CORE DESIGN OF A CARTRIDGE TYPE PEBBLE BED REACTOR

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ABSTRACT

A low-power pebble bed HTGR (60 MWt, 23 MWe) is proposed for the applications of heat and power cogeneration or distributed electricity generation in developing countries. No on-line fuelling or defuelling systems are envisaged, as the pebble bed reactor will be of the cartridge type, refuelled off-line once every three years. Fuel elements with composition as proposed for the PBMR plant, with 8.1% enrichment and 9 g of heavy metal, will be used. Excess reactivity will be controlled by B_4C as burnable poison in the reflector. Optimization of burnable poison distribution will be discussed both for a cylindrical and an annular core. It is shown that in an annular core burnable poison can be distributed exclusively in the inner reflector in such a way that the reactor will be able to operate for three years with an overreactivity margin as low as 5%. The outer reflector can then be reserved for the control rods. The use of a 2D model allowed us to study the axial dependency of the B-10 burnup. By varying the axial distribution of the burnable poison we could also achieve a further overall decrease in reactivity and a slight increase in core lifetime.

INTRODUCTION

Until now, nuclear power has been successful in the market of large-scale electricity generation. Other markets, like heat and power cogeneration or distributed electricity generation in developing countries are still waiting to be penetrated by the uranium based energy source.

For these applications, the power level required per location will be much smaller than for the existing nuclear plants. ACACIA-Indirect (AdvanCed Atomic Cogenerator for Industrial Applications), a 60 MWth, 23 MWe (max.) nuclear plant design with indirect Brayton cycle is proposed [1]. In the literature several pebble bed core types have been proposed [2] with varying levels of simplification of the fuel loading scheme: the MEDUL (MerfachDUrchLauf, multipass scheme), OTTO (once through than out), and the PAP (peu à peu, online fuelling and offline fuel discharge when the core is full) types. For the ACACIA-Indirect reactor we have chosen a pebble bed core of the cartridge type [3]. In this type the core is loaded in the beginning of cycle with fresh pebbles, and then operated for the longest possible residence time without refuelling and fuel shuffling. After this period the whole core is discharged and new pebbles are loaded for the next cycle. The biggest advantage is the reduction of capital and operation and maintenance costs, considering the substantial simplification of the hardware that can be achieved. The main disadvantage is the discharge of pebbles at the end of cycle with a relatively reduced burnup level. To circumvent this problem, one could think of a scenario where the discharged pebbles (or some of them) are reused in a reactor of the MEDUL type.

The core study here described had as main goal the investigation of the parameters needed to obtain an as flat as possible reactivity evolution curve during each fuel cycle. With a flat evolution curve and a sufficiently small excess reactivity the reactor can be controlled with the gas flow and with a minimum need of control rods worth. One of our goals is to keep the excess reactivity to values that

can be compensated with a total control rod worth comparable to values used in the HTR-Module design (~ 5%). The reduction of the use of active control elements can increase the control safety, improve the core power distribution and reduce the power peaking. In this situation the control elements could then be reserved exclusively for the shutdown of the reactor.

One of the requirements for the ACACIA core design is the use of available fuel manufacturing technology, in order to avoid extra costs associated to new development and licensing, and to the creation of a separate production line. The idea is to use the pebble fuel composition as proposed for the PBMR plant, with 8.1% enrichment and 9 g of heavy metal per fuel element.

The technique of using burnable poison in the reflector of a pebble bed reactor has been proposed in a paper by Van Dam [4]. Both the case of burnable poison (BP) homogeneously distributed in-core and the case of BP exclusively placed in the reflector region were discussed. The first solution turns out to be not the most satisfactory one because of the difficulty in finding a BP whose absorption cross section matches the absorption cross section of U-235. Consequently the reactivity surge cannot be reduced substantially. The second solution gave the best results with a considerable flattening of the reactivity curve. Another method suggested in the literature is the use of BP heterogeneously distributed in the fuel elements [5-8]. An appropriate flattening of the reactivity curve can be achieved by careful dimensioning of the burnable particles or rods. However, this solution demands development of fuel elements specific to each situation, with a consequent increase in costs. We have chosen in our study to reduce the excess reactivity by using B_4C as burnable poison placed in the reflector region. Instead of a 1-D diffusion approach as followed by Van Dam, we used a 2-D 16-neutrongroups approximation. Taking the z-direction explicitly in our model we could also (a) study the influence of the top and bottom reflectors on the burnup of the BP, (b) derive the axial heterogeneity of the burnup process, and (c) study the effect of a heterogeneous distribution of BP as a possible tool for tuning the shape of the reactivity curve.

A parameter study regarding core geometry, poison location, distribution and concentration is discussed in the next sections.

GENERAL CORE CHARACTERISTICS

In figure 1 the sketch of the ACACIA model can be seen, implemented in the modular code WIMS7B using the module SNAP. This 3D multi-group diffusion code solves the diffusion equations using finite difference methods in several geometries. A (r,z) geometry has been chosen in our case. Two separate models have been considered:

(1) a cylindrical core with radius 1.45 m and height 6.0 m (average core power density 1.4 MW/m^3), and
(2) an annular core with the same outer radius and with an inner reflector of radius 0.65 m placed in the centre of the core, and elongated to 7.5 m height to maintain the same average power density.

Both cores have a 0.5 m void on top of the bed till the top reflector, and are surrounded by a graphite outer reflector of 1.0 m thickness and an effective top and bottom reflector of 2.0 m, based on the earlier direct cycle ACACIA design with PAP fuelling [9]. In figure 1 only the annular core is shown. In the bottom, inner and outer reflectors 9 zones (3 axial and 3 radial zones) have been defined which burnable boron could be added to. These zones are indicated by the dashed lines . The core region has

also been divided into 9 zones, so that the burnup of each fuel zone could be followed separately. Although nine zones are far from ideal, it is judged suitable enough for the parameter study we are aiming at this stage.

A total of 55×247 meshes for the annular core (55×217 meshes for the cylindrical case) have been used with a mesh spacing of 5.0 cm. For the void regions effective diffusion coefficients have been calculated using the Behrens method [10].

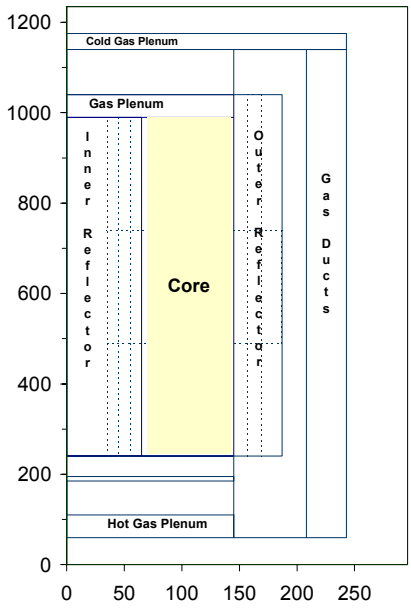

Fig 1. Sketch of the ACACIA model with annular core.

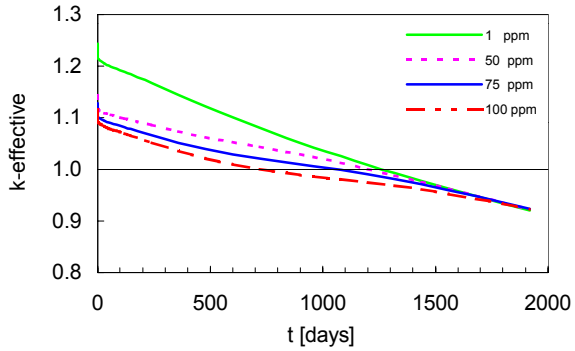

Fig 2. Reactivity as function of the number of full power days for different boron concentrations in the outer reflector of a cylindrical core.

The 16-neutrongroups nuclear data used in SNAP have been generated by condensation of 69-groups cell calculations, based on JEF2.2 data. The cell calculation is performed separately for each of the 9 fuel zones, where the double heterogeneity of the pebbles has been taken into account. Since WIMS cannot handle a spherical geometry containing grains (the TRISO coated particles) an equivalent cylindrical cell containing grains has been utilised as an approximation. In this approximation, the spherical pebble is represented by an infinite cylinder defined such that the mean chord length of the fuel zone is conserved. The outer radius of the other cylindrical shells is calculated based on the volume-ratio conservation. This equivalent cylindrical model is used by the WPROCOL module to calculate the collision probabilities applied by the WPIP module to determine the flux distribution. The resonance calculations for ^{238}U, ^{235}U, and ^{239}Pu are performed using the subgroup method. The other resonance absorbers are treated using the equivalence theory in slab geometry scaled to the chord length in the grains.

Following the solution of the diffusion equation, the calculation enters the burnup phase. The burnup calculation is performed by the module WBRNUP that integrates the depletion equations over a burnup step for each burnable material (each fuel zone and reflector zone containing BP). Before entering the burnup module the fuel fine structure (flux at each shell defined in the cell calculation) is reconstructed using the WUNSMEAR module. After performing the depletion calculation the new

material compositions are given back to the modules which perform the cell calculations, and a new calculation cycle is entered. Table I summarises the most important parameters used in our model.

Table I – General parameters used for the ACACIA-INDIRECT core model

Fuel enrichment	8.1 %
Heavy metal per fuel element	9 g
Number of fuel elements	213500
Packing fraction	0.61
Average discharge burnup	39 MW/kgHM
Temperature	900 °C
Average power density	1.4 MW/m^3
Cartridge lifetime	3 years
Core outer radius	1.45 m
Core height	6.0/7.5 (cyl./annular)
Inner reflector radius	0.65 m (annular core)
Thickness of borated reflector layer	0.42 m (outer reflector) 0.30 m (inner reflector) 0.45 m (bottom reflector)

CYLINDRICAL CORE

The results for the cylindrical core can be seen in fig. 2. The time evolution of the reactivity is shown for different initial boron concentrations (1, 50, 75 and 100 ppm of natural boron) as a function of the number of full power days. The 1-ppm case is considered as the reference case with virtually no burnable poison. A maximum cycle time of about 1300 days can be reached with this configuration. This is also the limit for the cases where BP is applied, unless the BP is distributed in such a way that the burnable profile is strongly modified to achieve a reactivity gain, as will be seen for an annular core. The initial boron concentration is the same for all 9 zones of the outer reflector.

From the reactivity curves it can be seen that for a cylindrical core the excess reactivity can be decreased but will keep a too steep descending tendency during the cartridge lifetime, while reducing the lifetime too much. This is specially the case for boron concentrations above 50 ppm. Additionally, the initial overreactivity to be compensated by control rods remains around 10%, which is about twice the control rod worth of the HTR-Module. Another disadvantage of poison in the outer reflector is the partial suppression of the control rod worth in the reflector because of the lowered thermal flux importance caused by the presence of the poison in this region.

Figure 3 shows the time evolution of the boron concentration in the 9 reflector. One notices that the depletion rate is larger for the radial layer adjacent to the core (layer #1), followed by the other two radial layers deeper into the reflector. The analysis of the axial dependency of the boron depletion shows a different behaviour: the central layer has the largest depletion rate followed by the bottom layer (adjacent to the bottom reflector) and then by the top layer. This behaviour is expected considering that the flux distribution shows a peak at the centre of the core, and the distribution is

slightly asymmetric in the axial direction. The flux is higher at the bottom half of the core because of the presence of the bottom reflector directly adjacent to the core. In particular for the top axial layer there is an incomplete depletion of boron even for a concentration as low as 50 ppm.

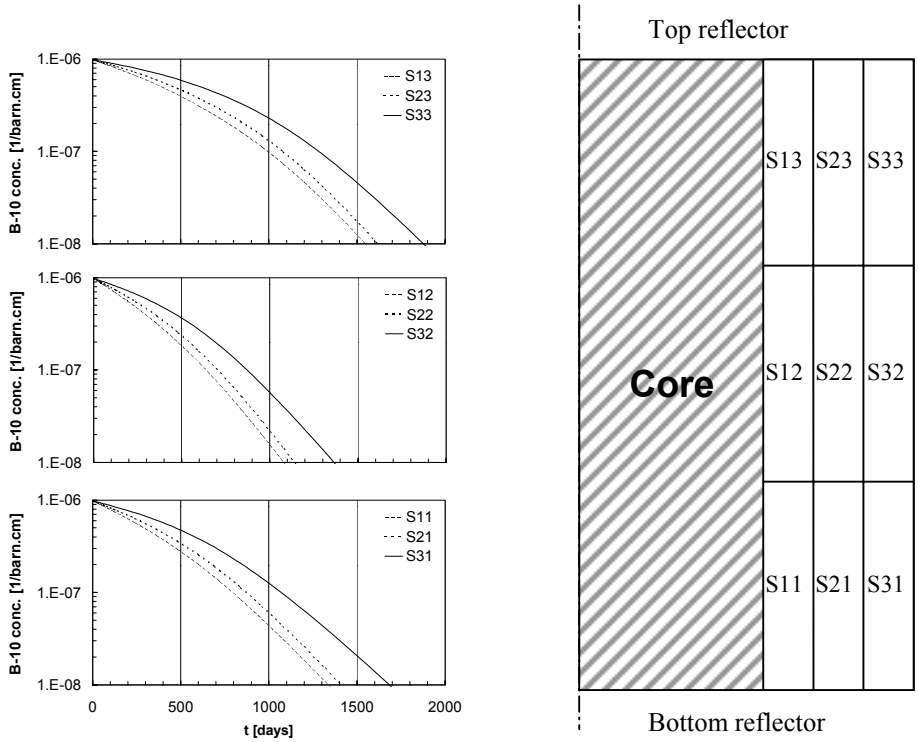

Fig 3. Depletion curves of B-10 in all nine borated zones in the outer reflector of a cylindrical core, for an initial boron concentration of 50 ppm.

ANNULAR CORE

The reactivity curve for the annular core has been compared with that for the cylindrical core without poisoning of the reflector, as shown in fig. 4. A cylindrical core with the same average power density and outer radius has a higher reactivity than an annular core, all over the cartridge lifetime. This can be explained partially by the increase of the outer surface through which leakage can take place (≈ 15%), whereas the volume of the core has been kept constant. On one side the inner reflector has a positive effect as far as the burnup profile is concerned. On the other side it will also contribute to an increase in leakage because a certain percentage will be scattered out of the core through the top and bottom surfaces of the inner reflector. With the introduction of the inner reflector the power distribution is pushed towards the outer surface with a consequent increase of the net leakage. The reduction in cartridge lifetime of about 80 days can be ascribed to the change in the burnup profile under the presence of the inner reflector. As we will discuss in the following paragraphs, using BP in the inner reflector can partially compensate this negative effect.
For the annular core, the effect of poisoning the bottom, inner and outer reflector has been examined separately.

Boron in the bottom reflector did not give a significant effect because of the small absorbing area compared to the reflector surface. This did not show as a tool to tailor the reactivity curve.

The influence on the reactivity by boron placed in the outer or inner reflector has been compared by performing calculations with an initial concentration of 50 ppm boron in the borated regions of the inner, outer, or of both reflectors. The results are given in fig 5. The reference case for 1 ppm of natural boron impurity has been given as well. The influence of the inner reflector is stronger particularly in the beginning of the lifetime; this is due to the "flux trapping" in the inner core resulting in a high thermal flux importance but also in a faster depletion of the boron in the region.

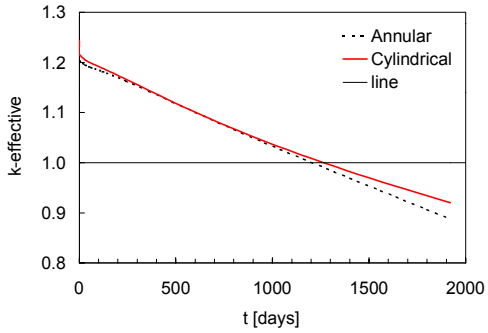

Fig 4. Comparison of reactivity for an annular and cylindrical core with the same average power density, without boron in the reflector

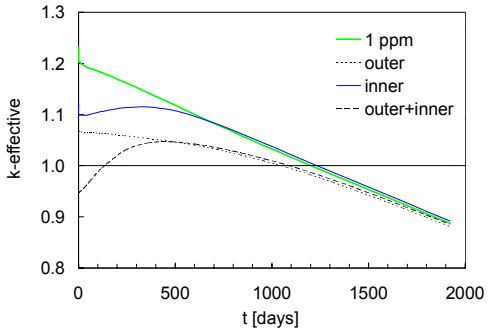

Fig 5. Reactivity effect for 50 ppm boron in the different reflector regions.

Again we see here that the boron in the outer reflector affects the reactivity curve over the whole lifetime, which indicates an incomplete depletion of the boron and consequently causes a reduction of the core lifetime. The depletion takes place in a similar manner as that pictured for the cylindrical core in fig. 3. For the case of the borated inner reflector the layer of boron is almost completely depleted in a period of about 800 days. In fig. 6 the time evolution of the ^{10}B concentration is shown for each of the nine zones of the inner reflector for an initial concentration of 50 ppm. Remarkable is the fact that the inner radial layer (the farthest from the core) has the highest depletion rate, contrary to that observed for a borated outer reflector. This can be explained by the flux trapping, responsible for the peaking of the thermal flux in the centre of the inner reflector (see fig. 7). For an initial concentration higher than 50 ppm this peaking disappears, and the thermal flux shows a positive slope in the inner reflector at the beginning of the cycle. The depletion curves then have a behaviour as displayed in fig. 3 for a cylindrical core. Later in the cycle the thermal flux peaks again in the centre and the situation inverts and the radial layer farthest from the core starts depleting the fastest (similar to the curves in fig. 6).

The reactivity curve for the case where both inner and outer reflectors are borated shows a behaviour, which resembles the summation of the separate effect of both reflectors. After about 500 days the two reactivity curves (outer reflector exclusively, and inner and outer combined) almost superimpose. The slight gain in reactivity is achieved when burnable poison is used in the inner reflector, with a consequent increase in the cartridge lifetime. This can be ascribed to a change in burnup profile.

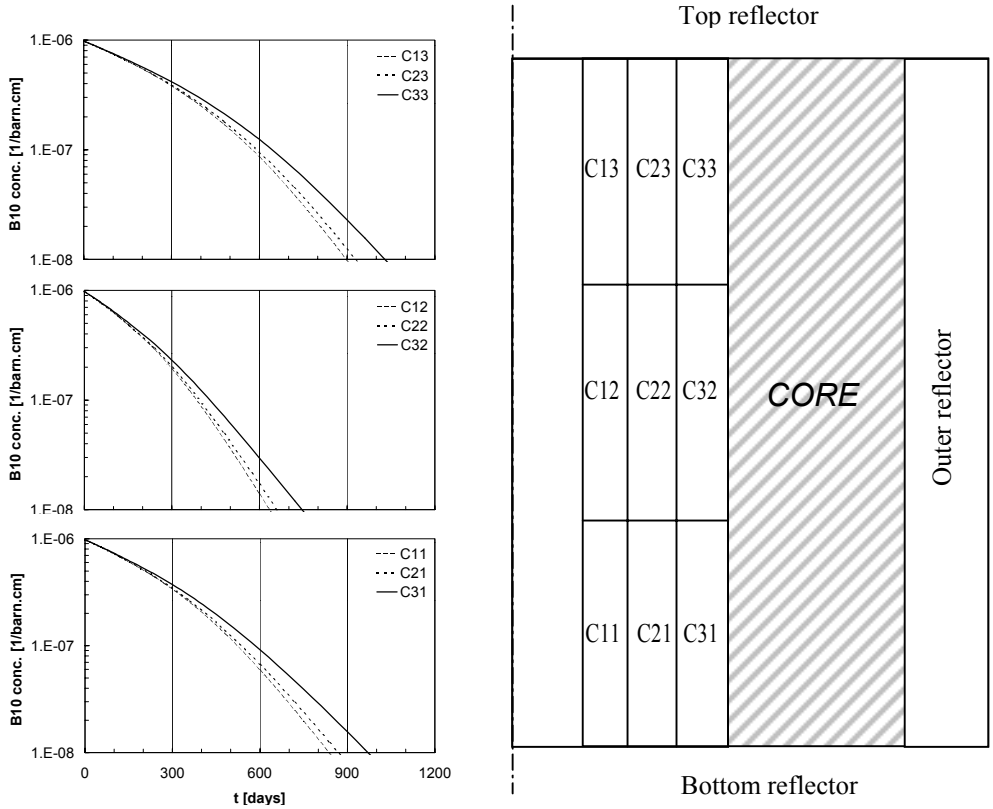

Fig 6. Depletion curves of B-10 in all nine borated zones in the inner reflector of an annular core, with an initial boron concentration of 50 ppm

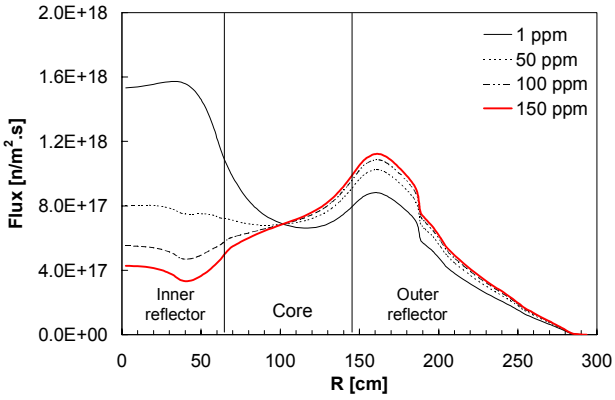

Fig 7. Thermal flux profile through the centre of an annular core for several initial B-10 concentrations in the inner reflector, in the beginning of cycle.

Considering the aspects described above, the use of boron exclusively in the inner reflector gives us good prospects to tailor the reactivity curve. The required effect of reflector poisoning was found for the annular core with inner reflector poisoning only. As shown in fig 8 an increasing boron content leads to a flattening of the reactivity curve, until there is so much boron that the reactivity increase due to the boron depletion cannot keep pace with the decrease by the fuel depletion. For a boron concentration of about 150 ppm the reactivity curve is almost flat until about 1000 full power days. The overreactivity to be compensated by control rods has been decreased to maximally 5%. It can also be seen that the period where k_{eff} >1 (i.e. the cartridge lifetime) increases as well with the boron concentration.

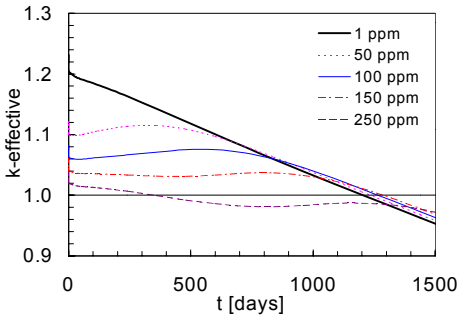

Fig 8. Reactivity as function of boron concentration in the inner reflector.

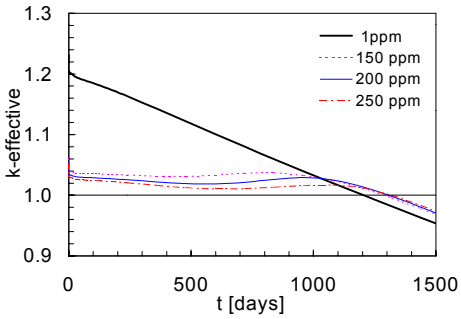

Fig 9. Reactivity as function of different boron contents in the middle section of the inner reflector.

The possibility of axial zoning of the burnable poison in the inner reflector has been investigated as well, see fig. 9. The two outer axial zones were given a concentration of 150 ppm whereas the middle zone was given up to 250 ppm. A further overall lowering of the reactivity curve can be observed. We notice as well a further gain in reactivity and core lifetime for an increasing boron concentration in the middle zone. This effect can be explained considering the time evolution of the power density profile. Figure 10 shows the power density profile for five time steps during the cartridge lifetime, for an initial boron concentration of 150 ppm in the outer axial zones of the inner reflector, and 250 ppm in the middle zone. The pictures display the region of the core exclusively (radial interval 65-145 cm). At the beginning of the cycle the power peak is pushed towards the outer reflector, because of the poisoning of the inner reflector. At that part of the core the fuel burn up rate is higher. Although the BP is distributed symmetrically the power density is slightly higher at the lower part of the core. This is because of the presence of the bottom reflector placed directly adjacent to the core. As the time progresses the BP depletes and the power peak slowly moves across the core towards the inner reflector, and at first primarily in regions direct adjacent to the top and bottom axial zones of the inner reflector. At this time step (t=720 days) even a hollow profile at the core centre is created, because of the higher initial boron concentration in the middle axial layer of the reflector. Further on in the cycle, as the BP in the middle zone becomes depleted, also the power peak becomes more regularly distributed along the inner reflector surface, with a slight asymmetry. At the end of the cycle the power density is slightly higher at the top half of the core, contrary to the situation at the beginning of the cycle. The burnup behaviour described here can explain the reactivity gain remarked in the cases where BP is used in the inner reflector. Contrary to the case without BP, the power peak is moving virtually all over the core that makes the fuel to be burnt more efficiently, with a consequent increase in cartridge lifetime.

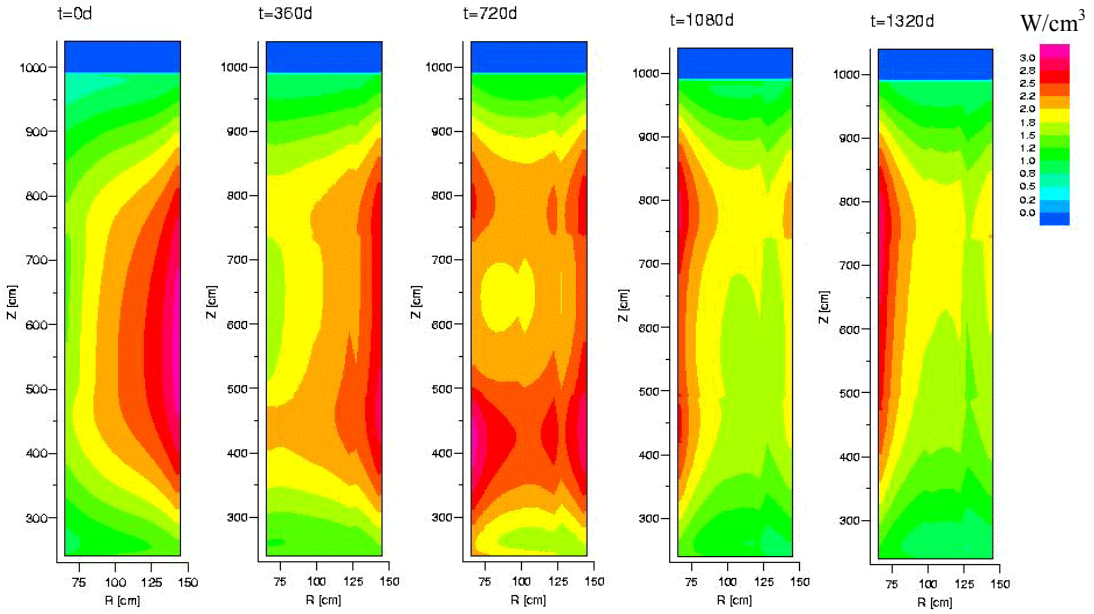

Fig 10. Evolution of power density profile for an annular core with initial boron concentration of 150 ppm (outer axial zones) and 250 ppm (middle zone) in the inner reflector.

The results presented so far show that there are tools to obtain an almost flat reactivity curve with a core lifetime of about 3 years. At this stage flatness is more important than the absolute difference from k_{eff} =1 because this can be solved by geometrical means.

CONCLUSION AND PROSPECTS

A parameter study for the design of a pebble bed core of the cartridge type has been performed. The results show that a core lifetime of over three years can be achieved. We showed that there are tools to obtain an almost flat reactivity curve and an excess reactivity as low as 5%, using BP exclusively in the reflector.
Core designs with both cylindrical and annular shapes have been investigated. The cylindrical core design does not give good prospects. The excess reactivity cannot be reduced substantially while at the same time maintaining the cartridge lifetime envisaged. Only a partial depletion of the boron layer during the core lifetime is observed, even for an initial boron concentration as low as 50 ppm. Moreover, the BP placed in the outer reflector would partially suppress the worth of the control elements positioned in the reflector. This option has been dropped.

The use of an annular core offers much better prospects. The reactivity worth of the inner, outer and bottom reflector has been studied. Poisoning of the bottom reflector does not give any significant reactivity effect, whereas the reactivity worth of BP in the outer reflector is comparable to that observed for a cylindrical core. On the other side, poisoning of the inner reflector proved to be a suitable tool to tailor the reactivity curve. The boron layer is almost completely depleted during the cycle and a reasonably flat reactivity curve can be obtained with a sufficiently low excess reactivity. Another interesting effect noticed is a slight gain in reactivity at the end of life for increasing boron concentration. This translates into a slight increase in core lifetime. Also shown is that an axial-

dependent distribution of BP in the inner reflector can also be used for fine-tuning the reactivity curve. A further overall decrease in reactivity and increase in core lifetime can be achieved with an increasing boron concentration in the middle axial zone of the inner reflector. The reactivity gain observed for the annular core design can be explained by a tailoring of the power density distribution, which allows for a more efficient fuel burnup.

So far no thermal-hydraulic feedback has been included in the calculations. In the continuation of our study, nuclear data will be generated with boron concentrations within the bandwidth obtained with the present study. These nuclear data will be used in the full 3-D reactor code PANTHERMIX with thermal-hydraulic feedback for the calculation of neutron fluence, power and temperature fields. Transient analysis will also be carried out for the core and the entire plant system.

REFERENCES

1. D.F. da Cruz, J.B.M. de Haas, and A.I. van Heek, "ACACIA-Indirect: A Small Scale Nuclear Power Plant for New Markets", *1st International Topical Meeting on High Temperature Reactor Technology*, Petten, The Netherlands, April 22-24, pp. 185-189 (2002).
2. E. Teuchert, H. Gerwin and K.A. Haas, "Simplification of the Pebble Bed High Temperature Reactor", *International Specialist's Meeting on Potential of Small Nuclear Reactors for Clean and Safe Energy Sources*, Tokyo, October 23-25, (1991).
3. H. Sommers and B. Ribbat, "GHR 10 MW: The Technical Concept of the Gas Cooled Heating Reactor", *Nuclear Engineering and Design*, **109**, pp. 123-128 (1988)
4. H. van Dam, "Long-term Control of Excess Reactivity by Burnable Poison in Reflector Regions", *Annals of Nuclear Energy*, **27**, pp. 63-69 (2000).
5. K. Yamashita, "Optimization Method of Rod-Type Burnable Poisons for Nuclear Designs of HTGRs", *Journal of Nuclear Science and Technology*, **31**, pp. 979-985 (1994).
6. J.L. Kloosterman, H. van Dam, and T.H.J.J. van der Hagen, "Design of Spherical and Hollow Burnable Particles for UO_2 Fuels in High Temperature Reactors", *1st International Topical Meeting on High Temperature Reactor Technology*, Petten, The Netherlands, April 22-24, pp. 75-79 (2002).
7. R.F. Turner, A.M. Baxter, O.M. Stansfield, and R.E. Vollman, "Annular Core for the Modular High-Temperature Gas-Cooled Reactor (MHTGR)", *Nuclear Engineering and Design*, **109**, pp. 227-231 (1988).
8. A.I. Kiryushin, *et al.*, "Project of the GT-MHR High-Temperature Helium Reactor with Helium Turbine", *Nuclear Engineering and Design*, **173**, pp. 119-129 (1997).
9. E.C. Verkerk, "Dynamics of the Pebble-Bed Nuclear Reactor in the Direct Brayton Cycle", PhD Thesis, Delft University of Technology, 2000.
10. R.V. Meghreblian and D.K. Holmes, *Reactor Analysis*, McGraw-Hill Book Company, New York (1960).