Design of burnable poison particles to reduce the reactivity swing in batch-wise fueled High Temperature Reactors
(Fuel cycles with burnable poison)

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SUMMARY

Burnup calculations have been performed on a standard HTR fuel pebble (fuel zone with radius of 2.5 cm surrounded with a 0.5 cm thick graphite layer) and burnable poison particles (BPPs) containing B$_4$C made of pure $^{10}$B or containing Gd$_2$O$_3$ made of natural Gd. Two types of fuel were considered: UO$_2$ fuel made of 8% enriched uranium and PuO$_2$ fuel made of plutonium from LWR spent fuel (1st generation Pu). The radius of the BPP and the number of particles per fuel pebble were varied to find the flattest reactivity-to-time curve.

For the UO$_2$ fuel, the reactivity swing is lowest (around 2%) for spherical BPPs made of B$_4$C with radius of 75 $\mu$m. In this case around 1070 BPPs per fuel pebble are needed. For the PuO$_2$ fuel to get a reactivity swing below 4%, the optimal radius of the spherical BPP is the same, but the number of particles per fuel pebble should be around 1600. The optimal radius of the Gd$_2$O$_3$ spherical particles in the UO$_2$ fuel is about ten times that of the B$_4$C particles. The reactivity swing is around 3% when each fuel pebble contains only 9 BPPs with radius of 840 $\mu$m. The results of the Gd particles illustrate nicely the usage of black BPPs introduced by Van Dam [1].

For coated BPPs that consist of a graphite kernel with a radius of 300 $\mu$m covered with a $^{10}$B$_4$C burnable poison layer, similar values for the reactivity swing can be obtained. Cylindrical BPPs seem to perform worse. In general, the modification of the geometry of the BPP is an effective means to tailor the reactivity curve of HTRs.
1. INTRODUCTION

During the operation of a nuclear reactor, especially when it operates with batch-wise fuel loads, the reactivity loss due to fuel burnup and fission product poisoning must be compensated by some means of long-term reactivity control. An elegant way to accomplish this is to use burnable poison particles (BPP) originally introduced by Van Dam. This is especially of interest to the gas-cooled High Temperature Reactor (HTR), because this reactor 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 to ensure the containment of fission products up to a fuel temperature of 1600 °C [2]. Together with the use of BPPs to reduce or eliminate the role of the active reactivity control mechanisms, this paves the way for long-term unattended reactor operation for HTRs with batch-wise fuel loads, like a common block-type HTR or a cartridge-fueled pebble-bed HTR. This could make HTR technology applicable to areas like ship propulsion and cogeneration of heat and electricity in remote areas.

By lumping the burnable poison into spherical particles, one has two design parameters to achieve a flat reactivity curve (size and concentration of the BPP) instead of only one for the case of homogeneous poisoning (concentration of the burnable poison). For a small BPP that absorbs all impinging neutrons, a so-called black particle, the effective absorption cross section is equal to its geometrical cross section independent of the composition of the particle. This means that the neutron absorption rate depends on the size of the particle, but not on its actual composition. Then, the effective absorption cross section for a spherical particle is a quadratic function of time [1]:

\[ \Sigma_a(t) = N_p \pi R_0^2 \left(1 - \frac{\Phi_o t}{4NR_0}\right)^2. \]  

Here, \( N_p \) is the number density of the burnable poison particles, \( R_0 \) the initial radius of the particle, \( \Phi_o \) the local unperturbed flux, and \( N \) the atomic density of the absorbing nuclide in the particle. For more details, see the paper of Van Dam [1] or Kloosterman et al. [3,4]. The BPP themselves contain either B\(_4\)C made of pure \(^{10}\)B or Gd\(_2\)O\(_3\) made of natural Gd (see Table I). From a neutronics point of view, the main difference between these two materials is the mean free path for thermal neutrons, which is about four times larger for the B\(_4\)C particle. As a fuel we used either UO\(_2\) or PuO\(_2\) particles embedded in a graphite pebble with a diameter of 5 cm surrounded by a graphite layer with thickness of 0.5 cm. More details about the fuel composition are given in Table II.

Under the same assumption (black particle), the macroscopic absorption cross section of a cylindrical BPP (a 'needle') is a linearly decreasing function of time [1]:

\[ \Sigma_a(t) = N_p \frac{\pi}{2} R_0 \left[1 - \frac{\Phi_o t}{4NR_0}\right]. \]
where \( \ell \) is the length of the burnable needle in the sense that \( N_p \ell \) is the total length of all BPPs per unit volume. Equations (1) and (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 aim of this project is to find the radius and the concentration of the BPPs that minimize the reactivity swing at a specific value for \( k_{\infty} \). To this end, we have modeled one BPP (see Fig. 1) surrounded by a smeared fuel layer for which we calculated the \( k_{\infty} \) as a function of time with the BPP radius and the outer radius of the smeared fuel layer as parameters.
2. CALCULATIONAL SCHEME

From the SCALE code system [5], 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 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, both for the burnup calculations as well as for the neutron spectrum calculations, are based on the JEF-2.2 nuclear data library [6,7].

In all calculations, a macro cell was modeled containing one BPP (made of either B$_4$C or Gd$_2$O$_3$) surrounded by smeared fuel. The latter contains all nuclides present in a standard fuel pebble, i.e. the nuclides from the TRISO coated fuel particles (containing 25 fission products and actinide nuclides), the carbon from the graphite matrix in between the fuel particles, and the carbon from the 0.5 cm thick outer layer.

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

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 by an equivalent amount of graphite. The Dancoff factor used in the resonance shielding was calculated by an analytical procedure [8] and takes into account the double heterogeneity of the fuel. Secondly, a macro-cell calculation was done to calculate the neutron flux density in the BPP, 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 BPP using the nuclide cross sections updated at each time step. The whole sequence of micro-cell calculations, macro-cell calculations, and burnup calculations for the fuel layer and the
burnable particle layers were repeated ten times to calculate the $k_{eq}$ and the composition of each layer as a function of burnup. Furthermore, at each burnup time step, the temperature reactivity coefficient was calculated.
3. RESULTS

3.1 UO$_2$ fuel with B$_4$C spherical particles

This section presents the results for the spherical BPP made of B$_4$C. For one choice of the BPP and the fuel, there remain only two parameters to be varied: the radius of the BPP and the number of BPPs per fuel pebble. The latter number is presented in a more abstract way by the fuel volume ratio (FVR), i.e. the ratio of the volume of one fuel pebble with radius of 3 cm and the volume of all BPPs in that pebble.

There are two output parameters of major interest: the initial $k_{\text{eff}}$ and the reactivity swing $\Delta \rho$. Because the definition of these parameters is not unambiguous, we will clarify their definition. The initial $k_{\text{eff}}$ is the value of the $k_{\text{eff}}$ curve directly after saturation of all short-lived fission products like Xe and Sm. In practice, the value of the $k_{\text{eff}}$ after 10 days of burnup is used for this. The reactivity swing $\Delta \rho$ is defined as the maximum difference of the $k_{\text{eff}}$ between 10 days of burnup and the burnup value for which the $k_{\text{eff}}$ of the reference curve (with no BPP) crosses the initial $k_{\text{eff}}$ value of the BPP curve. This makes sense as one would like to achieve a reactivity curve as flat as possible. Figure 2 illustrates the parameters defined above.

Figure 3 shows the initial $k_{\text{eff}}$ and the reactivity swing $\Delta \rho$ of the fuel for radii of the BPP varying from 10 to 200 $\mu$m and for FVR varying from 10,000 to 200,000. The initial $k_{\text{eff}}$ increases when either the FVR or the BPP radius increases. The latter can be understood from the theory: for a fixed volume of the poison (constant FVR), the larger the radius of the BPP, the more heterogeneously distributed the 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 to first find the combinations of BPP radius and FVR that fulfills the requirement on the initial $k_{\text{eff}}$ (this could be, for example, that in order to have a critical reactor, the initial $k_{\text{eff}}$ must be equal to 1.1). Secondly, from these results found, one should extract those values for the BPP radius and the FVR that give the lowest reactivity swing. The third plot in Fig. 3 shows the absolute deviation of the initial $k_{\text{eff}}$ and its target value (arbitrarily chosen to be 1.1), while the fourth plot shows this parameter summed to the reactivity swing. Two regions are most favorable: a BPP radius of 75 $\mu$m with a FVR of 60,000 and a BPP radius of 90 $\mu$m with a FVR of 50,000. The reactivity swing in these two regions is below 2% while the initial $k_{\text{eff}}$ deviates from 1.1 no more than 1%. However, most probably a broad range of BPP radii (say between 70 and 90 $\mu$m) can be applied, which relaxes the requirements in the manufacturing process of the particles. Actually, the $k_{\text{eff}}$ for a BPP radius 70 $\mu$m and FVR=50,000 is shown in Fig. 2 as a function of time. More results for this case among which the fuel temperature coefficient as a function of burnup are given in Ref. [4].
3.2 UO₂ fuel with Gd₂O₃ spherical particles

Figure 4 shows the results for the spherical BPP containing Gd₂O₃. Surprisingly, for a specific radius of the BPP, the FVR is smaller for the Gd₂O₃ case, which means that this kind of particles is less absorbing than the B₄C ones. For example, for a BPP with radius of 200 μm to obtain $k_{\infty}=1.1$, we must chose FVR=30,000 for the B₄C particle, but only FVR=17,200 for the Gd₂O₃ particle. Figure 5 shows the reason for this unexpected behavior. The macroscopic absorption cross section of Gd is larger than that of $^{10}$B only for energies below 0.2 eV. Above this energy the reverse is true, which is also due to the fact that the atomic density of boron in B₄C is about 15 times (!) larger than the atomic densities of the two absorbing Gd isotopes in Gd₂O₃. Because the configurations chosen give the same $k_{\infty}$, the fraction of neutrons absorbed in the BPP is also the same (about 0.16). However, for the Gd₂O₃ particle these are only thermal neutrons with energy below 0.2 eV, while for the B₄C particle about one third of the absorption rate is due to neutrons with energy above 0.2 eV. In conclusion: although the Gd₂O₃ particle is more absorbing (less grey) for thermal neutrons, the total spectrum-averaged neutron absorption rate is larger in the B₄C particle.

From Fig. 4 it seems that with the use of a Gd₂O₃ particle, it is not possible to reach a reactivity swing less than 5% at a target $k_{\infty}$ of 1.1. Fortunately, more accurate calculations with more zones in the BPP and more neutron spectrum calculations during the lifetime of the fuel show slightly better results. Figure 6 shows the $k_{\infty}$ for a BPP with a radius of 840 μm and a FVR of 5,000. The reactivity swing is about 3%, which is comparable to the results obtained with the B₄C particles (see Section 3.1). The most notable difference with the B₄C particles is the fact that the optimum radius of the Gd₂O₃ particles is about 10 times as large, which could be an advantage for the manufacturing process of the BPPs.

3.3 PuO₂ fuel with B₄C spherical particles

The B₄C spherical BPP was also applied in combination with PuO₂ fuel ("first generation") with composition given in Table II. The burnup behaviour of the PuO₂ fuel differs considerably from that of the UO₂ fuel. The $k_{\infty}$ curve of the latter fuel decreases almost linearly in time to a value of about unity (see Figs. 2 and 6), while that of the PuO₂ fuel decreases gradually in time till $k_{\infty}\approx1.25$, after which it suddenly drops (see Fig. 7). This effect is due to the consumption of all the actinides in the particle.

The results of these studies can be seen in Fig. 8, which shows the $k_{\infty}$, the reactivity swing $\Delta\rho$, the deviation of the $k_{\infty}$ from its target value (1.1) and the sum of this parameter and the reactivity swing ($\Delta k+\Delta\rho$). The optimum size of the BPP is around 90 μm, which is very similar to the results obtained for the UO₂ fuel (see Section 3.1 and Fig. 3), although the FVR is lower than that of the
UO₂ fuel (25,000 versus 60,000 for UO₂). This last difference is not that easy to understand. Before saturation of the short-lived fission products, the \( k_{\infty} \) values for the UO₂ and PuO₂ fuels with no BPP are 1.44 and 1.38, respectively (after saturation these numbers are 1.39 and 1.34). This means that for the UO₂ fuel to reach \( k_{\infty} = 1.1 \), a larger fraction of neutrons needs to be absorbed in the BPP, from which at first instance one would expect that the FVR for the UO₂ fuel would be smaller. But the reverse is true! Figure 9 shows the neutron spectra in the fuel zones for both fuel types, together with the cumulative neutron absorption rate in the BPP. Two interesting points can be observed. First, because of the harder neutron spectrum in the PuO₂ fuel, neutron absorption in the BPP takes place at higher energies where the absorption cross section of the \( ^{10}\text{B} \) is lower. Thus more \( ^{10}\text{B} \) or a lower FVR is needed to achieve a sufficiently large reduction of the \( k_{\infty} \). Secondly, for both cases the spectrum integrated neutron fraction absorbed in the BPP is the same (about 0.16) while the \( k_{\infty} \) with no BPP is about 5% larger for the UO₂ fuel. Apparently, the BPP in the PuO₂ fuel absorbs many neutrons that would otherwise be captured at lower energies by the plutonium isotopes. For this effect, the strong capture resonance of \( ^{240}\text{Pu} \) at 1 eV could be responsible, which gives a large value for the capture-to-fission ratio of reactor grade plutonium around 1 eV (see Fig. 10).

Figure 7 shows the \( k_{\infty} \) as a function of irradiation time for two values of the BPP radius and the FVR in the region of the minimum in Fig. 8. Clearly the reactivity swing is considerably reduced to values of about 4%. Because of the different burnup behavior of the plutonium in the particle, the reactivity swing in the PuO₂ fuel is slightly larger than for the UO₂ fuel.

Up to 700 EFPD, the uniform temperature coefficient of the standard PuO₂ fuel is between -7 and -8 pcm/K, while this is between -5 and -6 pcm/K for the case of a BPP with radius of 90 \( \mu \text{m} \) and a FVR of 25,000. Despite the fact that the fuel contains no uranium, these values are negative and sufficiently large for the safe operation of an HTR. For the UO₂ fuel considered in Section 3.1, the uniform temperature coefficient has a similar value of about -8 pcm/K [4].

### 3.4 UO₂ fuel with B₄C cylindrical particles

For a black burnable particle, the boron depletion rate in a cylindrical geometry differs from that in spherical (see Section 1). Therefore, the calculations for the spherical BPPs 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. Figure 12 shows for these cases the $k_e$ as a function of the irradiation time with the fuel volume ratio as a parameter.

In general, the reactivity swing seems somewhat larger than for spherical BPP. This together with the fact that the small needles with radii of several tens of microns are probably very difficult to manufacture, kept us from studying this concept further.

### 3.5 UO₂ fuel with B₄C coated particles

When studying the concept of spherical BPPs, we first concentrated on larger ones with a radius of a few hundred microns [9]. 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 B₄C fully enriched in $^{10}$B. The results of the optimization procedure are shown in Fig 13. The best result at an initial $k_e$ 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 wants to use larger particles, compared to the spherical particles with a radius of about 70 μm, 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.
4. CONCLUSIONS

With Burnable Poison Particles (BPPs) 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 BPPs containing B$_4$C with radius of 75 $\mu$m through the fuel zone of a standard HTR fuel pebble with outer radius of 3 cm, the reactivity swing is 2% at a $k_{\infty}$ of 1.1. This means the burnable poison occupies a volume 60,000 less than that of the fuel pebble (FVR=60,000).

Using Gd$_2$O$_3$ as a burnable poison gives an optimum radius of about 840 $\mu$m and an FVR of only 5,000. This latter number corresponds to 9 spherical BPPs per fuel pebble. The low number for the FVR reflects the fact that the natural Gd in the particle absorbs fewer neutrons despite the fact that the thermal cross sections of the $^{155}$Gd and $^{157}$Gd isotopes are much larger than that of the $^{10}$B. This is due to the relatively large microscopic absorption cross section of $^{10}$B in the epithermal range and the high atomic number density of the boron in B$_4$C. For the Gd$_2$O$_3$ particles, the resulting reactivity swing is 3%, which is very similar to that obtained with the B$_4$C particles. The bigger size of the Gd$_2$O$_3$ particles could be advantageous for the manufacturing process of the BPPs.

The B$_4$C particles used in UO$_2$ fuel (radius between 70 and 90 $\mu$m) can also be used to reduce the reactivity swing in PuO$_2$ particles. The reactivity swing at a target $k_{\infty}$ of 1.1 is about 4% for spherical BPPs with radius of 85 $\mu$m and an FVR of 27,500 (corresponding to 1600 BPPs per fuel pebble). The uniform temperature coefficient is comparable to that of the UO$_2$ fuel (-7 to -8 pcm/K). From theory, the burnup behavior of cylindrical BPPs 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 BPPs, 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.
5. **ACKNOWLEDGEMENTS**

The author wishes to acknowledge the European Commission for co-funding this work under project number FIKI-CT-2000-00020 entitled “High Temperature Reactor Physics and Fuel Cycle Studies” (HTR-N). The results in this study have been published before in Refs [3,4,9,10].
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5. SCALE-4.2, 1994, Modular code system for performing standardized computer analyses for licensing evaluations, Oak Ridge National Laboratory, Tennessee.


Table I:
Definition of the burnable poison particles used.

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Table II:
Definition of the fuel used. The UO₂ fuel is very similar to that foreseen in the PBMR, the PuO₂ fuel has been defined within the framework of the HTR-N1 project [11], and can be assumed to be extracted from LWR spent UO₂ fuel.

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Figure 1: Schematic representation of the calculation model for the accurate set of calculations with the BPP divided into ten concentric zones surrounded with a smeared fuel layer. For the 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 time step with updated atomic nuclide densities.
Figure 2. Illustration of the parameters used to characterize the fuel with BPPs. The initial $k_{\infty}$ is the value after saturation of short-lived fission products (in this paper after 10 days of burnup). The maximum irradiation time is achieved when the reference $k_{\infty}$ curve (with no BPP) reaches the value of the initial $k_{\infty}$. In this plot this occurs after 1520 days of burnup. The reactivity swing is the spread of the $k_{\infty}$ between 10 and 1520 Effective Full Power Days (EFPD). Here, 1520 EFPD correspond to a burnup of 57,422 MWd/tU.
Figure 3: The $k_e$ (top left) and the reactivity swing $\Delta \rho$ (top right) as a function of the BPP radius and the fuel volume fraction. The bottom left plot shows the deviation of the initial $k_e$ from the target value (1.1), while the bottom right plot shows the sum of this and the reactivity swing (bottom right). The minimum in the latter plot is observed at a BPP radius of about 75 $\mu$m and a fuel volume ratio of 60,000 at which the reactivity swing is about 2%.
Figure 4: The $k$ (top left) and the reactivity swing $\Delta\rho$ (top right) as a function of the BPP radius and the fuel volume fraction. The bottom left plot shows the deviation of the initial $k$ from the target value 1.1, while the bottom right plot shows the sum of this and the reactivity swing (bottom right). The minimum in the latter plot is observed at a BPP radius between 840 and 880 $\mu$m and a fuel volume ratio of 5,000 at which the reactivity swing is almost 6%. Note the different scales along the $y$ axes.
Figure 5: Macroscopic absorption cross section for the two burnable poison materials. Below 0.2 eV the absorption cross section of the Gd is largest, which also shows up in the cumulative absorption rate per fission neutron (right axis). The latter two curves are for a BPP with radius of 200 µm and a FVR of 17,200 for the Gd₂O₃ particle and 30,000 for the B₄C. The $k_n$ in both cases is the same, which can be derived from the fact that the cumulative absorption in the BPP is the same (0.16 per fission neutron).
Figure 6: The $k_{\text{inf}}$ as a function of irradiation time for the UO$_2$ fuel with a BPP made of Gd$_2$O$_3$. For a BPP with radius of 840 $\mu$m and an FVR of 5000 the reactivity swing is about 3% between 10 and 1520 EFPD. Here, 1520 EFPD correspond to a burnup of 57,422 MWD/tU.
Figure 7: The $k_{\text{inf}}$ as a function of irradiation time for the PuO$_2$ fuel with a BPP made of B$_4$C. For a BPP with radius of 80 µm and an FVR of 27,5000 the reactivity swing is just below 4% between 10 and 620 EFPD. Here, 620 EFPD correspond to a burnup of 620,000 MWD/tPu.
Figure 8: The $k_{\infty}$ (top left) and the reactivity swing $\Delta\rho$ (top right) as a function of the BPP radius and the FVR. The bottom left plot shows the deviation of the initial $k_{\infty}$ from the target value 1.1, while the bottom right plot shows the sum of this and the reactivity swing (bottom right). The minimum in the latter plot is observed at a BPP radius of about 90 $\mu$m and a FVR of 25,000 at which the reactivity swing is less than 6%.
Figure 9: The neutron spectrum in the fuel zone for the both fuels with a B$_4$C particle in the center. Also shown is the fraction of neutrons absorbed in the BPP (right axis).
Figure 10: The capture-to-fission ratio ($\alpha$) of reactor grade plutonium (see Table II) as a function of energy.
Figure 11: Contour plot of $|k_{\text{ref}}-1.05|$ summed to the reactivity swing $\Delta \rho$ as a function of the BPP radius and the FVR for cylindrical BPPs with buckling height of 400 cm.
Figure 12: The $k_{\infty}$ as a function of burnup with the FVR as a parameter for cylindrical BPPs.
Figure 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 FVR for coated BPPs. The radius of the graphite kernel of the BPP is 300 $\mu$m.