School of Nuclear Science and Engineering

COLLEGE OF ENGINEERING

Steady State Modeling of the Minimum Critical Core of TREAT using MAMMOTH

PHYSOR 2016

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May 3rd, 2016

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Outline

- Purpose and Motivation
- Research Objectives
- Modeling Approach
  - Cross Sections, Energy Group Structures, Spectral Analysis
  - Simulation Tool, MAMMOTH
- MAMMOTH Models
  - Diffusion Constant Treatment
  - Homogenizations
- Results
- Future Work

Purpose and Motivation

- Historical methods were iterative and only accurate within $\pm 10\%$.
  - Long and expensive pre-experiment characterization.

- High fidelity TREAT simulation model will provide:
  - Reduce number of calibration experiments.
  - Predictive capability for TREAT.
  - Preservation of time and money for facility and experimenters.

- Full 3D multiphysics capability
  - Power distribution, thermal fluids, fuels performance.
  - Accurately capture feedback effects and rapid transient behavior in both reactor and experiment test vehicle.

Research Objectives

- Accurately calculate fundamental neutronics properties.
  - Power Distribution.
  - Eigenvalue.
  - Reaction Rates.
- Observe phenomena as a function of temperature.
  - Spectral hardening.
  - Increased neutron leakage and capture.
- Establish appropriate treatment of diffusion coefficients in highly anisotropic regions.
- Provide preliminary base model for transient modeling.

Cross Section Preparation

- Full 3D cross sections developed through SERPENT
  - Monte Carlo reactor physics analysis software developed at VTT in Finland
  - Continuous energy using ENDF/B-VII.r1
  - No energy, spatial, or angular discretization approximations.
- Near void regions (air channels) developed using DRAGON5
  - SERPENT does not calculate accurate cross sections for near void regions
- Flux and volume weighted

$$\Sigma_{x,i}^{g} = \frac{\int_{D_i} \int_{E_{g-1}}^{E_g} \phi(r,E)\Sigma_x(r,E)\,dE\,dV_i}{\int_{D_i} \int_{E_{g-1}}^{E_g} \phi(r,E)\,dE\,dV_i}$$

Justification for 3D Cross Sections

- Key neutronics parameters are lost in simplified geometries

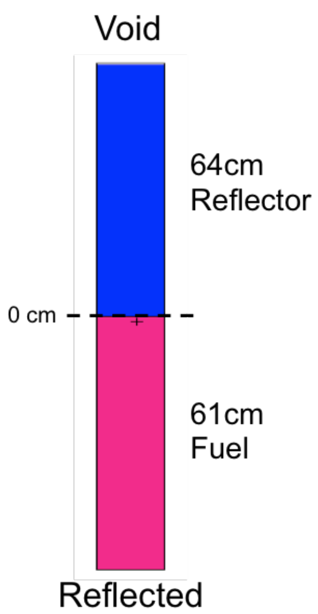
Parameter	TREAT Fuel	TREAT Assembly	TREAT Full Core
Ave. Num. of Collisions to Thermal	94.60	96.75	96.89
Ave. Num. of Collision while Thermal	47.96	62.88	95.79
Dist. traveled to thermal energy (cm)	48.04	53.72	52.59
Dist. Traveled while thermal (cm)	48.51	54.70	55.39

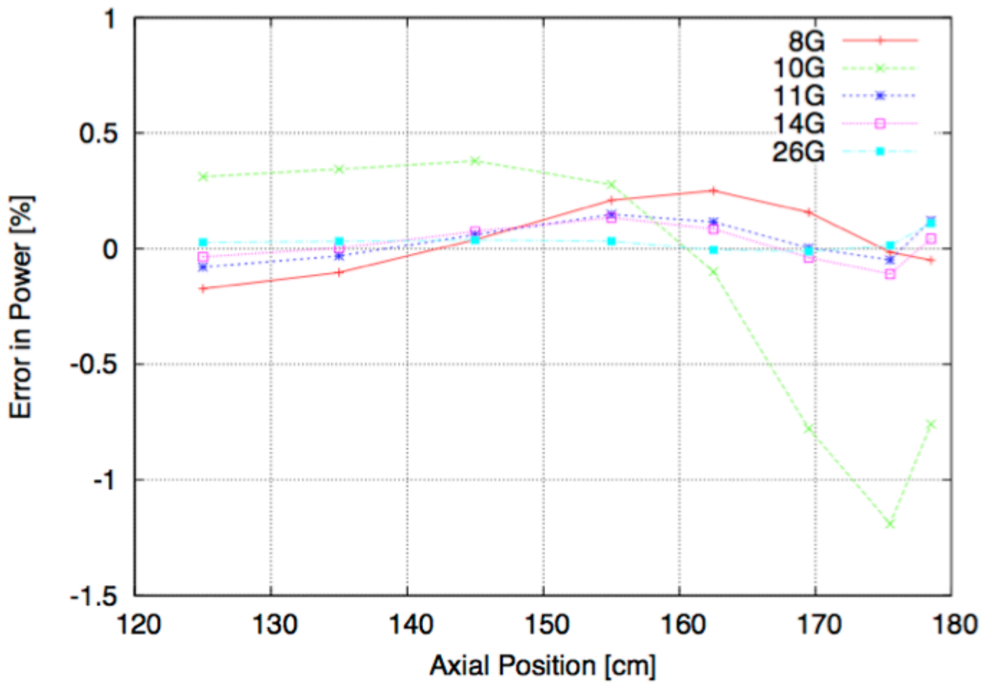
Based on SERPENT Minimum Critical model with ENDF/BVII.r1 data

- RMS linear distance of 76cm before being absorbed.
- Active fuel length - 122 cm
- Graphite reflector length - 63 cm

Energy Group Structure Analysis

- Tested several group structures on 3D half assembly model
  - Reflective boundary conditions on bottom and sides and vacuum on top (extrapolation distance…)
- 26, 14, and 11 group
- 10 equal lethargy bin group
- 8 HTR group
- 11 group best compromise





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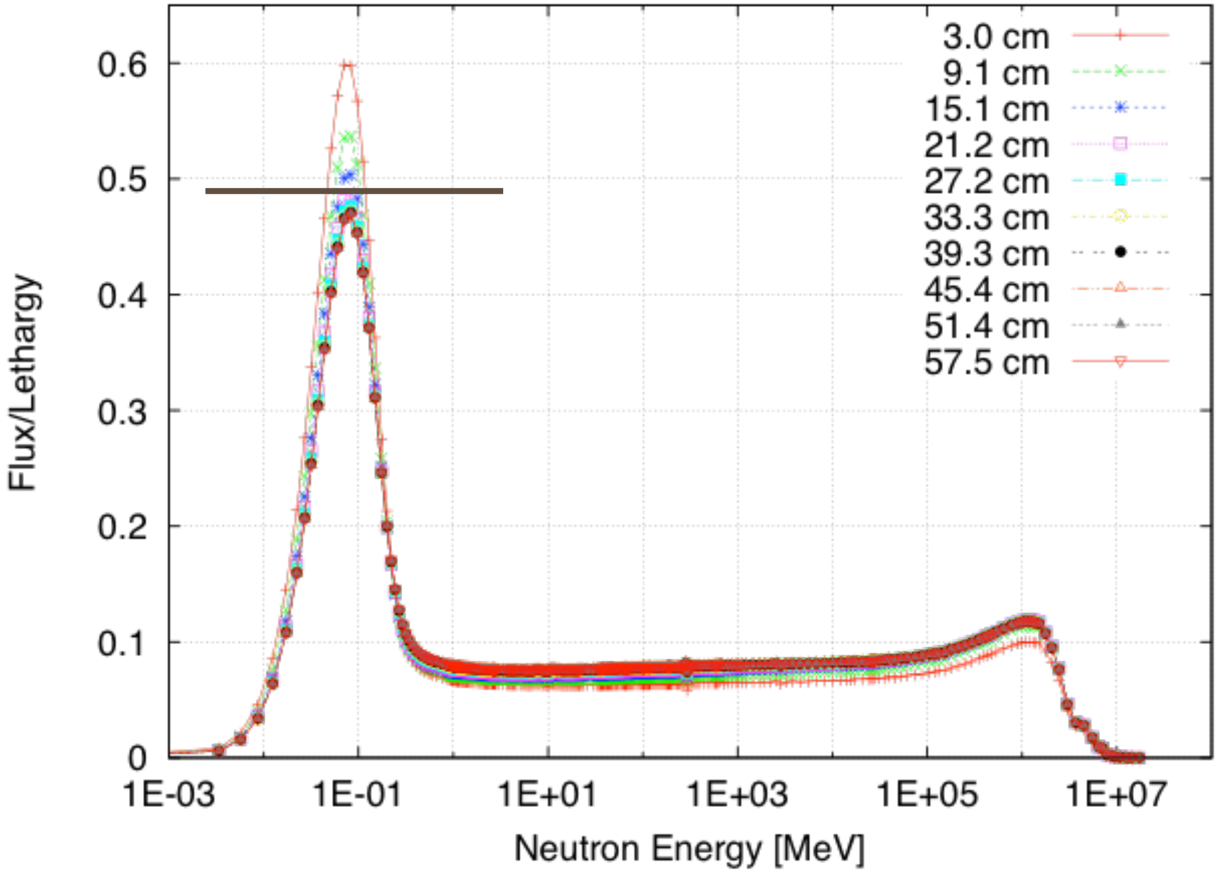
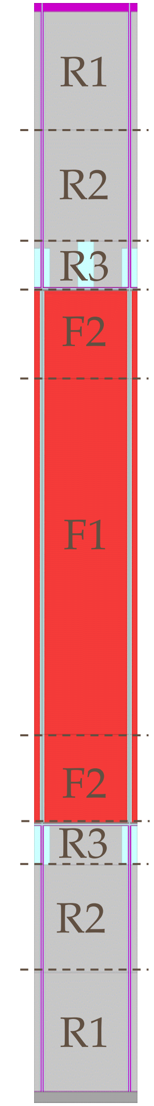
Spectral Analysis for Axial Cross Sections





Based on SERPENT half assembly model with ENDF/BVII.r1 data

Simulation Tool – MAMMOTH

- MAMMOTH – Multiphysics reactor analysis package.
  - Rattlesnake, BISON, RELAP-7
  - Linked with single executable.

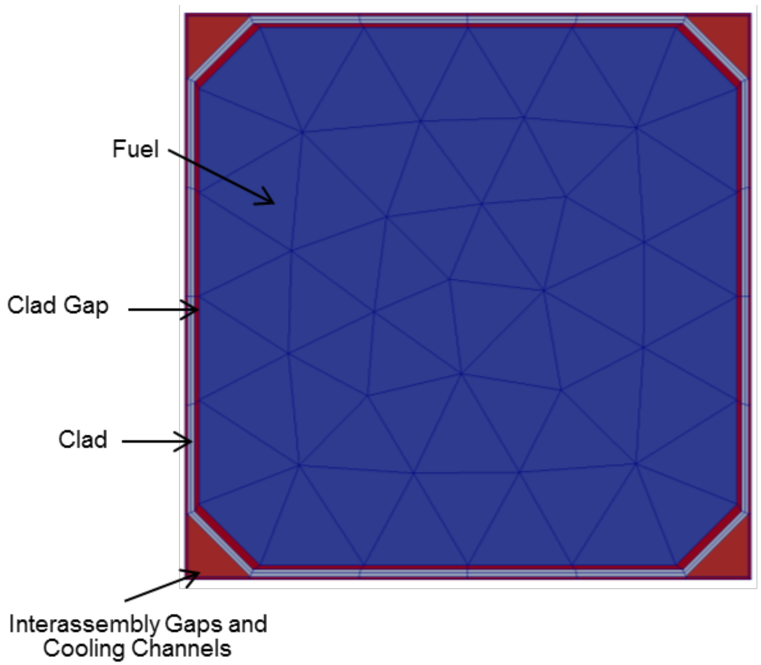
- Steady state neutronics calculations with Rattlesnake
  - Solves S_N or P_N discretization schemes of the SAAF transport formulation
  - Diffusion scheme
  - Solves eigenvalue or transient problems with arbitrary order of anisotropic scattering
  - Nonlinear diffusion acceleration (NDA)
  - Superhomogenized cross sections.
  - Improved quasi static (IQS) methods.

Diffusion Coefficient Treatment

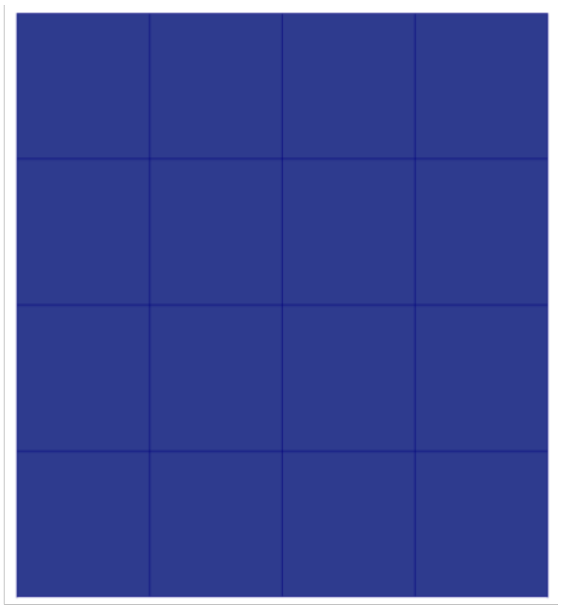
- $\frac{1}{\sigma_t}$ streaming term of second order SAAF transport formulation leads to numerical instabilities for near void regions → air channels
- In addition, void regions present complications in the calculation of diffusion coefficients for some Monte Carlo solvers, like SERPENT 2.
- Alleviated through:
  - Removal of near-void through homogenized models
  - Artificially increasing the value of the isotropic diffusion coefficient
    - Enforce higher diffusion in the air channel
    - Preserves neutron population in active core
- To improve the solutions, anisotropic diffusion coefficients are necessary
  - Currently testing implementation

Homogenization 1 - Full Radial Hom.

- All radial volumes are homogenized into a single volume.



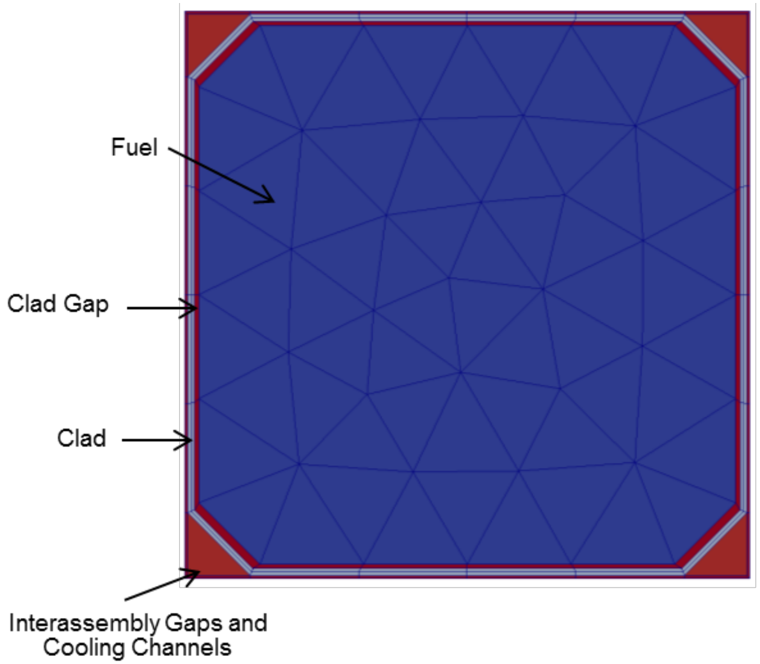
Heterogeneous



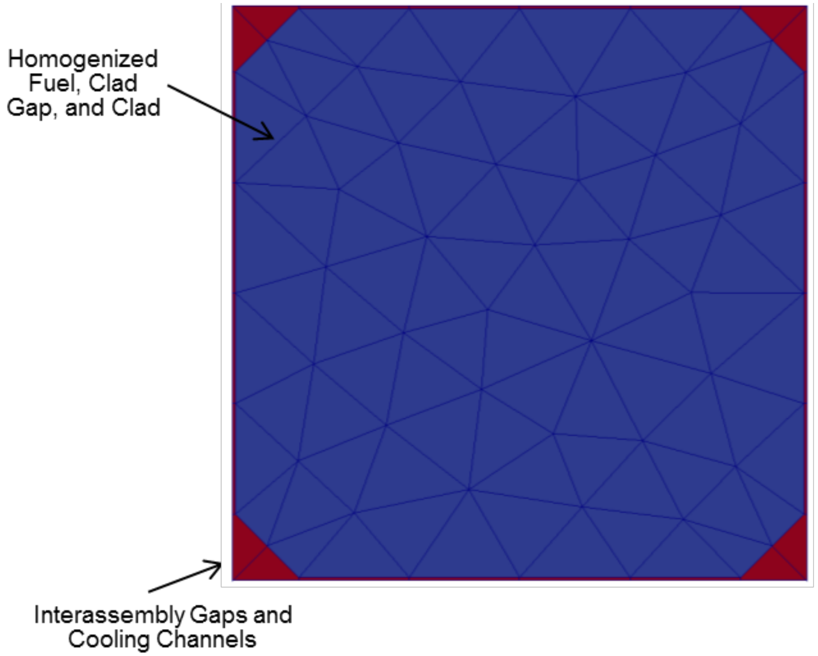
Full Hom.

Homogenization 2 – Full Fuel Hom. w/ Explicit Ch.

- Fuel, clad gap, and clad are homogenized.
  - Air channels and interassembly gap are explicitly modeled.
  - Solved via diffusion only.



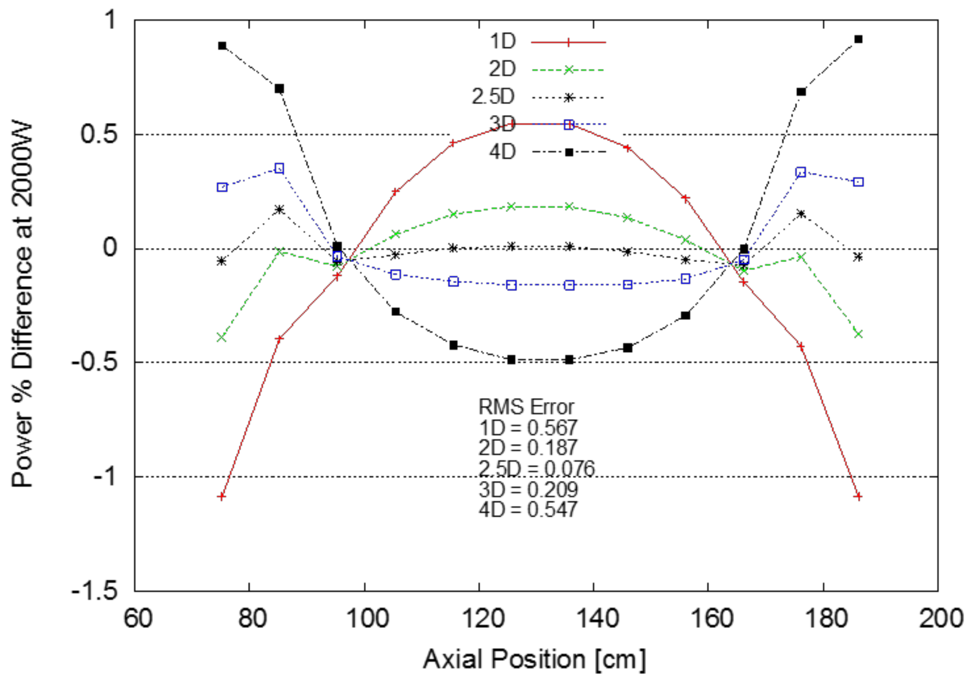
Heterogeneous



Full Fuel Hom. w/ Explicit Ch.

Diffusion Treatment - Full Fuel Hom. w/ Explicit Ch.

- Air channels and inter-assembly gap are left explicitly modeled to treat streaming in air channel.
- Artificially adjust group wise diffusion coefficients
  - Attempt to preserve accurate neutron population within active core.
  - Force neutrons out of core, inherently increase reflection back into core and better maintain balance.



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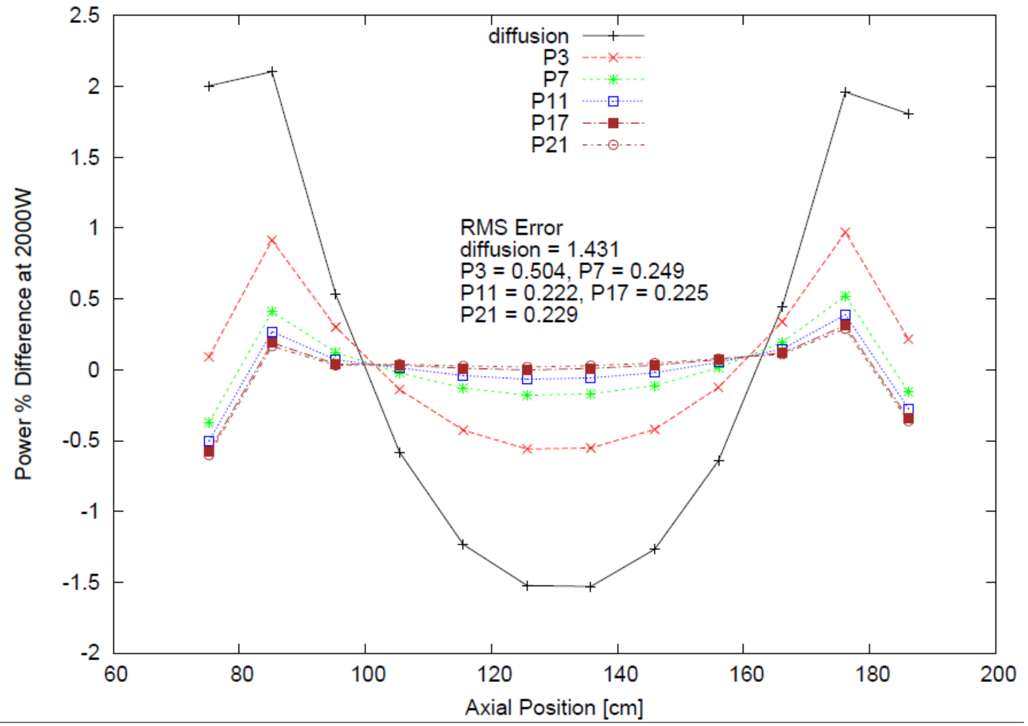
Transport solves for Single Assembly

- High order angular discretization is needed to accurately capture the streaming effect.
  - P_{17} involves calculation of $(N+1)^2$ moments (324).



Model Comparison – Single Assembly

- Max difference < 0.6%
- 12.7% improvement in eigenvalue for models with explicit channels.
- Accurate power dist. suggest inaccuracies in graphite reflector regions.

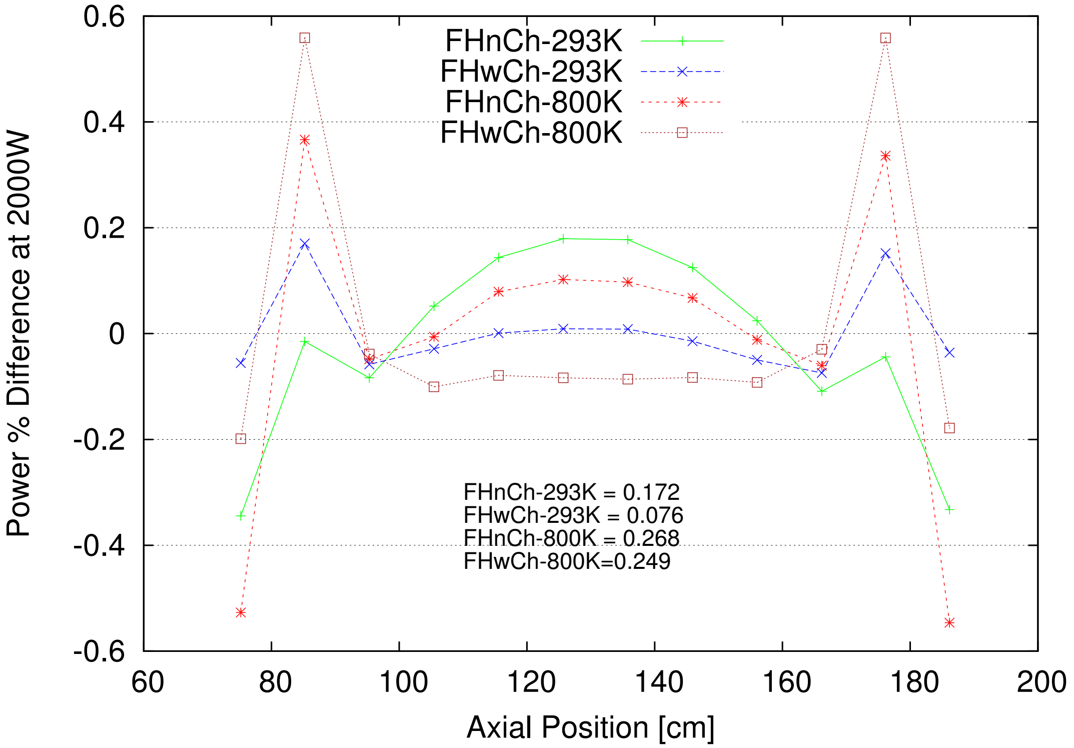
k_{eff} = 1.43190 (508.85 pcm)

%Difference

Fiss = -0.723 %

Capture = -0.586 %

Leakage = -16.605 %



Temp (K)	% Contrib. Fission	% Contrib. Capture	% Contrib. Leakage
293	58.93	38.23	2.93
800	56.36	40.34	3.37

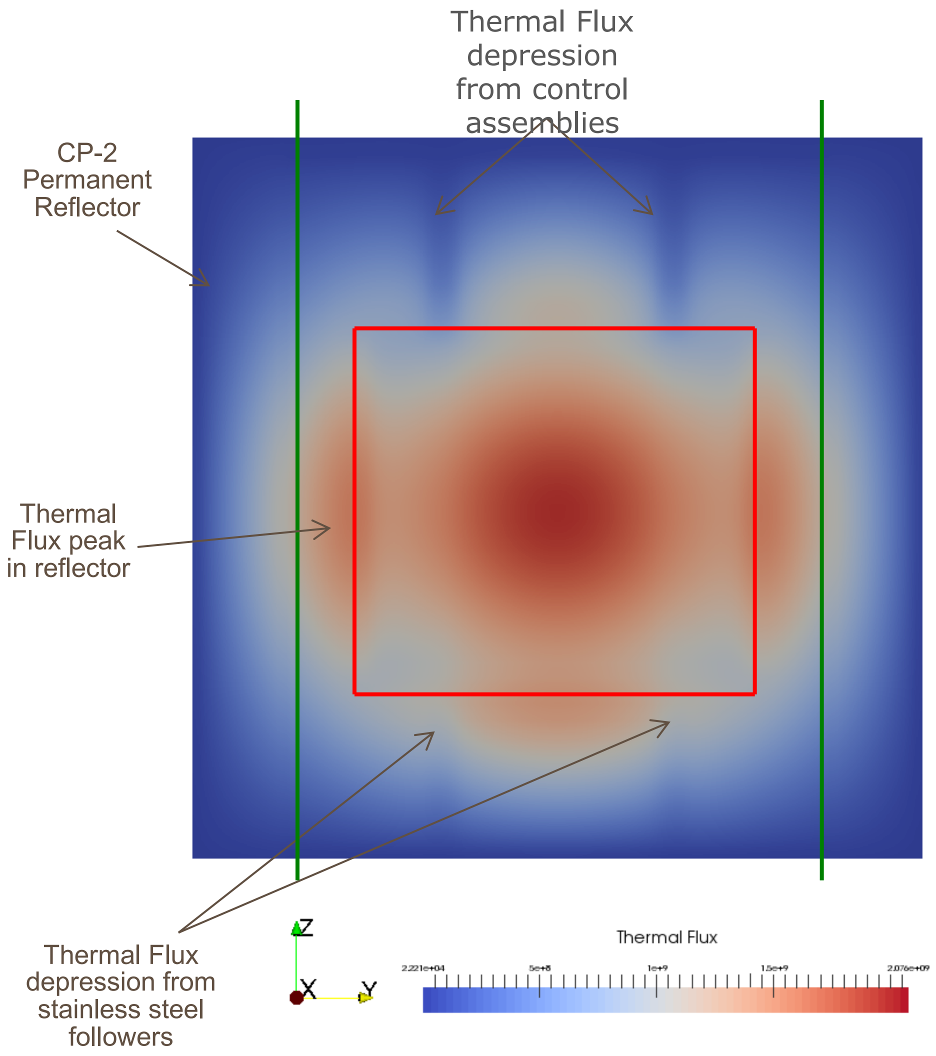
Minimum Critical Core Map

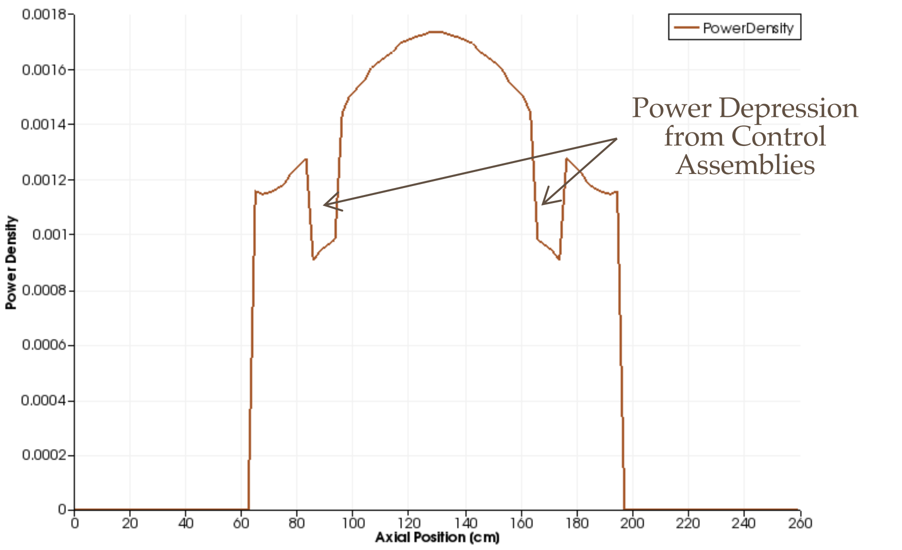
- 138 Fuel Assemblies
- 8 Control Assemblies
- Reflector Assemblies:
  - 40 Zr Clad
  - 175 Al Clad

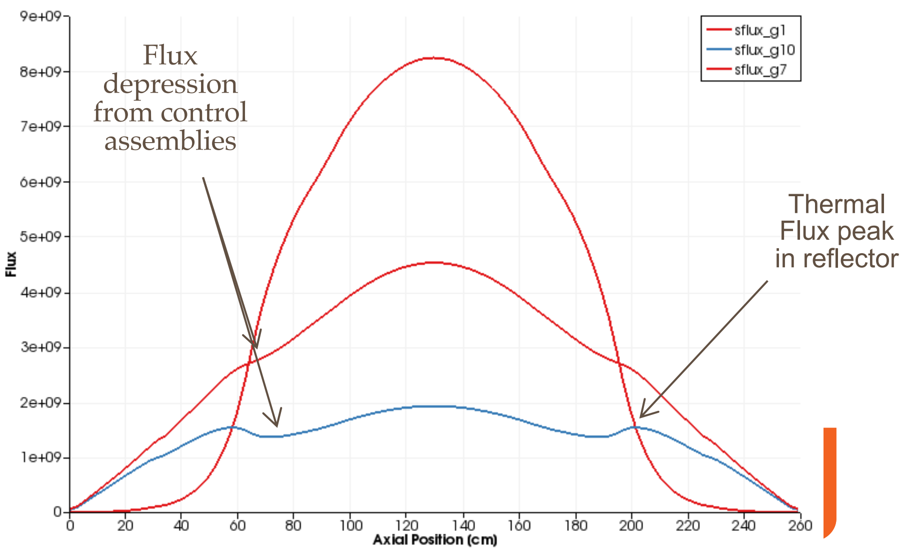
	A	B	C	D	E	F	G	H	J	K	L	M	N	O	P	R	S	T	U
1	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
2	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
3	4	4	4	4	4	4	2	2	2	4	2	2	2	4	4	4	4	4	4
4	4	4	4	4	4	2	1	1	1	2	1	1	1	2	4	4	4	4	4
5	4	4	4	4	2	1	1	1	1	1	1	1	1	1	2	4	4	4	4
6	4	4	4	2	1	1	1	3	1	1	1	3	1	1	1	2	4	4	4
7	4	4	2	1	1	1	1	1	1	1	1	1	1	1	1	1	2	4	4
8	4	4	2	1	1	3	1	1	1	1	1	1	1	3	1	1	2	4	4
9	4	4	2	1	1	1	1	1	1	1	1	1	1	1	1	1	2	4	4
10	4	4	4	2	1	1	1	1	1	1	1	1	1	1	1	2	4	4	4
11	4	4	2	1	1	1	1	1	1	1	1	1	1	1	1	1	2	4	4
12	4	4	2	1	1	3	1	1	1	1	1	1	1	3	1	1	2	4	4
13	4	4	2	1	1	1	1	1	1	1	1	1	1	1	1	1	2	4	4
14	4	4	4	2	1	1	1	3	1	1	1	3	1	1	1	2	4	4	4
15	4	4	4	4	2	1	1	1	1	1	1	1	1	1	2	4	4	4	4
16	4	4	4	4	4	2	1	1	1	2	1	1	1	2	4	4	4	4	4
17	4	4	4	4	4	4	2	2	2	4	2	2	2	4	4	4	4	4	4
18	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
19	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4

1	Fuel Assembly
2	Zr Clad Dummy Assembly
3	Control Assembly
4	Al Clad Dummy Assembly

Min. Crit. Core Results Visual Data Representation







Full Radial Hom. – Min. Crit. Core Results

- Axially integrated, radial power distribution
  - Spatially dependent cross sections.
  - Fuel cross sections are flux weighted across core.
- % Difference would be improved with more radial cross section regions.

k_{eff} = 1.01961 (1388.79 pcm)

<u>%Difference</u>
Fiss = -1.407%
Capture = -13.518%
Leakage = 33.963%

0.000	0.000	0.000	-0.554	-0.419	0.059	0.000	0.024	-0.478	-0.603	0.000	0.000	0.000
0.000	0.000	-0.354	-0.454	-0.335	-0.097	0.139	-0.087	-0.386	-0.529	-0.478	0.000	0.000
0.000	-0.362	-0.340	-0.224	-0.082	0.045	0.188	0.035	-0.105	-0.261	-0.447	-0.504	0.000
-0.537	-0.482	-0.203	0.024	0.134	0.255	0.316	0.244	0.089	0.024	-0.256	-0.530	-0.630
-0.424	-0.339	-0.041	0.141	0.328	0.381	0.399	0.357	0.281	0.117	-0.092	-0.368	-0.437
0.065	-0.072	0.074	0.283	0.384	0.434	0.440	0.415	0.358	0.224	0.037	-0.086	0.042
0.000	0.163	0.186	0.327	0.394	0.425	0.428	0.428	0.391	0.266	0.156	0.132	0.000
0.081	-0.051	0.090	0.256	0.384	0.410	0.419	0.410	0.366	0.236	0.025	-0.108	0.074
-0.375	-0.321	-0.042	0.110	0.326	0.386	0.387	0.350	0.305	0.093	-0.065	-0.338	-0.414
-0.517	-0.472	-0.231	0.015	0.105	0.256	0.296	0.249	0.100	0.008	-0.232	-0.471	-0.533
0.000	-0.361	-0.366	-0.213	-0.066	0.057	0.167	0.064	-0.051	-0.233	-0.366	-0.359	0.000
0.000	0.000	-0.362	-0.478	-0.339	-0.089	0.161	-0.078	-0.322	-0.484	-0.391	0.000	0.000
0.000	0.000	0.000	-0.509	-0.420	0.082	0.000	0.080	-0.403	-0.549	0.000	0.000	0.000

Full Distribution

RMS	2.2013
Min	-2.3900
Max	1.6860

Axially Integrated

RMS	0.3163
Min	-0.6304
Max	0.4398

Temp (K)	% Contrib. Fission	% Contrib. Capture	% Contrib. Leakage
293	42.00	43.68	12.16
800	38.01	46.18	13.26

Full Fuel Hom. w/ Explicit Ch. – Min. Crit. Results.

- Axially integrated, radial power distribution
  - 29.7% improvement in RMS power distribution over fully homogenized model
- RMS can be further improved with more spatial dependent cross section regions.

k_{eff} = 1.00575 (24.68 pcm)

%Difference
Fiss = -0.056%
Capture = -12.180%
Leakage = 40.195%

0.000	0.000	0.000	-0.464	-0.354	0.007	0.000	-0.020	-0.381	-0.514	0.000	0.000	0.000
0.000	0.000	-0.277	-0.309	-0.238	-0.012	0.144	-0.019	-0.253	-0.362	-0.346	0.000	0.000
0.000	-0.266	-0.194	-0.144	-0.032	0.045	0.153	0.057	-0.059	-0.160	-0.241	-0.352	0.000
-0.470	-0.303	-0.144	0.013	0.074	0.184	0.209	0.177	0.055	0.019	-0.162	-0.337	-0.537
-0.351	-0.264	-0.041	0.074	0.196	0.249	0.240	0.224	0.186	0.072	-0.035	-0.242	-0.396
-0.022	-0.042	0.053	0.168	0.223	0.251	0.261	0.281	0.256	0.173	0.069	-0.011	0.007
0.000	0.127	0.140	0.211	0.235	0.277	0.279	0.274	0.265	0.208	0.162	0.158	0.000
0.042	-0.019	0.062	0.175	0.242	0.269	0.281	0.270	0.242	0.158	0.048	-0.033	-0.006
-0.327	-0.191	-0.030	0.112	0.194	0.245	0.261	0.238	0.201	0.072	-0.041	-0.215	-0.344
-0.461	-0.277	-0.112	0.026	0.077	0.182	0.235	0.183	0.069	0.034	-0.090	-0.268	-0.432
0.000	-0.252	-0.168	-0.137	-0.054	0.057	0.161	0.080	-0.019	-0.104	-0.164	-0.232	0.000
0.000	0.000	-0.212	-0.301	-0.213	0.012	0.180	-0.005	-0.181	-0.245	-0.237	0.000	0.000
0.000	0.000	0.000	-0.421	-0.302	0.024	0.000	0.032	-0.317	-0.411	0.000	0.000	0.000

Full Distribution

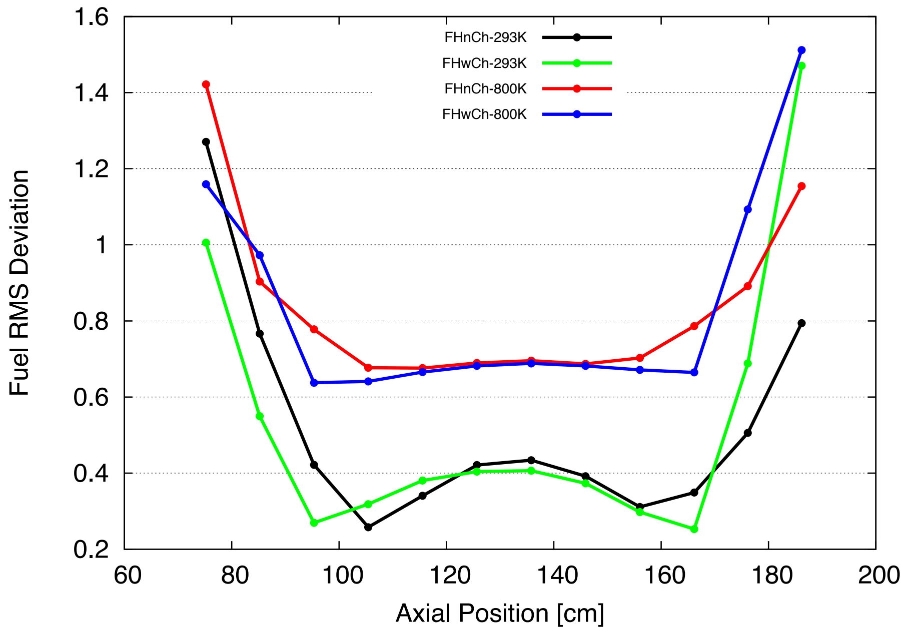
RMS	2.3777
Min	-0.7384
Max	3.5893

Axially Integrated

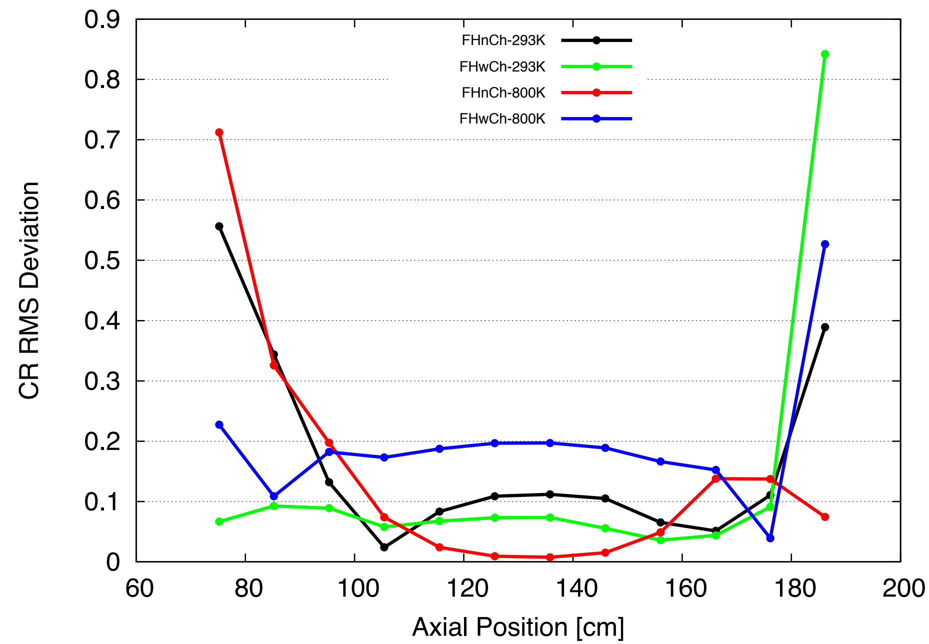
RMS	0.2228
MAX	0.2812
MIN	-0.5368

Temp (K)	% Contrib. Fission	% Contrib. Capture	% Contrib. Leakage
293	41.38	43.75	12.55
800	37.46	46.01	13.92

Axial Power Distribution Deviation



- Maximum difference < 1.6%
  - Occurs at peripheries – graphite reflector regions.
- Increased error at bottom of fuel region unclear.



- 88.01% improvement at bottom of core with explicit channels model.
- Diffusion simulation results are poor at the top of the core when B_4C rods are present at that location.

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Conclusions

- Objectives of research:
  - Identification and quantification of key neutronics properties.
  - Effects of spatial homogenization and angular discretization.
  - Developed appropriate diffusion coefficient treatment.
- Single assembly, infinite lattice:
  - 0.076% APD deviation for full fuel homogenization with explicit channels model.
  - Showed high degree of anisotropy (required high order P_N solution).
- Min. Crit. Core:
  - 2.38% RPD deviation for full fuel homogenization with explicit channels model.
  - Including the streaming effects of the cooling channels, an 88.01% improvement was observed in control rod modeling.

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Future Work in Steady State Calculations

- Develop directional diffusion coefficients from:
  - High fidelity first order transport solution based on:
    1. Fick's Laws
    2. Eddington Tensor
- Superhomogenized cross sections (SPH)
  - Currently under testing for MAMMOTH
  - Preserves reaction rates (especially in reflector region)
- Enhance fidelity in control assemblies and reflector regions
  - Currently drives accuracy of power distribution in full core calculations

Questions?