Design of Plutonium-Burning Very High Temperature Reactors

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Overview

- The Scale system has been used to analyze the design of Pu burning VHTR's.
- Multigroup Transport Calculations make necessary the calculations of the Dancoff factors associated with the small fuel kernels. This was done with the code MCNP
- A full assembly was selected for the parametric analysis toward the definition of a system that maximizes the Plutonium burning and minimizes the burnup reactivity swing
- Comparisons with MCNP calculations are shown at beginning of life; they show reasonable agreements which give confidence in the procedures used to compute the Dancoff factors.
- It is also shown that shielding effects due to the huge 240Pu resonance at 1.057 eV are of paramount importance.

CALCULATIONS OF THE DANCOFF FACTORS FOR VHTR's

- Double heterogeneity effects:
  - 1) Small fuel kernels of oxide fuel (radius ~ 100 microns) are dispersed in a graphite matrix (the compact)
  - 2) The compact is arranged in fuel cells either spherical (3D), the case of pebble bed reactors, or cylindrical, the case of prismatic fuels (2D)
- Resonant neutrons leaving one kernel can have an interaction not only inside the cluster where the kernel is located but also in clusters that belong to other pebbles or fuel rods.
- Therefore the Dancoff factors for the kernels are space dependent

Dancoff Factors for Pebbles

- Case: 3 cm outside radius, 2.5 cm fuel compact radius
- The random distributions of the fuel kernels and the pebbles were substituted with deterministic arrays, simple or body centered cubic lattices that preserve the average number of kernels per unit volume and hexagonal compact for the pebbles.
- *Note that a recent work by Brown (LANL) and Martin, 2004, makes reference to a version of the MCNP code with stochastic geometry capabilities*.
- The use white boundary conditions at the boundary of the pebble and its associated void means that the interactions between pebbles are substituted with a boundary condition >>> check this simplifying approximation
- *For Example:*

  For each resonant neutron leaving the central kernel 0.2835 have 1st collision with other kernels of the same pebble and 0.1635 leave the pebble without interactions

Effects of the Boundary Conditions at the Pebble Surface in the Calculations of Dancoff Factors[a]

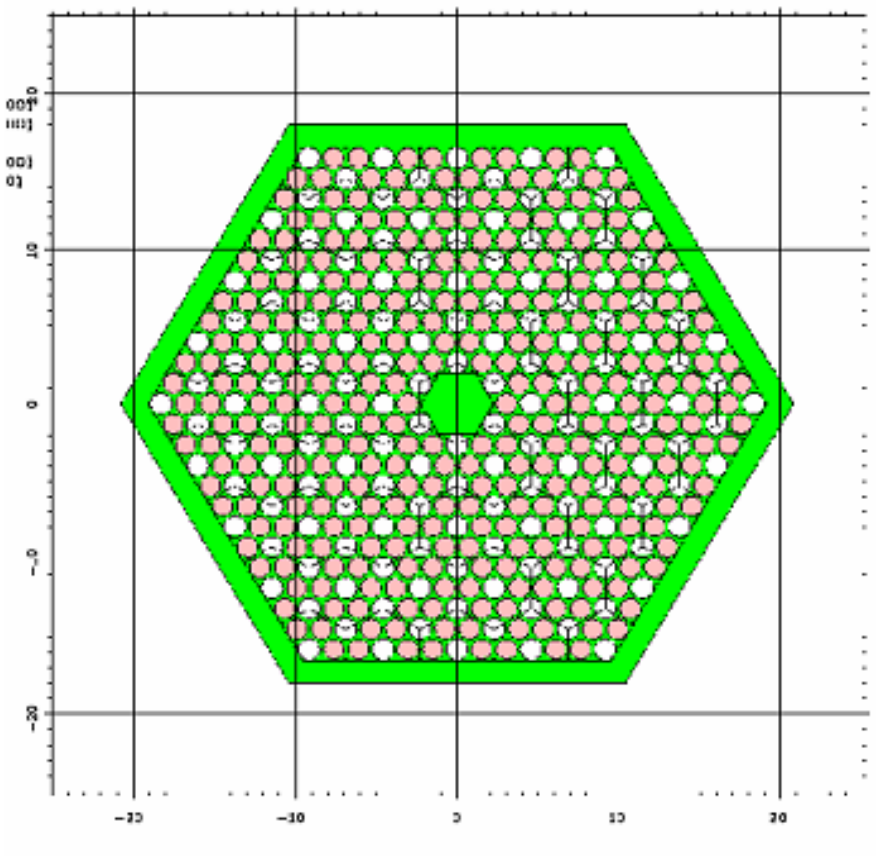
Case	Dancoff	Boundary Conditions	Comment
1	0.3731	exact	Infinite cubic lattice
2	0.3138	white	Only one pebble
3	0.3394	exact	Infinite Reactor

[a]500 microns diameter kernels in graphite, 125 kernels/cc, and simple cubic lattice.

Dancoff Factors for Prismatic Fuel

Case:

1) Radii for holes, 0.635 cm for the fuel compact and 0.684 cm for the coolant
2) Hexagonal lattice of side 2.64 cm (one coolant hole per two fuel holes)
3) The flat to flat distance of the assembly is 33.05 cm.



Dancoff Factors for a Central Fuel Kernel Located in a Central Compact in a Prismatic Assembly

Case	Radius Kernel Microns	Density Kernels/cc	Simple Cubic Lattice	Body Centered Cubic Lattice
1	100	413.357	0.1560	0.1599
2	150	122.472	0.1099	0.1045
3	200	51.670	0.0939	0.0793
4	250	26.455	0.0555	0.0597

Influence of the Media around a Central Compact on the Dancoff Factors (DF) for a Central Fuel Kernel

Case	Number of Rods Around	DF for 100 micron kernels	Escape	DF for 250 micron kernels	Escape
1	0, isolated	0.0738	0.633	0.0230	0.677
2	3: 1st neighbors	0.0995	0.396	0.0335	0.391
3	12: 3(1st neighbors) 9(2nd neighbors)	0.1295	0.165	0.0455	0.194
4	All Assembly	0.1599	0	0.0597	0

Parametric Analysis of VHTR's with Pu Fuel

System variables:

- keff at beginning of life (BOL)
- Fuel enrichment as function of burnup
- Pu burning as function of burnup as function of two design parameters:
  - Fuel kernel radius and
  - Moderation ratio (nC/nPu)

For

- Oxide Pu-Np fuel with isotopics typical of discharged LWR fuel elements.

Composition of the Oxide Pu-Np Fuel Kernel

Plutonium Isotopics

Isotope	at %
Pu-238	1.58
Pu-239	60.10
Pu-240	24.27
Pu-241	8.77
Pu-242	5.28
Sum	100
Fissile Content (of HM mix)	65.29

Np/Pu Composition

Actinide	at %	g/cc kernel
Np	5.20	8.82
Pu	94.80	0.48
Sum	100	9.30

Atom Density = 0.06312 a/b-cm

Mass Density = 10.36 g/cc of kernel

O/HM Atom Ratio = 1.7

Sensitivities to the Fuel Kernel Radius

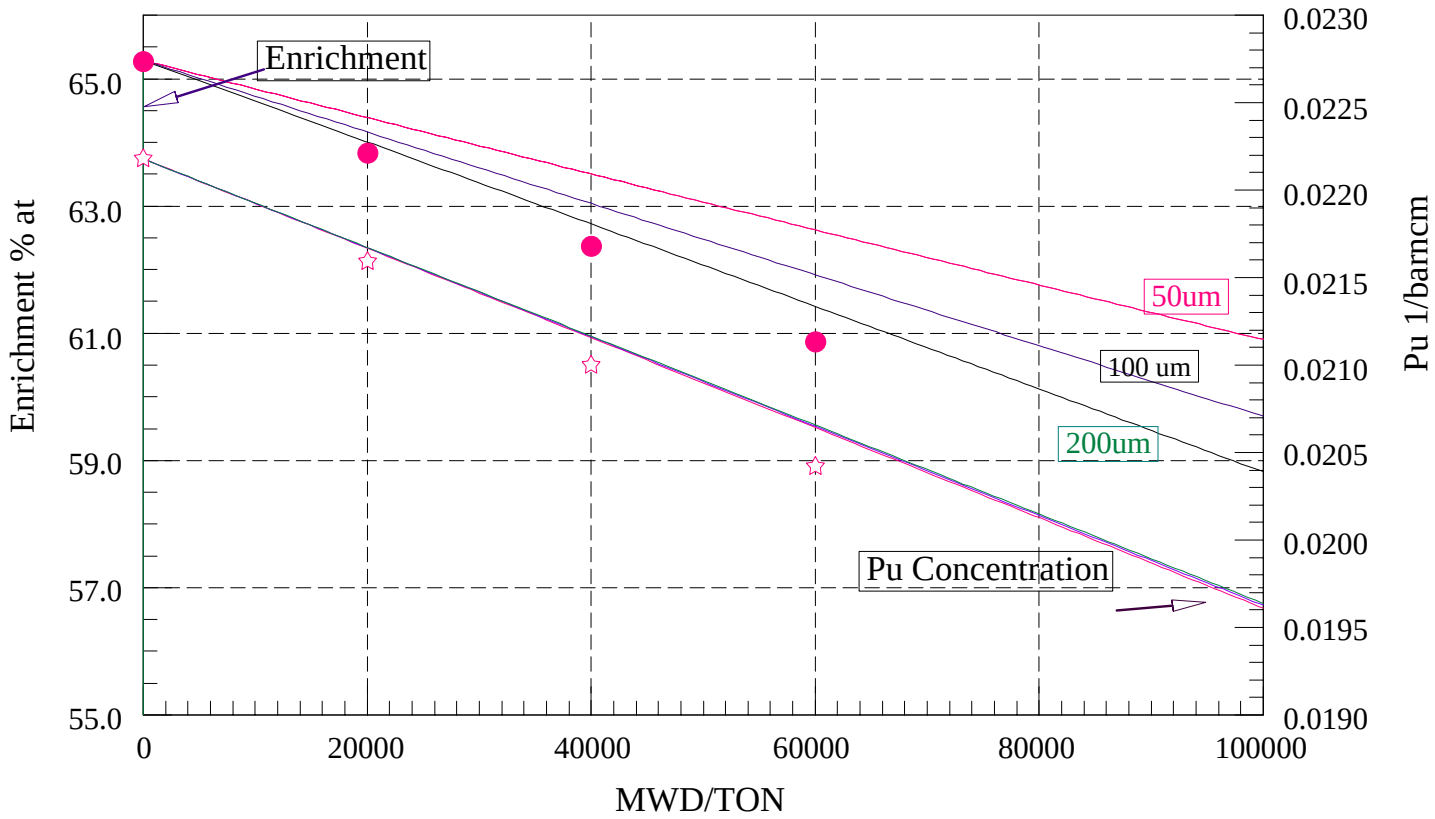
Case: Constant Fuel Loading n(C)/n (Pu) ~ 4,000.

Keff (MCNP) at BOL of the Prismatic Assembly

Case	Fuel Kernel Radius (microns)	Kernels/cc compact	K
1	50	3306.855	1.288(2)
2	100	413.357	1.368(1)
3	150	122.476	1.410(1)
4	200	51.670	1.430(1)

The monotonic behavior of k's as function of the increasing radius (or shielding) is defined by the resonances of the fertile material, ^{240}Pu, which has a very important one at 1.057 eV.

The possibility appears then to reduce the burnup reactivity swing by reducing the shielding in the kernels (or their radius), so ^{240}Pu is more likely transformed into ^{241}Pu.



Sensitivity to the Moderation Ratio

n(C)/n (Pu) ~ 4,000 of previous calculations changed by:

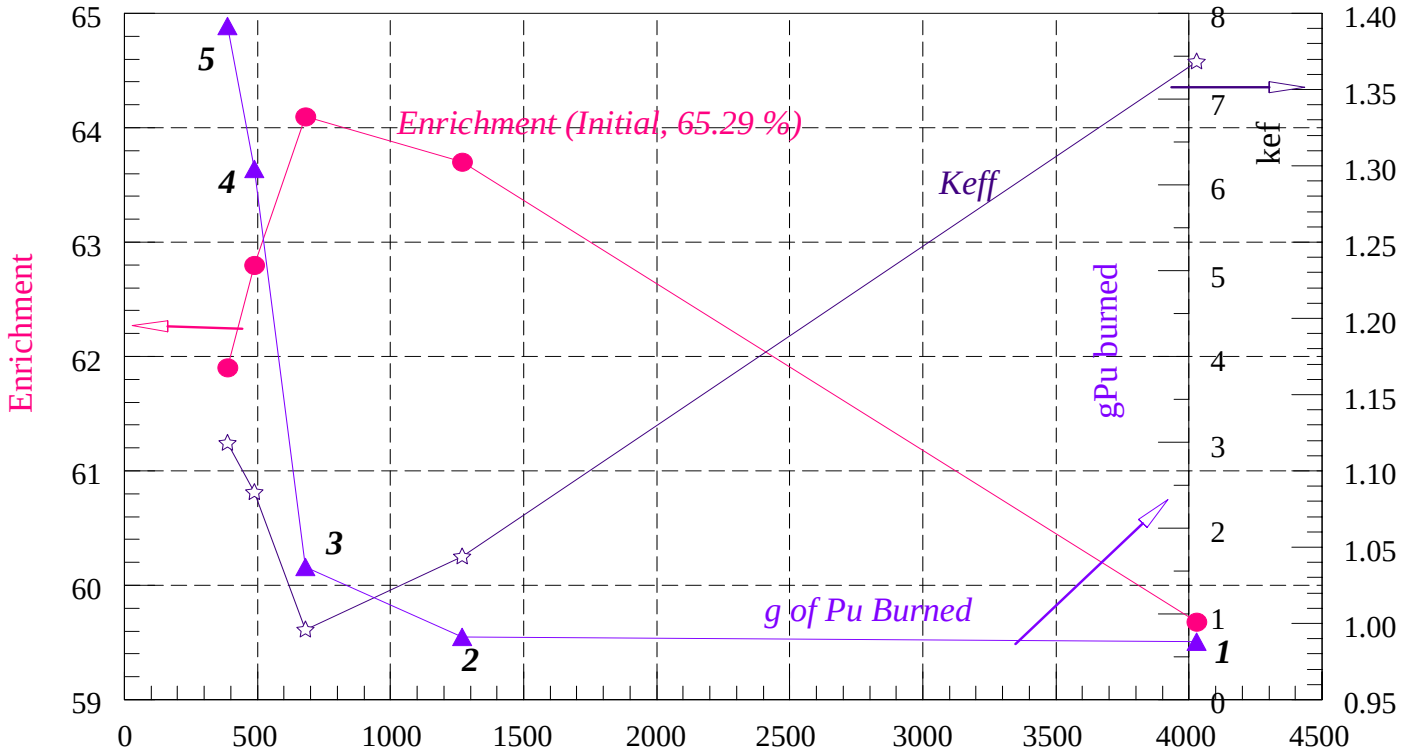
1) Changing the density of the graphite to 0.5 g/cc (for example using graphite foam developed at ORNL)

or

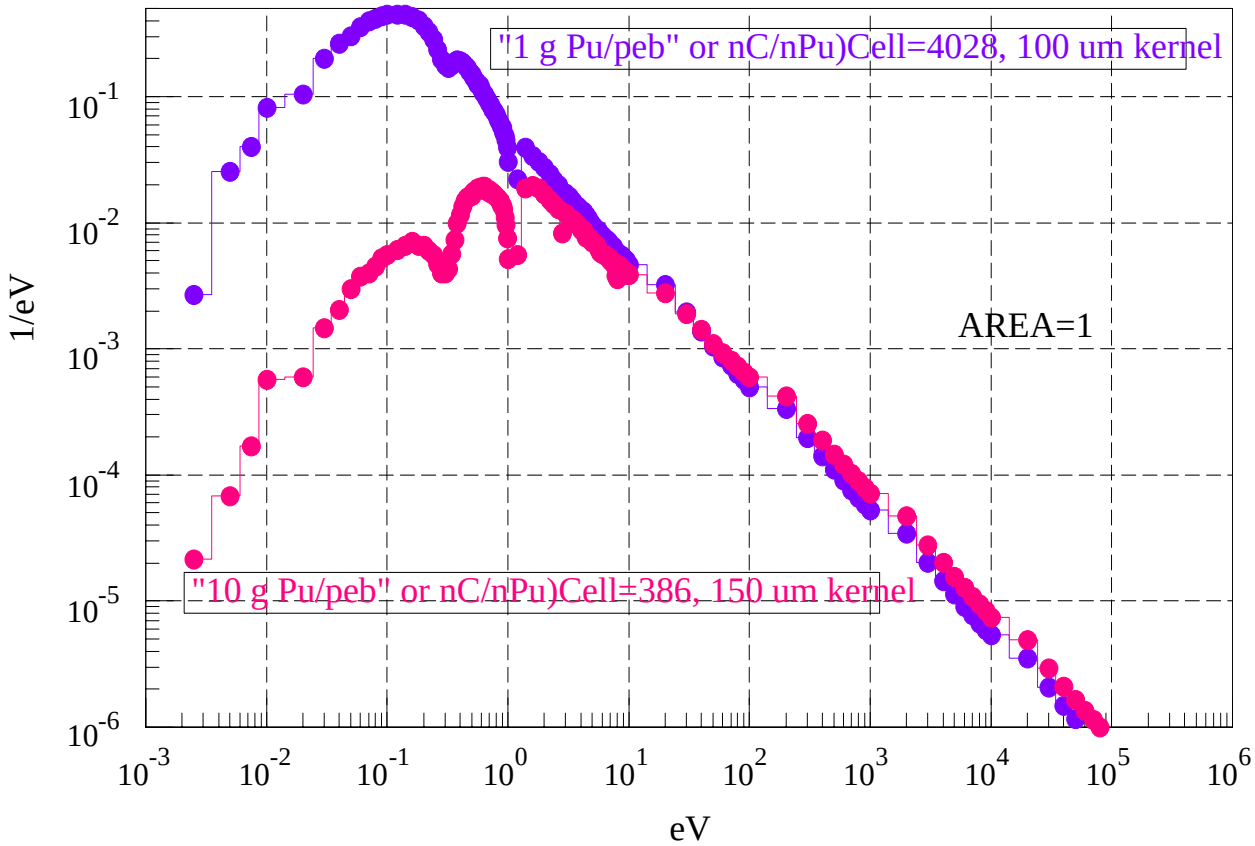
2) By increasing the number of fuel kernels and keeping the normal graphite density.

System variables calculated as function of the moderation ratio:

- k at BOL and
- Enrichment as function of burnup
- Pu burning as function of burnup



Case	Descriptive Name "gram Pu/pebble"	Material for matrix	Material for assembly	Fuel kernel radius microns	Kernels/cc compact
1	1	Graphite	Graphite	100	413.357
2	1	Foam	Foam	100	413.357
3	2	Foam	Foam	100	826.714
4	8	Graphite	Graphite	150	979.809
5	10	Graphite	Graphite	150	1224.771


"1 g Pu/peb" or nC/nPu)Cell=4028, 100 um kernel
"10 g Pu/peb" or nC/nPu)Cell=386, 150 um kernel
AREA=1
1/eV
eV
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-3
10^-2
10^-1
10^0
10^1
10^2
10^3
10^4
10^5
10^6

Analysis of Pu Burning in VHTR's With the SCALE System

- **The sequence in our Assembly level Scale calculations is the following:**

  1) BONAMI.

  2) NITAWL,

  3) XSDRNPM transport calculation to perform spatial average of cross sections at the level of microcell: kernel-layers-matrix,

  4) XSDRNPM transport calculations of the macrocell corresponding to the compact, the graphite of the assembly and the coolant void; in this step we produce a second spatial average

  5) XSDRNPM transport calculations of the homogeneized assembly to compute k and the spatial-energy average of the cross sections..

  6) COUPLE and ORIGEN-S to calculate number densities of actinides and fission products (plus the radioactivity in, and the radiation from, the assembly

- **1 step more than available in the SCALE module SAS2 because of the 2nd periodicity.**

Case of Prismatic Assembly of the Figure with Constant Fuel Loading SCALE and MCNP at BOL

Case	Kernel radius microns	Dancoff Factor	k MCNP	k SCALE	dk (%)
1	50	0.2900	1.288(2)	1.282	-0.6
2	100	0.1599	1.368(1)	1.357	-1.1
3	150	0.1045	1.410(1)	1.396	-1.4
4	200	0.0783	1.430(1)	1.422	-0.8
5	250	0.0597	1.451(1)	1.426	-2.5

Burnup Dependent Calculations with the Scale System

Case VHTR Assembly of Figure 1
100 micron kernel DF=0.16

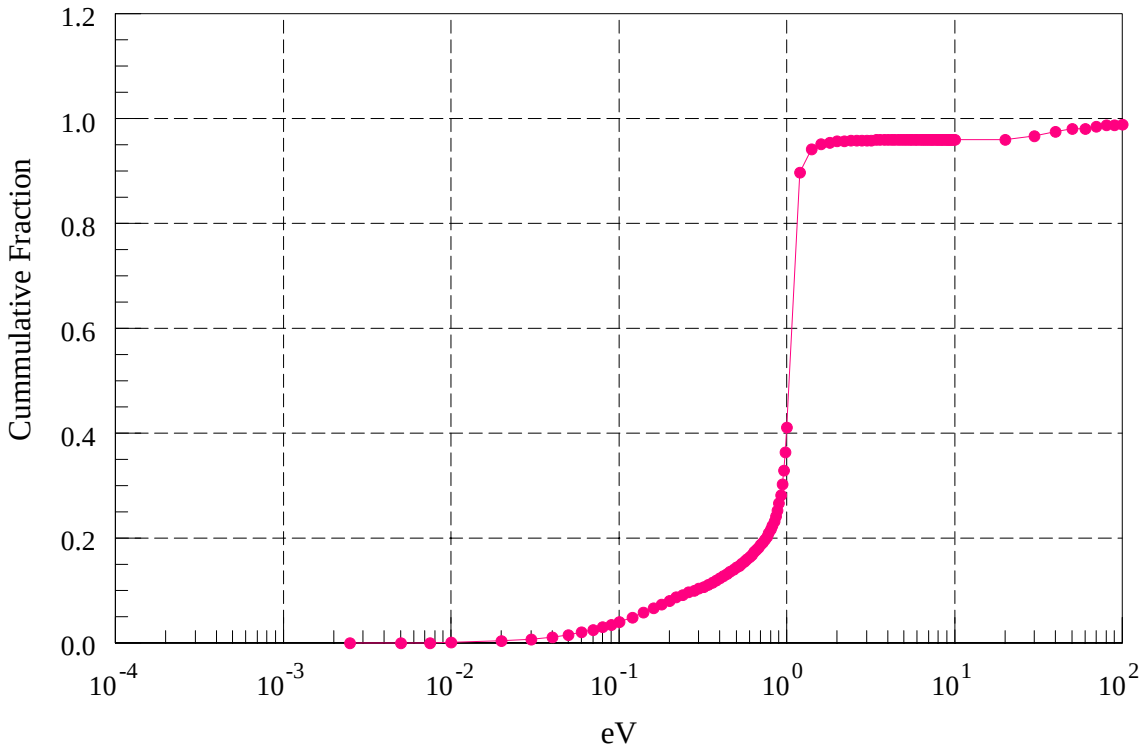
k=k (Burnup)

Calculation	0	20 GWD/TON	40 GWD/TON	60 GWD/TON
Fuel Kernel	1.145	1.116	1.097	1.080
Compact Cell	1.297	1.275	1.257	1.241
Assembly	1.357	1.335	1.318	1.302

Effects of the 1.057 eV 240Pu Resonance

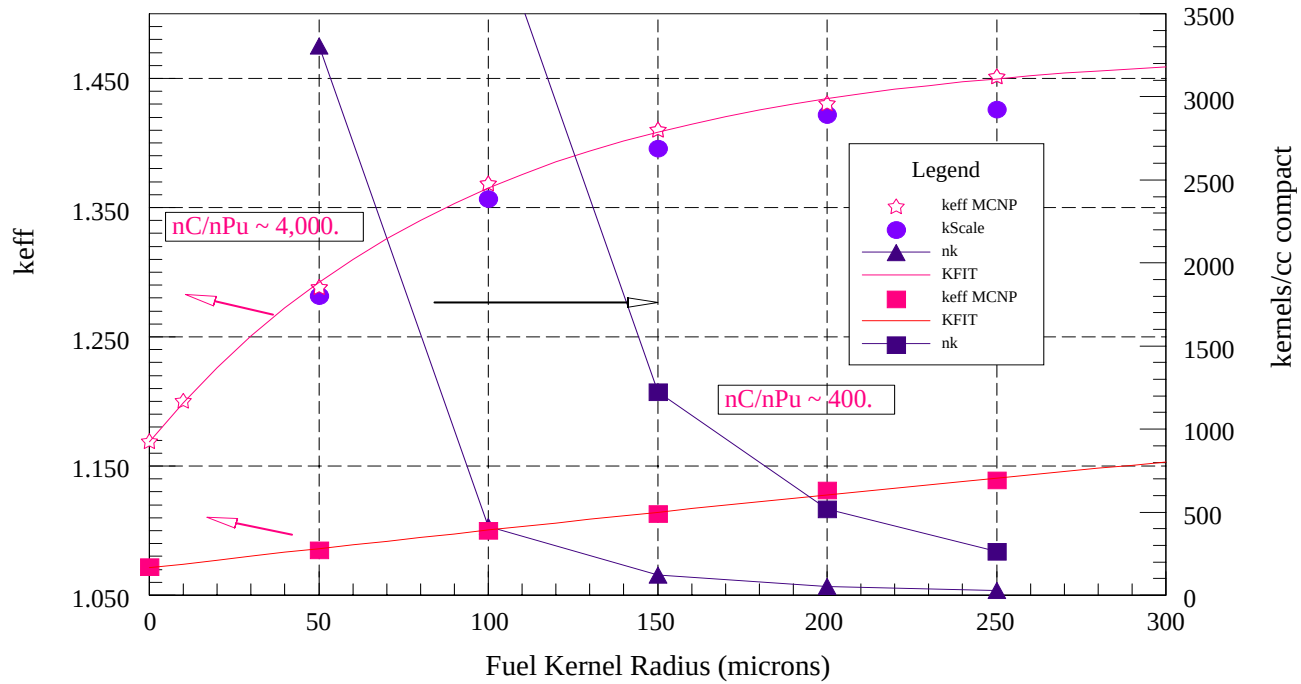
- ^{240}Pu has a huge resonance at 1.057 eV with peak values larger than 100,000 barns
- In comparison its equivalent in Uranium systems ^{238}U has a large resonance at 6.67 eV with a peak value around 7,000 barns.
- The escape to resonance absorption when neutrons are being moderated is mainly defined by the 1.057 eV resonance.

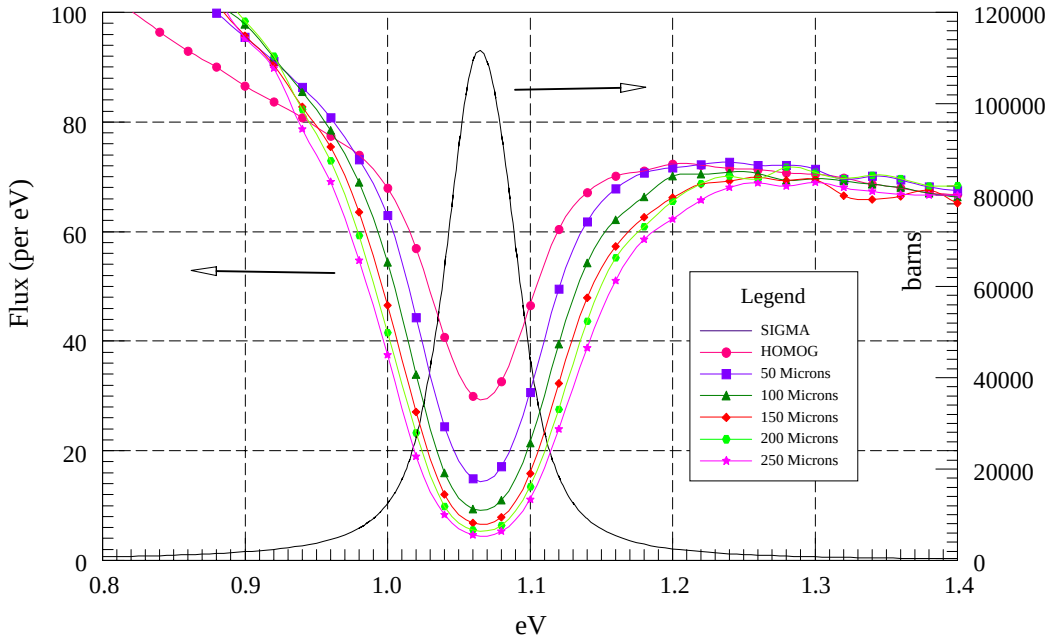
Cumulative absorption fraction for ^{240}Pu inside a 100 micron fuel kernel (T=300K).



Uranium VHTR's ~2 to 3 % effects on k's are due to shielding effects in the fuel kernels. Effects are much larger in the case of Plutonium kernels.

For the well moderated case, the Figure shows Δk as large as 29%. The fits of k as function of the radius of the kernels, shown in the Figure, are similar for both cases; thus for larger heterogeneities the less moderated case might show similar Δk.





Energy dependent fluxes averaged inside the Plutonium fuel kernels, 50 to 250 microns radius, and the flux for the homogeneous case. The calculations are for the assembly of the Figure and for the well moderated case. The 240Pu absorption cross section corresponds to T=300K.

Conclusions

- Full assembly transport calculations were performed with the SCALE system to analyze the design of Pu burning VHTR's.
- A key step in the preparation of multigroup cross sections in SCALE is the consideration of the double heterogeneities and the calculation of Dancoff factors.
- Because of the low absorption of graphite the Dancoff factors are space dependent and their calculation depends on how realistic is the modeling.
- We used the Monte Carlo code MCNP to investigate this issue.
- The huge 240Pu resonance at 1.057(" *the mother of all resonances*") dominates the shielding in the fuel kernels with the result that Plutonium fuel kernels produce shielding effects 10 times larger than similar Uranium kernels.
- The size of the kernel influences then the burnup reactivity swing because of its influence in the creation of 241Pu. Although temperature coefficients were not calculated in this work one can envision that they could show similar characteristics.