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Author(s)

J.L. Kloosterman, H. van Dam and T.H.J.J. van der Hagen

Organisation, Country

Delft University of Technology
Interfaculty Reactor Institute
Netherlands

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DESIGN OF SPHERICAL AND 'HOLLOW' BURNABLE PARTICLES FOR UO_2 FUELS IN HIGH TEMPERATURE REACTORS

J.L. KLOOSTERMAN, H. VAN DAM, AND T.H.J.J VAN DER HAGEN

Interfaculty Reactor Institute
Delft University of Technology
Mekelweg 15, NL 2629 JB Delft
The Netherlands
E-mail: J.L.Kloosterman@iri.tudelft.nl

ABSTRACT

Burnup calculations have been performed on a standard HTR fuel pebble (R=3 cm) containing 9 grams of 8% enriched uranium and burnable particles made of B_4C highly enriched in B-10. The radius of the burnable particles and the number of particles per fuel pebble have been varied to find the flattest reactivity-to-time curve. It was found that for a target $k\infty$ of 1.1, a reactivity swing as low as 2.4% can be obtained when each fuel pebble contains about 1300 burnable particles with a radius of 70 μm. For other values of the target $k\infty$ even lower values can be obtained. For 'hollow' burnable particles that consist of a graphite kernel with a radius of 300 μm covered with a burnable poison layer of 30 μm, the reactivity swing is only 2%. In general, the modification of the geometry of burnable particles is an effective means to tailor the reactivity curve of HTRs.

1. INTRODUCTION

During the operation of a nuclear reactor, the reactivity effect of fuel burnup must be compensated by some means of long-term reactivity control, especially when the reactor operates with batch-wise fuel loads. An elegant way for such a control is the use of burnable poison in the fuel elements to balance the reactivity loss caused by fuel burnup and fission product poisoning by the reactivity gain due to the disappearance of the burnable poison.
The possibility of continuous fuel loading is a very nice feature of pebble-bed type High Temperature Reactors (HTRs) that enables one to reach a high fuel burnup. However, it is also likely to increase the manufacturing and operational costs of such a reactor. Besides the fact that fuel-loading machinery is complex and sensitive to malfunctioning, high-skilled operators are needed to guarantee long-term operation without interruption, which inherently limits the application of this reactor type to (co) generation of heat and electricity in well-developed countries. A batch-wise fuel load scheme in HTRs combined with burnable poison has some attractive properties not offered by the continuous loading scheme. The use of the burnable poison diminishes the role of the active reactivity control mechanisms, which paves the way for long-term unattended reactor operation. This makes the HTR technology applicable to ship propulsion and to (co) generation of heat and electricity for all kind of purposes in remote areas.
In this paper, we consider poisoning of the fuel in a heterogeneous way by mixing burnable particles in the fuel elements. The reason for this is given in chapter 2 of this paper. The burnable particles themselves contain B_4C made of boron highly enriched in the isotope B-10. As a fuel we used 8% enriched UO_2 particles embedded in a graphite pebble with diameter of 5 cm surrounded with a graphite layer with thickness of 0.5 cm. This fuel is very similar to that adopted by the PBMR [1,2]. The initial uranium mass per pebble was 9 gram. The core power density was 3 $W.cm^{-3}$, and assumed constant during the burnup. The temperature was 900 K in all calculations.

2. Theory

For absorbing nuclides homogeneously distributed in the core, the macroscopic neutron absorption cross section Σ_a is an exponentially decaying function of time t:

$$\Sigma_a(t) = \sigma_a N(t) = \sigma_a N_0 \exp(-\sigma_a \Phi_0 t). \quad (2.1)$$

Here, σ_a is the microscopic absorption cross section of the absorbing nuclide (e.g. B-10), N_0 its initial atomic density, and Φ_0 the neutron flux density.

For a small particle that absorbs all impinging neutrons, a so-called black particle, the effective absorption cross section is equal to its geometrical cross section [3]. This means that the neutron absorption rate depends on the geometry and size of the burnable particle, but not on its actual composition. For a spherical particle, the effective absorption cross section is a quadratic function of time:

$$\Sigma_a(t) = N_p \pi R_0^2 \left(1 - \frac{\Phi_0 t}{4 N R_0}\right)^2. \quad (2.2)$$

Here, N_p is the density of the burnable particles, R_0 the initial radius of the particle, and N the atomic density of the absorbing nuclide in the particle. Although Eq. (2.2) does not contain the microscopic absorption cross section σ_a of the absorbing nuclide, it is implicitly assumed that its value is such high that the burnable particle can be considered as ' black'. Equations (2.1) and (2.2) clearly illustrate that lumping the burnable absorber into particles enables one to tailor the time-dependence of the neutron absorption rate by the absorber. The purpose of this paper is to find the optimum radius of a burnable particle containing B_4C made of highly enriched boron.

3 Calculational scheme

From the SCALE code system [4], we used the BONAMI-S code for the resonance treatment in the unresolved energy region, the NITAWL-II code for the resonance treatment in the resolved energy region, and the XSDRNPM-S code for the cell-weighting calculations. The actual burnup calculations were performed by the ORIGEN-S fuel depletion code. All codes were coupled to each other via PERL scripts and via own-made FORTRAN programs. All nuclear data used are based on the JEF-2.2 nuclear data library.

In all calculations, a macro cell was modeled containing one burnable particle made of B_4C surrounded with a smeared fuel layer. The latter contains all nuclides present in a standard fuel pebble, i.e. the nuclides from the TRISO coated fuel particles (including fission products and actinides), the carbon from the graphite matrix in between the fuel particles, and the carbon from the 0.5 cm thick outer layer.

Because the SCALE code system cannot handle explicitly the double heterogeneity of the fuel, the cell-weighting procedure had to be split up in two parts. First, the homogenized resonance-shielded and cell-weighted cross sections of the fuel layer were calculated in a micro-cell calculation with the unit cell made up of a TRISO coated fuel particle with a nuclide composition characteristic for the actual burnup time step surrounded with an equivalent amount of graphite. Secondly, a macro-cell calculation was done to calculate the neutron flux density in the burnable particle, and to calculate the fission power density in the smeared fuel layer.

Besides the resonance-shielded cell-weighted cross sections to be used in the macro-cell calculation, also the resonance-shielded *zone*-averaged cross sections were calculated, and passed to the burnup data library. Burnup calculations were done for each fuel layer and for each layer of the burnable particle using the nuclide cross sections updated at each burnup time step. The whole sequence of micro-cell calculations, macro-cell calculations, and burnup calculations for the fuel layers and the burnable particle layers are repeated 10 times to calculate the $k\infty$ and the composition of each layer as a function of burnup. Furthermore, at each burnup time step, the temperature reactivity coefficient was calculated.

4 Results for spherical burnable particles

This section presents the results for the spherical burnable particles made of B_4C. For a specific composition of the burnable particle and the fuel pebble, there remain only two parameters to be varied: the radius of the burnable particle and the number of burnable particles per fuel pebble. The latter number is presented in a more abstract way by the ratio of the volume of one fuel pebble, and the volume of all burnable particles in that pebble.

There are two output parameters of major interest: the *initial* $k\infty$ and the *reactivity swing* Δk. Because the definition of these parameters is not unambiguous, we will clarify their definition. The *initial* $k\infty$ is the value of the $k\infty$ curve directly after saturation of all short-lived fission products like Xe and Sm. In practice, the value of the $k\infty$ after 10 days of burnup is used for this. The reactivity swing is defined as the variation of the $k\infty$ between 10 days of burnup and the burnup value for which the $k\infty$ of the reference curve (without a burnable particle) crosses the *initial* $k\infty$. This makes sense as one would like to achieve a reactivity curve as flat as possible. Fig 1 illustrates the parameters defined above.

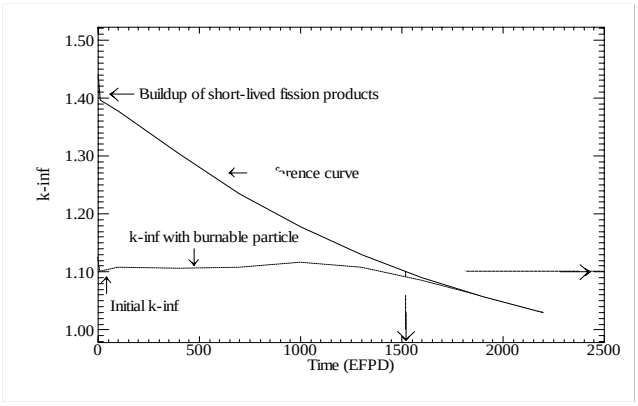

Fig 1. Illustration of the parameters used to characterize the fuel with burnable particles. The reactivity swing is the variation of the $k\infty$ between 10 EFPD and 1520 EFPD, where the reference curve crosses the initial $k\infty$ of 1.1.

Figures 2 and 3 show the initial $k\infty$ and the reactivity swing of the fuel for radii of the burnable particle varying from 10 to 200 μm and for the fuel volume ratio varying from 10,000 to 200,000. Figure 2 shows that the initial $k\infty$ increases when either the fuel volume ratio or the burnable particle radius increases. The latter can be understood from the theory in section 2: for a fixed volume of the burnable poison (constant fuel volume fraction), the larger the radius of the burnable particle, the more heterogeneously distributed the burnable poison, and the smaller the effective absorption cross-section. On the other hand, the reactivity swing shows a 'valley' ranging from the upper-left corner to the lower-right corner. The optimization procedure would be first to find the range of 'coordinates' (burnable particle radius and the fuel volume ratio) that fulfills the requirement on the initial $k\infty$ (this could be, for example, that in order to have a critical reactor, the initial $k\infty$ must be 1.1). Secondly, from the coordinates found, one should extract that pair that gives the lowest reactivity swing. The result is visualized in Fig. 4.

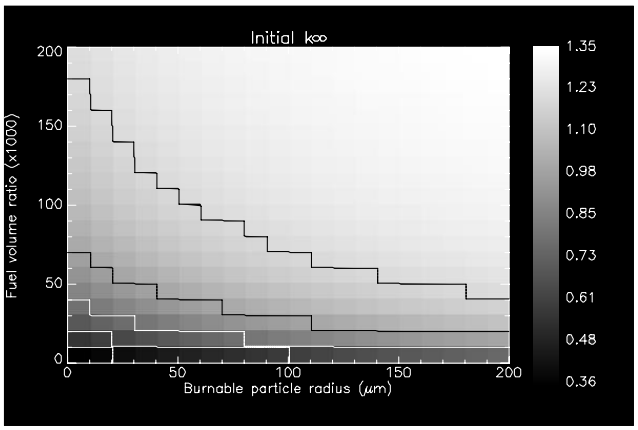

Fig 2. The initial $k\infty$ as a function of the BP radius and the fuel volume ratio.

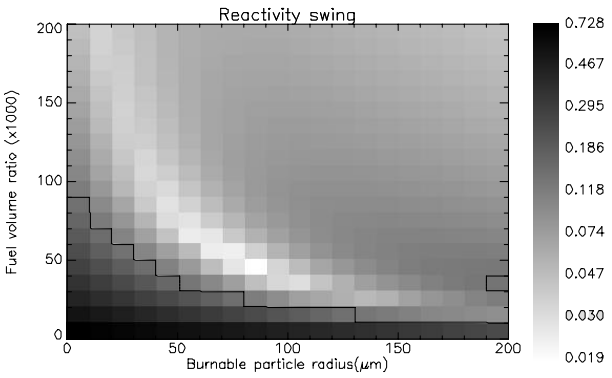

Fig 3. The reactivity swing as a function of the BP radius and the fuel volume ratio.

Figure 4 shows the absolute difference of the initial $k\infty$ and the target value (arbitrarily chosen to be 1.1) multiplied with the reactivity swing. The 'valley' in the plot shows the combinations of the BP radius and the fuel volume ratio that gives an initial $k\infty$ close to 1.1 and a reactivity swing as small as possible. Two combinations are most favorable: a BP radius of 70 μm with a VF ratio of 60,000, (reactivity swing of 2.4%) and a BP radius of 90 μm with a VF ratio of 50,000 (reactivity swing of 1.9%). However, a broad range of BP radii (say between 60 and 100 μm) can be applied, which relaxes the requirements in the manufacturing process of the particles. The reactivity curve for the first-mentioned fuel is shown in Fig 1, while the temperature reactivity coefficient is shown in Fig 5. At BOL the influence of the poison on the neutron spectrum is quite large and the UTC is more strongly negative. However, the burnup averaged UTC values differ not too much (≈1 pcm/K). With a UTC of -8 pcm/K and a reactivity swing of 2.4%, the temperature of the core would vary 300 K during the lifetime of the fuel. After about 2000 EFPD, virtually all boron has been burnt

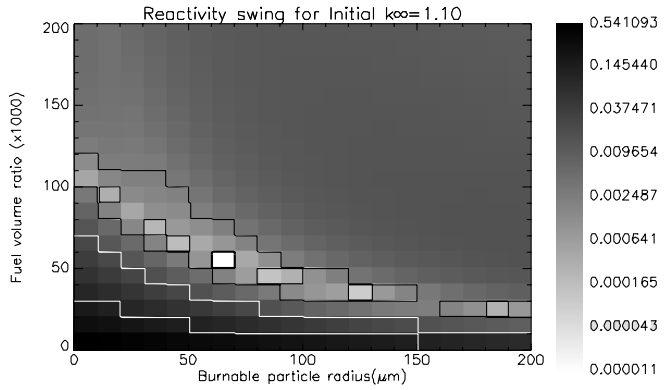

Fig 4. Result of the optimization procedure. The light 'valley' shows the range of parameters that gives the smallest reactivity swing at a target $k\infty$ of 1.10.

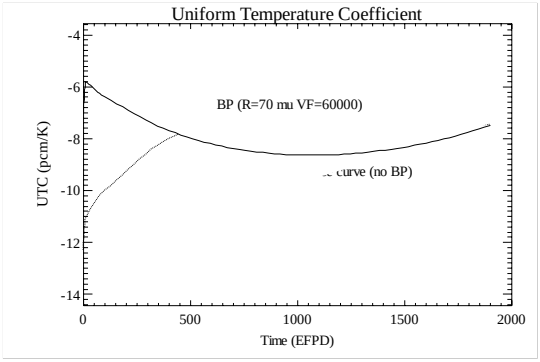

Fig 5. The UTC as a function of burnup for the fuel with a BP radius of 70 μm and a fuel volume ratio of 60,000 compared with the reference fuel. The average values are -7.6 pcm/K (reference curve) and -8.7 pcm/K.

(<0.1% left), and the UTC is the same for both curves.
Figures 6 and 7 show the relationship between the BP radius and the reactivity swing at the one hand, and between the fuel volume ratio and the reactivity swing at the other. Figure 6 shows that the larger the fuel volume ratio, the less influence the poison has on the reactivity. In Fig 7, the initial amount of poison is the same in all curves, and the effect of lumping the burnable poison into particles is clearly seen. The smaller the particle, the more homogeneously distributed the poison, and the lower the initial $k\infty$.

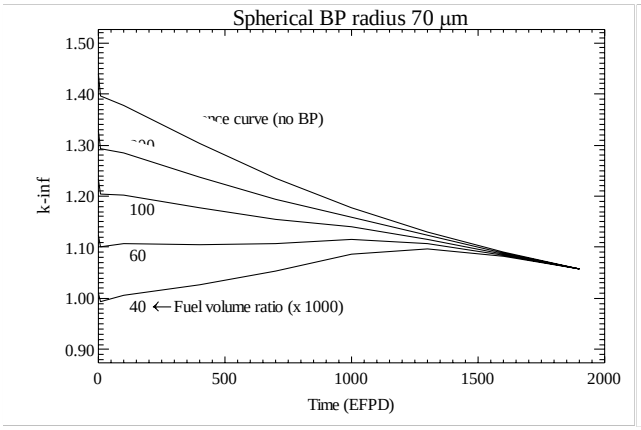

Fig 6. The $k\infty$ as a function of burnup with the fuel volume ratio as a parameter.

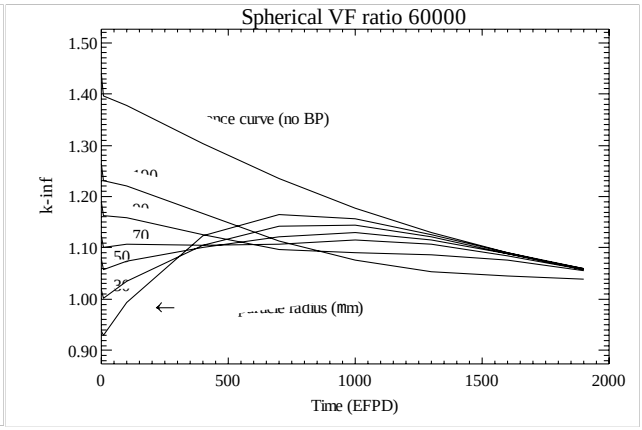

Fig 7. The $k\infty$ as a function of burnup with the burnable particle radius as a parameter.

5 Results for hollow burnable particles

Similar results can be obtained by using 'hollow' particles. These particles contain a graphite kernel with a radius of 300 μm covered with a thin layer of B_4C fully enriched in B-10. The results of the optimization procedure are shown in Fig 8. The best result at an initial $k\infty$ of 1.1 is obtained for a burnable poison layer with a thickness of 50 μm and a fuel volume ratio of 40,000. Then the reactivity swing is 5.8%. However, for a burnable poison layer of 30 μm and a fuel volume ratio of 50,000, the reactivity swing is 2% only at an initial $k\infty$ of 1.08. Some freedom in the choice of the target $k\infty$ can therefore lead to lower values for the reactivity swing. Calculations with a graphite kernel with radius of 500 μm give similar results.

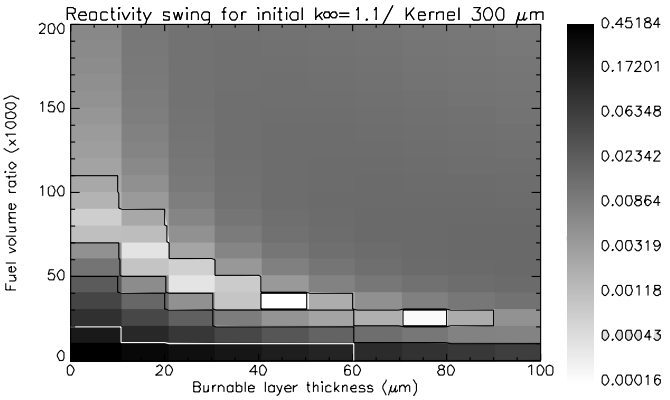

Fig 8. Result of the optimization procedure for a 'hollow' particle made of a graphite kernel (R=300 μm) covered with a B_4C layer with thickness between 10 and 100 μm.

6 Conclusions

With burnable particles mixed in the fuel of an HTR, it is possible to control the excess reactivity present at BOL. For 8% enriched UO_2 fuel, mixing 1300 spherical particles made of B_4C with radius of 70 μm through the fuel of a standard HTR fuel pebble (with radius of 3 cm), the reactivity swing is 2.4% at a constant $k\infty$ of 1.1. Using burnable particles with a radius of 90 μm, the reactivity swing drops to a value below 2%. This means that, with no active reactivity control mechanisms (e.g. no shim rods) and a uniform temperature coefficient of -8 pcm/K, the temperature of the core would vary between 250 and 300 K during the lifetime of the fuel.

The application of 'hollow' burnable particles, which consist of a non-poisonous graphite kernel covered with a B_4C burnable poison layer, gives similar results. Particles with a kernel radius of 300 μm and a burnable poison layer of 30 μm give a reactivity swing of 2% at an initial $k\infty$ of 1.08, while the reactivity swing is almost 6% for an initial $k\infty$ of 1.1. This example shows that some freedom in the selection of the target $k\infty$ may lead to even lower values of the reactivity swing. In general, we can conclude that modifying the geometry of burnable particles is an effective means to tailor the reactivity-to-time curve of HTRs. Further research will focus on the application of other burnable absorbers like Er and Gd, and other fuel types like PuO_2 fuel.

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