Applying burnable poison particles to reduce the reactivity swing in high temperature reactors with batch-wise fuel loading

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Abstract
Burnup calculations have been performed on a standard HTR fuel pebble with a radius of 3 cm containing 9 g of 8% enriched uranium and burnable poison particles (BPP) made of B\textsubscript{4}C highly enriched in \textsuperscript{10}B. The radius of the BPP 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 \( k_\infty \) of 1.1, a reactivity swing as low as 2\% can be obtained when each fuel pebble contains about 10\textsuperscript{7} BPP with a radius of \( 75 \times 10^{-6} \) m. For coated BPP that consist of a graphite kernel with a radius of \( 300 \times 10^{-6} \) m covered with a B\textsubscript{4}C burnable poison layer, a similar value for the reactivity swing can be obtained. Cylindrical particles seem to perform worse. In general, the modification of the geometry of BPP is an effective means to tailor the reactivity curve of HTRs.

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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 gas-cooled high temperature reactor (HTR) has some attractive properties not offered by other reactors. The application of TRISO coated fuel particles makes it possible to reach very high burnup values and ensures the containment of fission product up to a fuel temperature of 1600 °C (Kogeler and Schulten, 1989). Together with the use of burnable poison, which reduces the role of the active reactivity control mechanisms, this paves the way for long-term unattended reactor operation, which could make HTR technology applicable to areas like ship propulsion and (co)generation of heat and electricity in remote areas.

The HTR concept we had in mind when initiating this study is a mixture of the block-type HTR with batch-wise fuel loads and the pebble-bed type HTR with continuous loads. We consider a reactor that consists of a graphite-walled core cavity filled with fuel pebbles that contain not only TRISO coated fuel particles, but also some burnable poison particles (BPP). After some years of operation, all fuel pebbles are replaced with fresh ones. Because the core inventory is replaced as a whole, we call this concept the cartridge-fueled pebble-bed HTR. However, we want to emphasize that the concept of BPP described here is fully applicable to other batch-wise fueled HTRs as well. Also to the common block-type HTR?*
In this paper, we consider poisoning of the fuel in a heterogeneous way by mixing BPP in the fuel pebbles. The advantage of this innovative aspect is that by lumping the burnable poison, one has two design parameters to achieve a flat reactivity curve (size and concentration of the burnable poison particle) instead of only one for the case of homogeneous poisoning (concentration of the burnable poison nuclide). We further elaborate on this in Section 2 of this paper. The BPP themselves contain B_4C made of boron highly enriched in the isotope ^10B. As a fuel we used 8% enriched UO_2 particles embedded in a graphite pebble with a diameter of 5 cm surrounded by a graphite layer with thickness of 0.5 cm. Actually, these pebbles are very similar to the ones foreseen to be used in the PBMR (Gittus, 1999). The initial uranium mass per pebble was 9 g, and the average core power density, which was assumed constant during all the burnup calculations, 3 W cm^{-3}. The temperature was 900 K in all calculations. This paper is a slightly extended version of a paper published at the HTR-2002 conference (Kloosterman et al., 2002).

2. Theory

For absorbing nuclides homogeneously distributed in the core, neglecting spectral effects, the macroscopic neutron absorption cross-section $\Sigma_a$ is an exponentially decaying function of time $t$ (Duderstadt and Hamilton, 1976):

$$\Sigma_a(t) = \sigma_a N(t) = \sigma_a N_0 \exp(-\sigma_a \Phi_0 t). \quad (1)$$

Here, $\sigma_a$ is the microscopic absorption cross-section of the absorbing nuclide (in our case ^10B), $N_0$ its initial atomic density, and $\Phi_0$ is the neutron flux density. For a small burnable poison particle that absorbs all impinging neutrons, a so-called black particle, the effective absorption cross-section is equal to its geometrical cross-section. This means that the neutron absorption rate depends on the geometry and size of the particle, but not on its actual composition. For a spherical particle, the effective absorption cross-section is a quadratic function of time (van Dam, 2000):

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

Here, $N_p$ is the density of the BPP, $R_0$ the initial radius of the particle, and $N$ is the atomic density of the absorbing nuclide in the particle. Although Eq. (2) does not contain the microscopic absorption cross-section $\sigma_a$ of the absorbing nuclide, it is implicitly assumed that its value is such high that the burnable particle can be considered as ‘black’.

Under the same assumption, the macroscopic absorption cross-section of a cylindrical burnable particle (a ‘needle’) is a linearly decreasing function of time (van Dam, 2000):

$$\Sigma_a(t) = N_p \frac{\pi}{2} R_0 \ell \left[1 - \frac{\Phi_0 \ell}{4N R_0^2}\right]. \quad (3)$$

where $\ell$ is the length of the burnable needle in the sense that $N_p \ell$ is the total length of all BPP per unit volume. Eqs. (1)-(3) 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 aim of this paper is to find the radius and the concentration of spherical or cylindrical BPP containing B_4C made of highly enriched boron that minimize the reactivity swing. To this purpose, we have modeled one burnable poison particle surrounded by a smeared fuel layer. We calculated the $k_{\infty}$ as a function of burnup for 50 values of the radius of the burnable particle and for 20 values of the outer radius of the smeared fuel layer.

3. Calculation scheme

From the SCALE code system (SCALE-4.2, 1994), 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 XSDRNP-S code for the cell-weighting calculations. The actual burnup calculations were done using 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 (JEF-2.2, 2000).

In all calculations, a macro-cell was modeled containing one burnable poison particle made of B_4C surrounded with smeared fuel. The latter contains all nuclides present in a standard fuel pebble, i.e. the
Fig. 1. Schematic representation of the calculation model for the accurate set of calculations with the burnable poison particle divided into 10 concentric zones (although only eight are drawn in the figure) surrounded with three smeared fuel layers of equal volume. For each fuel layer, micro-cell calculations on a TRISO coated particle with graphite are done to determine the zone-weighted and cell-weighted cross-sections for each fuel layer. The cell-weighted cross-sections are subsequently used in the macro-cell calculations to determine the power and flux spatial distribution, while the zone-weighted cross-sections of the fuel are used to update the burnup data library. This process is repeated each burnup time step with updated atomic nuclide densities.

Two sets of calculations were done: global parameter studies using a macro-cell containing one burnable particle zone surrounded with one smeared fuel layer. The results of these studies are the $k_{\infty}$ as a function of time. A more accurate set of calculations was done with the burnable poison particle divided into 10 concentric zones and the fuel layer divided into 3 concentric zones (see Fig. 1). The $k_{\infty}$ values of these two sets of calculations are virtually the same, but because of the larger number of burnup zones, the latter set of calculations gives a better insight into the spatial boron distribution as a function of time. Furthermore, in that case the fuel temperature coefficient of reactivity and other parameters were calculated at various burnup time steps.

Because the SCALE code system cannot handle explicitly the double heterogeneity of the fuel, the cell-weighting procedure had to be split into two parts (see Fig. 1). 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. The Dancoff factor used in the resonance shielding was calculated by an analytical procedure (Bende et al., 1999) and took into account the double heterogeneity of the fuel. 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 poison 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 all the fuel layers and the burnable particle layers were 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

4.1. Spherical particles

This section presents the results for the spherical BPP made of B$_4$C. 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 poison particle and the number of BPP per fuel pebble. The latter number is presented in a more abstract way by the fuel volume ratio (VF), i.e. the ratio of the volume of one fuel pebble and the volume of all BPP in that pebble.

There are two output parameters of major interest: the initial $k_{\infty}$ and the reactivity swing $\Delta r$. Because the definition of these parameters is not unambigu-
ous, 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 maximum difference 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 $k_{\infty}$ value. This makes sense as one would like to achieve a reactivity curve as flat as possible. Fig. 2 illustrates the parameters defined above.

Fig. 3. Contour plot of the initial $k_{\infty}$ as a function of the burnable particle radius and the fuel volume ratio for spherical burnable particles. Two trends are visible. First increasing the volumetric fuel ratio $V_F$ (this is the ratio of the volume of the fuel layers and the volume of the burnable particle) with constant BP radius shows that the influence of the burnable particle diminishes if one adds fuel. Secondly, increasing the BP radius with constant $V_F$ ratio shows that the spatial self-shielding effect becomes stronger for larger BP particles.
Figs. 3 and 4 show the initial $k_{\infty}$ and the reactivity swing of the fuel for radii of the burnable poison particle varying from 10 to 250 $\mu$m and for the fuel volume ratio varying from 10,000 to 200,000. Fig. 3 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: for a fixed volume of the burnable poison (constant fuel volume fraction), the larger the radius of the burnable poison particle, the more heterogeneously distributed the burnable poison, and the smaller the effective absorption cross-section. On the other hand, the reactivity...
swinging in Fig. 4 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 equal 1.1). Secondly, from the coordinates found, one should extract that pair that gives the lowest reactivity swing.

Fig. 5 shows the absolute deviation of the initial $k_{\infty}$ and its target value (arbitrarily chosen to be 1.1) summed to the reactivity swing as a function of the burnable particle radius and the fuel volume ratio. Two regions are most favorable: a BPP radius of 75 $\mu$m
with a VF ratio of 60,000 and a BPP radius of 90 μm with a VF ratio of 50,000. The reactivity swing in these two regions is below 2% while the initial $k_{\infty}$ deviates from 1.1 not more than 1%. However, most probably a broad range of BPP radii (say between 70 and 90 μm) can be applied, which relaxes the requirements in the manufacturing process of the particles.

The reactivity curves for the two selected BPP are shown in Fig. 6, while the temperature reactivity coefficient is shown in Fig. 7. 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 ($\approx$ 1 pcm/K). With a UTC of $-8$ pcm/K and a reactivity swing of 2%, the temperature of the core would vary 250 K during the lifetime of the fuel. After about 2000 EFPD, virtually all boron has been burnt (<0.1% left), and the UTC is the same for both curves.

Fig. 8. The $k_{\infty}$ as a function of burnup for a spherical burnable particle with a radius of 70 μm with the fuel volume ratio as a parameter.

Fig. 9. The $k_{\infty}$ as a function of burnup for a spherical burnable particle with fuel volume ratio of 60,000 with the BP radius as a parameter.
Fig. 10. The $^{10}$B nuclide density as a function of burnup with the zone number as a parameter. The boron in the outer zone depletes first.

Fig. 8 and 9 show the relationship between the BPP radius and the reactivity swing at the one hand and between the fuel volume ratio and the reactivity swing at the other. Fig. 8 shows that the larger the fuel volume ratio, the less influence the poison has on the reactivity. In Fig. 9, 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 $k_{\infty}$.

Finally, Fig. 10 shows the boron concentration in each of the 10 zones in the burnable particle as a...
function of irradiation time. Clearly, due to the spatial self-shielding effect, the boron in the outer zone depletes first, but the particle by far cannot be considered as ‘black’.

4.2. Cylindrical particles

For a black burnable particle, the boron depletion rate in a cylindrical geometry differs from that in spherical (see Section 2). Therefore, the calculations for the spherical BPP were repeated for cylindrical ones or burnable ‘needles’. Note that in these calculations, the micro-cell calculations shown in Fig. 1 were still performed in spherical geometry, but that only the macro-cell geometry was cylindrical with an axial buckling height of 400 cm. Because part of the neutron leakage was already included using this buckling height (the $k_{\infty}$ values with no burnable particle are about 5% smaller), the target value for the $k_{\infty}$ was lowered to 1.05.

The reactivity swing for a target $k_{\infty}$ of 1.05 (as in the previous section, this is the sum of the reactivity swing and the absolute difference between the initial $k_{\infty}$ and its target value of 1.05) is shown in Fig. 11. Values smaller than 5% can be obtained for radii between 20 and 30 μm. Fig. 12 shows for these cases the $k_{\infty}$ as a function of the irradiation time with the fuel volume ratio as a parameter.

Fig. 12. The $k_{\infty}$ as a function of burnup with the fuel volume ratio as a parameter for cylindrical burnable particles.

4.3. Coated particles

When studying the concept of spherical BPP, we first concentrated on larger ones with radius of a few hundred microns (Berthou et al., 2001). Because these large particles did not completely deplete, we introduced the concept of “hollow” or coated particles. These particles contain a graphite kernel with a radius of 300 μm covered with a thin layer of B$_4$C fully enriched in $^{10}$B. The results of the optimization procedure are shown in Fig. 13. The best result at an initial $k_{\infty}$ of 1.1 is obtained for a burnable poison layer with a thickness of 25 μm and a fuel volume ratio of 60,000 (reactivity swing 2.2%), or for a burnable poison layer of 35 μm and a fuel volume ratio of 50,000 (reactivity swing 2.7%). Calculations with a graphite kernel with radius of 500 μm give very similar results. Although the concept of coated particles seems attractive if one
Fig. 13. Contour plot of $|k_{\infty} - 1.1|$ summed to the reactivity swing $\Delta \rho$ as a function of the burnable layer thickness and the fuel volume ratio for coated burnable particles. The radius of the graphite kernel of the burnable particle is 300 $\mu$m.

wants to use larger particles, compared to the spherical particles with a radius of about 70 $\mu$m, they do not give better results. Only if, for example, the manufacturing process would favor this concept, one could use coated particles instead of solid spherical ones.

5. Conclusions

With BPP mixed in the fuel of an HTR, it is possible to control the excess reactivity present at beginning of life. For 8% enriched UO$_2$ fuel, mixing 1070 spherical particles made of B$_4$C with radius of 75 $\mu$m through the fuel of a standard HTR fuel pebble with radius of 3 cm, the reactivity swing is 2% at a $k_{\infty}$ of 1.1. Using 740 BPP with a radius of 90 $\mu$m gives similar results. 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 varies about 250 K during the lifetime of the fuel.

From theory, the burnup behavior of cylindrical BPP differs from that of spherical ones, if the particles are large enough to be considered as ‘black’. The reactivity swing calculated for these burnable ‘needles’ is, however, larger than that of the spherical particles, although it is not clear this will be the case for all values of the target $k_{\infty}$.

The application of ‘hollow’ or coated burnable particles, which consist of a non-poisonous graphite kernel covered with a B$_4$C burnable poison layer, gives results similar to the spherical particles. If not for other reasons like the manufacturing process, these particles have no large benefits compared to the solid spherical burnable particles.

Although the idea of burnable particles to tailor the reactivity as a function of time originated from the theory of ‘black’ particles, the burnable particles made of B$_4$C containing highly enriched $^{10}$B cannot be considered suchlike. Therefore, it is interesting to investigate the behavior of stronger neutron absorbers like Gd. This will be subject of further studies.

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