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The Pebble Bed Modular Reactor Layout and Neutronics Design of the Equilibrium Cycle

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The Pebble Bed Modular Reactor (PBMR) is a high-temperature helium-cooled, graphite moderated pebble bed reactor with a multi-pass fuelling scheme. The design, that displays the characteristics of Generation IV reactors, has reached a high level of maturity. Excess reactivity is limited by continuous refueling while adequate passive heat removal ensures an inherent safe design with no event with significant fission product release being possible.

The core neutronic design for the 400 MWth PBMR is performed by the VSOP99 code system. The design is for an annular core with an outer diameter of 3.7 m and an inner diameter of 2 m shaped by the fixed central reflector. The effective cylindrical core height is 11 m. For the equilibrium core VSOP results show that the fuel sphere powers (maximum 2.7 kW) and operational temperatures (<1100 ˚C) fulfil the design criteria. Adequate reactivity control and long-term cold shutdown are provided by two separate and diverse systems while the overall negative reactivity temperature coefficient is illustrated over the total operational range.

KEYWORDS: HTGR, PBMR, pebble bed reactor, VSOP, core neutronics

1. Introduction

The Pebble Bed Modular Reactor (PBMR) concept can be described as a high-temperature helium-cooled, graphite moderated pebble bed reactor. Coupled to the reactor is a power conversion unit, which comprises of a turbo-generator unit based upon a recuperated, direct, closed-circuit helium cycle. The design is for 400 MWth. In the multi-pass fuel management scheme the fuel pebbles are re-circulated until it reach the target burn-up. On average, fuel spheres will pass six times through the reactor before being discharged to spent-fuel tanks.

The paper summarizes the PBMR core neutronic design as characterized by the steady-state equilibrium cycle. A description of the methods and models employed as well as some detail on the geometry, dimensions and relevant information are provided. A short description of the VSOP [1] code system, the models employed and approximations required are given in Section 3. Results are shown in Section 4 and include power, flux, temperature and burn-up distributions, core behaviour in operational power changes (100%-40%-100% power load follow), control system reactivity and graphite structure fast neutron doses. All of these results show a positive outcome as measured against the design criteria.

Note that no event or transient analysis or safety studies are included in the paper as it falls outside the scope of the steady-state core neutronics design. The equilibrium core as discussed here does, however, represent the starting condition of most events to be analysed insofar the starting temperatures, core structure and fuel sphere fluences, power and decay heat distribution and available excess reactivity is concerned.

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2. The PBMR Design Description

2.1 Characteristics and Design Criteria

The following are the most important characteristics of the PBMR:

- a continuous power rating of 400 MWth,
- an annular core with an outer diameter of 3.7 m and a 'fixed central reflector' with an outer diameter of 2 m,
- an effective cylindrical core height of 11 m,
- a graphite side reflector of ~90 cm,
- the Reactivity Control System (RCS) consisting of 24 partial length control rod positions in the side reflector, with 12 upper and 12 lower rods, when fully inserted. The rods have an effective length (neutron absorbing material) of 6.5 m,
- the Reserve Shutdown System (RSS) consisting of eight Small Absorber Sphere (SAS) systems positioned in the fixed central reflector and filled with 1 cm diameter absorber spheres containing B_4C when required,
- three fuel loading positions and three fuel unloading tubes, positioned equidistant in the centre of the fuel annulus.

In addition to the features identified above the following design criteria were adhered to:

- the maximum fuel temperature under normal operating conditions may not exceed 1 130 ºC,
- a load follow capability of 100% - 40% - 100% power which, from the core neutronics perspective, defines the excess reactivity required during full power operation to overcome the xenon build-up,
- a level for the maximum power production per pebble was set at 4.5 kW (although much higher values should be achievable),
- at any given time in the operating life of the plant, the reactor must be able to shut down, using the RCS, followed by the RSS,
- at any given time in the operating life of the plant, it must be shown that the reactor can be brought to a cold shutdown condition (100 °C) using the RSS only,
- for a postulated event with loss of coolant, the maximum nominal fuel temperature is to remain below a limit so that the total additional radioactivity released from the core to the environment, will not lead to a public dose that exceeds the limits laid down by the regulator.

2.2 Reactivity Control and Shutdown System

Two reactivity control systems are provided to compensate for excess reactivity, to ensure an adequate shutdown margin, and to control changes in reactivity that occur during operation. The first system, called the RCS, consists of 24 active control elements divided into two groups of 12 (with every other control rod belonging to a group). When fully inserted, Group 1 is positioned in the upper half of the core, while Group 2 is positioned in the lower half, with the two groups of control elements overlapping in the centre. The RCS are positioned in borings in the side reflector, 13 cm in diameter (11 cm with a sleeve in place) and with the boring centre points positioned at a distance of 1.9715 m from the core centre. The RCS control rods consist of a 0.8 cm thick B_4C annulus with an outer diameter of 10.0 cm, a density is 2.2 g/cm^3, and with an inner and outer incoloy structure.

The second system, the RSS, consists of eight reserve shutdown units making use of Small Absorber Spheres (SAS). The RSS are positioned in borings in the inner reflector that are, as in the case of the RCS, 13 cm in diameter (11 cm with a sleeve in place), and with the boring centre points positioned at a distance of 0.863 m from the core centre. The RSS borings can be filled with SAS with a diameter of 1 cm, containing 10% B_4C, and with an overall density of 1.7 g/cm^3. A packing density of 0.61 was used for the SAS.

The two systems are totally diverse in design with no common mode failures. This contributes to the defence in depth of the design.

2.3 Pebble Flow Characteristics

Information on how pebbles will flow in a pebble bed is available from the German experimental and reactor program [2] and for the PBMR annular core design from flow simulations performed by the PFC^{3D} code. It was found that the pebble flow is essentially vertical with pebbles moving only a few ball diameters in the horizontal or azimuthal direction. The bottom cones introduce non-vertical flow when directing the fuel spheres to the three unloading tubes. This effect is only noticed in the lowermost part of the pebble-bed close to the cones.

The major influence on flow speed and therefore core residence time is fuel spheres touching the side (inner or outer) reflectors. Typically fuel spheres within 1½ sphere diameter of the reflector will touch the side reflector during its path through the reactor and can therefore be delayed significantly relative to the other fuel spheres. Within the restrictions of the 2-D VSOP representation the different flow speeds and flow lines are simulated in the VSOP model. Since the multi-pass fuel reload philosophy assumes a statistical distribution of fuel spheres of different burn-up (and pass through the core) in the same core volume, the core neutronics results are not too sensitive to variations in the flow paths or speeds. This can be expected since large variations in the predicted flow lines are only expected in the bottom of the reactor (close to the unloading tubes), neutronically an area of low importance.

2.4 Fuel Sphere Specification

Details of the fuel design are summarized in Table 1. The uranium loading is 9 g per fuel-sphere with the U^{235} enrichment at 9.6 wt%. The inner 5 cm of the fuel sphere contains about 15 000 coated particles within a graphite matrix and surrounded by an outer graphite fuel free zone. Each coated particle acts as a fission product barrier.

Table 1 Fuel sphere design parameters

Fuel spheres:	Units	Values
Pebble radius	cm	3.0
Thickness of fuel free zone	cm	0.5
Density of graphite in matrix/fuel free zone	g/cm^3	1.74
U-235 enrichment of uranium	wt%	9.6
Coated particles:		
Kernel diameter	µm	500
Kernel density	g/cm^3	10.4
Coating material		C / C / SiC / C
Layer thickness	µm	95 / 40 / 35 / 40
Layer densities	g/cm^3	1.05 / 1.90 / 3.18 / 1.90

3. Calculational Methods and Models

3.1 The VSOP99 Code System

V.S.O.P. (99) is a computer code system for the comprehensive numerical simulation of the physics of thermal reactors. It entails the setup of the reactor and of the fuel element, processing of cross sections, neutron spectrum evaluation, neutron diffusion calculation in two or three dimensions, fuel burn-up, fuel shuffling, reactor control, thermal hydraulics and fuel cycle costs calculations. The thermal hydraulics part (steady state and time-dependent) is restricted to HTRs and to two spatial dimensions. The code can simulate the reactor operation from the initial core towards the equilibrium core. The code system contains some important features required for pebble bed reactor analysis such as treatment of double heterogeneous fuel, the different fuelling mode simulations, and 2-D thermal hydraulic capabilities including the pebble-bed thermal hydraulic correlations.

3.2 The VSOP99 Core Model

The PBMR is represented as a cylindrical core in a 2-D (r-z) or 3-D (ø-r-z) model. The fixed central reflector restricts the fuel pebbles to an annulus of 85 cm (see Fig. 1) with the control and shutdown systems respectively positioned in the side and central reflector.

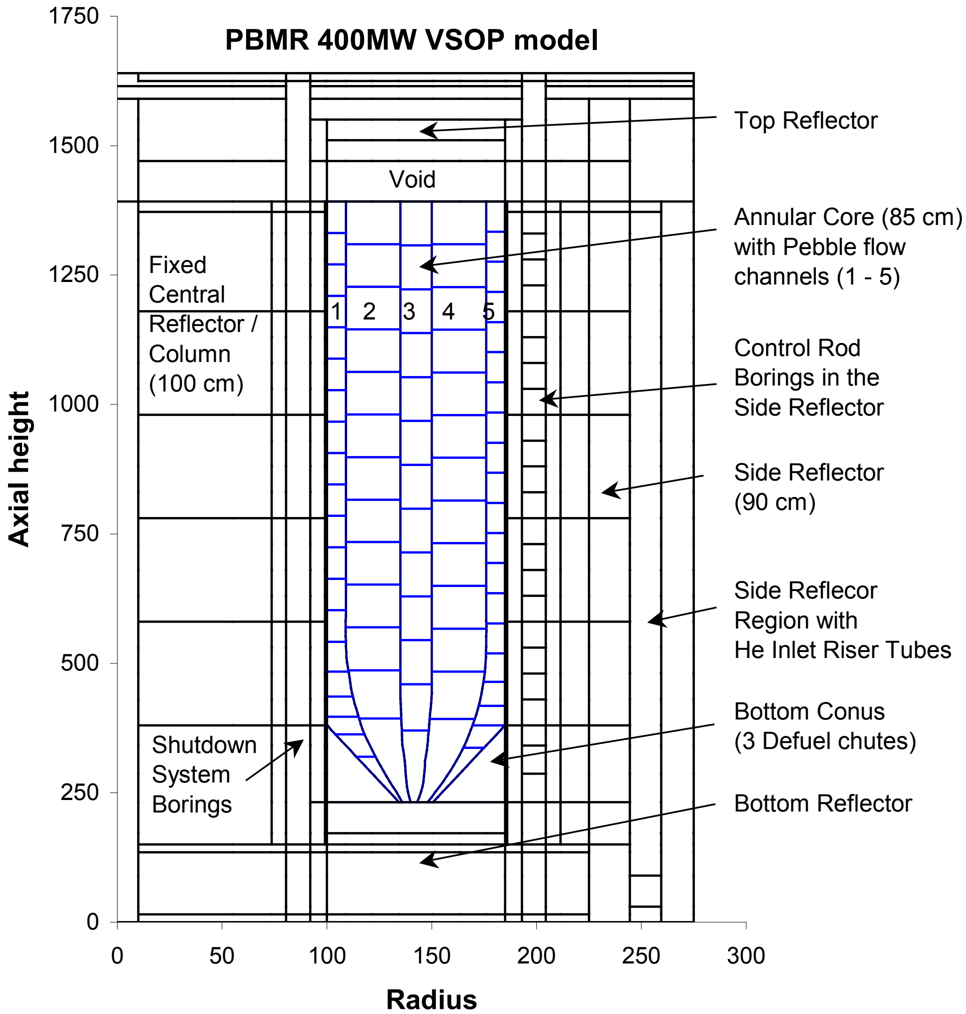

Fig. 1 VSOP core geometrical model (R-Z cut) showing five flow channels in the annular core, the reflector regions and positions of reactivity control systems.

The equilibrium cycle is calculated by performing quasi-static cycle depletion calculations while simulating the fuel management, control rod positions and temperatures. The pebble flow is modelled by the flow channels defining flow paths (channel boundaries) and flow speeds (number of axial meshes). This step-wise calculational process is continued until equilibrium is reached, i.e. the results for each burn-up period is reproduced. This is normally found after 300 cycles, i.e. fuel shuffling steps (depending on starting conditions, model and core residence time). The cycle achieved at this stage is accordingly termed the 'equilibrium cycle', and is characteristic of the largest part of the reactor operational conditions.

The helium (coolant) flows upward through the riser tubes in the side reflector and enter the cavity above the pebble-bed. Flow is then downward through the pebble-bed exiting through the bottom reflector. Some flow is directed to cool the control rods and the central reflector. The flow distributions and estimates of leakage through the graphite structures are taken from detailed CFD analysis.

3.3 Control Rods Model

Three-dimensional VSOP calculations making use of the Method of Equivalent Cross-sections (MECS) [3] are utilized to calculate the Reactivity Control and Shutdown System (RCSS) reactivity worths. From the 3-D calculations, the RCS equilibrium position, where the reactivity of the RCS is capable of overcoming the 100%-40%-100% power load follow, was determined to be at 200 cm inserted (from the bottom of the top reflector). To effect the same reactivity worth for the RCS extracted from the equilibrium position in the two-dimensional VSOP calculations, a ^{10}B concentration of about 1 x 10^{-4} g/cm^3, mixed with the graphite, was defined within a grey curtain with a thickness of 11.5 cm positioned 7.95 cm into the side reflector.

4. Results

4.1 Equilibrium core

All the results presented in this section are for the equilibrium cycle and with the control rods positioned at its equilibrium position. In Fig. 2a the relative axial power profiles are shown for the five radial regions or flow channels. The value shown is the average of the six "batches" that occupy the volume where a batch is defined as the fuel spheres that has seen the same number of passes through the core, i.e. Pass 1 is fresh fuel that pass through the reactor the first time, Pass 2 for the second time, etc. Channel 1, located closest to the fixed central reflector experience the largest power peaking at a position of about three metres below the upper surface of the pebble-bed. The corresponding maximum values for the other radial positions in the core are at a similar axial position but lower in value. The figure shows a volumetric power peaking factor of about 2.29 (associated to Channel 1).

When the burn-up of the different fuel spheres or batches occupying a volume are taken into account the relative peaking between the fuel spheres powers within the volume is between 1.30 and 1.36. To illustrate this consider Fig. 2b that show the batch relative powers for Channel 1. The average value shown is the volume averaged of Channel 1 as given in Fig. 2a. The other six profiles represent the detailed power distributions of the six batches or fuel spheres of different burn-up that occupy each volume within the channel. It is clear that the freshest fuel (Pass 1) delivers the highest power and that the power delivered decreases with burnup (number of passes) as expected. From Fig. 2b the overall peaking factor of just below 3.1 can be seen. In absolute terms this imply a maximum fuel sphere power of 2.72 kW per fuel sphere. This is well below the design criteria of 4.5 kW and is only experienced by a small fraction of relative fresh fuel and only for a short time of its lifetime in the core.

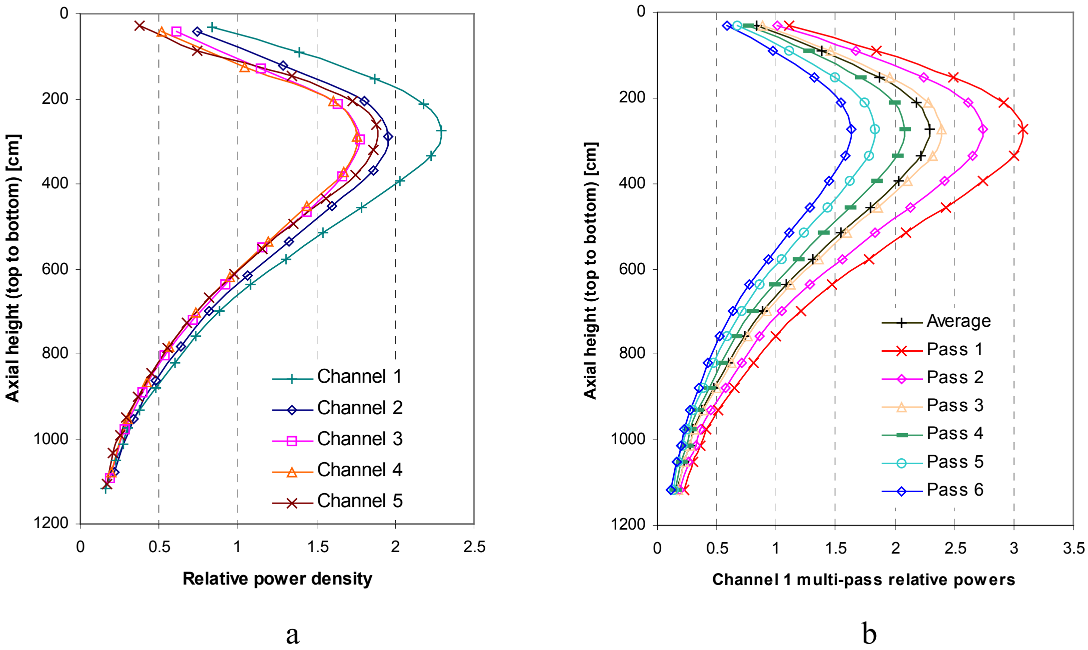

Fig. 2 (a) Volume averaged relative axial power profile in the radial flow channels, and (b) detailed power distribution of multi-pass fuel batches for channel 1.

Fig. 3 shows the burn-up distribution of all the batches within the equilibrium core. Fresh fuel is introduced into the five calculational channels and achieves different burn-up depending on the power delivered and transit time as it move through the core. The VSOP fuel management model takes an average from the 1st pass fuel that exits the core and re-introduces it to the top of the pebble-bed as 2nd pass fuel.

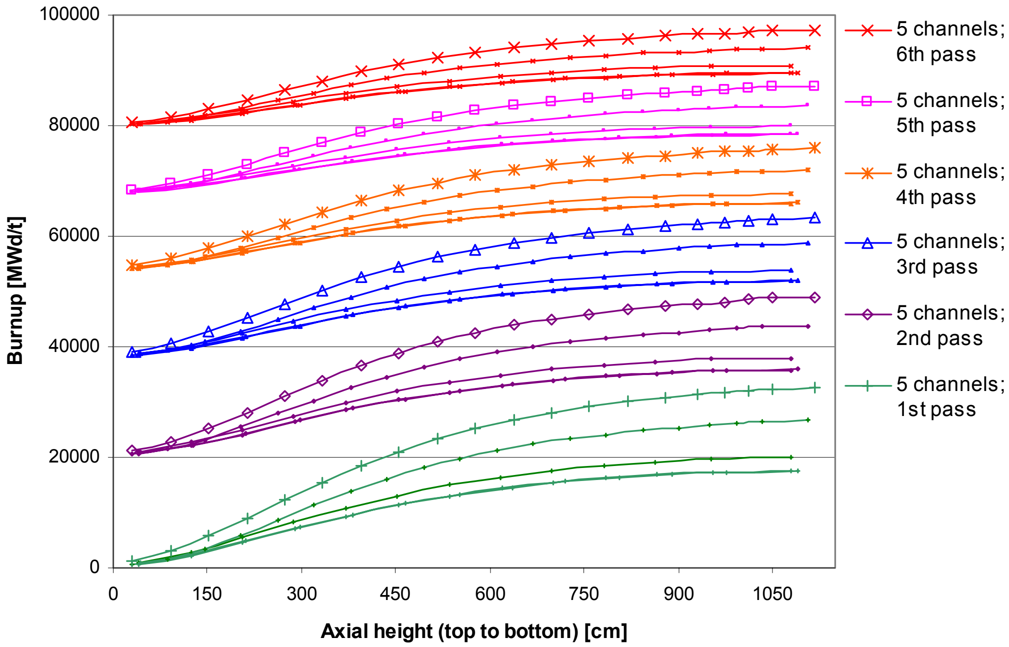

Fig. 3 Accumulative burn-up of the fuel in five radial channels during six passes

The same averaging is done for the 2nd pass fuel to create the starting burn-up for 3rd pass fuel and so on. This explains why the starting burn-up of each of the passes is the same for the five flow channels. The approach assumes an equal distribution of different pass fuel spheres in each channel volume. For a reactor containing over 450 000 fuel spheres and with fairly large volumes, such a statistical representation should be acceptable.

The average discharge burn-up can now be determined from the discharge burn-up values of the five channels after the 6th pass, about 90 800 MWd/t. In practice a range of discharge burn-up values will be achieved since the burn-up of a fuel sphere can only be measured once it is unloaded. To achieve the average discharge burn-up, and to maintain a critical core, some fuel spheres with lower than the target burn-up will also be unloaded while some fuel spheres may achieve a considerable larger burn-up. This must of course be taken into account as part of the fuel qualification program.

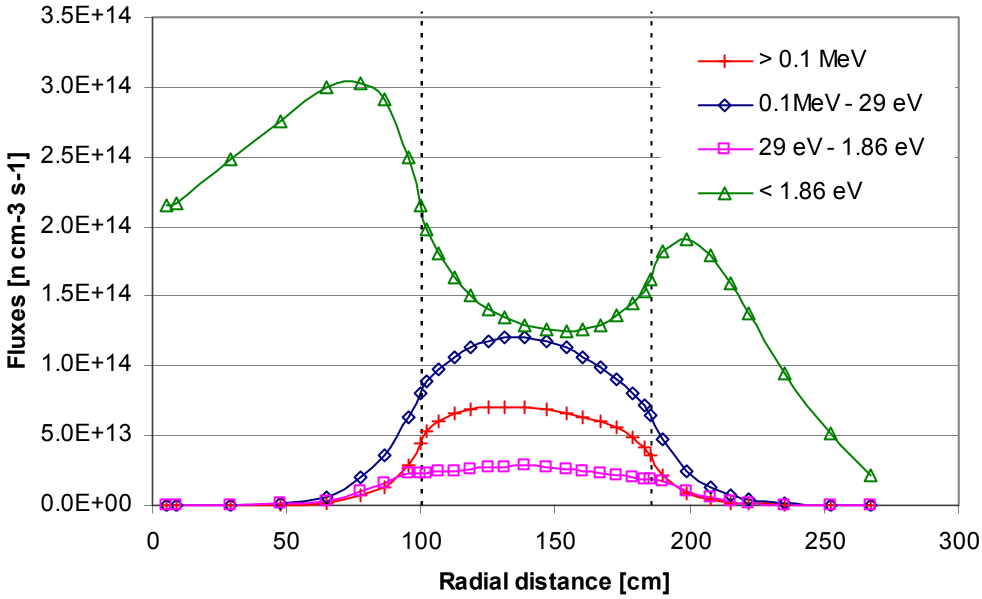

Fig. 4 Thermal and fast flux distribution in the 400 MWt design

Fig. 4 shows a radial flux profile for the equilibrium core at the peak axial flux position (about 3 m below the top of the pebble bed). The 4-group fluxes, as calculated by the VSOP finite-difference (Citation) calculation, are shown. The thermal peak in the graphite inner and outer reflector can clearly be seen. It can also be noted that the fast flux (>0.1MeV) is larger in the central reflector than the side reflector, implying more damage and thus a shorter lifetime of the inner graphite structures. A summary of the maximum fast fluence experienced by the fuel and respective reflector areas after an effective 35 years of full power operation (EFPY) is given in Table 2.

Table 2 Fast fluence (> 0.1 MeV) on graphite structures

Description	Units	Value
Fuel spheres	$10^{21}/cm^2$	2.63
Maximum upper reflector edge (35 EFPY)	$10^{22}/cm^2$	< 0.6
Maximum outer reflector side (35 EFPY)	$10^{22}/cm^2$	4.3
Maximum inner reflector side (35 EFPY)	$10^{22}/cm^2$	5.4
Maximum lower reflector edge (35 EFPY)	$10^{22}/cm^2$	< 0.6

The fast fluence and burnup seen by the fuel spheres are within the technical experience and irradiation tests performed in the German program [4]. The calculated fluence on the graphite inner reflector and also, to a lesser extent on the outer reflector, implies a change-out or replacement of these structures during the lifetime of the reactor. Provision for this has been made in the power plant development specification.

The fuel temperature during normal operation plays an important part in the amount of fission product and activation products being released from the fuel, in particular Ag110m. The diffusion process of these radionuclides through the coated particles increase rapidly with increased temperatures and since they are either circulated in the helium circuit or plate out on cold surfaces, they may pose problems during maintenance. A design criterion, to restrict the maximum fuel temperature during normal operation to below 1130 ˚C, was therefore imposed. In Fig. 5 the fuel average and maximum temperatures are shown for the five flow channels. It is clear that the maximum fuel temperature criterion was met. The temperature profiles show the heat-up from the top of the pebble-bed to the bottom. Interesting to note that whereas the average fuel sphere temperature reaches a maximum in the bottom of the reactor where the coolant temperature also reach a maximum, the axial peak of the maximum fuel temperature is reached much higher in the pebble-bed. It is dominated by the temperature gradient across the fuel sphere and therefore closely coupled to the power being delivered.

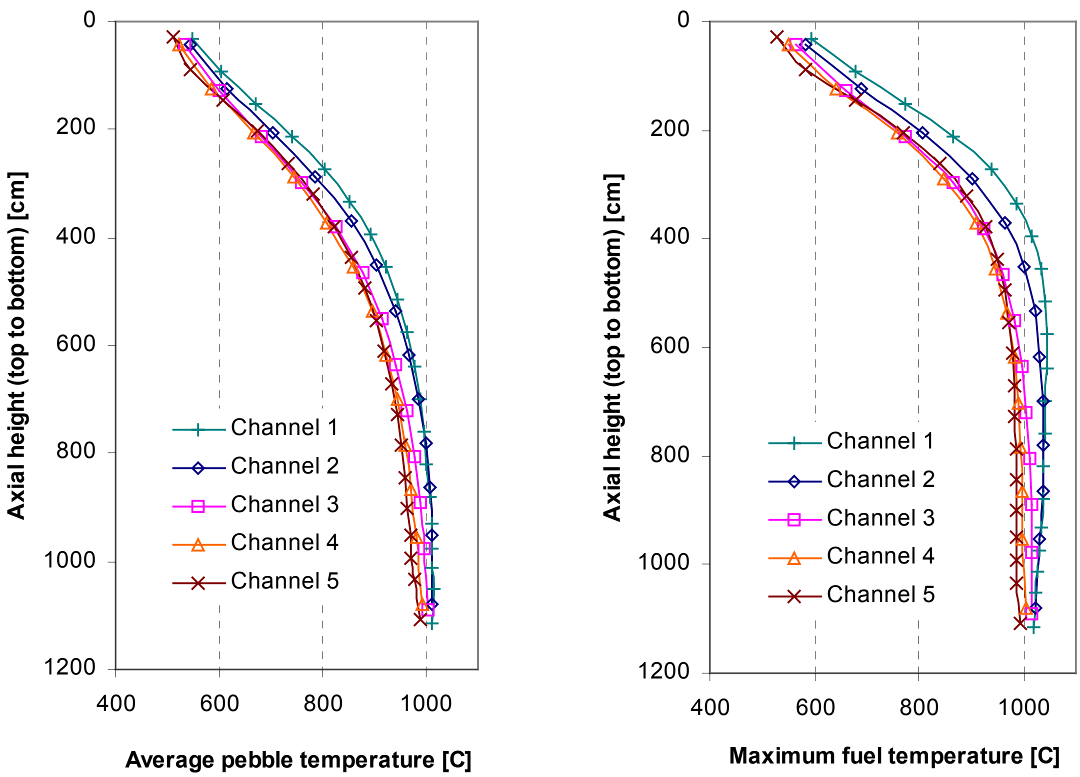

Fig. 5 Fuel pebble average and maximum (centre) temperatures in ˚C for the pebble flow channels

4.2 Load Follow Requirements

The load follow requirement of 100% - 40% - 100% power requires the control rods to be inserted some distance into the core in order to bind enough excess reactivity to overcome the negative reactivity effect of xenon build-up in the case of a power reduction. Fig. 6 shows the calculated k-eff behaviour during a postulated load follow of 100%-40%-100% power with no control rod movement simulated. After the power decrease the xenon concentrations increase with the corresponding decrease in k-eff. This determines the excess reactivity requirements if such load-follow ability is required. Since this requirement must be fulfilled by the RCS, it prescribes the equilibrium operation control bank insertion depth.

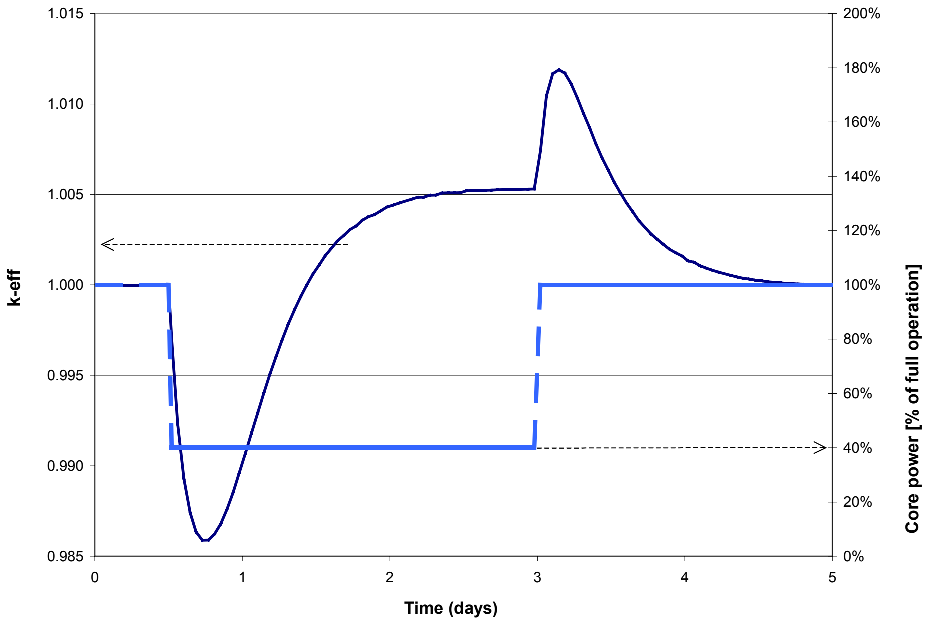

Fig 6. Reactivity behaviour due to xenon during a 100%-40%-100% power change

As can be seen from the figure the k-eff would decrease to about 0.986 within a few hours after the power has been reduced to 40%. This reduction in reactivity must of course be compensated by control rod extraction. The PBMR load-follow requirement implies all the control rods to be inserted a minimum of two metres (relative to the bottom of the top reflector) at full power operation. The excess reactivity bound by the control system is also beneficial at base load operation since it allow continual operation for a few days in the event that fuel loading and recirculation may not be possible.

A balance should be found between an excess reactivity load follow requirement, neutron economy and most importantly restricting the excess reactivity from a safety perspective. The design value of 1.4 %Δk is low enough to ensure that fuel temperatures are kept low enough to prevent any large fission product releases, even in the event of total control rod withdrawal at maximum speed.

4.3 Temperature Reactivity Coefficients

The temperature coefficients are separated into the reactivity coefficient of fuel (or Doppler coefficient), the moderator (or graphite in the fuel) and the two radial reflector regions. In each case isodeltic temperature coefficients were calculated, i.e. the temperatures of all the material not of interest (for example the moderator and reflector temperatures) were kept unchanged (at the equilibrium core conditions), while all the temperatures of interest (for example the fuel temperature) were increased by a constant difference (+50 °C). These results are presented in Table 3.

The reactivity coefficients of temperature are dependent on the temperature itself and are therefore calculated as part of coupled neutronics thermal-hydraulics calculations that takes the actual conditions into account. However, to illustrate the approximate behaviour over the whole operational temperature range the reactivity coefficients are shown in Fig. 7. It can be seen that although the reflector areas displays a positive reactivity coefficient, the overall value is negative.

Table 3 Isodeltic temperature coefficients

Temperature coefficients at operating conditions	Unit	Value
Fuel (Doppler coefficient of ^{238}U)	Δk/°C	-3.30E-5
Moderator	Δk/°C	-3.28E-5
Central graphite reflector	Δk/°C	+1.66E-5
Outer reflector	Δk/°C	+1.26E-5
TOTAL	Δk/°C	-3.66E-5

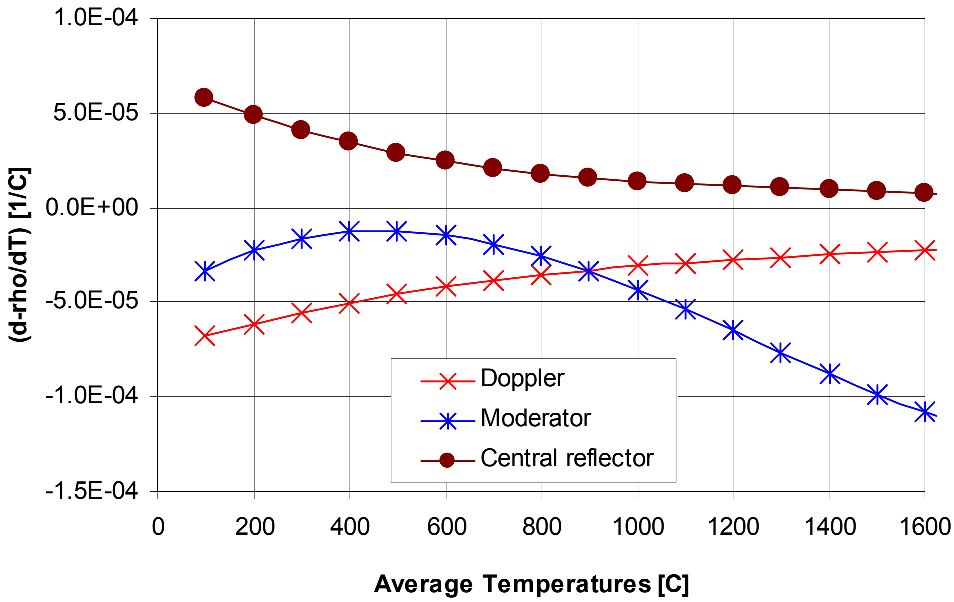

Fig 7. Isothermal reactivity temperature coefficients.

4.4 Reactivity Control and Shutdown Capabilities

The characteristics of stepwise insertion of 24 RCS rods are presented in Fig. 8. Group 1 comprises 12 RCS rods and travel only in the upper part of the core, while group 2 comprises 12 additional RCS rods that can travel to the lower part of the core when hot shutdown is required. During normal operation the two RCS banks move together. It must be noted that the full efficiency of the RCS is reached at an insertion depth of just less than 10 m below the top reflector. The insertion of the second group of RCS beyond a depth of 10 m below the top reflector will result in an increase in k_{eff}. Limiting the insertion depth by design will prevent this. From the figure it is also clear that the reactor will be shut down with $k_{eff} = 0.92$ using the RCS alone. However, note that the cool down of the reactor will increase the reactivity and the most reactive state of the reactor will only be reached after xenon has decayed. These are however long-term effects that will take several days to materialize. The fast shutdown requirement for the RCSS is therefore easily met, even without inserting the RSS.

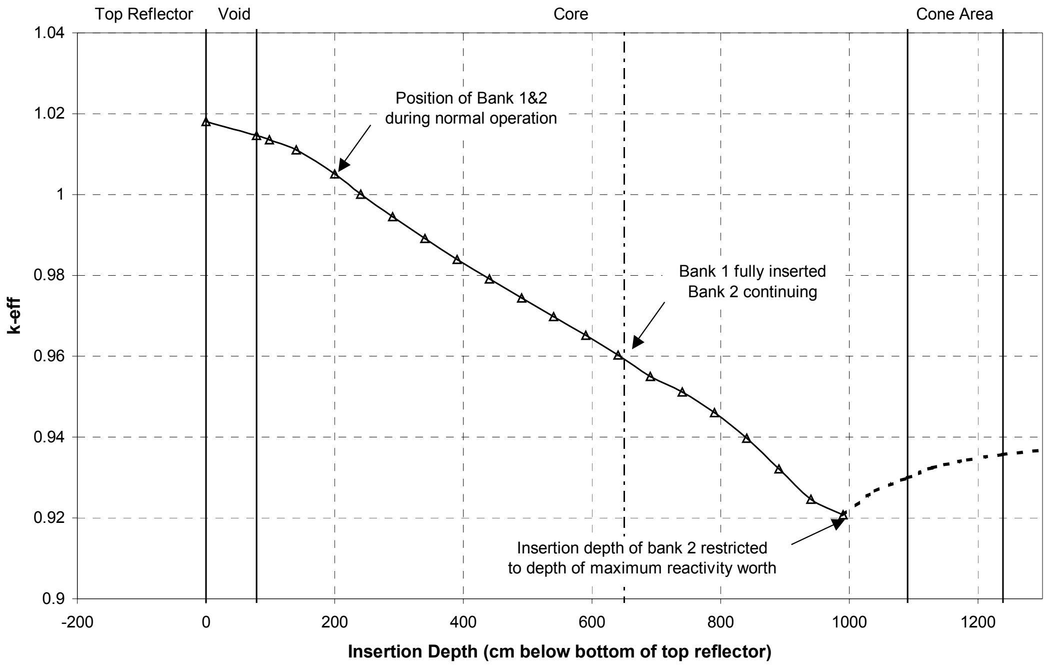

Fig 8. Reactivity effect of RCS.

Insertion of the eight RSS units in the inner reflector decreases the k_{eff} by 12 %Δk. This is considerably more that the positive reactivity effect of cold conditions (100 °C assumed for all core structures and fuel) and xenon decay. The RSS is therefore able to shut the reactor down at cold conditions for a long time, fulfilling the core design criteria.

5. Conclusion

The PBMR core neutronic design calculations were performed with the VSOP99 code system and the results show that the core design fulfils all the design parameters and operating envelope. For example, due to the multi-pass re-fueling scheme the power peaking is reduced and the resultant power per fuel sphere is much lower than the fuel design limits. It was also possible to illustrate that the control rods position, as determined for the equilibrium cycle, can overcome the negative xenon reactivity requirement for the defined load follow capabilities. Some of the safety characteristics can also be illustrated with VSOP such as the negative reactivity temperature coefficient and shut down capabilities.

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