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Effect of Fuel Particles' Size Variations on Multiplication Factor in Pebble-Bed Nuclear Reactor

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ABSTRACT

The pebble-bed reactor (PBR) spherical fuel element consists of two radial zones: the inner zone, in which the fissile material in form of the so-called TRISO particles is uniformly dispersed in graphite matrix and the outer zone, a shell of pure graphite. A TRISO particle is composed of a fissile kernel (UO_2) and several layers of carbon composites. The effect of TRISO particles' size variations and distance between them on PBR multiplication factor is studied using MCNP code. Fuel element is modelled in approximation of a cubical unit cell with periodic boundary condition. The multiplication factor of the fuel element depends on the size of the TRISO particles due to resonance self-shielding effect and on the inter-particle distance due to inter-kernel shadowing.

1 INTRODUCTION

PBRs are graphite moderated and reflected nuclear reactors loaded with randomly packed spherical fuel elements and cooled by helium gas. Although pebble-bed reactors exist today only as pilot scale facilities, the growing recognition of their unique characteristics makes them leading candidates for the future electricity generating market [1]. These characteristics include inherent safety, fuel-cycle flexibility and high thermal efficiency. Moreover, applications other than electricity supply (e.g. desalination and hydrogen production) are also being considered. PBRs can also be used for the purpose of incineration of the transuranic actinides contained in light water reactors spent fuel [2].

The key feature of the PBR is the use of coated fuel kernels dispersed in spherical fuel elements (pebbles). Each pebble measures 60 mm in diameter and consists of two radial material zones: the inner spherical zone contains fissile material in the form of the so-called TRISO particles embedded in a matrix of graphite material and the outer zone, a 5mm thick shell of pure graphite. Each fuel element contains around 10,000 to 15,000 (depends on the design) TRISO particles dispersed in graphite. TRISO (Tri-isotropic) coated fuel particle is a spherical layered composite about 1mm in diameter. It consists of a kernel of fissile material surrounded by a porous graphite buffer layer that absorbs radiation damage and allows space for fission gases produced during irradiation. Surrounding the buffer layer are a layer of dense pyrolytic carbon, a SiC layer, and a dense outer pyrolytic carbon layer. The pyrolytic carbon

layers shrink under irradiation and provide compressive forces that act to protect the SiC layer, which is the primary pressure boundary for the micro-sphere.

The composition and the diameter of the fuel kernel will be selected according to the design and capabilities of a specific PBR. The fuel kernels are mostly composed of uranium dioxide (UO_2) or uranium oxycarbide (UCO). When PBR is used for incineration of transuranic actinides, part of the kernels will be composed of transuranic actinides such as plutonium, americium and other minor actinides. The kernel diameter is based on the specific PBR design and usually varies from 350 to 500 μm. Smaller kernels will be used for incineration of plutonium. Fuel kernel's design specifications require that the fuel kernel diameter can deviate maximally 10% from specified value in 95 % of all cases [3].

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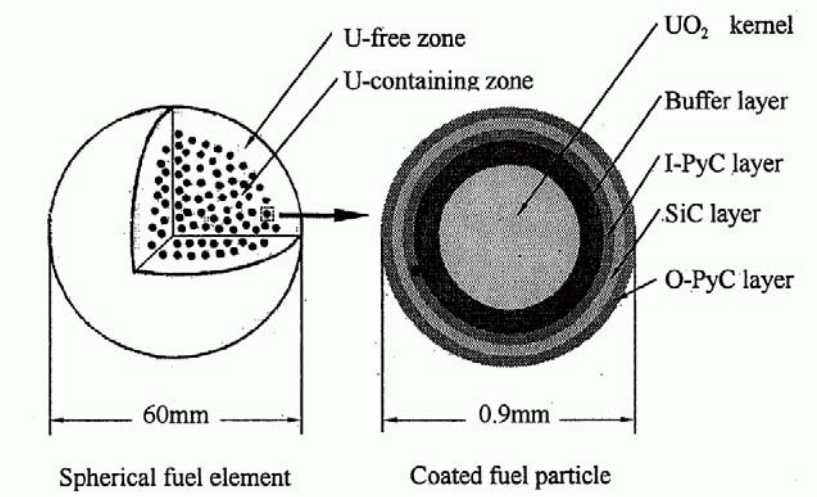

Figure 1**:** PBR spherical fuel element and coated fuel particle [1]

The fuel kernels are normally uniformly dispersed in the graphite matrix of the fuel element. During manufacturing of the spherical fuel element it might happen (e.g. due to vibrations or shaking) that the fuel kernels grouped themselves into clusters. In such case the neutronic characteristics of the fuel element could change significantly.

The purpose of this work is to calculate the multiplication factor of the PBR core for various fuel kernels sizes, and also various kernel arrangements. Fuel kernel radius is varied within the 100 – 350 μm range. Anything else is outside technical feasibility. The distance and arrangement between TRISO particles is varied from completely uniform cubical arrangement to contact clusterring of eight neighbouring particles (Figure 7). As the multiplication factor depends also on the enrichment of uranium, it was studied also for various enrichments.

The reference results in open literature are rather rare, therefore the consistency of our results is verified by explaining the underlying basic reactor physics.

2 CALCULATIONAL MODEL

MCNP code [4] was used in the multiplication factor calculation. MCNP is a general-purpose, continuous-energy, generalized-geometry Monte-Carlo transport code. The calculations reported in this paper were performed with version 4C2 of the code.

As we were interested only in qualitative behaviour of multiplication factor, it was sufficient to calculate multiplication factor of an infinite medium (k-inf), that is an infinite lattice of fuel kernels dispersed in graphite. Since it is not possible with MCNP to calculate k-

inf directly, we modelled a cubic unit cell with periodic boundary conditions at four lateral planes and reflective boundary condition at lower and upper plane to simulate an infinite medium. Periodic boundary condition was applied only at four planes because of MCNP limitations which require that all periodic planes must have a common rotational vector normal to the geometry top and bottom.

The cubic unit cell consisted of eight (2x2x2) cells, each containing one fuel kernel. The side of the cubic unit cell measured 4 mm and the sides of the inside cells measured 2 mm. The radius of the kernels was varied in the following way. At the beginning half of the kernels measured 350 μm in radius and the other half 100 μm. Then we gradually decreased the radius of the bigger kernels from 350 μm to 100 μm and increased the radius of the smaller ones the other way round in such a way that the total volume of all the fuel kernels remained constant. In this manner we kept the fuel to moderator ratio constant. We have done such calculations at different enrichments of uranium. Although the kernels were divided in two groups with different radii as explained earlier, only the radius of one group is shown on the x axis in the figures.

The effect of mutual shielding of kernels on k-inf was studied with uniform fuel kernels (280 μm in radius) whose position in the cell was varied.

Calculations were performed at two different temperatures, that is room temperature (300 K) and operating temperature (1200 K).

3 DEPENDENCE OF K-INFINITY ON FUEL KERNEL SIZE

Calculated k-inf as a function of fuel kernel radius at fuel enrichment of 8 % is presented in Figure 2. The entire range of technically feasible fuel kernel radii was considered, including extreme values used only for actinide incineration or other special purposes.

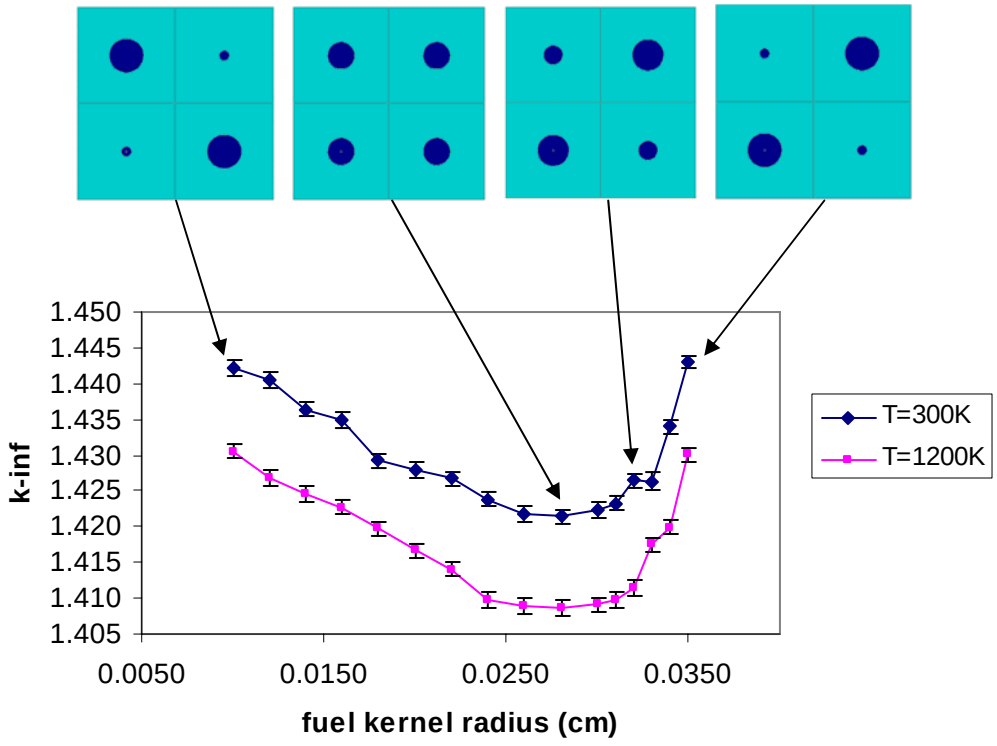

Figure 2**:** K-infinity as a function of fuel kernel radius at two different temperatures and fuel enrichment of 8 %. Above the chart there are views of the MCNP model of the cubic unit cell.

It is observed that k-inf strongly depends on average fuel kernel radius. The k-inf reaches a minimum when all the kernels are of the same size. At that point the total kernel surface reaches its maximum. The dependence of k-inf becomes more evident if we plot k-inf as a function of the surface of all the kernels inside the cubic unit cell (Figure 3). It can be seen from Figure 3 that k-inf decreases almost linearly with increasing total kernel surface. As the outer layers of the fuel particle shield its interior from resonance energy neutrons, thereby decreasing the net resonance absorption. The effect can therefore be explained by increased resonance absorption of neutrons in ^{238}U due to increased kernel surface, or more precisely due to larger fuel kernel surface to volume ratio. As total surface of the kernels increases, the net resonance absorption is increased, leading to reduction of the k-inf.

To conclude, the smaller and more uniform kernels we use, the smaller is the multiplication factor. Knowing that in reality the radius varies for up to 10 % from its specified value, this should be considered in fuel design and fabrication. In applications such as incineration of transuranic actinides it is important that all of the material in the kernel is exposed to neutrons to minimize self-shielding. In other words, fuel kernel diameter should be comparable with the resonance neutron mean free path. This is accomplished with a small diameter kernel, or a diluted or low-density kernel.

We can also see from Figure 2 that PBR features negative temperature effect.

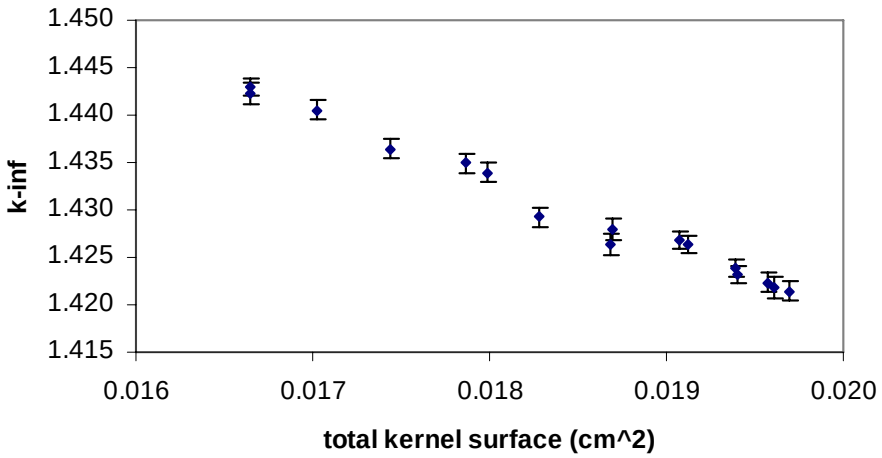

Figure 3**:** K-infinity as a function of the net fuel kernel surface.

The PBR fuel enrichment depends on the design of the specific PBR. Calculations of k-inf at various fuel enrichments were also performed. The results are presented in Figure 4. We can observe that the dependence of k-inf on kernel radius diminishes when uranium enrichment increases. The net resonance absorption is reduced due to smaller quantities of the primary resonance absorber, ^{238}U, in the fuel, thereby the self-shielding effect lessens. It can be seen that k-inf is independent of fuel kernel radius for 100 % enriched uranium.

We investigated only the neutronic characteristics of the fuel kernel, however we should be aware that when changing the fuel kernel radius, the mechanical properties of a TRISO particle are also changed. For example if the buffer layer thickness is maintained constant, then the free volume of this layer is determined by the kernel diameter. Therefore the pressure in the smaller TRISO particles builds up more quickly and the risk of SiC layer failure will occur sooner. This effect should also be investigated in the future PBR fuel design.

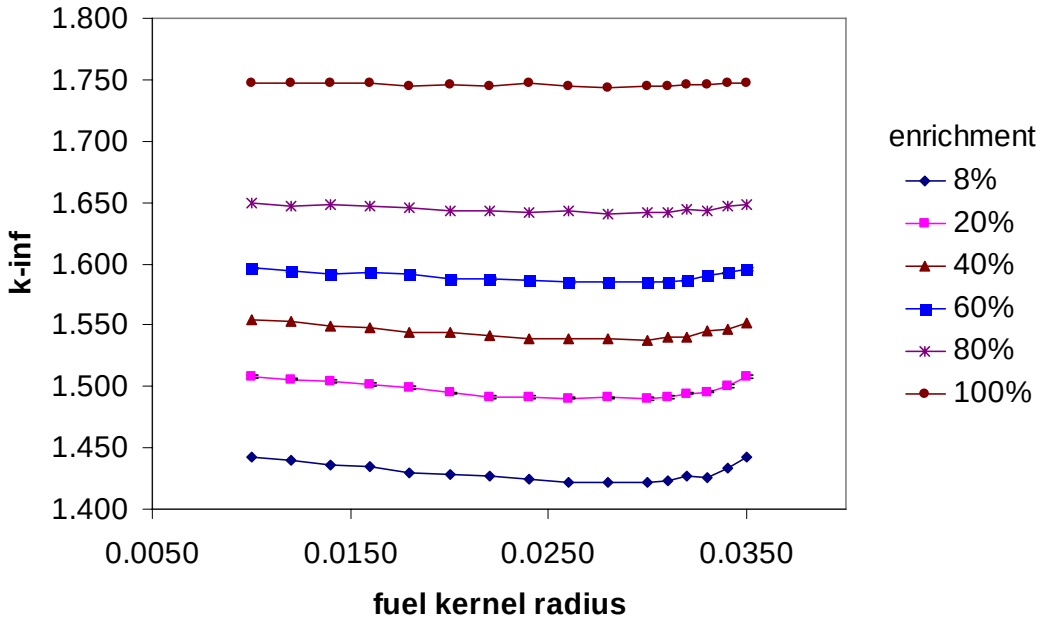

Figure 4**:** K-infinity as a function of fuel kernel radius at various enrichments

4 DEPENDENCE OF K-INFINITY ON FUEL KERNEL POSITION

Calculated k-inf as a function of inter-kernel distance at fuel enrichment of 8 % is presented in Figure 5. It is observed that k-inf increases with decreasing inter-kernel distance. When fuel kernels are very close together, they behave as a single, only bigger particle, i.e. they "shadow" each other so that the inner parts of the kernels are exposed only to fast and thermal neutrons, while resonance energy neutrons are absorbed in the outer parts of the kernels. Their effective surface is decreased, thereby decreasing the net resonance absorption. This effect is analogous to self shielding effect of a single particle.

Note that the inter-kernel distance refers to the distance between kernels inside the cubic unit cell and not to the "real" distance between them. The kernels that are very close to periodic or reflective boundary are actually very close to other, virtual kernels. That is the reason why k-inf increases when inter-kernel distance increases over 0.1 cm.

As MCNP computer code does not feature the calculation of k-inf, appropriate boundary condition on the most outer surface of the system must be applied, so that quasi infinite medium is modelled. When investigating the effect of inter-kernel distance on k-inf, different boundary conditions, that is periodic, reflective and white, were applied at the surfaces. The results are shown in Figure 6.

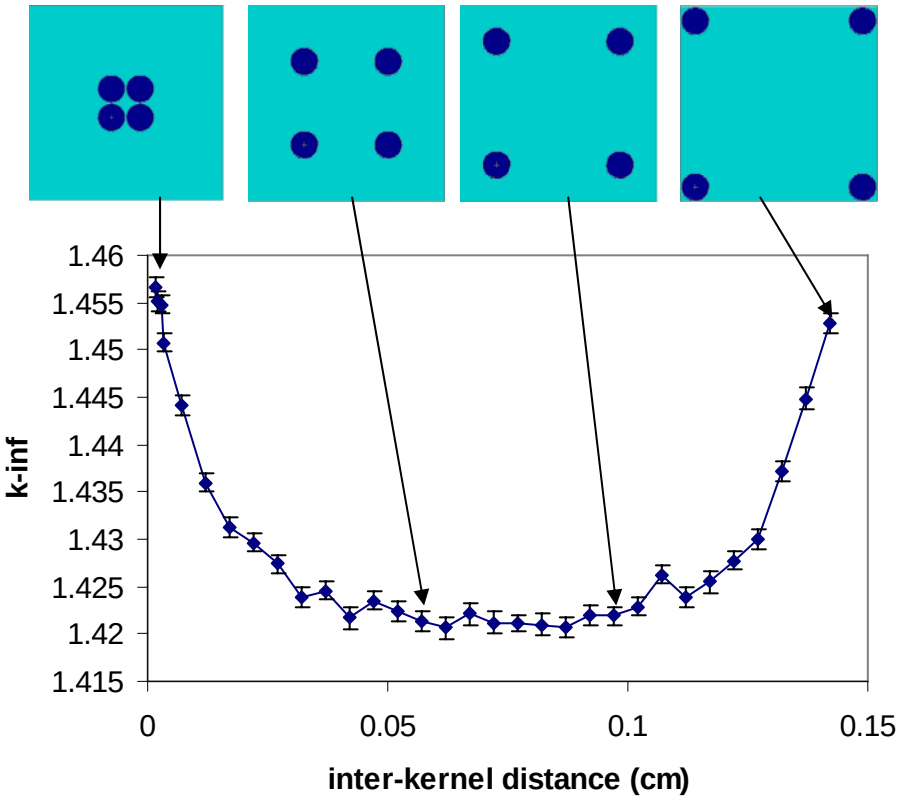

Figure 5: K-infinity as a function of inter-kernel distance at fuel enrichment of 8 % and periodic boundary condition at the unit cell surfaces.

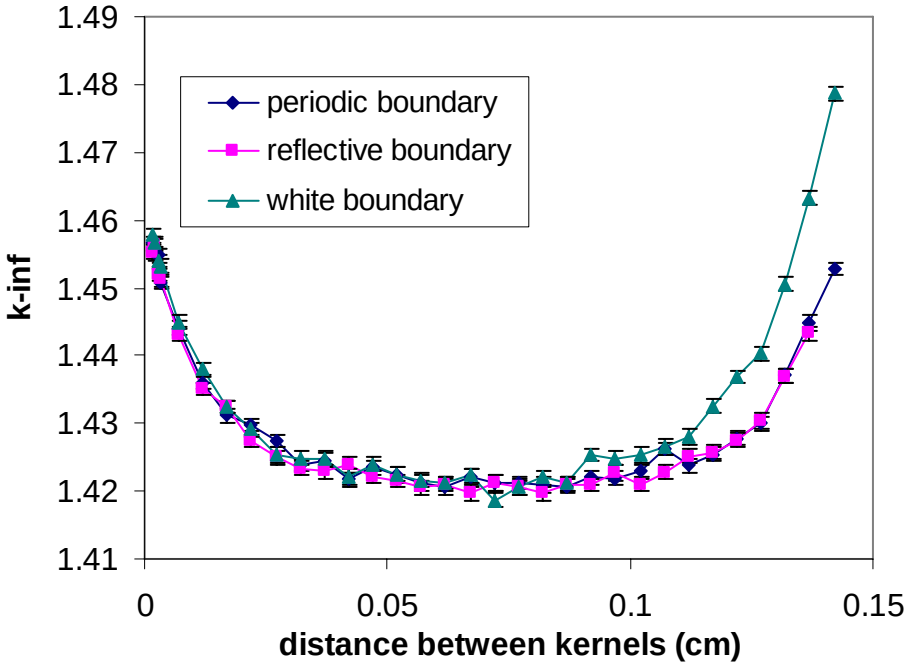

Figure 6: K-infinity as a function of inter-kernel distance at fuel enrichment of 8 % and various boundary conditions at the unit cell surfaces.

It can be observed, that when fuel kernels are more than 1 mm away from the boundary surface, there are practically no differences in k-inf at various boundary conditions. When fuel kernels are closer than 1mm to the boundary, the same results are obtained with periodic and reflective boundary condition, while the results from the white boundary condition model deviate strongly (more than 1 %) from the other results. This is expected as the WBC is an effective and physically incorrect boundary condition effectively smearing the angular distribution of re-entering neutrons at the boundary surface.

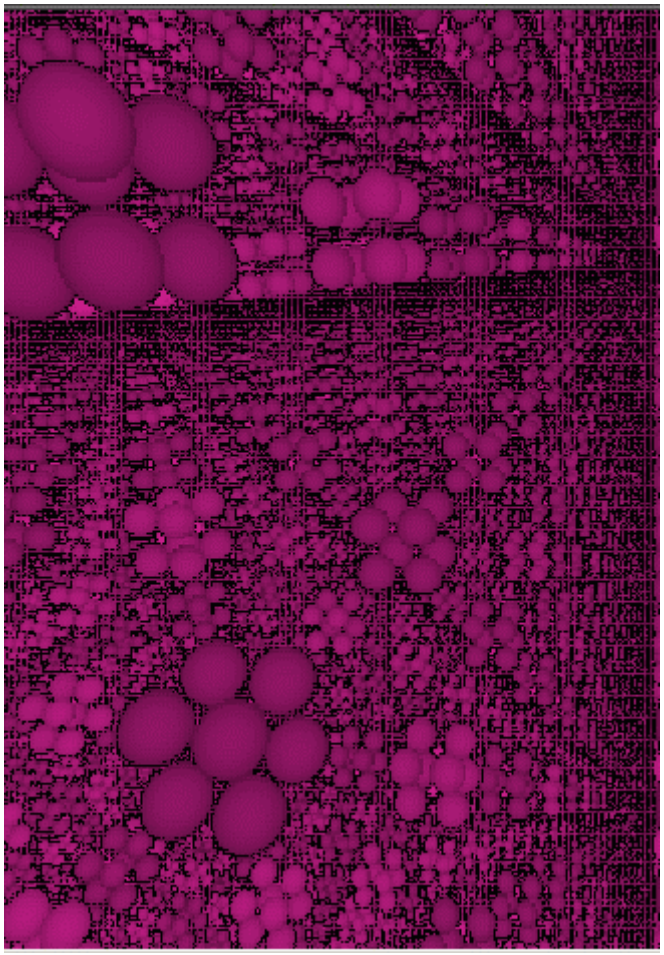

Figure 7: A 3D view of fuel kernels in the fuel element, MCNP model

5 CONCLUSION

It was shown that the fuel kernel radius or the total surface of the fuel kernels has strong influence on multiplication properties of the PBR due to resonance self-shielding effect in ^{238}U. In general, k increases when kernel surface to volume ratio decreases.

The inter-kernel distance also significantly effect multiplication properties of the PBR. The kernels could cluster due to manufacturing process failure. The fuel kernel distribution in the pebbles should be controlled for uniformity in order to avoid clustering effects and excess of reactivity.

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