

# ***Idaho National Laboratory Reactor Analysis Applications of the Serpent Lattice Physics Code***

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## ***Outline***

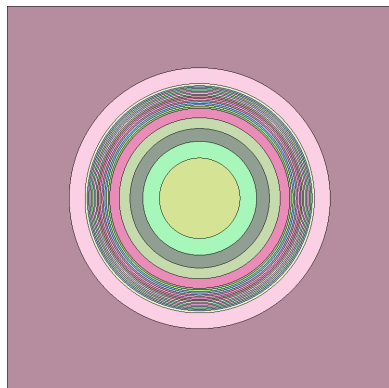
- Intra-Pin Power and Flux Distribution for BISON Fuel Performance Calculations.
- Takahama Benchmark Validation Analysis
- TREAT Core Analysis
- Multi-SERTTA Experiment modeling
- NRAD facility modeling
- Wish List

## *Intra-Pin Power and Flux distribution for BISON.*

- Most fuels performance codes have surrogate models for the “external” physics.
  - Example: Limited (Material dependent models such as the  $\text{UO}_2$  Lassmann model) depletion models to produce the intra-pin power density
- The goal is to show a higher fidelity fuel performance calculation where the surrogate models are replaced with the relevant physics.
  - Replace the internal BISON depletion model with neutronics
- Produce a coupled system of codes that is easily maintainable and tested regularly.
  - Each application is a application is based on MOOSE and has their own tests.
- A goal is to be able to analyze different fuel types without having to invent new surrogate models for the external physics. (i.e.  $\text{U}_3\text{Si}_2$ )
- A goal is to be able to analyze conditions where the intra-pin power distribution is not axi-symmetric (azimuthal dependence).

# Intra-Pin Power and Flux Distribution for BISON

- The master application is MAMMOTH:
  - BISON: fuels performance
  - Rattlesnake: neutronics
- Serpent: intra-pin fuel, cladding, and water region cross sections.
- Macroscopic cross section are tabulated over intra-pin burnup (MWd/kgHMI) and temperature (K).



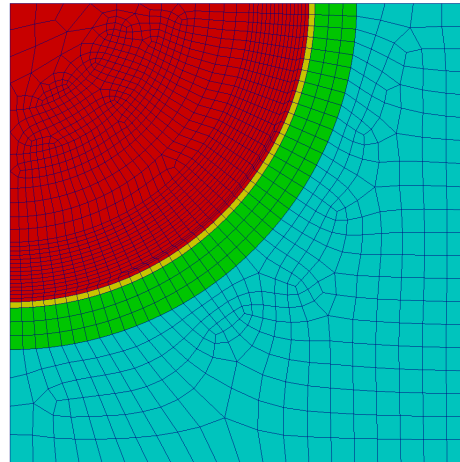
Serpent Pin Cell

Parameter	Value
Fuel Pin Radius	4.09575 (mm)
Fuel Pin Initial Temperature	600 (K)
Outer Cladding Thickness	0.5715 (mm)
Initial Gap Thickness	0.08255 (mm)
UO <sub>2</sub>	4.45 wt.
Cladding Initial Temperature	600 (K)
Water Temperature	585 (K)
Pitch	12.5984 (mm)
Linear Heat Rate	19.2 W/m

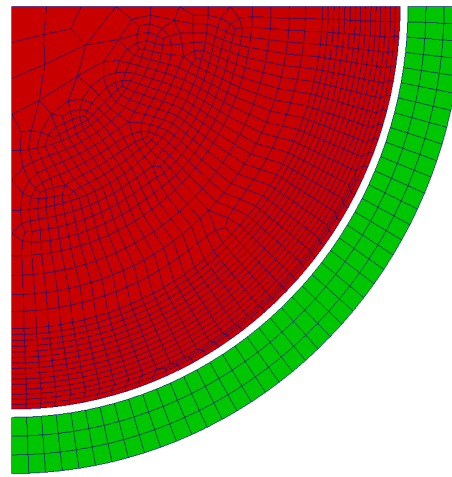
# *Intra-Pin Power and Flux Distribution for BISON*

- Rattlesnake reads in the Serpent cross tabulation.
- At each “time” step Rattlesnake performs a macroscopic depletion calculation over the fuel portion of the quarter pin cell.
- At each depletion step MAMMTOH calls BISON to perform a fuels performance calculation.
- Temperature, Fast Flux, Intra fuel pin power density etc. are exchanged between BISON and Rattlesnake.

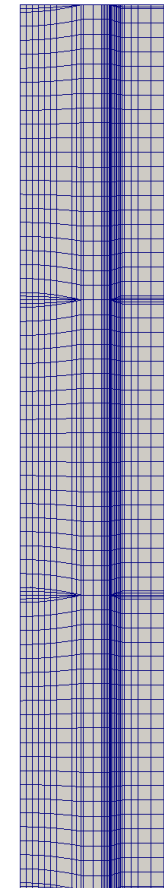
Rattlesnake Domain



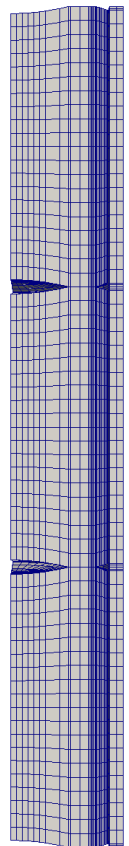
BISON Domain



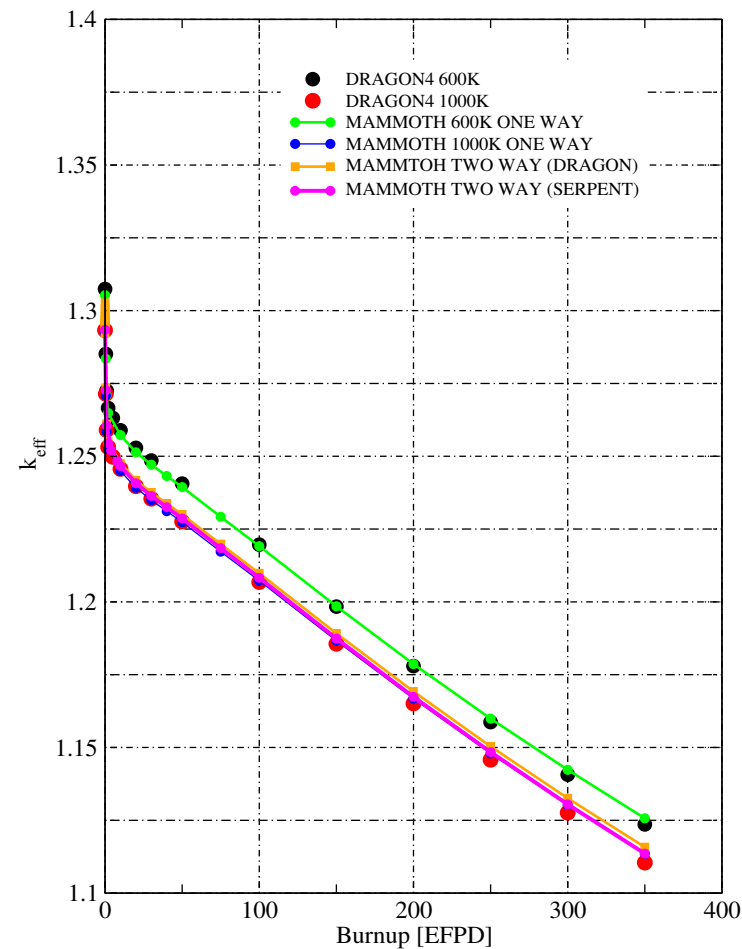
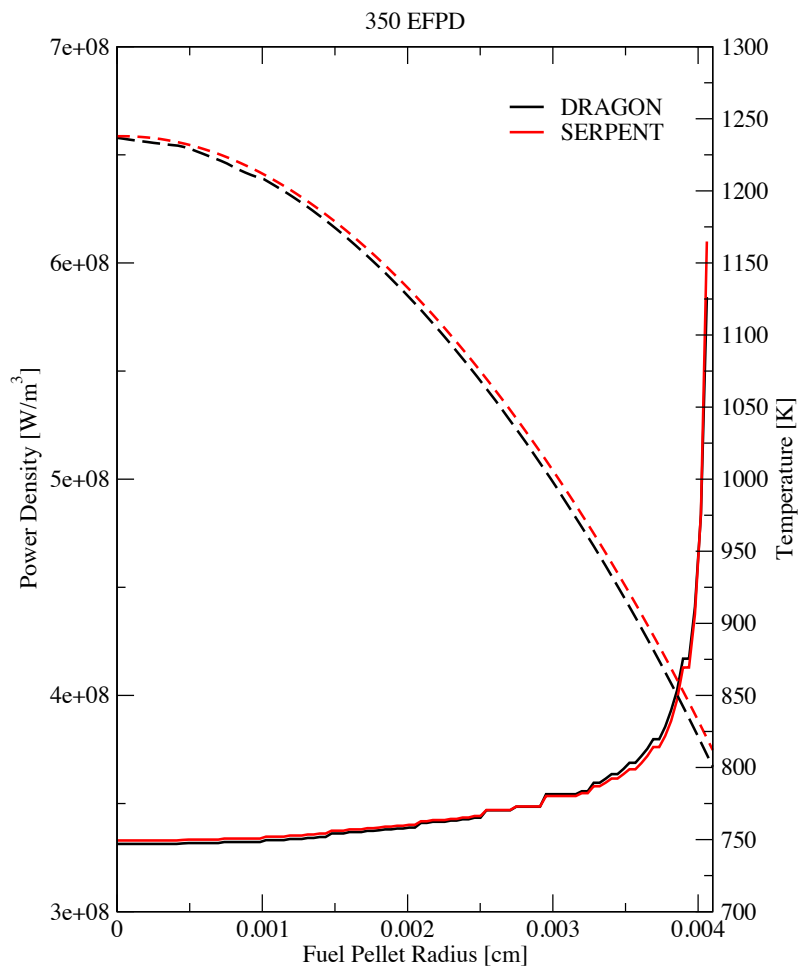
Rattlesnake Domain



BISON Domain

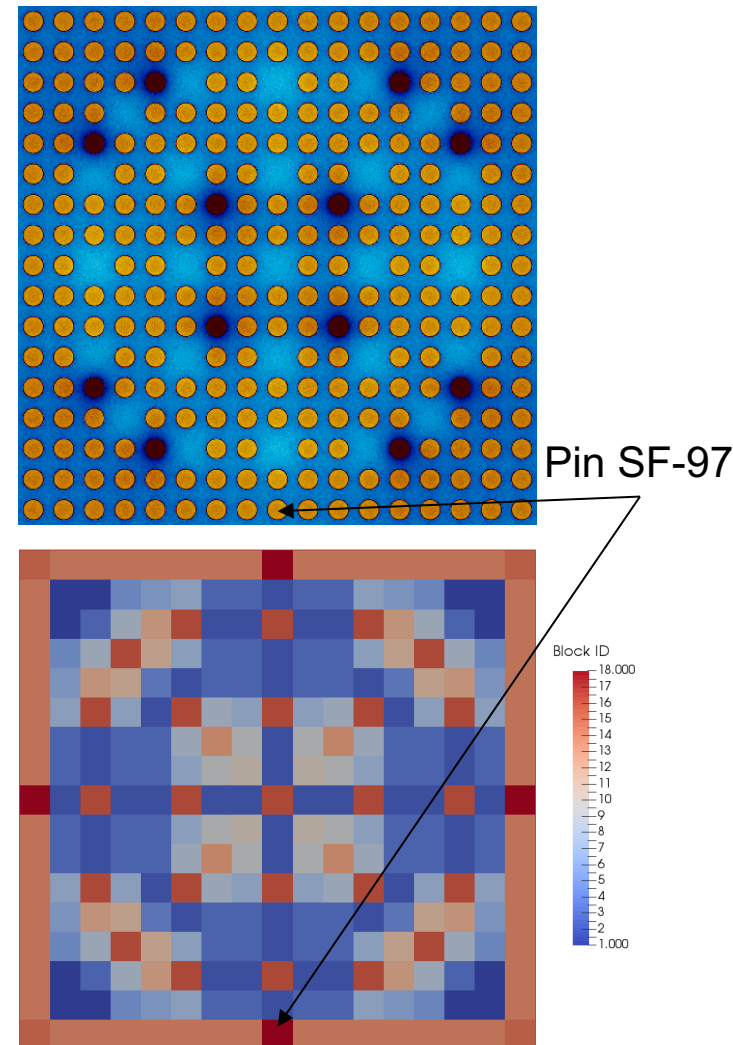


# Intra-Pin Power and Flux Distribution for BISON



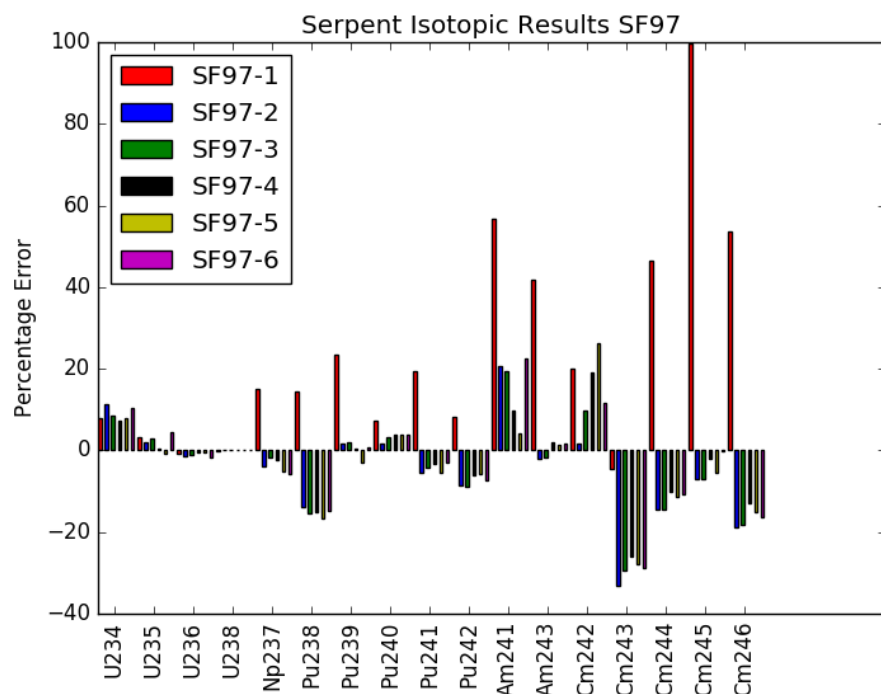
# Takahama Benchmark SF97 Analysis

- The Takahama Benchmark is an isotopic analysis of high burnup PWR spent fuel samples from the Takahama-3 reactor.
- Original codes for validation: SAS2 and HELIOS.
- Validation of MAMMOTH tool set
- Provide BISON (fuel performance) tools with reasonable power history and coupled spatial distributions (power density, fast neutron flux, etc.) distribution during normal operation.
- DATA: specification of power history at different rod axial levels, boron let down, and end of life isotopic content.
- Serpent calculated pin homogenized cross sections at each depletion point.

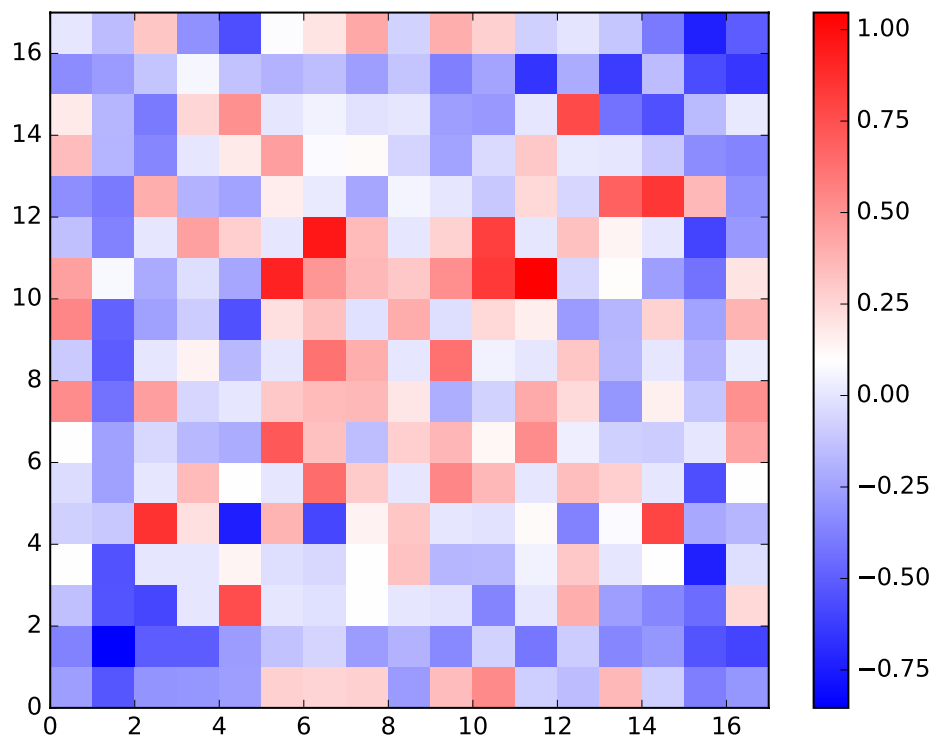




# Reactor Physics Analysis: Takahama Benchmark SF97



SF97-4: 385 Days

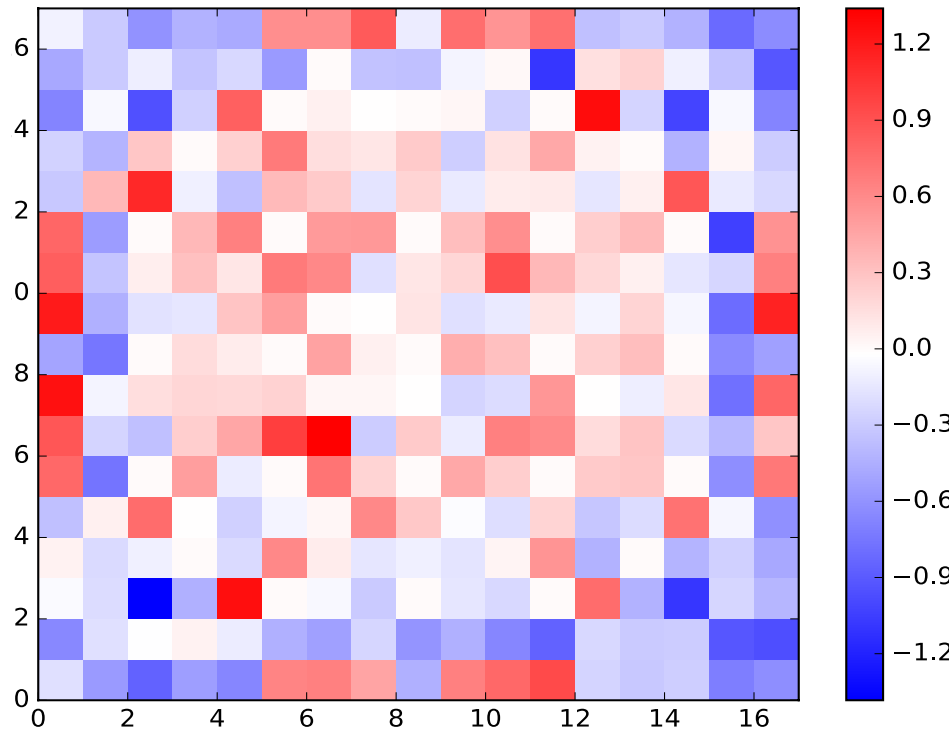


RMS = 0.34% , Max = 1.05%, Min = -0.85%



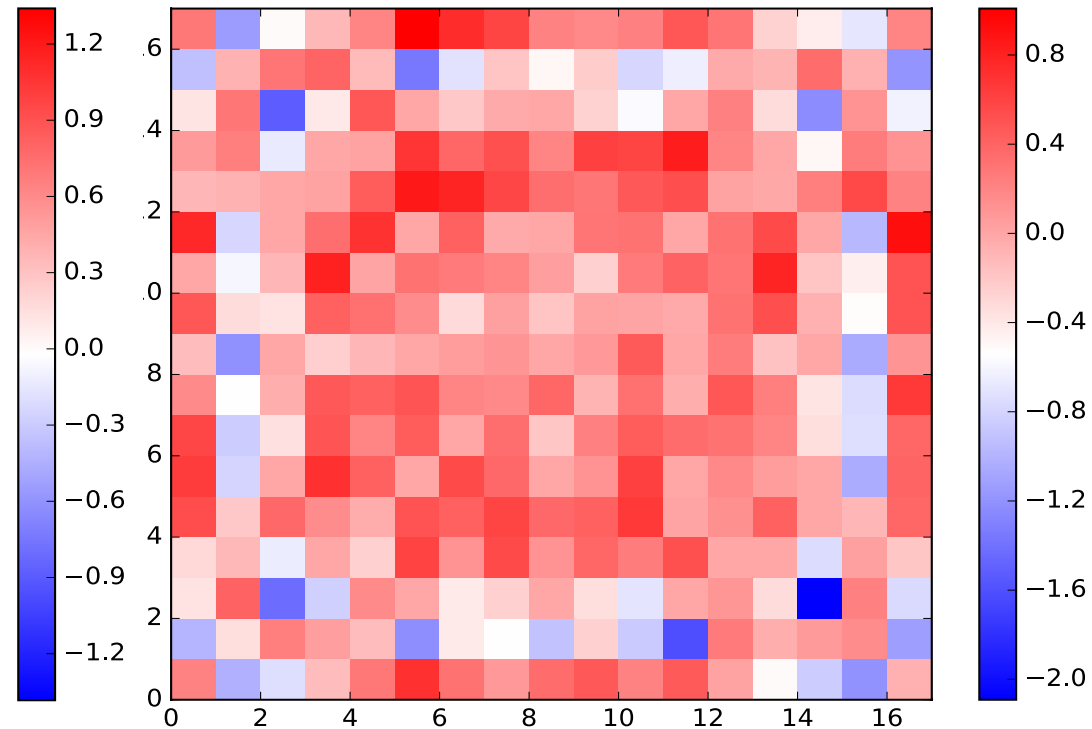
# Takahama Benchmark SF97 Analysis

SF97-4: 875 Days



RMS = 0.47% , Max = 1.34%, Min = -1.38%

SF97-4: 1343 Days



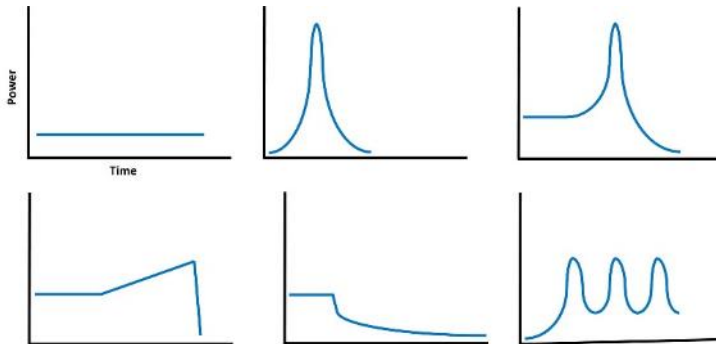
RMS = 0.50% , Max = 1.01%, Min = -2.09%

# TREAT Core Analysis

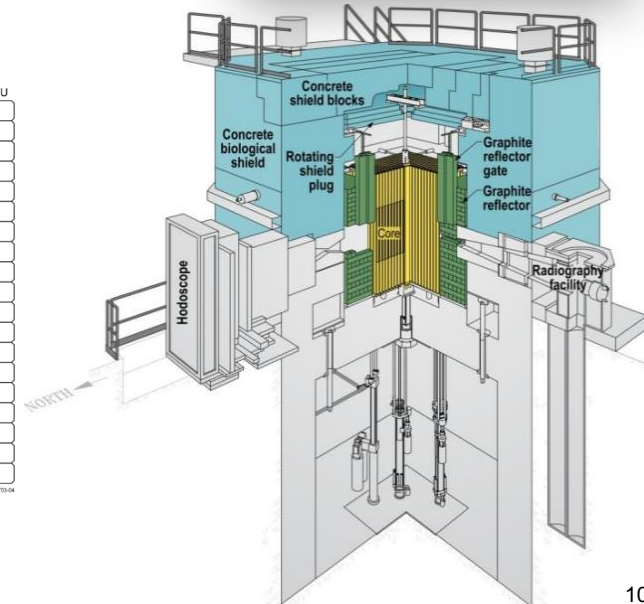
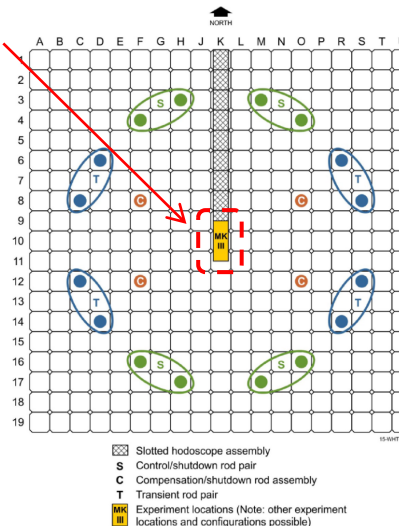
- Transient Reactor Test (TREAT) resuming operations [**very soon**] in order to support fuel safety testing and other transient science
- Zircaloy-clad graphite/fuel blocks comprise core, cooled by air blowers
  - 120 kW steady state, 19 GW peak in pulse mode
  - Virtually any power history possible within 2500 MJ max core transient energy
  - No reactor pressure vessel/containment, facilitates in-core instrumentation
- Experiment design
  - Reactor provides neutrons, experiment vehicle does the rest
  - Tests typically displace a few driver fuel assemblies (each 10cm square, 122cm L)



Insert Experiment  
Here (or anywhere  
else really)

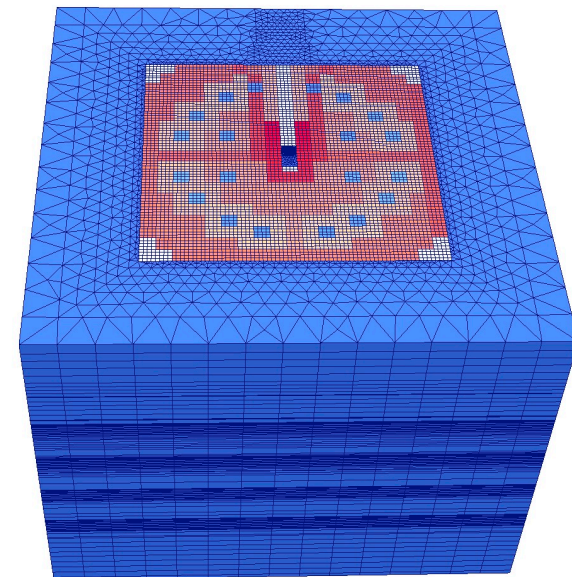
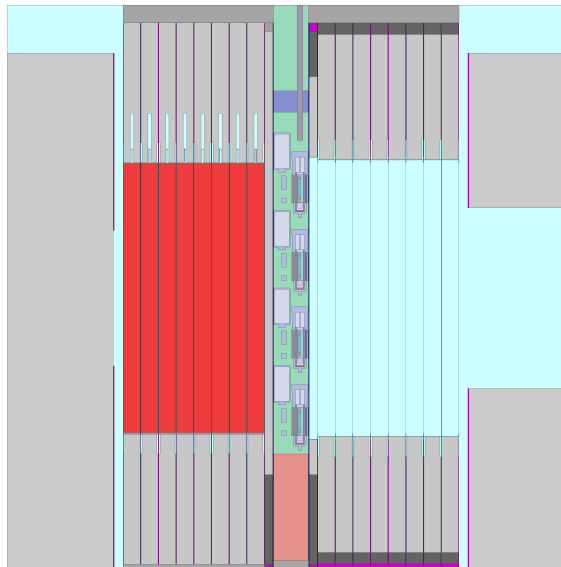
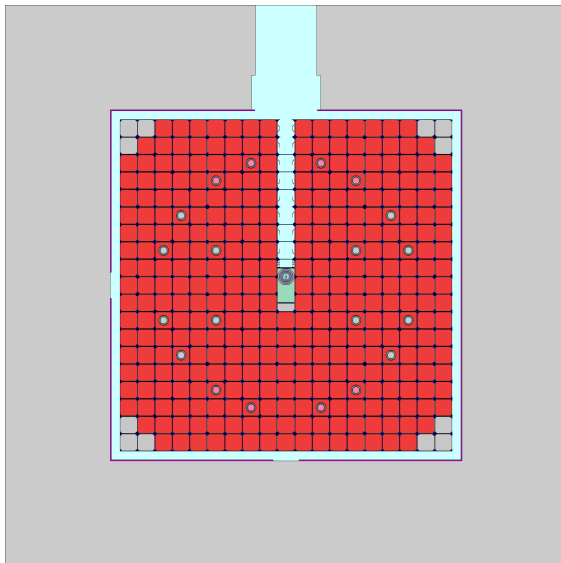


Example Transient Shapes



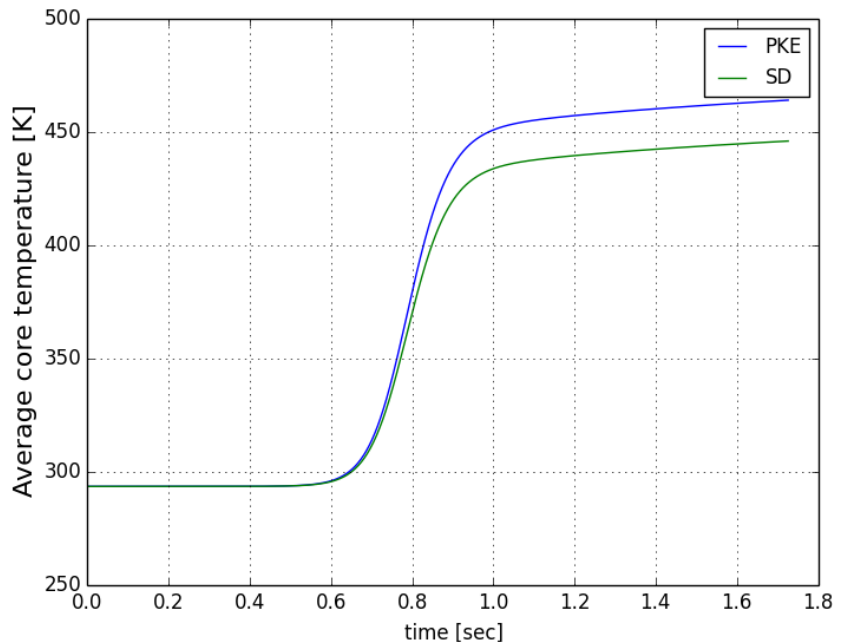
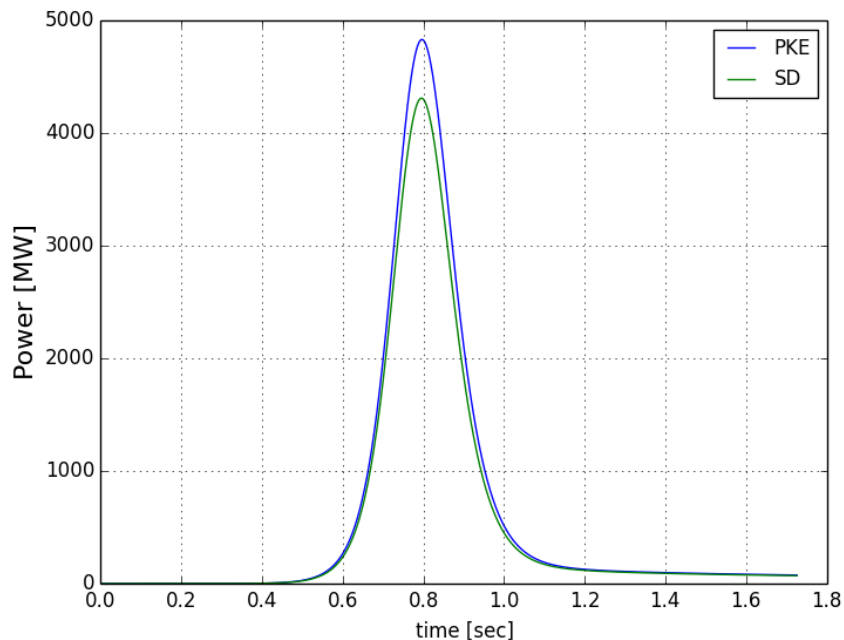
## ***TREAT Core Analysis***

- Serpent generated cross sections for the homogenized fuel elements from an eigenvalue calculation.
- Use core isothermal fuel temperature states and transient CR position for the tabulation.
- Tensor Diffusion Coefficients (TDC) are computed in optically thin regions with Rattlesnake 1<sup>st</sup> order  $S_N$ .
- Superhomogenization method is employed for equivalence calculations to prepare the final cross section tabulation.



## MAMMOTH Core Results

- MAMMOTH is used for transient analysis with an adiabatic fuel model.
- PKE: (Point Kinetics), SD: Spatial Dynamics
- Comparison of temperature limited transient (safety case without rod re-insertion) with PKE vs. SD.



## Multi-SERTTA (PWR-condition static water, fresh fuel) One of many vehicles as part of the Accident Tolerant Fuel (ATF) program

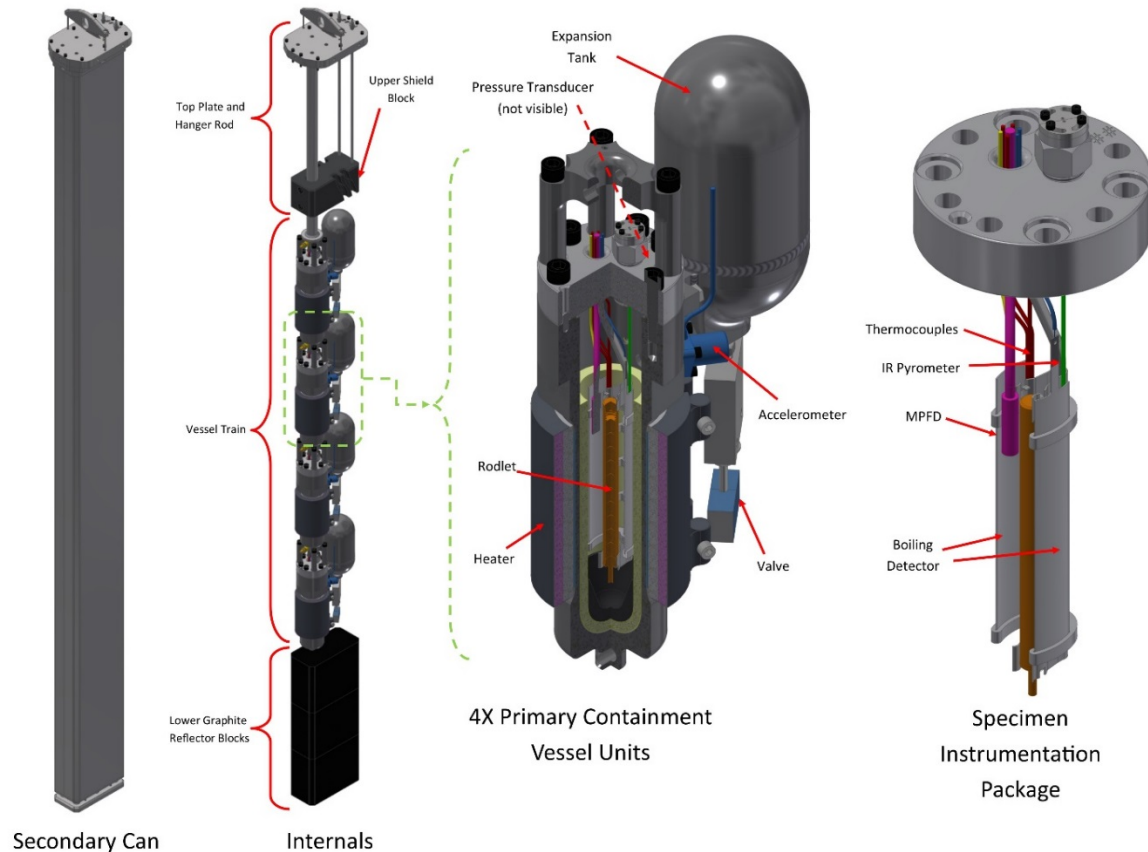
- Impressive instrument array (including fast-response temperature and boiling detection)
- 4X vessels filled with one 10-pellet PWR rodlet each
- Filled with static PWR-condition water (280C, 16MPa)



1 of 4 fabricated prototype vessels (welding to be performed)



Crane-Suspended Handling Mockup in Front of Reactor

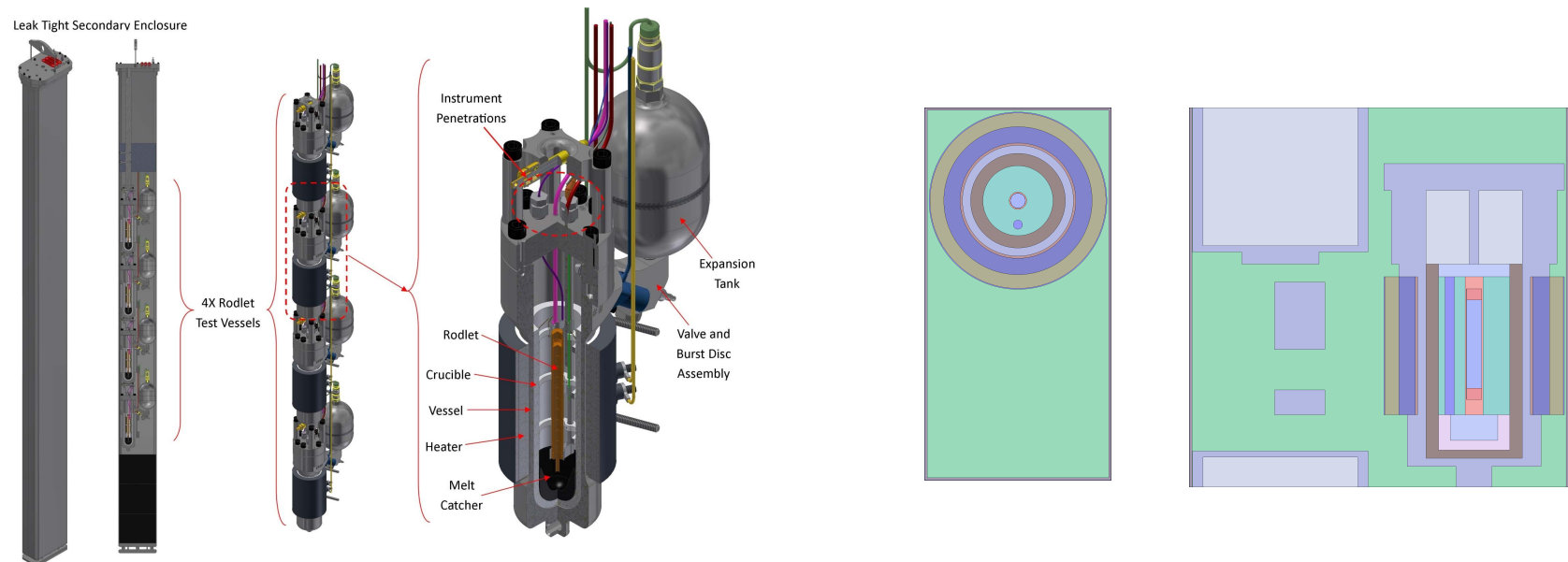


- Current efforts to prepare for construction and irradiation of a water-filled nuclear mockup in 2019
- Quite relevant for PWR-condition transient boiling, but these tests not likely until well into 2020



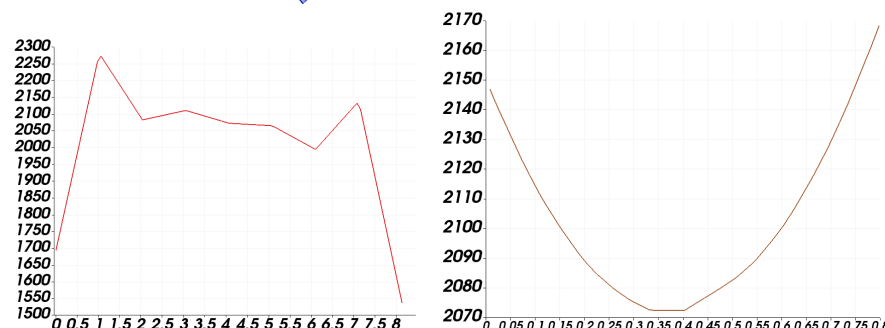
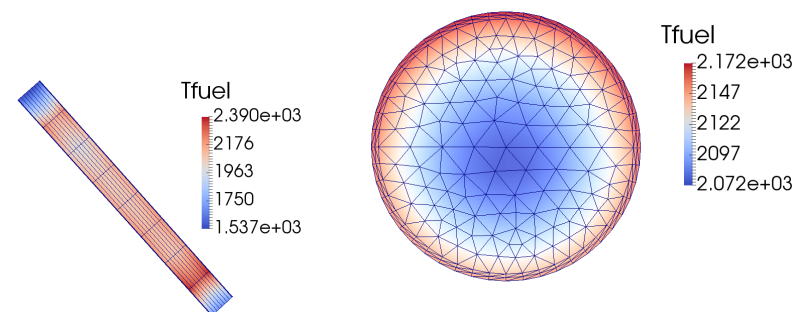
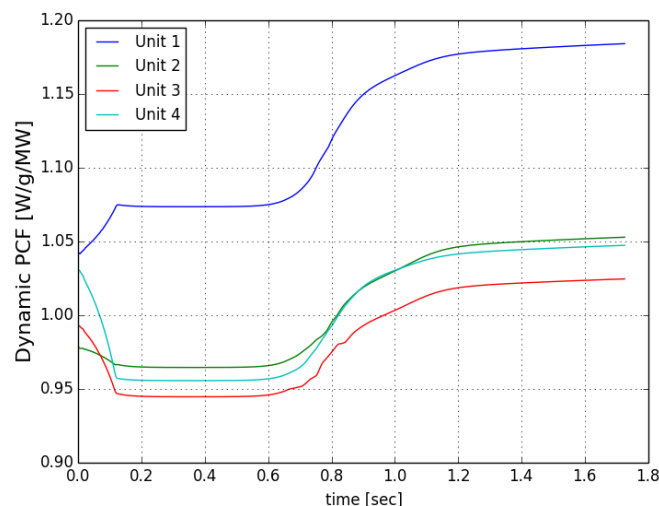
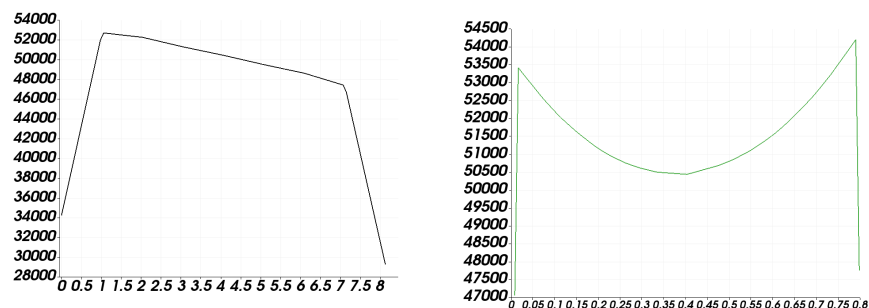
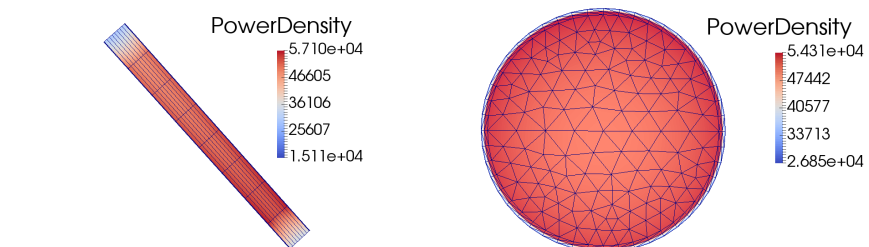
## Multi-SERTTA experiment

- The cross sections for the multi-SERTTA were developed using a source calculation in Serpent from the various core isothermal fuel temperature states saved at the experiment vehicle surface.
- Developed cross section tabulations as a function of local fuel temperature, average core fuel temperature near experiment and CR position.



# MAMMOTH SERTTA Stack 4 at 0.8 sec

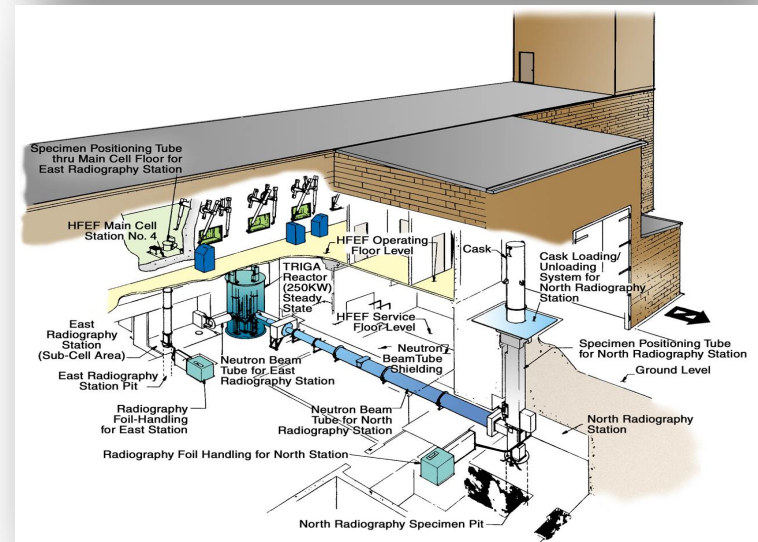
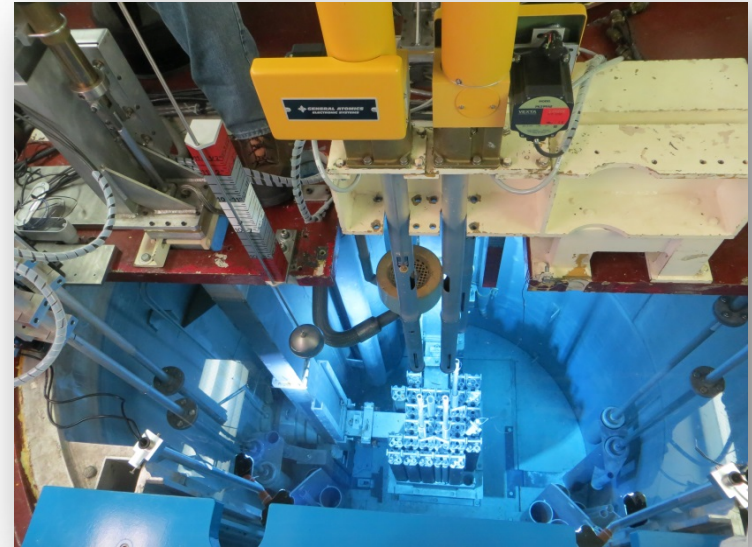
- Calculated fuel temperature approach melting point for  $\text{UO}_2$ .
- First time a dynamic power coupling factor (DPCF) has been computed. Shows effects from the rod withdrawal on all units.





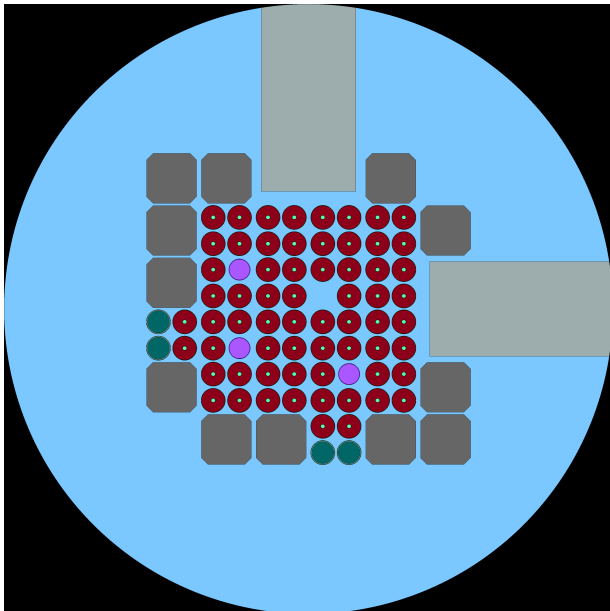
# Neutron Radiography (NRAD) Facility

- Similar to X-ray, neutron radiography provides images of structures that X-rays cannot penetrate.
- Neutron radiographs:
  - Significantly reduce the time and cost for conducting examinations of irradiated samples
  - Allow researchers to see inside them to evaluate features for further study
- Irradiated specimens to be radiographed are:
  1. Mounted in custom-designed fixtures
  2. Lowered in an elevator from the main HFEF hot cell down into the east beam line



# Neutron Radiography (NRAD) Facility

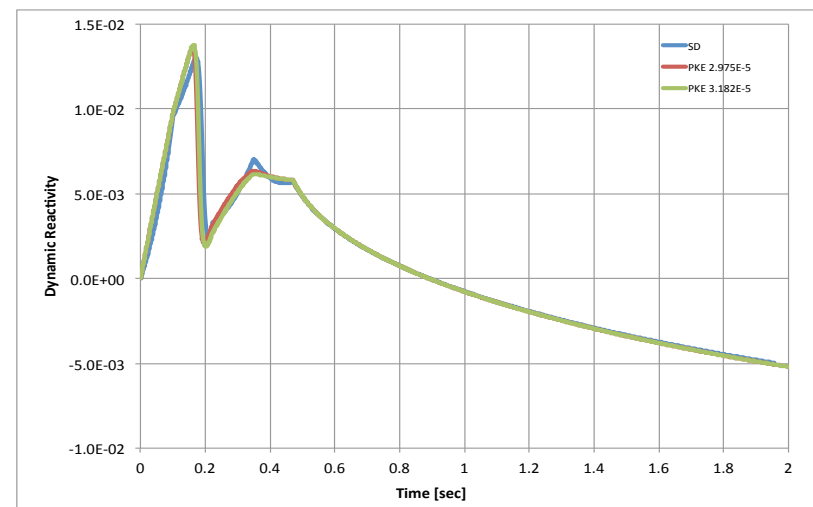
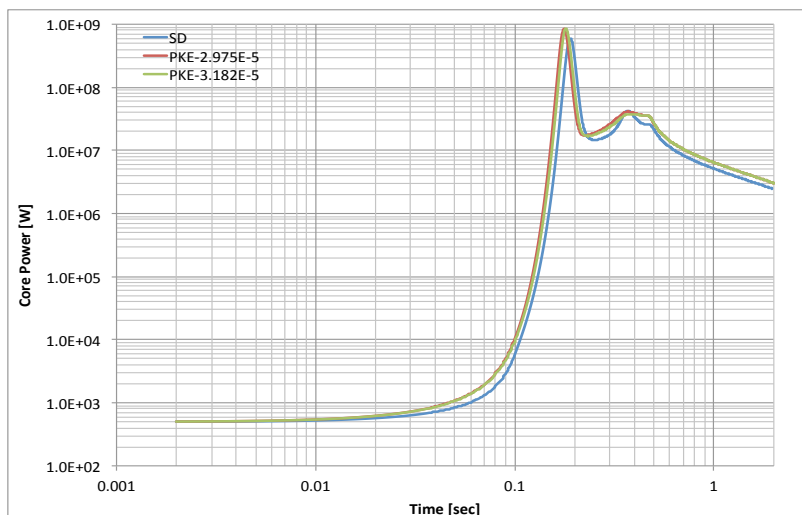
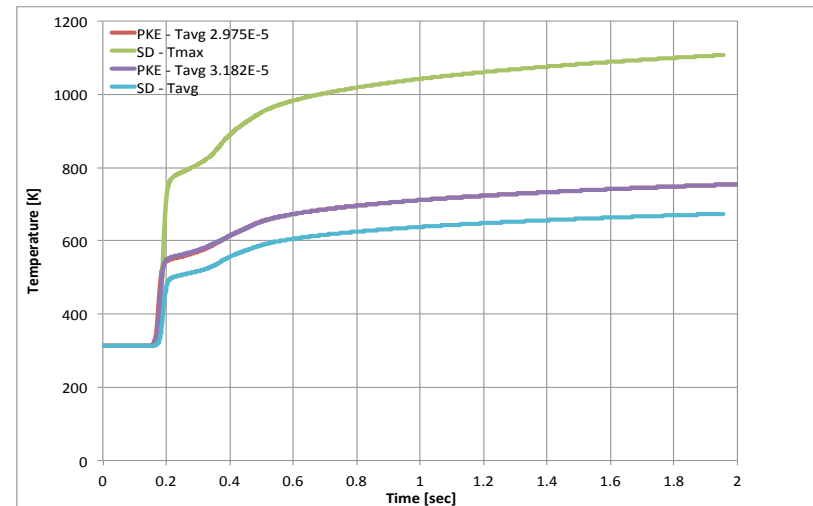
- 300-kilowatt TRIGA (Training, Research, and Isotopes, General Atomics) research reactor
- **Motivation:** to study differences between transient simulations using a Point Reactor Kinetics (PRK) model versus a spatial dynamics model for the NRAD core with MAMMOTH.
- Serpent used to generate reference solution and cross section for the core.



Prompt Fuel Temperature Coefficient of Reactivity					
	GA Post Startup BOL		Serpent (CRs banked)		
Temp. (°C)	k-eff	$\Delta \rho$ / °C	k-eff	$\Delta \rho$ / °C	% Diff.
23	1.02109		1.01291		
200	1.01129	5.36E-05	1.00287	5.58E-05	-4.1
280	1.0056	6.99E-05	0.99688	7.49E-05	-7.1
400	0.99551	8.40E-05	0.98656	8.74E-05	-4.1
700	0.96382	1.10E-04	0.95412	1.15E-04	-4.4
1000	0.92827	1.32E-04	0.92498	1.10E-04	16.9

# MAMMOTH Transient Results

- Comparison of MAMMOTH Spatial Dynamics (SD) vs. PKE with two different values of mean generation time.
- The SD model predicts a peak power of 600.0 MW, whereas both PRK results are approximately at 855 MW.



## *Wish list*

- More flexibility in cross section generation:
  - Overlay grid for cross section generation and burnup regions.
  - Radial and azimuthal regions for pins.
  - Compute a local burnup value.
- More memory efficient functionalization of temperature dependence of cross sections.
- Robust and well tested variance reduction techniques for cross section generation.
- Integrated isotope dependent and energy dependent heating values.
- For detectors, use local isotopes at current conditions instead of providing redefining the isotope.
  - e.g.: det 1 du 1007 dr -8 92235
- Cumulative Migration Method (MIT?)
  - Improve diffusion coefficients both isotropic and directional.

***QUESTIONS ?***