Reactor Physics Analysis of the VHTGR Core

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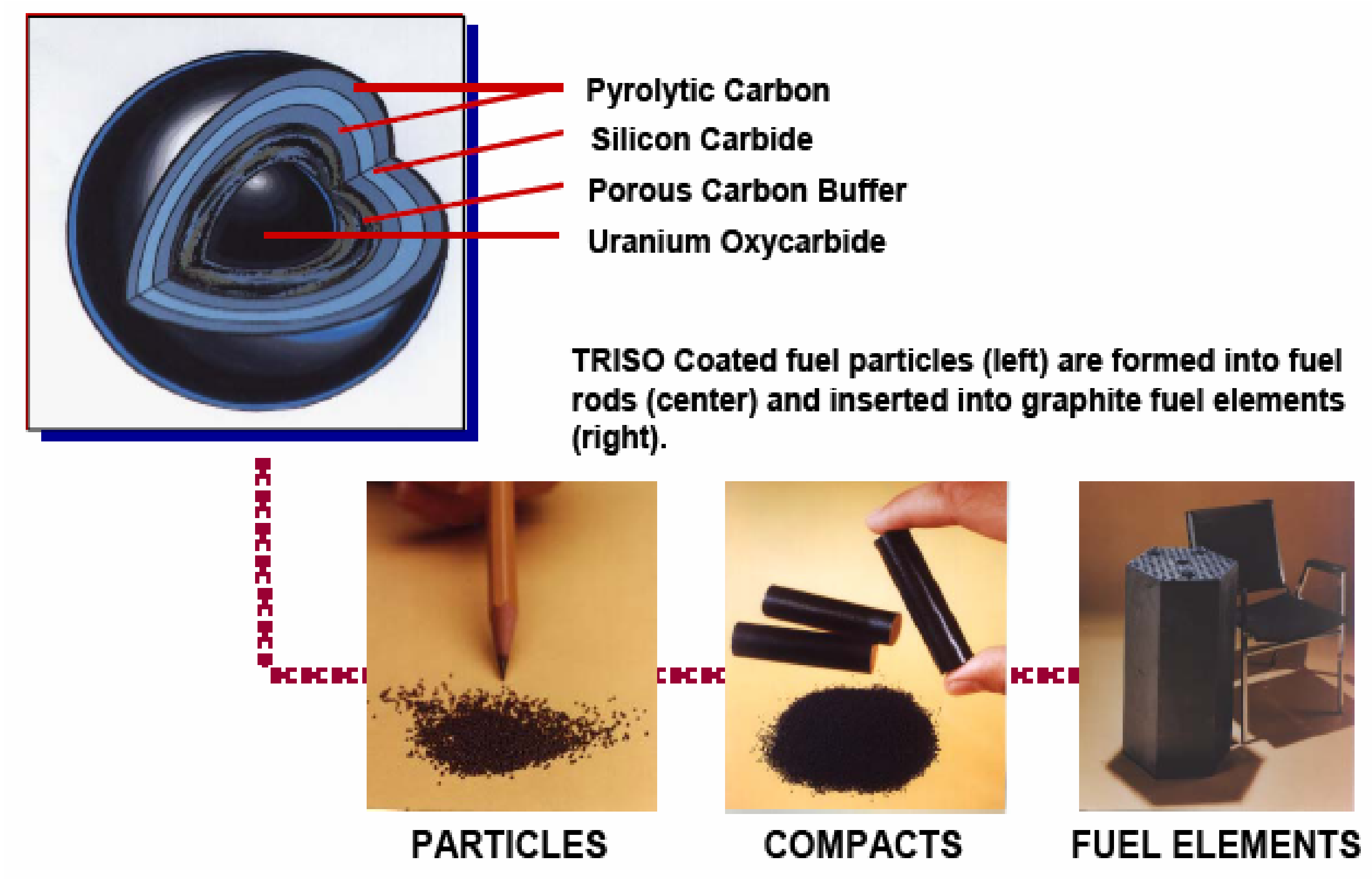
Introduction

- **This is one of the tasks of the I-NERI project**
  - **I-NERI Project: Develop safety analysis codes and experimental validation for the VHTGR**
  - **Develop reactor physics models for power distribution and decay heat**
  - **Perform coupled neutronic/thermal-hydraulic analysis of VHTGR**

Development of MCNP models

- ❑ Detailed microsphere models for analysis of double heterogeneity
- ❑ Assembly-level model for analysis of detailed geometry
- ❑ Full-core models for global calculations of flux and power distributions

VHTGR fuel (from General Atomic)



MCNP5 Simulations of Microsphere Cells

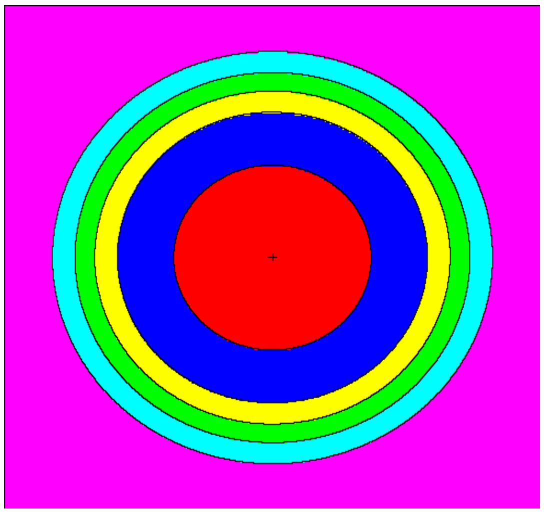
- Single microsphere cell consists of fuel microsphere and graphite matrix to yield packing fraction = 0.289
- Enrichment=10.36%
- Microsphere cell is either heterogeneous (explicit modeling of all regions: fuel kernel, carbon buffer, SiC, and inner/outer pyrolytic carbon shells) or homogenized mixture of microsphere and graphite matrix
- Analyzing two region microsphere cell: fuel kernel and remainder of microsphere/graphite matrix
- Reflecting boundaries on six surfaces of cube

Sensitivity calculation – thermal expansion

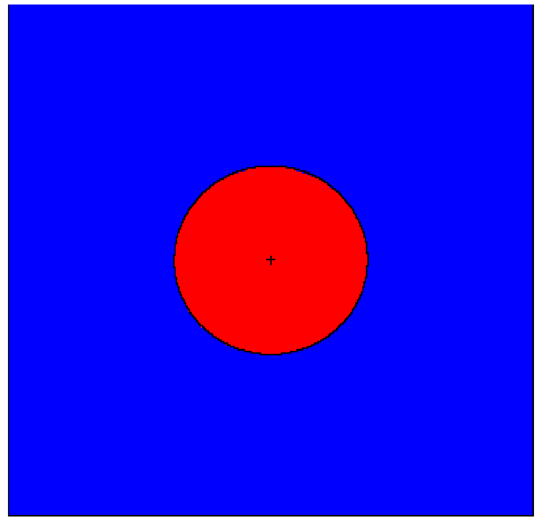
- Thermal expansion of graphite taken from CERN report (temperature dependent)
- MCNP full core calculation (hexagonal block core with reflectors and homogeneous blocks)
- All linear dimensions multiplied by $1 + \alpha\Delta T$
- All densities divided by $(1 + \alpha\Delta T)^3$
- Results indicate thermal expansion is negligible:

Case	keff	std dev
Room temp	1.43953	0.00094
1000 C	1.43800	0.00081
2000 C	1.43788	0.00076

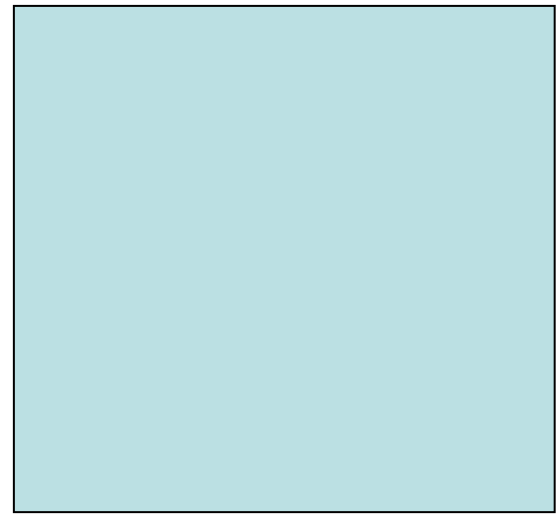
Microsphere cells – microsphere in graphite matrix cube



Fully Heterogeneous



Two-Region Heterogeneous



Homogeneous

Reflecting b.c. on all sides of cubes

MCNP5 Simulations of Microsphere Cells

Configuration	Kernel location	keff	std dev
Homogeneous microsphere cell	**- - -**	**1.0995**	**.0004**
Two-region heterogeneous microsphere cell	**Centered**	**1.1535**	**.0004**
Fully heterogeneous microsphere cell	**Centered**	**1.1533**	**.0003**
Fully heterogeneous microsphere cell (LANL)	**Random**	**1.1515**	**.0004**

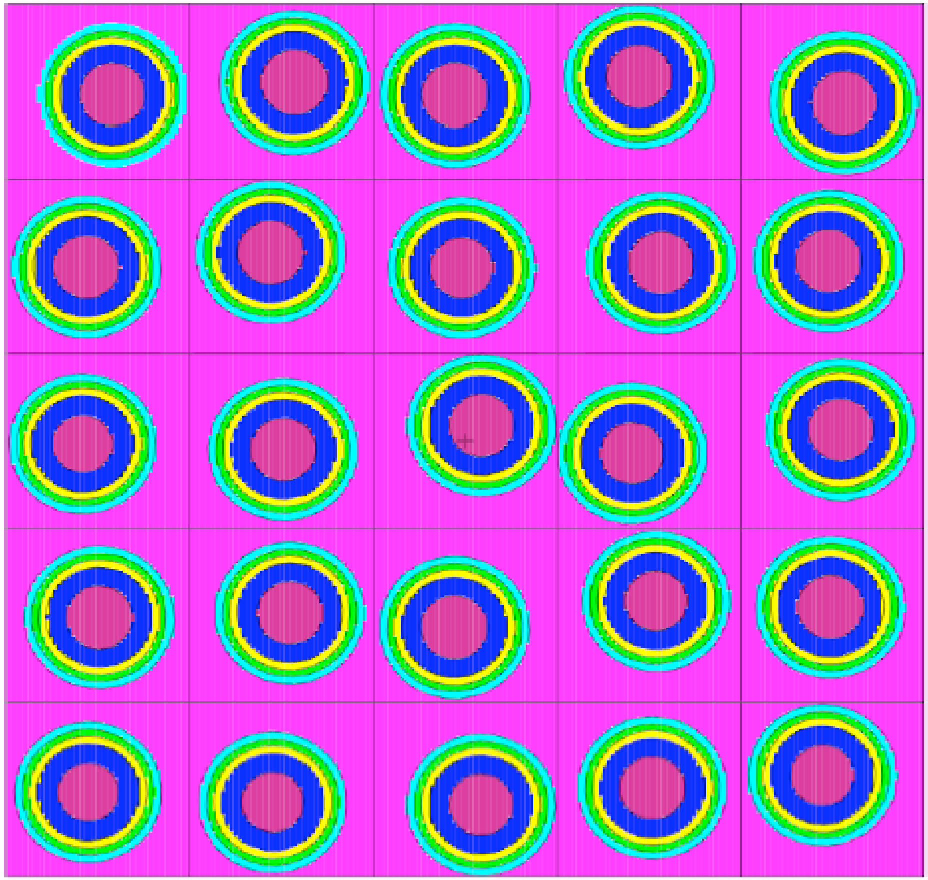
Essential to model the microsphere heterogeneity (at least the fuel kernel portion of the microsphere)

Alternative method – using modified version of MCNP5 to treat stochastic geometry

- Forrest Brown - head of Los Alamos MCNP team
- Modified MCNP5 to effectively *move the microsphere randomly* within the graphite cube every time the neutron crossed the cell boundary
- Analyzed a 5x5x5 array of heterogeneous microsphere cells with reflecting b.c. on all sides – used UM data
- Compared with 25 realizations of an explicit 5x5x5 simulation with randomly oriented spheres

*Forrest B. Brown and William R. Martin, "Stochastic Geometry in MCNP5," submitted to Winter 2004 ANS Conference in Washington, DC, LANL report LA-UR-04-4432, June 2004.

5x5x5 lattice of cubic microsphere cells

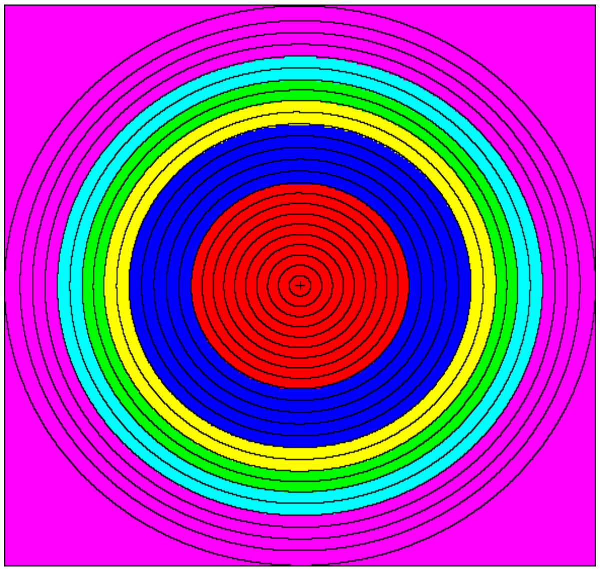


- Reflecting b.c on all sides
- Spheres randomly oriented wholly within graphite cubes
- "On the fly" randomization versus 25 realizations of 5x5x5 lattice

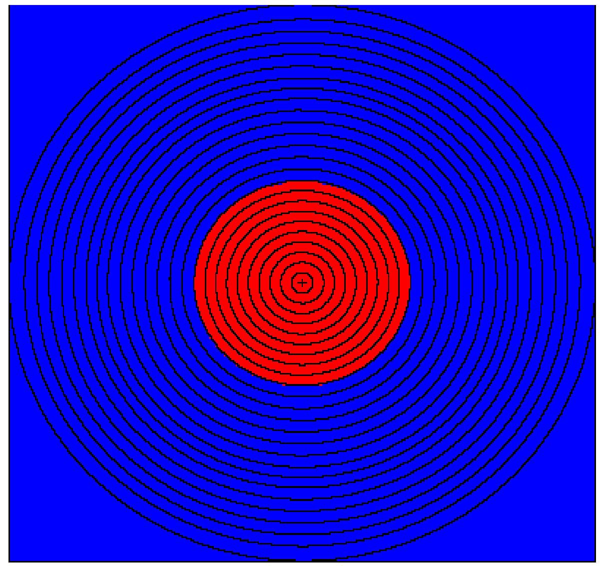
LANL MCNP5 simulation results

Configuration	Kernel locations	keff	std dev
5x5x5 lattice of heterogeneous microsphere cells	Centered	1.1531	.0004
5x5x5 lattice of heterogeneous microsphere cells	Random – on the fly	1.1515	.0004
Multiple (25) realizations of 5x5x5 cells	Random	1.1513	.0005
Single heterogeneous microsphere cell (UM)	Centered	1.1537	.0011

Microsphere cells– multi-group radial flux profiles analysis



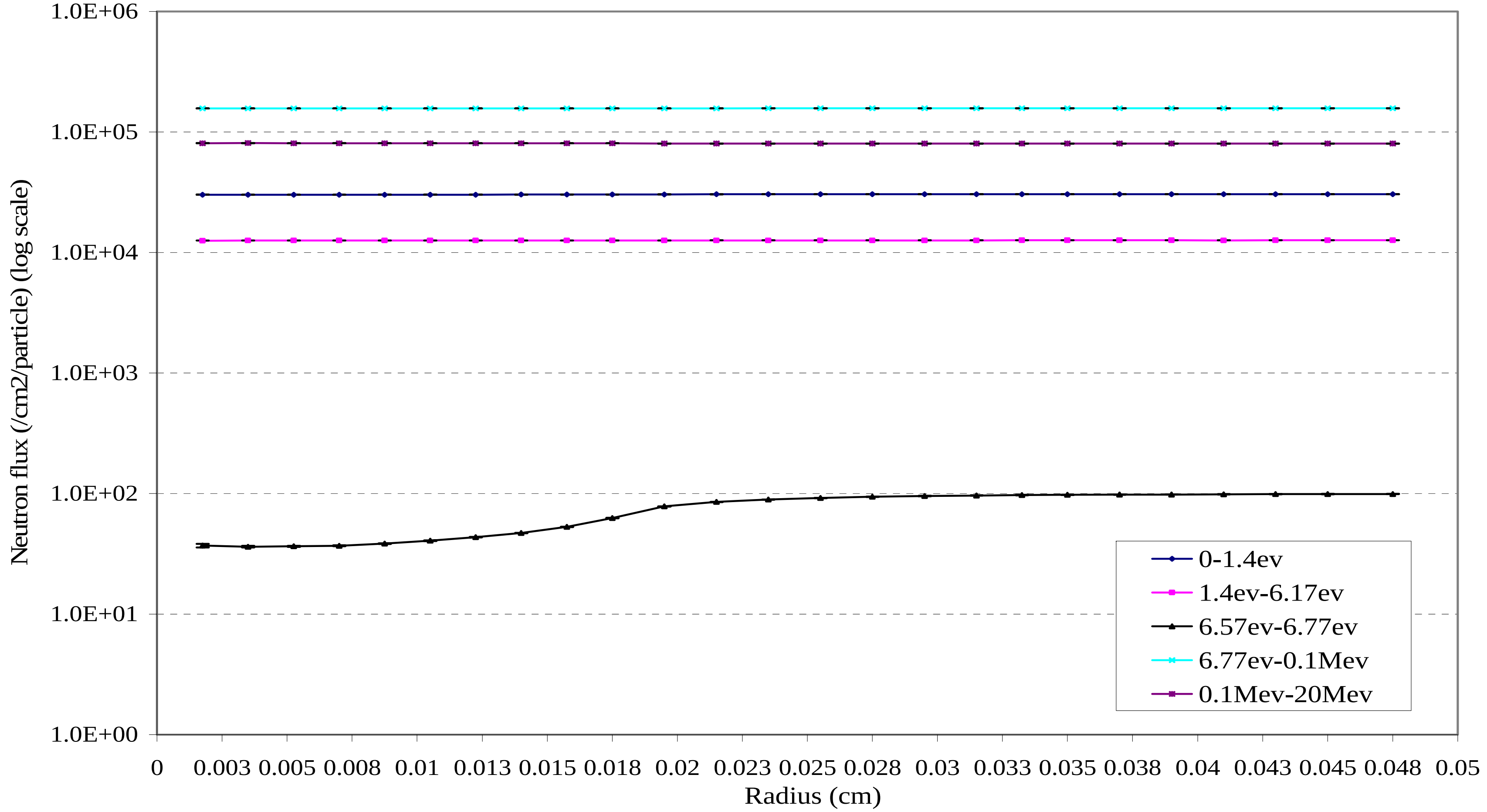
Fully Heterogeneous



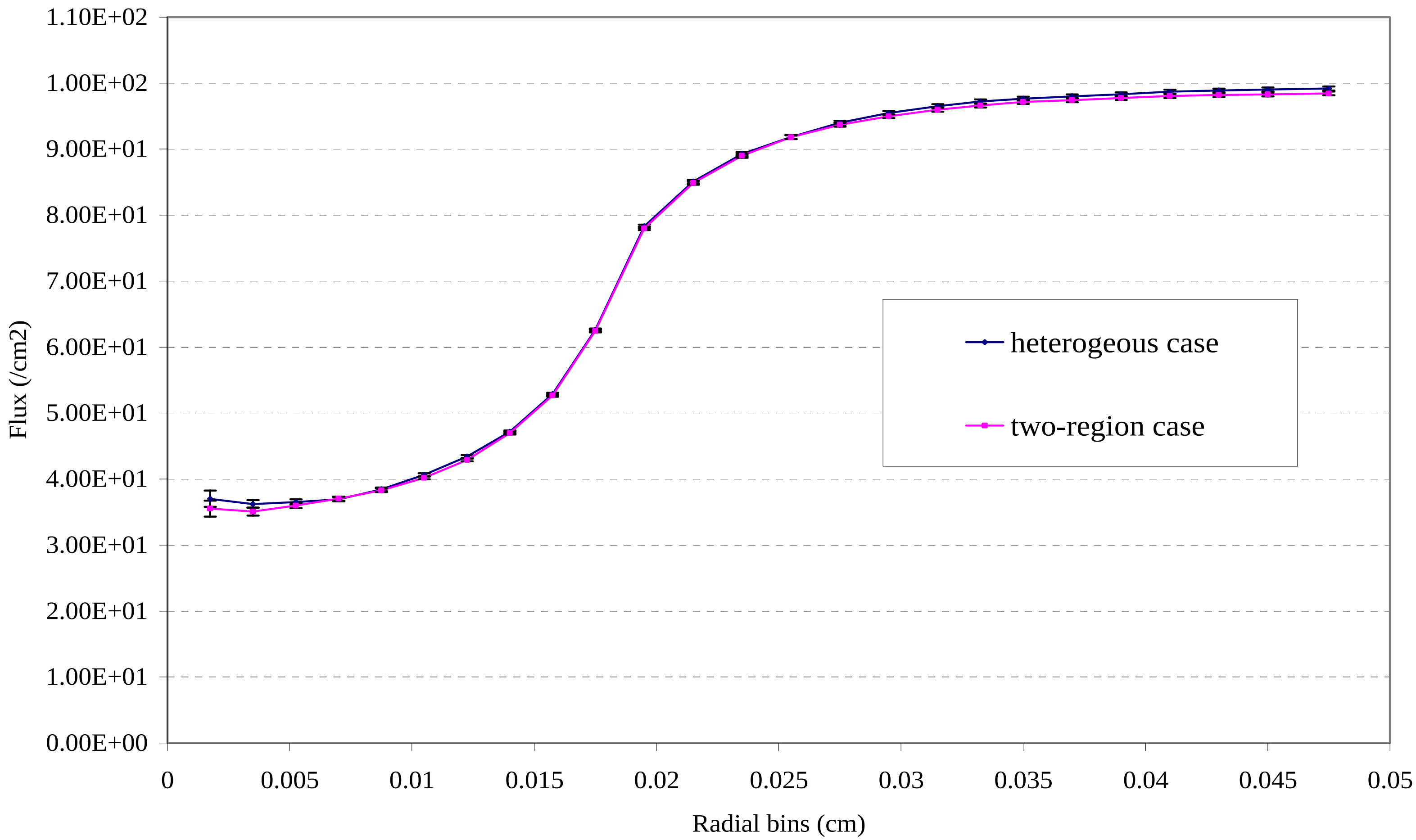
Two-Region Heterogeneous

Reflecting b.c. on all sides of cubes

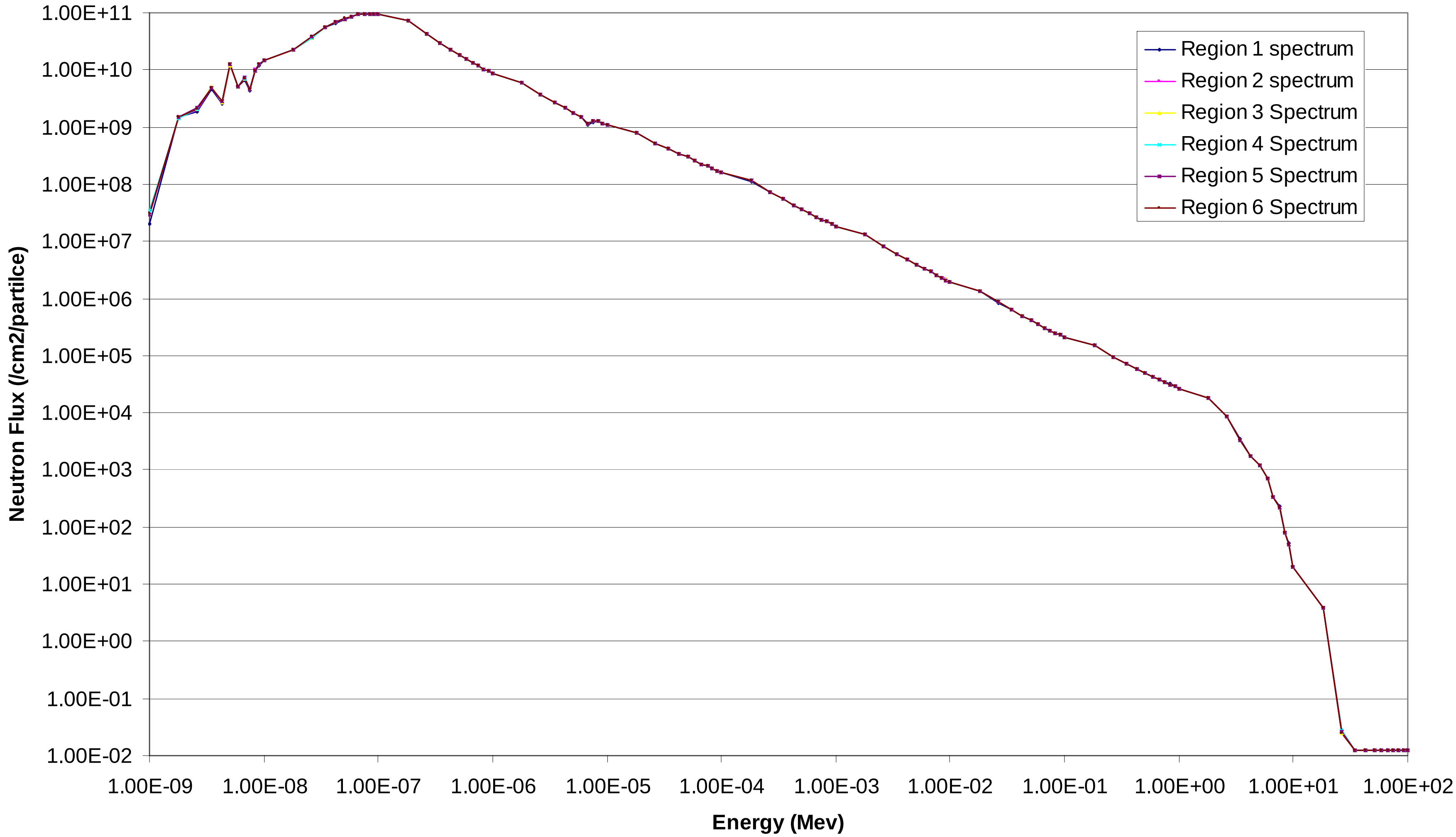
Radial neutron flux profile in a fully heterogeneous microsphere cell



Comparison of the radial neutron flux profiles in resonance energy range 6.57ev - 6.77 ev



Neutron spectra in microsphere regions



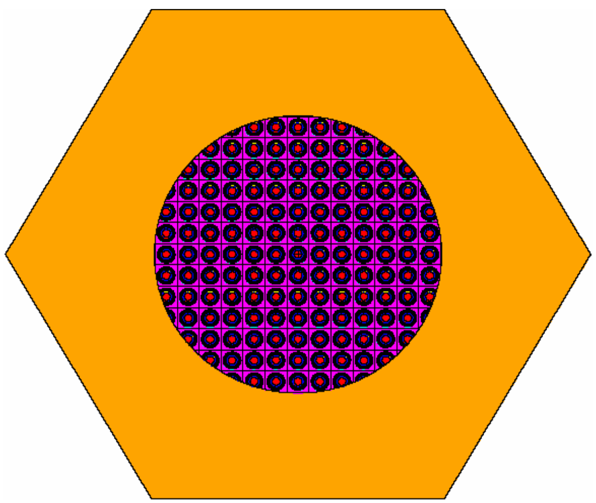
Preliminary conclusions – heterogeneous microsphere cells

- Essential to model the detailed geometry of the microsphere
- The location of the microsphere within the graphite cube has .2% effect on k_{eff} – for the infinite lattice of microspheres
- The microsphere is small neutronically for all neutrons except resonance neutrons
- Should be OK to treat only the fuel kernel and homogenize the outside layers of the microsphere with the graphite matrix

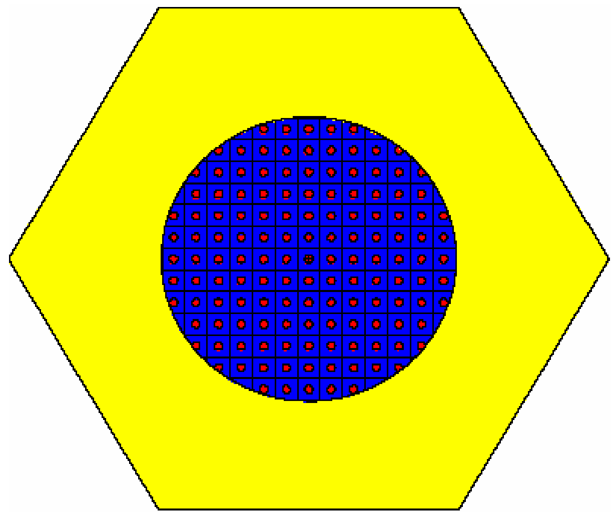
MCNP5 Simulations of Fuel Compact Cells

- Fuel compact and corresponding graphite block (boron-10: 6.9ppm)
- Hexagonal graphite block with cylindrical fuel region
- Fuel region consists of cubical microsphere cells (homogeneous and heterogeneous)
- Cubical microsphere cells “clipped” by cylindrical fuel boundary
- Coolant holes and inner/outer/axial reflectors are not represented in the fuel compact cell – only the relative changes in k_{eff} are significant

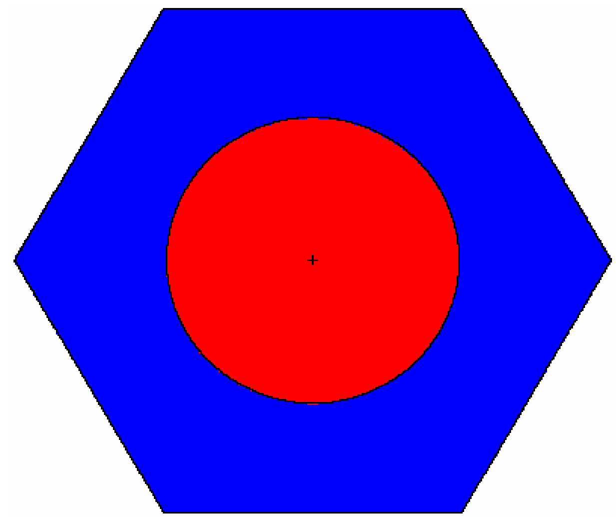
Fuel compact cells – graphite block with microsphere cells



Fully Heterogeneous



Two-Region Heterogeneous



Homogeneous

Reflecting b.c. on all surfaces of fuel compact cell

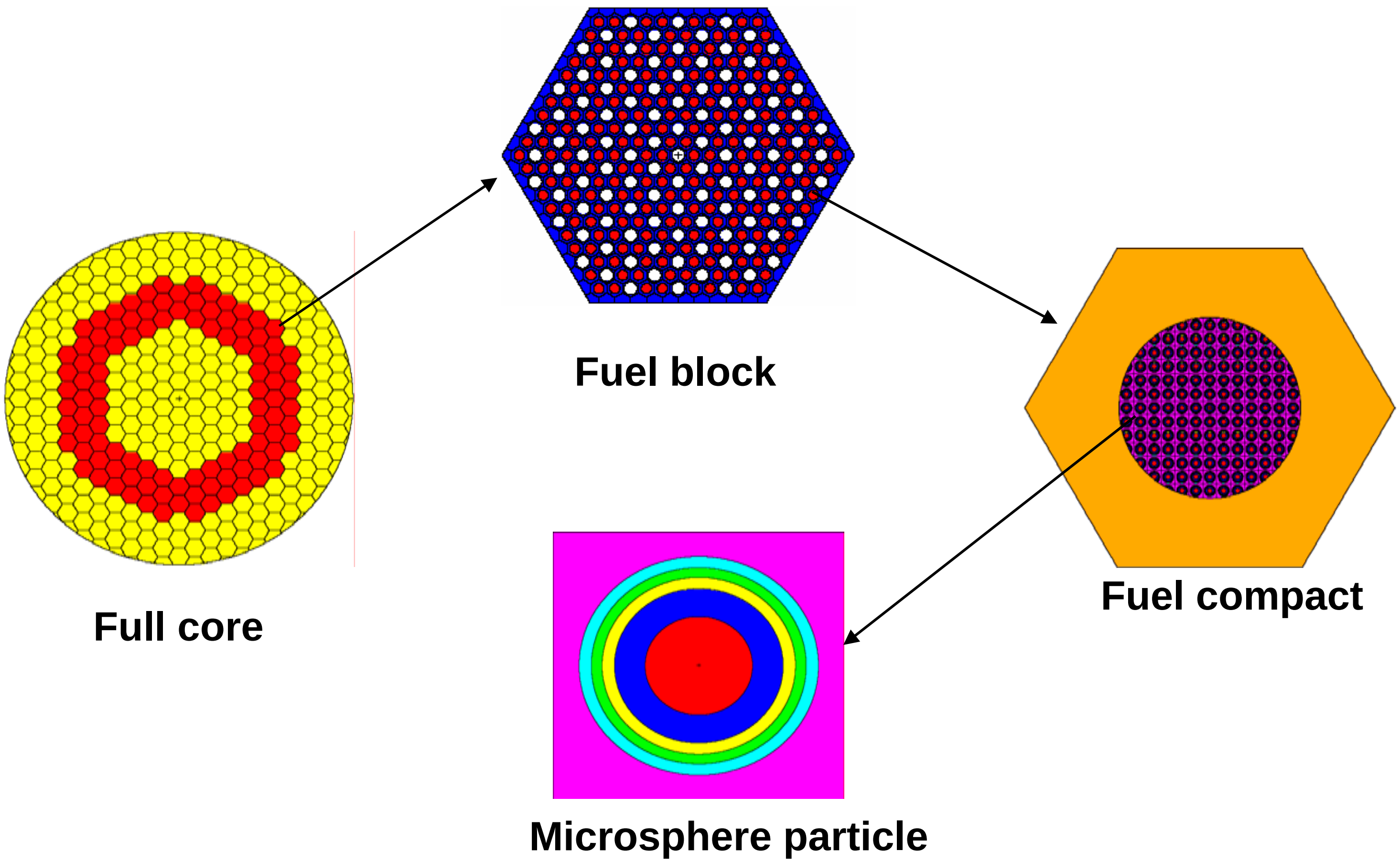
MCNP5 Simulations of Fuel Compact Cells

fuel compact	keff*	std dev	time (min)
Homogeneous case	**1.2885**	**.0004**	**359.26**
Two-region heterogeneous case	**1.3408**	**.0004**	**1462.44**
Fully heterogeneous case	**1.3401**	**.0004**	**2872.42**

***These configurations do not account for coolant holes or reflector regions – change in keff is important**

The same conclusion: essential to model the microsphere heterogeneity (at least the fuel kernel portion of the microsphere)

Full core reactor – double heterogeneity



MCNP5 Simulations of the Full Core

full core	keff	std dev	time (min)
Homogeneous case	**1.0153**	**.0002**	**250.24**
Fuel block-level heterogeneous case	**1.0583**	**.0001**	**663.74**
Doubly heterogeneous-two region	**1.0949**	**.0004**	**2272.51**
Doubly heterogeneous-fully	**1.0949**	**.0003**	**4847.45**

The same conclusion: essential to model the microsphere heterogeneity (at least the fuel kernel portion of the microsphere)

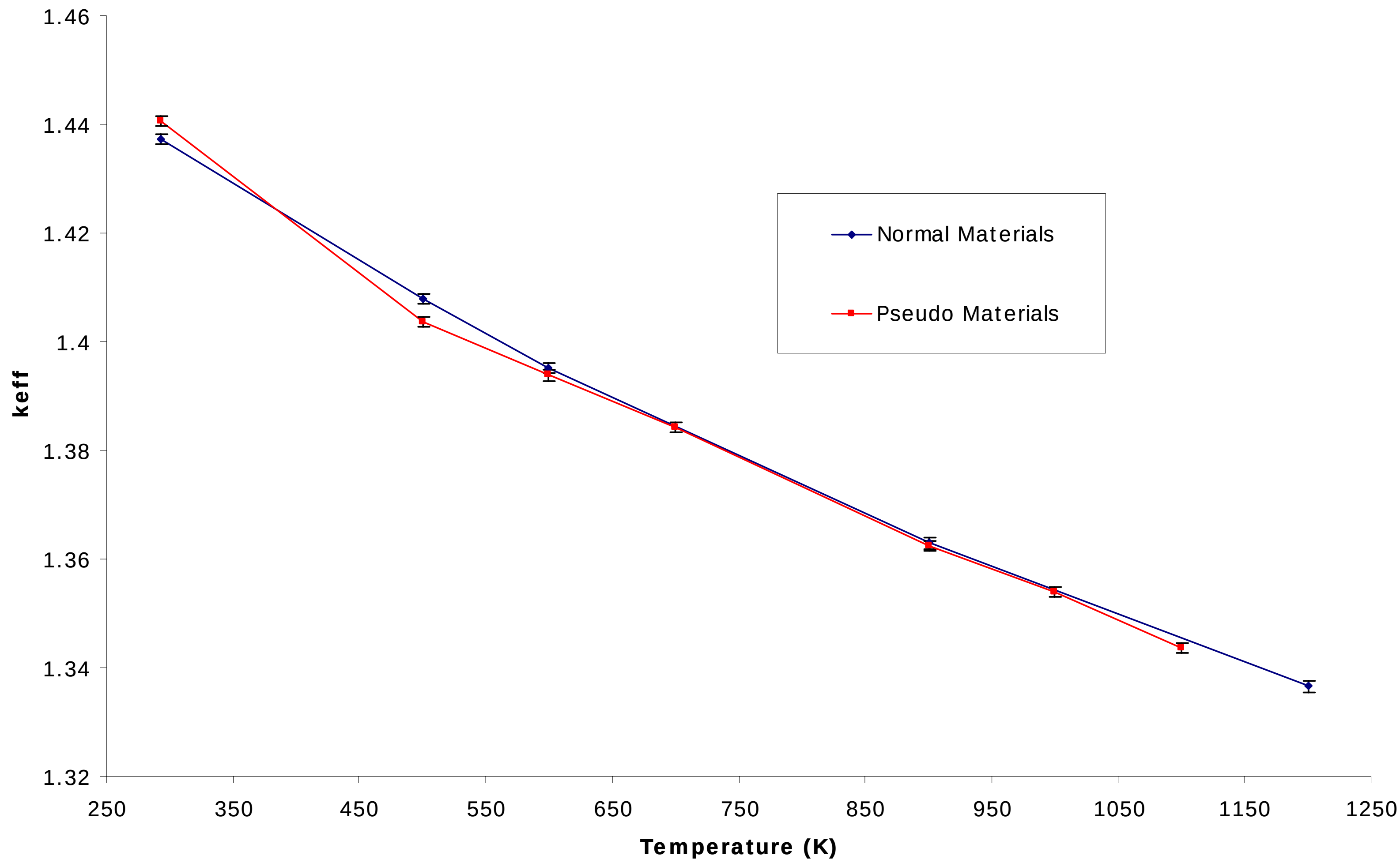
Coupled Nuclear-T/H Calculations

- Need to represent feedback effect of axial temperature rise of 350 K on VHTR core power distribution.
- Used a pseudo-material scheme to interpolate MCNP cross section libraries at a few temperature points.
- Used homogenized assembly model in 12 axial zones and 3 rings (30/37/36 assemblies) with MCNP5.
- INEEL provided UM access to RELAP5/ATHENA.
- Performed 4 iterations between MCNP5 and RELAP5.

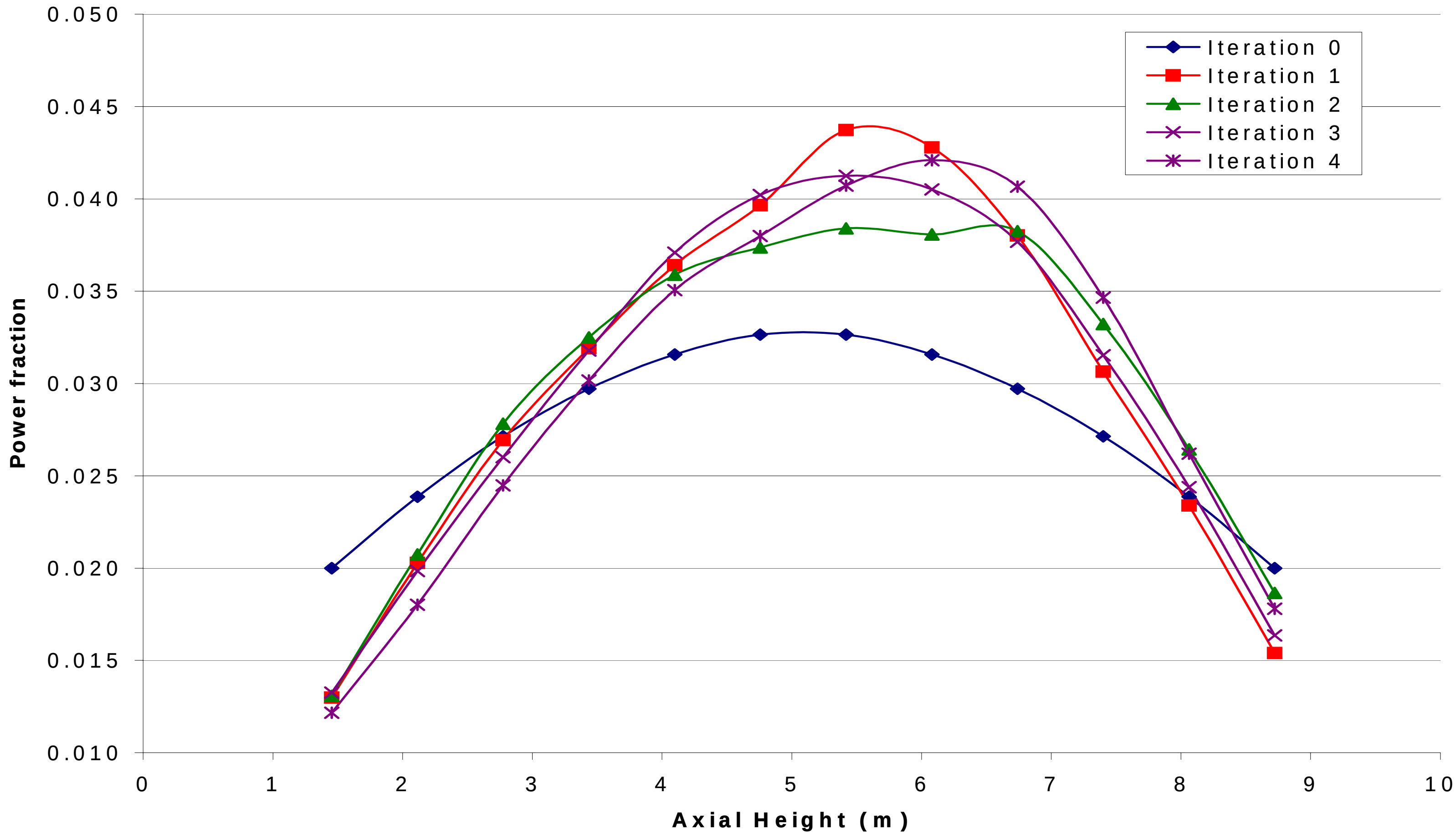
Pseudo-materials

- MCNP5 cross section data only provided at specific temperatures, e.g., 294K, 500K, 600K, 900K, and 1200K
- Coupled neutronic/T-H feedback calculations will require cross sections in the range 294K-1400K or higher
- Pseudo-materials are proposed by mixing generated cross sections linearly with temperature
- Example: to get a material at 1000K, create a mixture consisting of 2/3 of material at 900K and 1/3 at 1200K
- A Python script was written that reads in temperatures and existing libraries and generates material data cards that can be used directly in the MCNP5 input file

Comparison of k_{eff} with pseudo-materials



Axial power distribution in the middle core ring



Conclusions and future work

- Critical to model double heterogeneity of the fuel microspheres
- May be sufficient to treat only the fuel kernel portion
- Coupled neutronic/T-H calculations are more slowly converging than originally envisioned
- Need to study further the effects of criticality calculations due to the stochastic distribution of the microsphere fuel particles