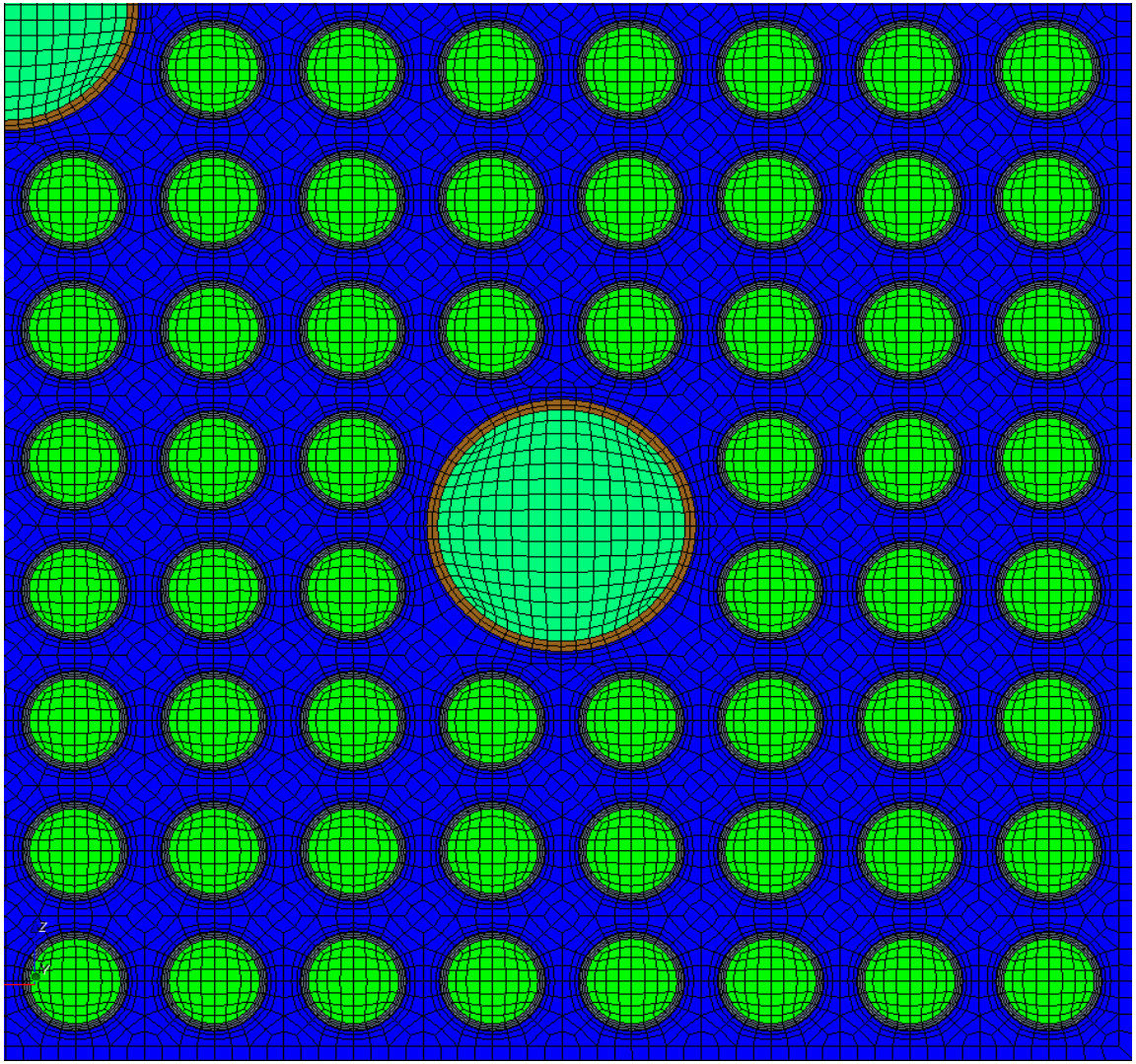
Problem Description (cont.)

- Core design is:
  - Checkerboard – alternate high/low enriched assemblies to manage peaking
  - "Ring-of-fire" – put higher power assemblies near core periphery, use leakage of neutrons to help offset excess reactivity



CASL-U-2011-0075-000-a

STAR-CCM+ Mesh



Non-conformal with DeCART mesh

Model Details

- DeCART discretizations

Parameter	Value
Number of Neutron Energy Groups	47
Number of Axial Planes	20
Number of Flat Flux Regions	16,134,160
Number of Uniform Cross Section Regions	2,096,500
Number of Characteristic Ray Segments	765,911,600

- STAR-CCM+ discretizations

Region	Cells	Faces	Vertices
Fluid	124,427,845	357,919,713	138,800,560
Fuel	65,295,300	182,058,660	80,377,234
Fuel Rod Cladding	78,354,360	208,023,144	105,701,568
Guide Tube Water	5,810,175	16,706,395	6,566,014
Guide Tube Cladding	2,582,300	6,422,820	3,922,890
Total	276,469,980	771,130,732	335,368,266

Discretizations are somewhat coarse

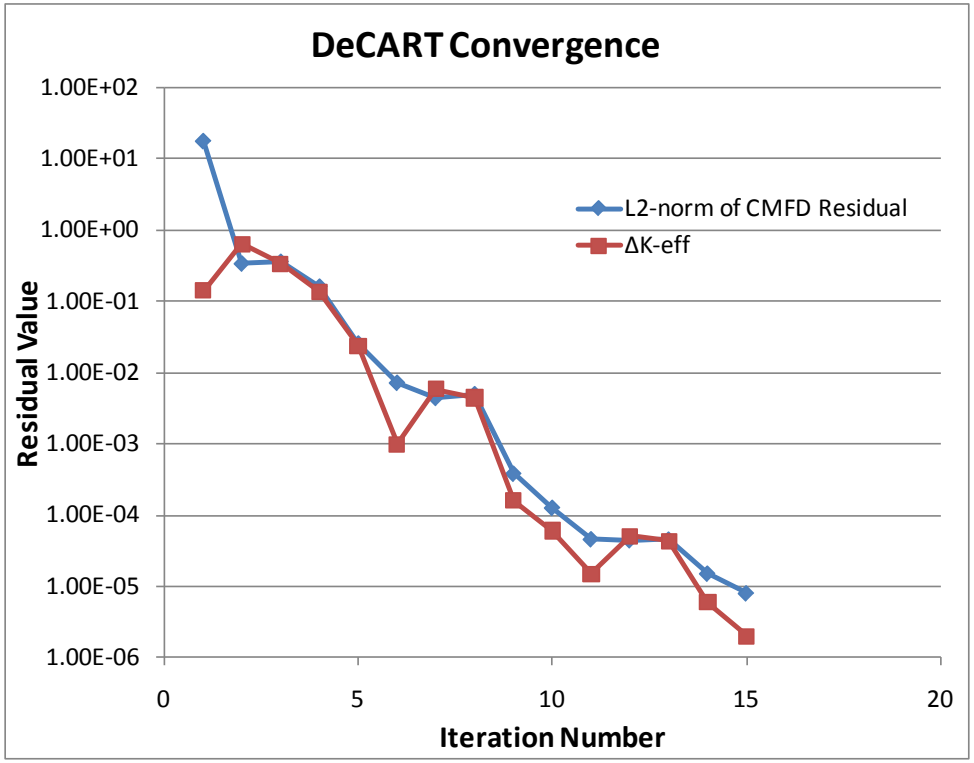
Calculation Details

- Two calculations were run
  - DeCART coupled to STAR-CCM+
    - STAR-CCM+ was run with 256 processors
    - DeCART was run with 80 processors
  - DeCART with internal simplified T/H solver
    - Run with 80 processors
  - Solved with a Fixed Point Gauss-Seidel iteration.

- Internal simplified T/H solver
  - 1-D heat conduction in pin
  - Heat Transfer Coefficient from Dittus-Boelter Correlation
  - Only energy balance for Fluid
    - Properties obtained from steam tables
    - No cross flow
    - Mass flow distributed evenly

- Frost was used instead of Jaguar for a variety of reasons which are discussed in the report.

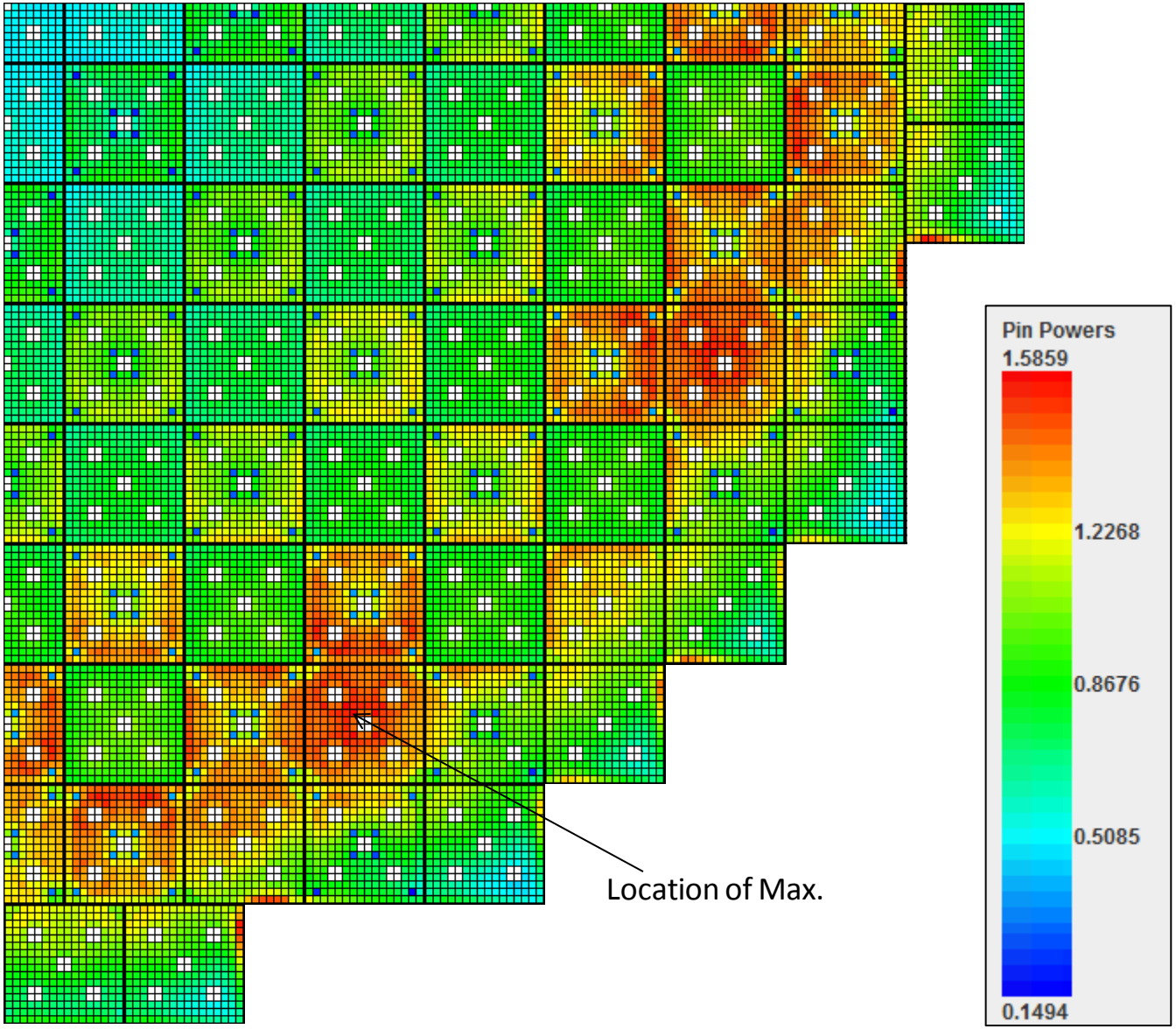
Stand-alone Results



Global Parameter	Value
Critical Boron Concentration	967.98 ppm
Core Average Coolant Density	0.72403 g/cc
Core Average Fuel Temperature	542.19 °C
Average Outlet Temperature	315.41 °C
Quarter Core Total Power	972.312 MW
Maximum Pin Averaged Fuel Temperature	865.97 °C
Maximum Centerline Fuel Temperature[1]	1162.6 °C
Maximum Relative Pin Peaking Factor (F_q)	2.3148
Maximum Radial Pin Peaking factor (F_{xy})	1.5859
Maximum Axial Pin Peaking factor (F_z)	1.4470

Stand-alone Results (cont.)

Axially Integrated Pin Powers



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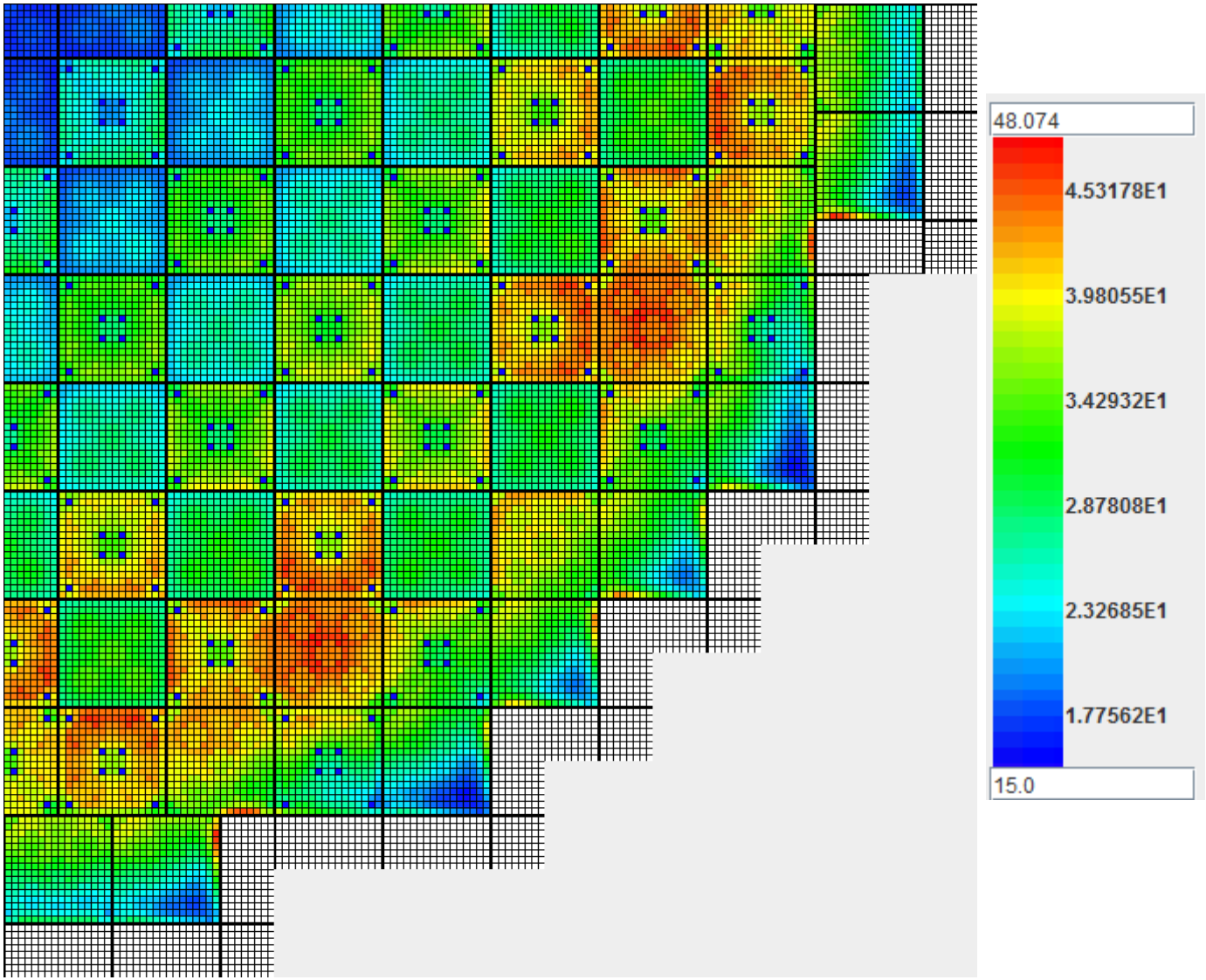
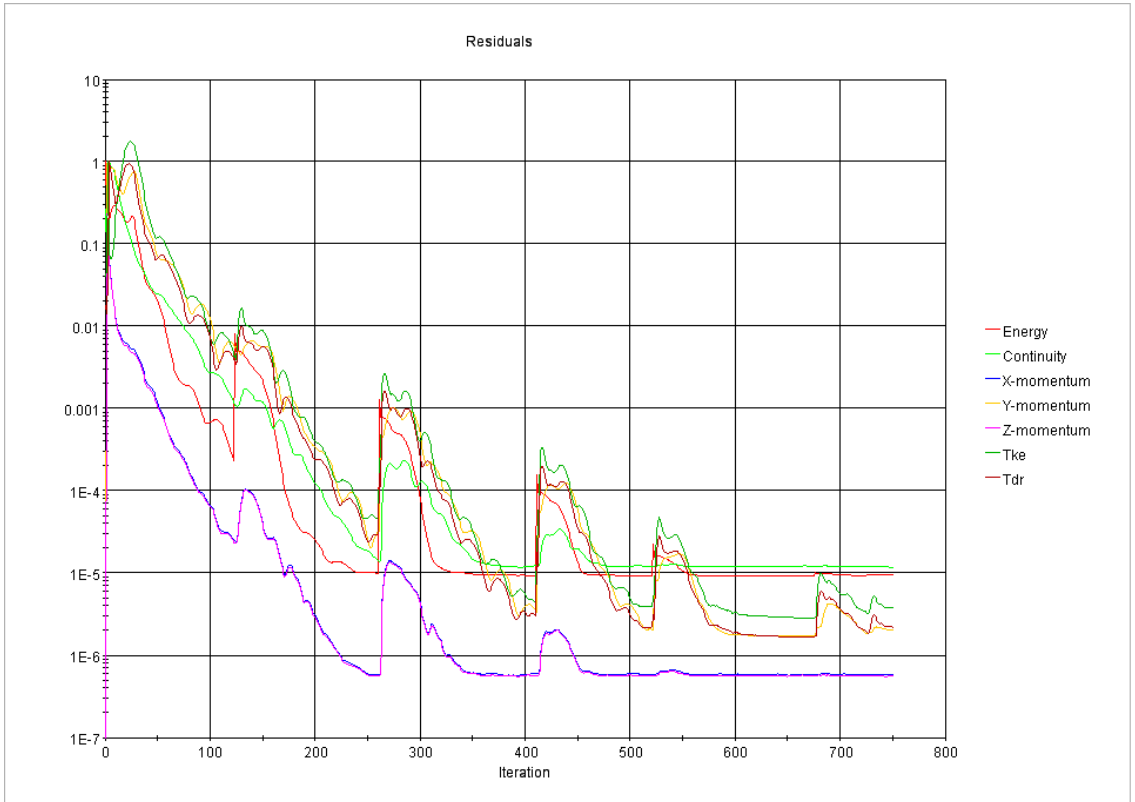
Stand-alone Results (cont.)

Temperature Rise (°C)



Coupled Results

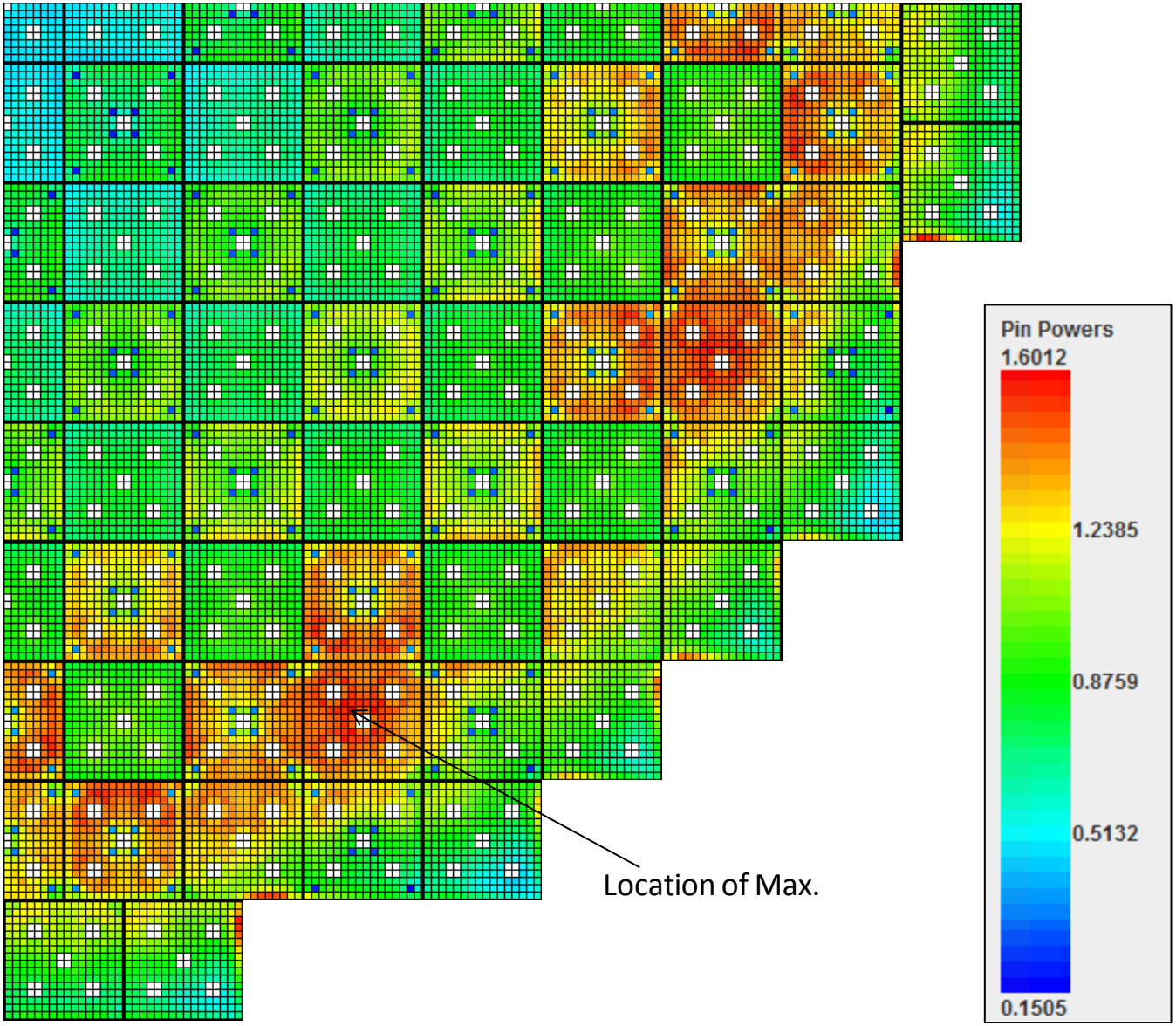


Global Parameter	Value
Critical Boron Concentration	982.48 ppm
Core Average Coolant Density	0.72945 g/cc
Core Average Fuel Temperature[1]	463.52 °C (464.89 °C)
Average Outlet Temperature	316.36 °C
Quarter Core Total Power[2]	967.618 MW
Maximum Fuel Temperature[3]	975.06 °C
Maximum Relative Pin Peaking Factor (F_q)	2.3595
Maximum Radial Pin Peaking factor (F_{xy})	1.6012
Maximum Axial Pin Peaking factor (F_z)	1.4608

[1] - The value is computed by STAR-CCM+, the value in parentheses is the value computed by DeCART.
[2] - This value is computed by STAR-CCM+
[3] - This is the maximum value of all STAR-CCM+ cells, which differs from the temperature at the true centerline of a cylinder as calculated by DeCART.

Coupled Results (cont.)

Axially Integrated Pin Powers



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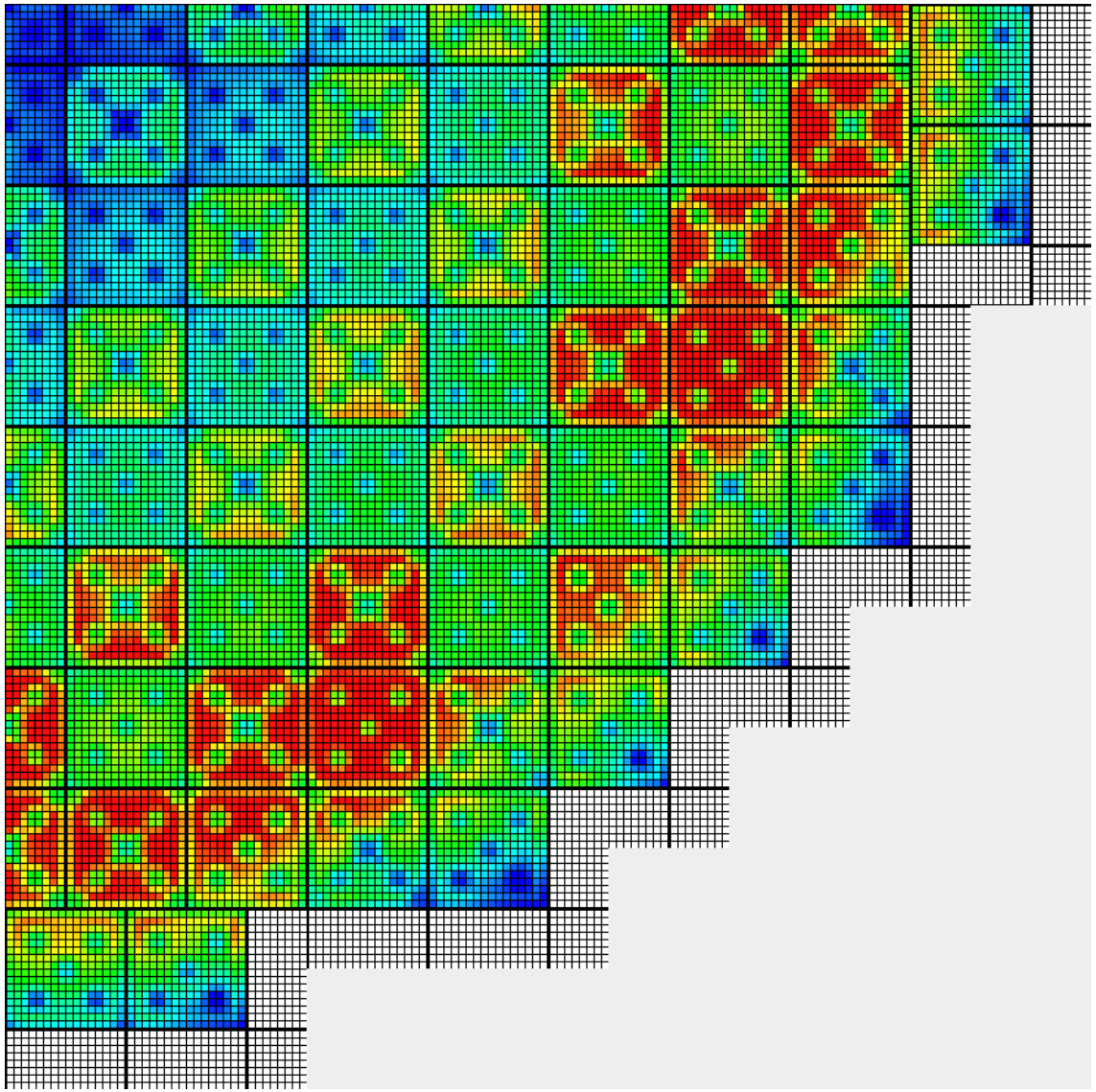
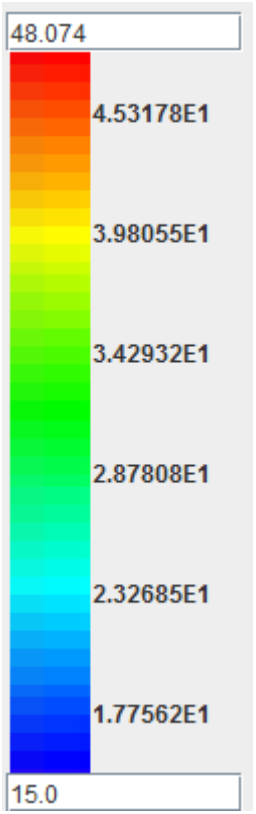
Coupled Results (cont.)

Temperature Rise (°C)





°C

Comparison of Results

- Comparison of Global Parameters

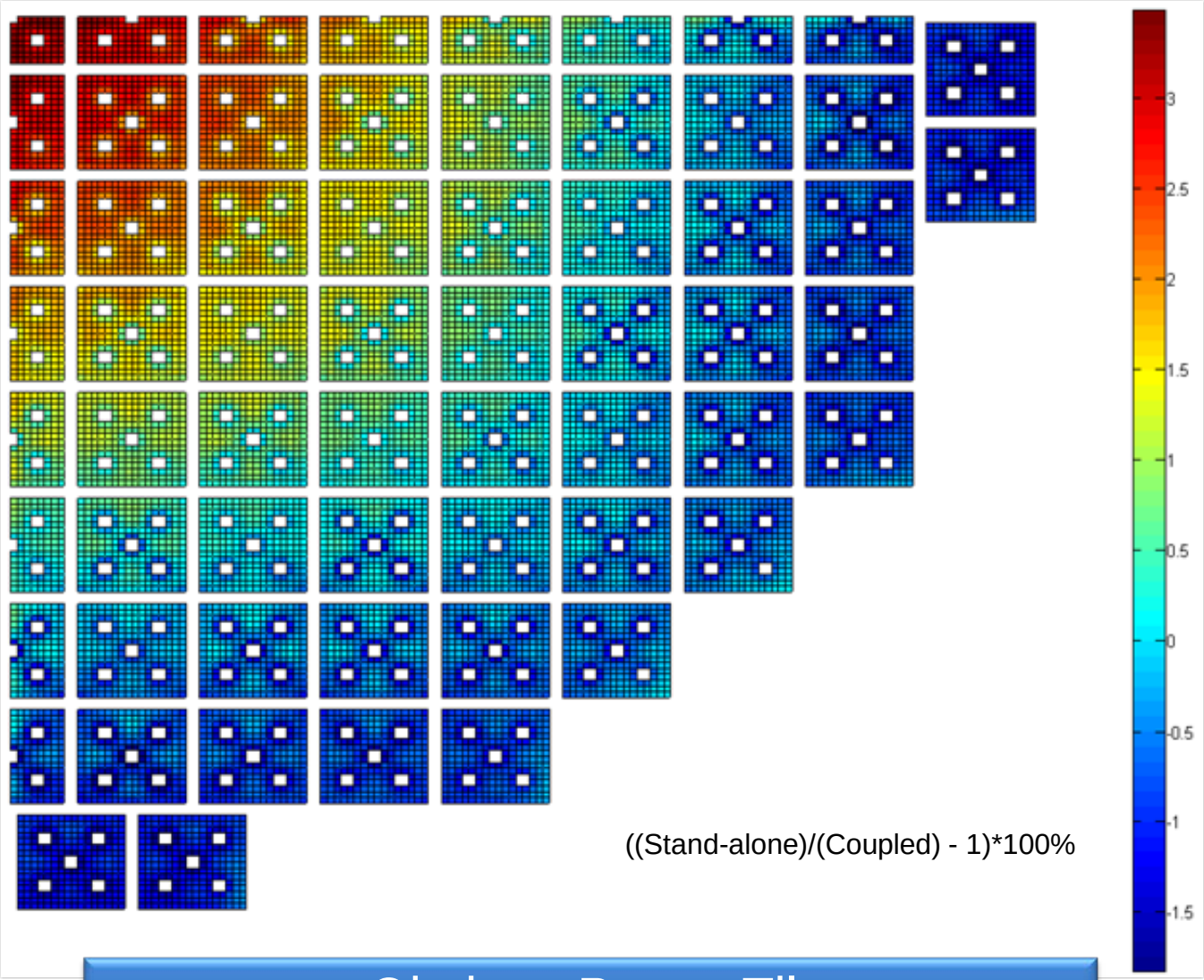
Global Parameter	Difference
Critical Boron Concentration	-14.5 ppm (-1.48%)
Core Average Coolant Density	-0.00545 g/cc (-0.75%)
Core Average Fuel Temperature	78.67 °C (16.97%)
Average Outlet Temperature	-0.95 °C (-0.30%)
Quarter Core Total Power	4.694 MW (0.49%)
Maximum Relative Pin Peaking Factor (F_q)	-0.0447 (-1.89%)
Maximum Radial Pin Peaking factor (F_{xy})	-0.0153 (-0.95%)
Maximum Axial Pin Peaking factor (F_z)	-0.0138 (-0.94%)

- Comparison of Pin Powers

Predicted value	Difference Type	Value
Axially Integrated Relative Pin Power	Maximum Absolute Difference	0.0242
	Maximum Relative Difference (%)	3.37
	RMS (%)	1.12
Radially Integrated 1-D Relative Axial Power	Maximum Absolute Difference	0.1887
	Maximum Relative Difference (%)	60.22
	RMS (%)	18.29
MOC Region Power Density	Maximum Absolute Diff. (W/m^3)	2.9304E+07
	Maximum Relative Difference (%)	28.84
	RMS (%)	7.80
MOC Region Temperature	Maximum Absolute Diff. (°K)	229.01
	Maximum Relative Difference (%)	29.61
	RMS (%)	7.45

Comparison of Results (cont.)

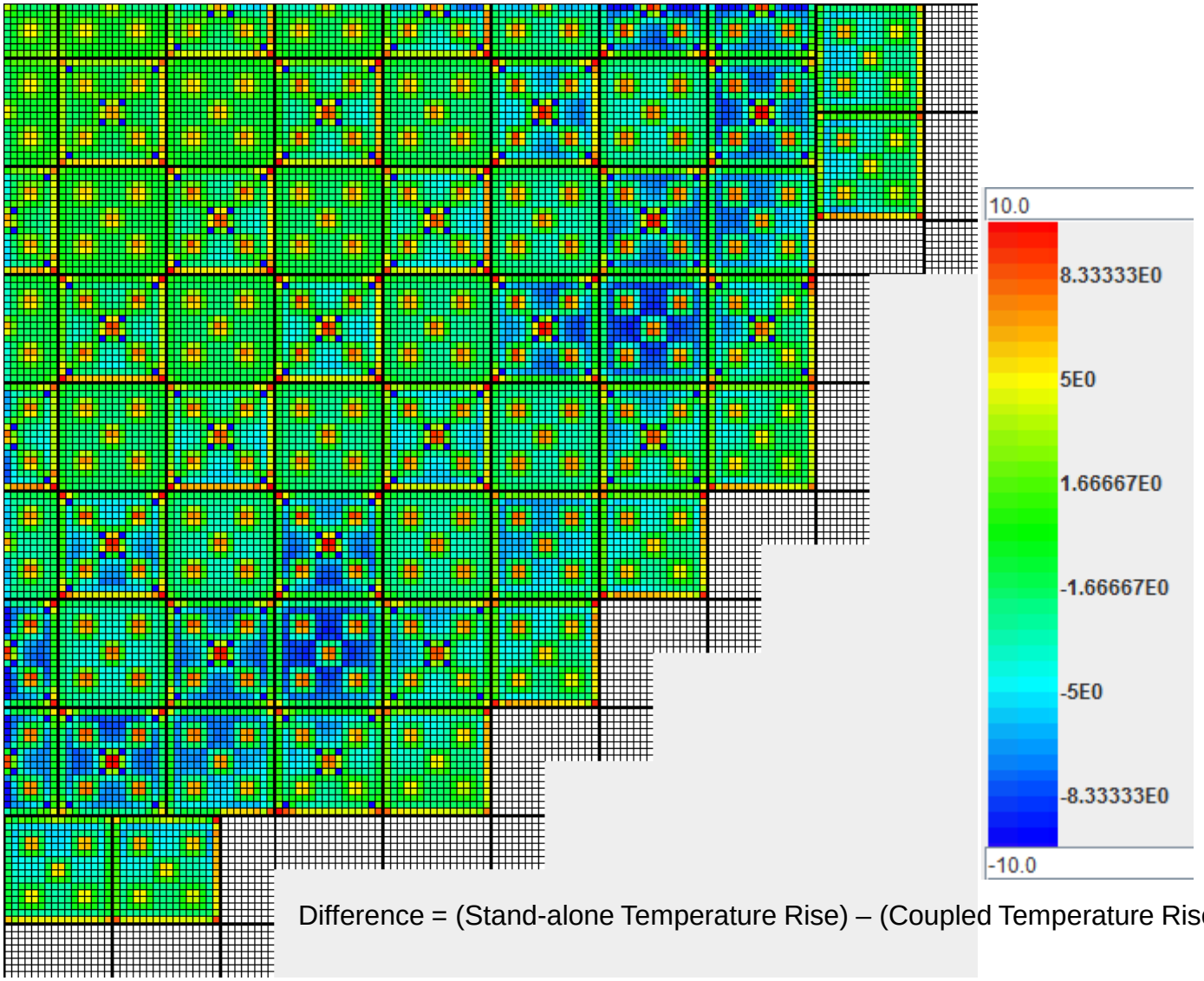
Axially Integrated Pin Power Difference distribution



Obvious Power Tilt

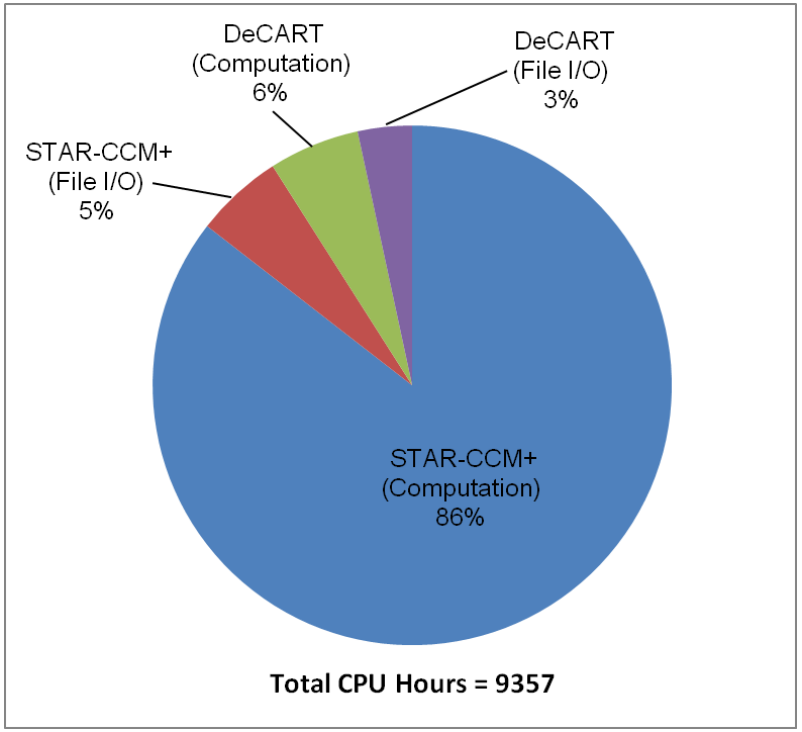
Comparison of Results (cont.)

Difference in Temperature Rise (°C)



Difference = (Stand-alone Temperature Rise) – (Coupled Temperature Rise)

Computational Performance



CPU Hour Requirements of Coupled Simulation by Component Task

Times for Different Calculations

Calculation Component	Est. Real Time (min)	CPU Hours
DeCART Fixed Point Iter.	105.57	140.76
STAR-CCM+ Fixed Point Iter.	399.00	1702.40
DeCART Total (Coupled)	633.43	844.58
STAR-CCM+ Total (Coupled)	1995.00	8512.00
Total (Coupled)	**2628.43**	**9356.58**
DeCART Total (Stand-alone)	**86.59**	**115.46**

100x computation time needed for CFD!

Milestone Discovery and Innovation

- Differences from comparison show
  - Simplified T/H solver provides a reasonable estimate of the feedback when computing some global parameters
  - Obvious tilt in comparison of power distributions. This might be due to differences in the mass flux distributions, but needs to be investigated further.
  - Differences in the temperature rise are caused by differences in the specific heat of the fluid defined in STAR-CCM+ and the steam tables used by DeCART.

- Simplified T/H seems good enough to get in the ball-park (probably into the infield)

Milestone Completion

- Demonstrating convergence of the full core coupled calculation and an analysis of the results documented in a report satisfies the completion of this milestone.

- Deliverables
  - Non-proprietary coupled model specifications
    - Contained in report.
  - Quarter-core models for STAR-CCM+ and DeCART.
  - A report describing the work that was done and the results and analysis from the simulations.
    - Available on sharepoint and delivered on time.

Milestone Lessons Learned

- Lots of technical problems with Jaguar resulted in preferred use of Frost.
- Results require further study.
  - Several questions remain open based on what was observed and analyzed.
  - Some data has not been analyzed yet and there may be several key things to still uncover.
    - e.g. Use results to compute DNB margin.
- Recommend that milestones be added to
  - further analysis
  - Perform similar study for Watt's Bar