DOE NE IRP Kickoff Meeting
Idaho National Laboratory
November 19-20, 2015

Computational and Experimental Benchmarking for Transient Fuel Testing
Description of Task 1.2

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Task 1 Neutronics Benchmarks

A comprehensive neutronics benchmarking analysis will be conducted using PROTEUS (DoE NEAMS code), PARCS/AGREE (U.S. NRC code) and Open MC (Monte Carlo code). An IRPhEP will result from this comprehensive benchmarking analysis.

[Led by the University of Michigan]

1.1. Steady-State – Two steady state condition benchmarking tests will be selected and studied.

1.2. Transient – Two transient condition benchmarking problems will be selected and studied.

Task 1 - Steady State Simulation

Table 1: Task outline and ownership

Task #	Task Title	Sub-Task Owner
1.	Neutronics Benchmark Task Lead – T. Downar, UM	
1.1	Steady State (SS)	
1.1.1	Survey candidate problems	T. Downar, UM
1.1.2	Preliminary SS modeling of candidate problems	T. Downar, UM
1.1.3	Down-select to two problems for benchmark evaluation	T. Downar, UM
1.1.4	SS modeling with deterministic U.S. NRC codes PARCS/AGREE	T. Downar, UM
1.1.5	SS modeling with deterministic NEAMS code PROTEUS	C. Lee, ANL
1.1.6	SS modeling with Monte Carlo code OPENMC	K. Sun, MIT
1.1.7	Comparison of experimental data & model results	T. Downar, UM
1.1.8	Benchmark level evaluation of selected problems	T. Downar, UM
1.1.9	Evaluation of uncertainties in selected problems	T. Downar, UM
1.1.10	Preparation of IRPhEP documentation	T. Downar, UM
1.1.11	Submission of SS benchmark for peer review	T. Downar, UM

Task 1 – Transient Simulation

1.2	Transient (TR)	
1.2.1	Survey available TREAT TR data for benchmark problem	T. Downar, UM
1.2.2	Preliminary TR modeling of candidate problems	T. Downar, UM
1.2.3	Down-select to two problems for benchmark evaluation	T. Downar, UM
1.2.4	Perform TR modeling with deterministic U.S. NRC codes PARCS/AGREE	T. Downar, UM
1.2.5	Perform TR modeling with deterministic NEAMS code PROTEUS	C. Lee, ANL
1.2.6	Perform TR modeling with Monte Carlo code OPENMC	W. Martin, UM
1.2.7	Benchmark level evaluation of selected problems	T. Downar, UM
1.2.8	Evaluation of uncertainties in selected problems	T. Downar, UM
1.2.9	Preparation of IRPhE Documentation	T. Downar, UM
1.2.10	Submission of TR benchmark for peer review	T. Downar, UM

Task 1.2.6 Perform TR Modeling with OpenMC

- An alternative transient methodology based on steady state Monte Carlo (OpenMC).
- OpenMC analyzes the state of the reactor and estimates quantities that allow the determination of the eigenvalue spectrum and associated forward and adjoint eigenfunctions.
- Takes advantage of the capability of Monte Carlo to model arbitrarily complex geometries with continuous energy cross sections.
- This is a research project due to the relatively recent development of the methodology and the fact it has yet to be applied to transient applications with reactivity feedback.

Description of the TRM Method - 1

- Based on PhD work of Ben Betzler at the University of Michigan in 2014.
- The forward and adjoint α-eigenvalue equations with delayed neutron precursors are the starting point for the method.
- A transition rate matrix (TRM) formulation of the adjoint system is obtained by using OpenMC [4] to estimate the adjoint TRM elements. This is possible even though OpenMC is a steady-state forward Monte Carlo code and is not aware of delayed neutrons.
- The forward TRM is then determined by taking the transpose of the adjoint TRM.
- A standard linear algebra package (LAPACK) is then used to determine all of the forward and adjoint eigenfunctions and eigenvalues for this system.

Description of the TRM Method - 2

- The evolution of the system response to a specified source is obtained by standard eigenfunction expansion using bi-orthogonality of the forward and adjoint eigenfunctions:

$$\psi(\mathbf{r}, E, \hat{\boldsymbol{\Omega}}, t) = \sum_{n=1}^{\infty} A_n(t)\psi_n(\mathbf{r}, E, \hat{\boldsymbol{\Omega}})$$

$$A_n(t) = A_n(0)e^{\alpha_n t}$$

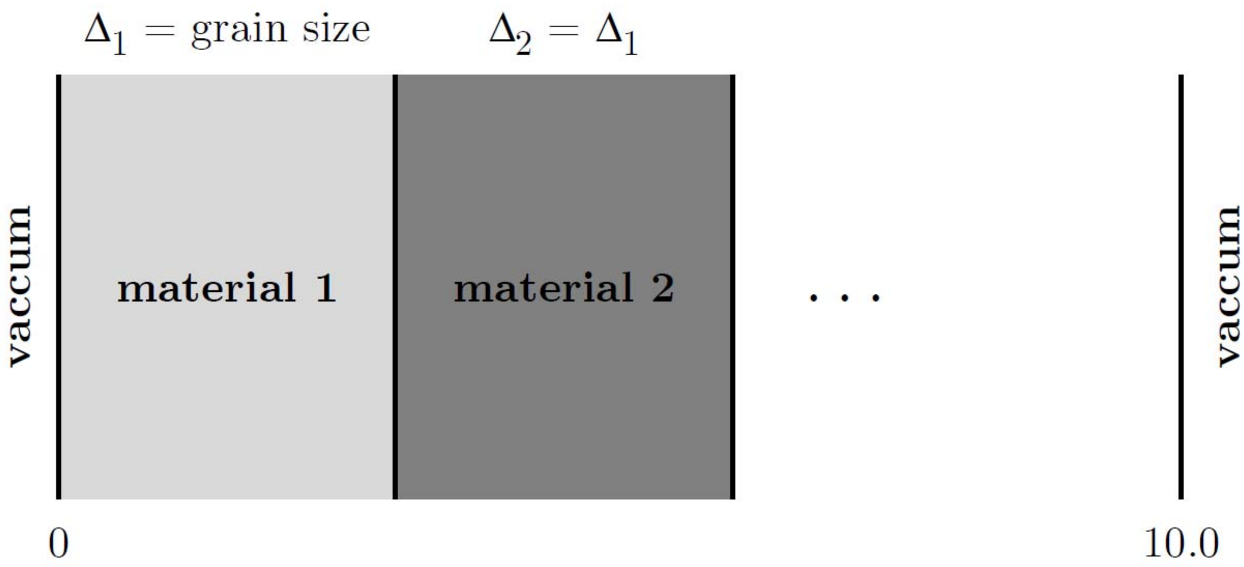
$$A_n(0) = \frac{\left\langle \psi_n^{\dagger}, S_0 \right\rangle}{\left\langle \psi_n^{\dagger}, v^{-1}\psi_n \right\rangle + \sum_m \left\langle C_{m,n}^{\dagger}, C_{m,n} \right\rangle}$$

Simple example – incident neutron pulse

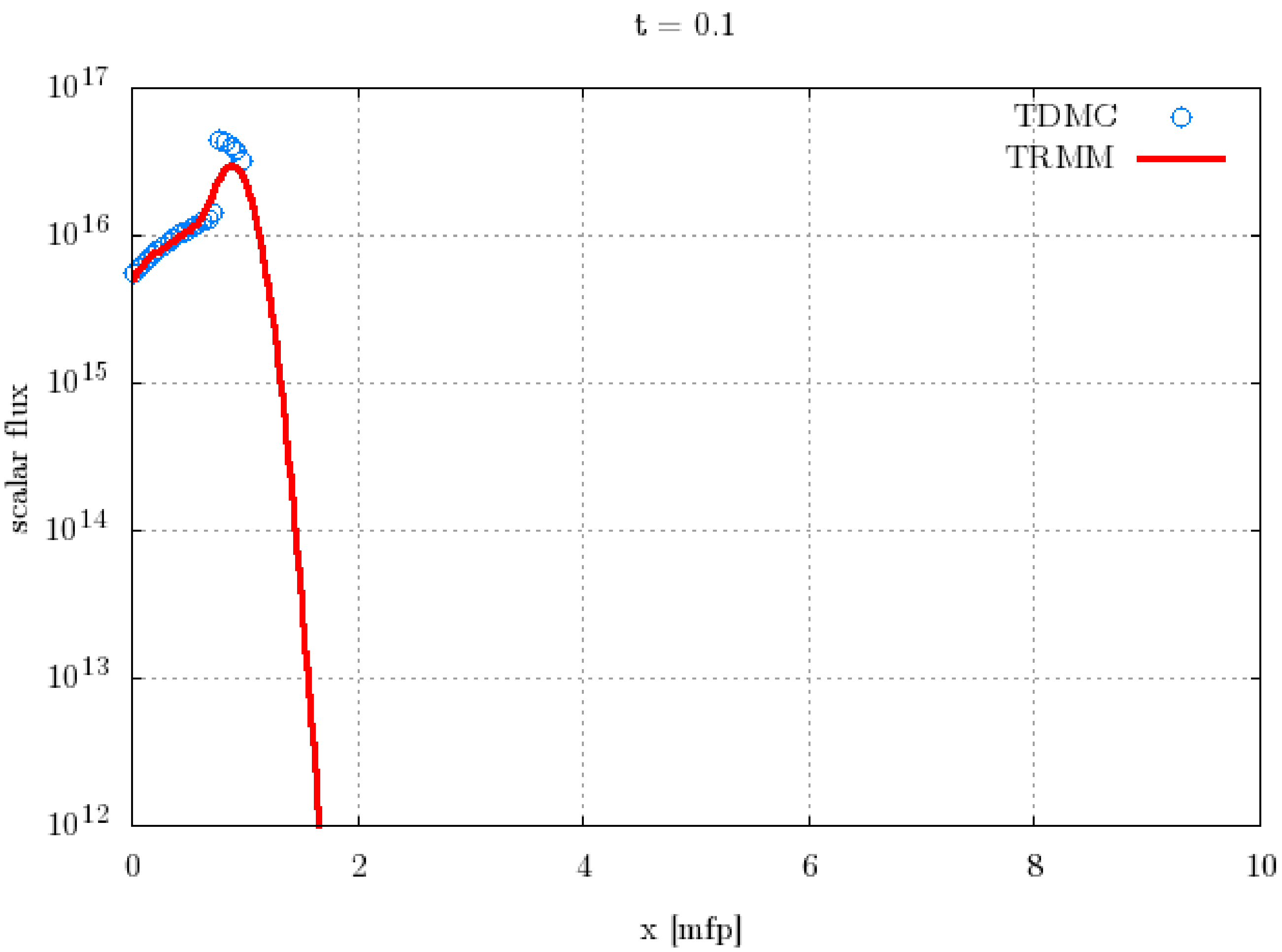
- Simple multiple slab problem
- First analyze state of the reactor with OpenMC and estimate matrix elements of the transition matrix
- Send matrix to external library to get eigenvalue spectrum and associated forward and adjoint eigenfunctions
- Expand time-dependent response and calculate expansion coefficients

Results: Multi-Region Problem

- Alternating materials of equal thickness
- Material 1 is purely scattering and material 2 has a small absorption cross section
- The speed is effectively 10 so the continuum portion of the spectrum starts at -10



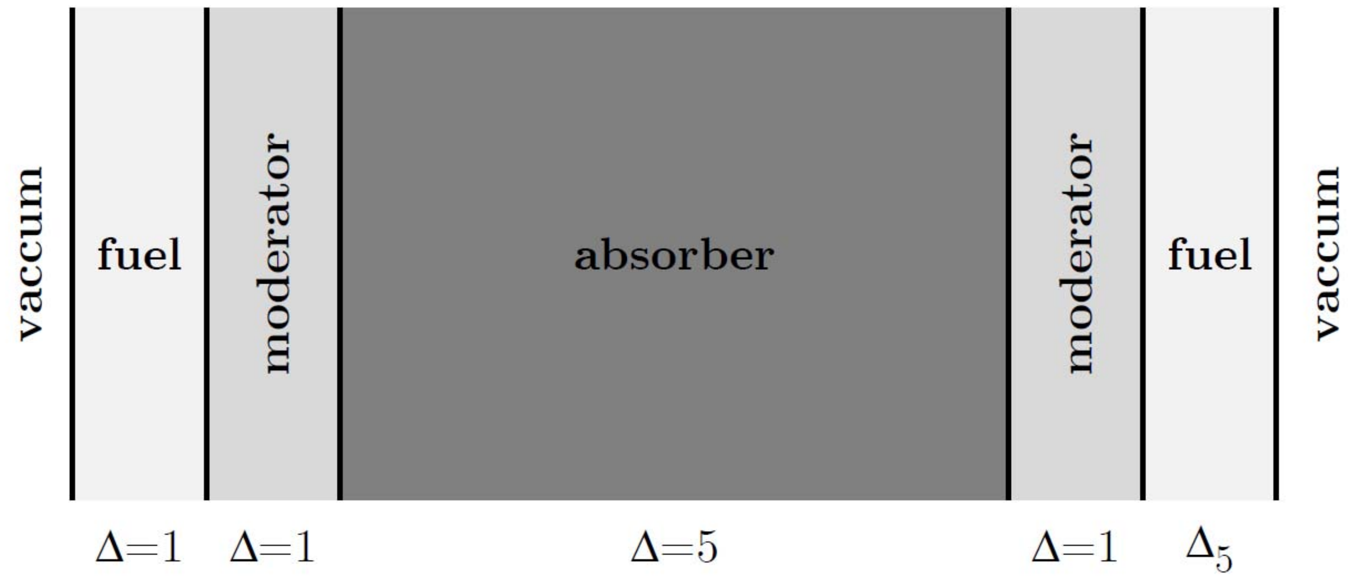
Eigenfunction expansion solution for incident pulse compared to time-dependent Monte Carlo



Second example – detector response

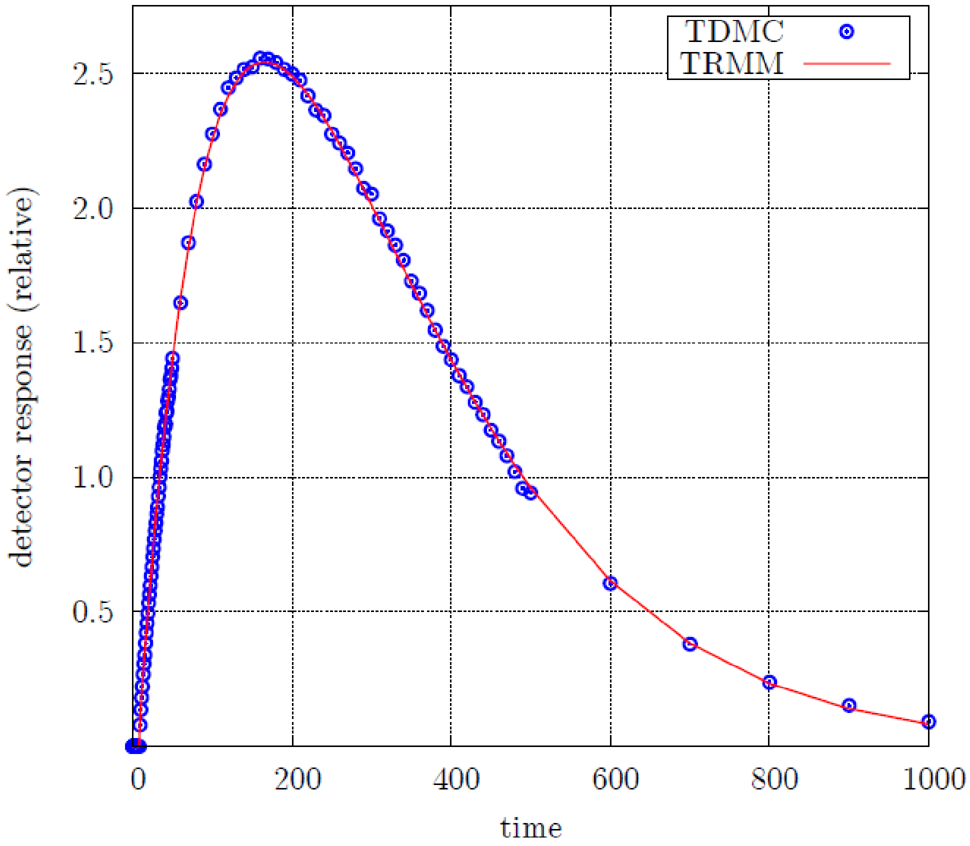
Five-region loosely coupled system

- **For this five-region problem, the right fuel region thickness is either 1 (symmetric) or 1.1 (asymmetric)**
- **The fuel is varied to make subcritical, near critical, and supercritical configurations**
- **All configurations have only two real eigenvalues**



The estimated detector response for critical symmetric problem for a detector in the right fuel region

- **Shows the ability of the TRMM to accurately predict the response in a given region of the problem**
- **The higher modes are still present throughout a large portion of the response, due to the proximity of the first two eigenvalues**

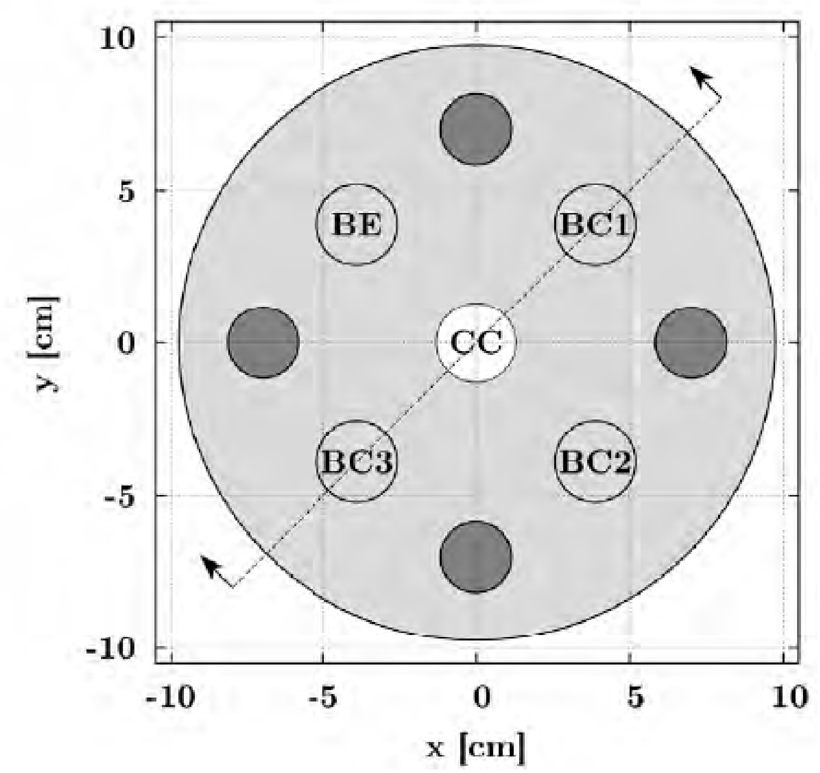


Additional comments

- Betzler used this method to analyze the time response of the Fort St. Vrain high temperature gas reactor to a 14 MeV pulsed neutron source.
- Also used to analyze Caliban
- It can be used for subcritical, critical, or supercritical systems.
- Primary impediment is the size of the phase space that is being evolved.

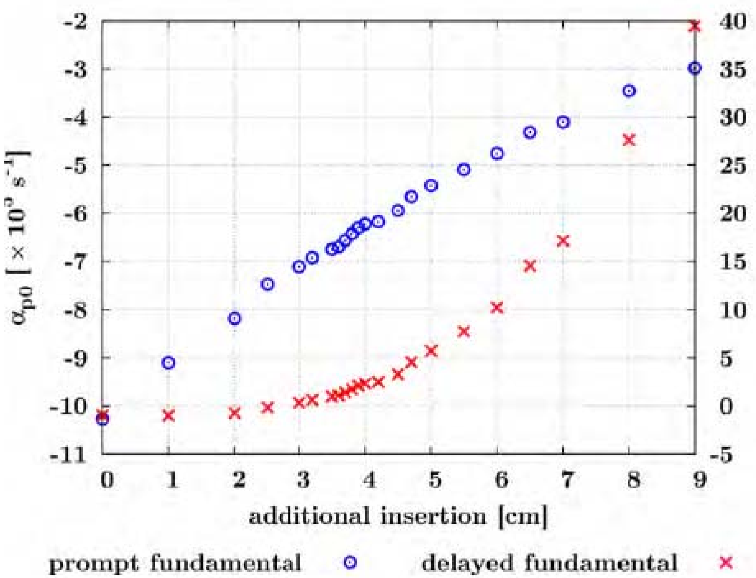
The fast-burst reactor CALIBAN

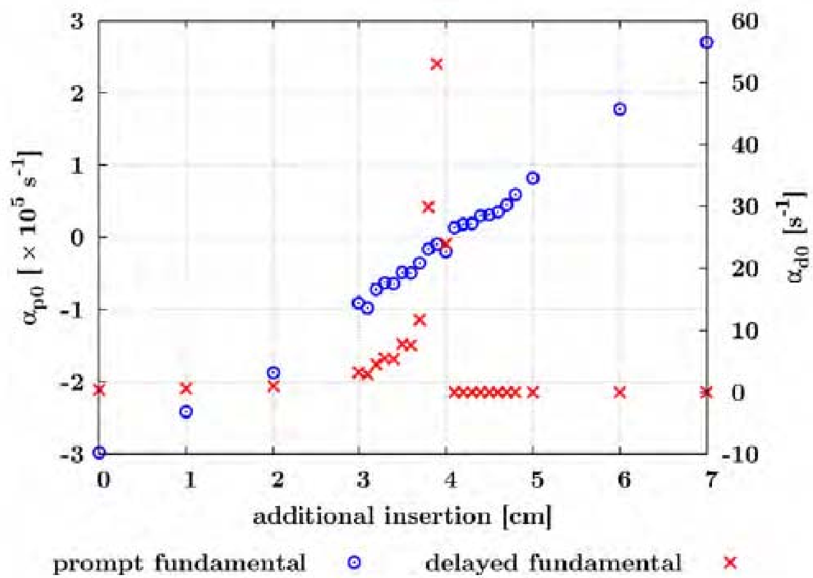
- **Measured data**
  - Fundamental eigenvalue
  - Inferred β_{eff}
  - Possible higher eigenvalues
- **With a coarse-interval TRM**
  - Track the behavior of the prompt and delayed fundamental eigenvalues
  - Show the change in criticality
- **With a large TRM**
  - Higher shape eigenfunctions
  - Demonstrate trend of higher eigenvalues
  - Apply to a system with a lower enrichment



Approach to critical and prompt critical

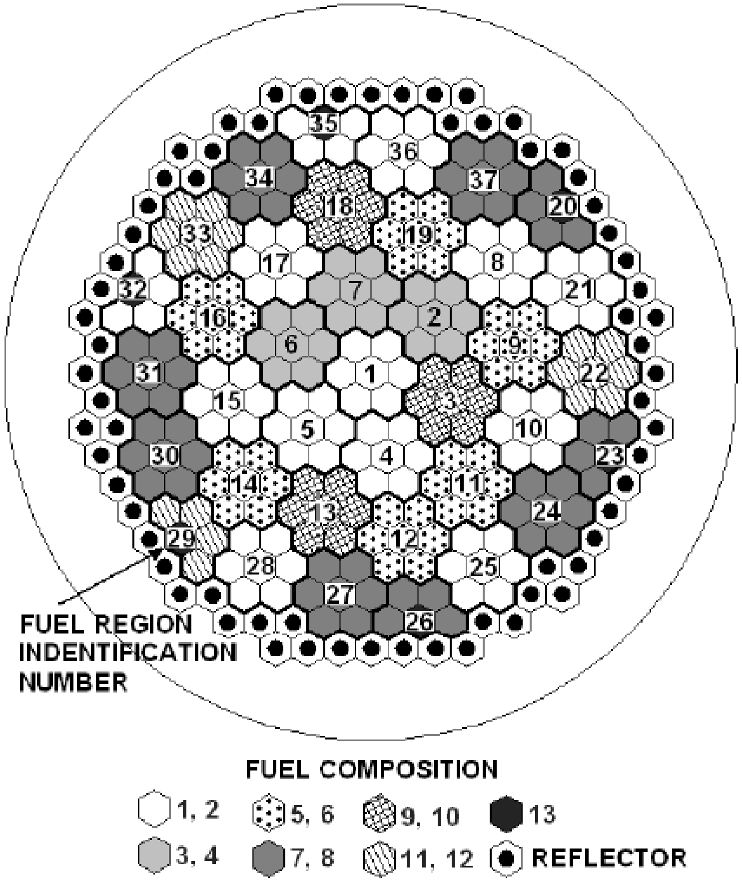
- **Additional insertion of the BC3 (left) and BC2 (right) control rods**
  - Critical (delayed supercritical) at 2.7 cm, prompt critical at 4 cm
- **Fundamental α eigenvalue under predicts the measured by 10%**
- **Calculates a β_{eff} 640 pcm compared to 633 pcm inferred**





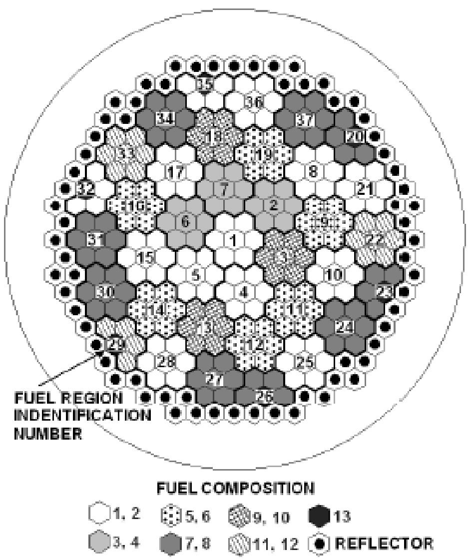
Fort St. Vrain pulsed neutron experiment

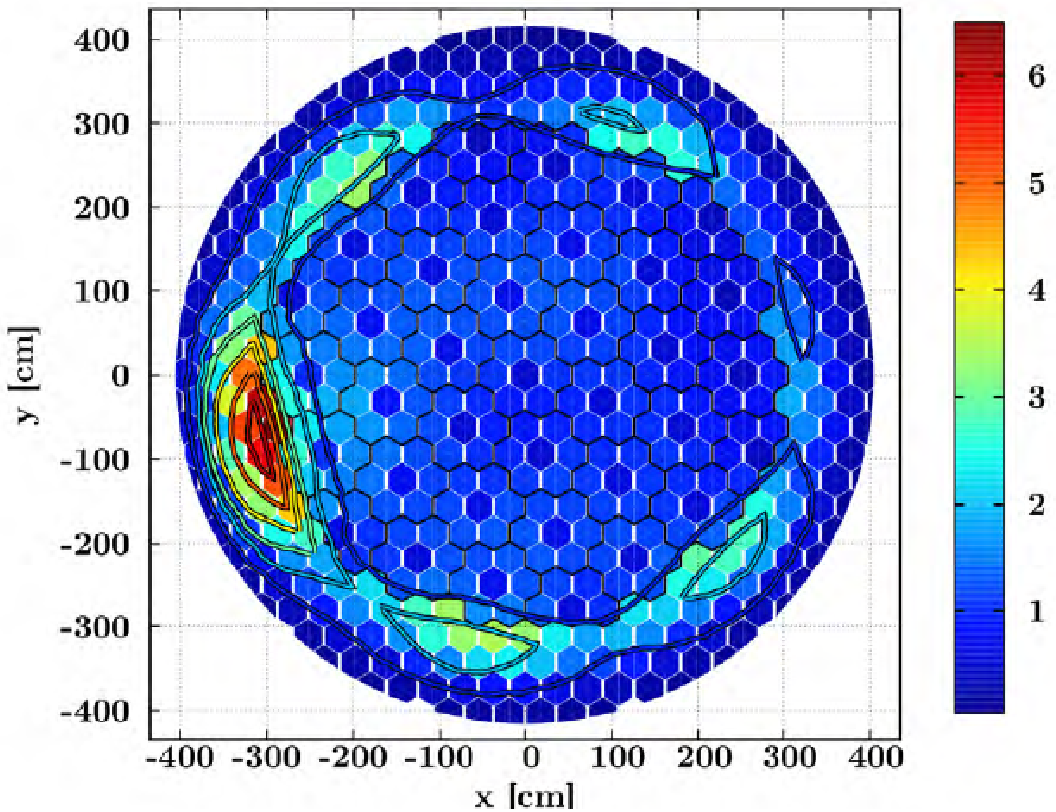
- **General Atomics High Temperature Gas-Cooled Reactor**
  - Graphite-moderated, prismatic core
  - Six stacked fuel blocks, 247 fuel columns distributed into 37 regions
  - Radially and axially asymmetric HEU-Th initial fuel loading
  - Multiple particle sized TRISO fuel formed in densely-packed compacts
  - Control rod pair runs axially through the center block (control block) of each fuel region
  - Pulsed neutron experiments on subcritical configurations during the startup physics tests



Fundamental eigenvalue and eigenfunction comparison

- **The fundamental eigenvalue is 6% smaller than measured**
  - Measured: $-164.6 \pm 4.9\ s^{-1}$ compared to TRMM: $-154.8\ s^{-1}$
  - Eigenfunction matches the GA calculation





Issues that need to be addressed for TREAT

- The current methodology has only been applied to the evolution of a reactor start without feedback
- On-the-fly $S(\alpha,\beta)$ and OTF free gas kernel needs to be incorporated into OpenMC
  - Andrew Pavlou just completed his PhD thesis on OTF $S(\alpha,\beta)$ and graphite was one of the materials he was analyzed
  - OTF free gas should be relatively straightforward if not already in OpenMC
- Current status
  - OTF Doppler is being put into OpenMC.
  - I am contacting Andrew Pavlou about putting OTF $S(\alpha,\beta)$ into OpenMC

Questions?