INL/CON-09-17220
PREPRINT

Core Analysis, Design and Optimization of a Deep-Burn Pebble Bed Reactor

PHYSOR 2010

B. Boer
A. M. Ougouag

May 2010

The INL is a
U.S. Department of Energy
National Laboratory
operated by
Battelle Energy Alliance

PHYSOR 2010 - Advances in Reactor Physics to Power the Nuclear Renaissance
Pittsburgh, Pennsylvania, USA, May 9-14, 2010, on CD-ROM, American Nuclear Society, LaGrange Park, IL (2010)

CORE ANALYSIS, DESIGN AND OPTIMIZATION OF A DEEP-BURN PEBBLE BED REACTOR

B. Boer and A.M Ougouag
Idaho National Laboratory
2525 N. Fremont Avenue
Idaho Falls, ID 83415, USA
Brian.Boer@inl.gov

ABSTRACT

Achieving a high fuel burnup in the Deep-Burn pebble bed reactor design, while remaining within prescribes safety limits for fuel temperature, power peaking and temperature reactivity feedback, is challenging. The high content of Pu and Minor Actinides in the Deep-Burn fuel significantly impacts the thermal neutron energy spectrum as compared to a 'standard' UO_2 fueled core. Regions in the pebble bed core near the graphite reflectors experience power and temperature peaking that result from the local softer neutron energy spectrum. Furthermore, the interplay of the Pu resonances of the neutron absorption cross sections at low-lying energies can lead to a positive temperature reactivity coefficient for the graphite moderator under certain operating conditions.

To investigate the aforementioned effects a new code system based on existing codes has been developed for neutronic, thermal-hydraulic and fuel depletion analysis of Deep-Burn pebble bed reactors. A core analysis of a Deep-Burn Pebble Bed Modular Reactor (400 MW_{th}) design has been performed for two Deep-Burn fuel types and possible improvements of the design with regard to power peaking and temperature reactivity feedback are identified.

Key Words: Deep-Burn, pebble bed, core analysis, optimization

1. INTRODUCTION

The Deep-Burn (DB) concept [1] focuses on the destruction of transuranic nuclides from used light water reactor fuel. These transuranic nuclides are incorporated into TRISO coated fuel particles and used in gas-cooled reactors with the aim of a fractional fuel burnup of 60 to 70% in fissions per initial metal atom (FIMA). This high performance is expected through the use of multiple recirculation passes of the fuel in pebble form without any reprocessing or other physical or chemical changes between passes. In particular, the concept does not call for reprocessing of the fuel between passes. In principle, the DB pebble bed concept employs the same reactor designs as the present low enriched uranium core designs, i.e. the 400 MW_{th} Pebble Bed Modular Reactor (PBMR) [2].

A negative temperature reactivity coefficient is key to (inherently) safe operation of the reactor. A sufficiently negative fuel and/or moderator temperature coefficient should be maintained for the entire operating domain of the reactor to allow for a self-shutdown during an uncontrolled power excursion or Loss Of Forced Cooling (LOFC) event. It is known from previous work [3, 4] that the moderator temperature coefficient (MTC) of Pu-fueled High Temperature Reactors is strongly affected by the resonances of the neutron absorption cross section of Pu-239 and Pu-241 in the thermal energy range. Evidence of this can be inferred from Fig. 1. As can be seen from the

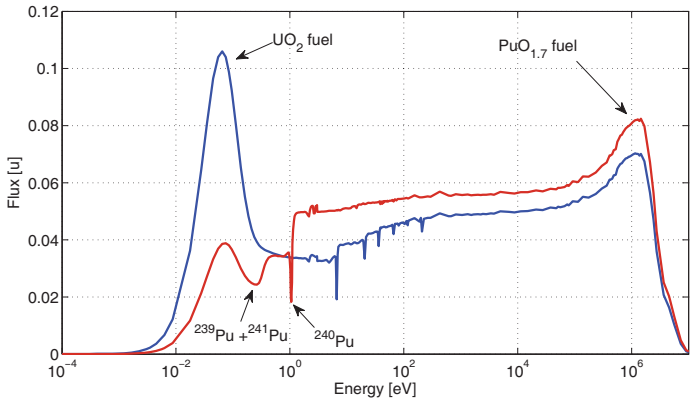


Figure 1. Neutron energy spectrum in a UO_2 and a Deep-Burn ($PuO_{1.7}$ fuel) HTR. The thermal spectrum of the Deep-Burn core is significantly influenced by the presence of the low lying resonances of the Pu isotopes (indicated with arrows).

figure, the thermal spectrum is significantly influenced by the presence of the low-lying resonances of the Pu isotopes (indicated with arrows). The location of the resonances with respect to slopes in the spectrum imply large sensitivity to changes in temperature or other causes of spectral shifts, and such changes may not be always favorable to desired safe behavior: depending on the fuel loading, temperature and burnup the MTC coefficient can be either negative or positive.

Figure 1 also shows that the DB design is significantly undermoderated in comparison to the LEU-fueled PBR design. It follows that if the same overall total power or overall average power density is sought, it can be expected that a high discharge burnup in such an undermoderated DB design would result in increased power and temperature peaking in the pebble bed near the inner and outer reflectors [4, 5]. In these regions the neutron energy spectrum is significantly impacted by neutrons that are thermalized in the graphite reflectors and are scattered back to the core. All these phenomena require analysis and careful design optimization if they are to be mitigated or avoided.

A new code system has been developed to quantify the Pu and MA destruction capability of the DB PBMR design, and for estimating safety parameters. These include the temperature reactivity feedback coefficients and the maximum fuel temperature. The codes used are SCALE-6 [6] for cross section generation, which is linked to the PEBBED code [7] for full core thermal-hydraulic, neutronic and depletion analysis. The two codes are linked together to form an automated capability. Two deep burn fuel types (Pu and Pu+MA, see Table I) have been investigated for both normal and transient conditions.

The outline of the rest of this paper is as follows. Section 2 presents the newly developed SCALE-PEBBED code system. Section 3.1 gives a description of the DB core design and its normal operating conditions. Analyses of the Pu and MA destruction capability of the design, the

Table I. Deep-Burn fuel compositions.

Fuel kernel	Fuel loading
Pu fuel	2.6% ^{238}Pu, 54% ^{239}Pu, 24% ^{240}Pu, 13% ^{241}Pu, 6.8% ^{242}Pu
Pu + MA fuel	6.8% ^{237}Np, 2.9% ^{238}Pu, 49% ^{239}Pu, 23% ^{240}Pu, 8.8% ^{241}Pu, 4.9% ^{242}Pu, 2.8% ^{241}Am, 0.02% ^{242m}Am, 1.4% ^{243}Am

temperature reactivity coefficients and transient behavior are presented in Secs. 3.2-3.4. Possible mitigation mechanisms to improve reactor performance are presented in Sec. 4. Section 5 concludes this paper.

2. CODE SYSTEM FOR NEUTRONIC AND THERMAL-HYDRAULIC ANALYSIS OF A DEEP-BURN PEBBLE BED REACTOR

A code-to-code coupling between PEBBED [7] and SCALE-6 [6] has been implemented, which allows PEBBED to read microscopic neutron cross sections in AMPX format generated with the CSAS5 module of SCALE-6. The fine (238) energy group structure from ENDF/B-VII is collapsed for this purpose to a broad group structure (28 groups) to be used in PEBBED. Thermal-hydraulic feedback is provided by the THERMIX(-KONVEK) code [8], which is a built-in routine of PEBBED. Short descriptions of the PEBBED code, the cross section generation procedure in SCALE-6 and the THERMIX code are given in the following sections.

2.1. Description of the PEBBED code

The PEBBED code [7] is a tool for analyzing the asymptotic fuel cycle in recirculating pebble bed reactors. Equations for neutron flux and nuclide distribution in a pebble-bed core are solved self-consistently via an iterative scheme. The neutronics solver uses either a standard finite difference technique or a nodal diffusion method. The burnup solver uses a semi-analytical method that guarantees convergence and accuracy. A key step in the algorithm is the computation of the entry plane density of each nuclide of interest in each axial pebble flow channel. These values depend upon the pebble loading and recirculation policy and the burnup accrued by pebbles on successive passes through the core. The current iterate of the flux is used to compute the exit plane nuclide density in a pebble after one pass through the core in each channel, based on the density of that nuclide in a fresh pebble. Pebbles are then distributed according to the recirculation scheme to generate the entry plane density in each channel on the following pass. This is repeated until the pebbles meet or exceed the discharge cutoff burnup. The exit plane values are then averaged according to the recirculation scheme in order to produce the actual entry plane nuclide densities.

2.2. Cross section generation procedure using SCALE-6

The CSAS(6) module from SCALE-6 [6] has been used for the calculation of reactivity coefficients and to generate the neutron cross sections for PEBBED. The cross section generation method used here is largely based on a benchmarked SCALE-6 procedure [9]. In this method two lattice cell calculations are performed; firstly, a fuel kernel surrounded by coating material and graphite matrix is treated. In a second step a graphite matrix containing TRISO fuel and graphite, which is surrounded by a graphite shell and helium, is used in an infinite lattice calculation. The resonance treatment has been performed using the Bondarenko method (BONAMI) for the unresolved resonances range and using CENTRM/PMC/CHOPS for the resolved resonances. CENTRM solves the 1-D transport equation using point wise cross sections to calculate the corresponding point wise spectrum. PMC uses the point wise cross sections, the CENTRM-calculated point wise spectrum, and the multigroup data (where point wise spectrum is not calculated) and generates resonance-corrected multigroup cross sections. Note that the NITAWL module, which uses the Nordheim Integral Method is omitted here.

The double heterogeneity (caused by shadowing effects of the fuel particles and fuel zones of the pebbles) is treated by first calculating the point-wise flux disadvantage factors for the particle-matrix unit cell and then using these factors to create the homogenized point-wise particle/matrix mixture cross sections. The homogenized point-wise cross sections are then used in the second pass to create the final resonance-shielded multigroup cross sections that represent the fuel pebbles. Finally, deterministic calculations have been performed for the given cell (TRISO or pebble) with the one-dimensional Discrete Ordinates code XSDRNPM. In this eigenvalue calculation a white boundary condition is used on the outer surface.

During a PEBBED calculation the SCALE-6 input files are updates for local temperature and burnup. To this end 90 different material zones have been defined of which 55 are in the pebble bed region of the reactor (core zone is divided into 5 radial and 11 axial zones), 4 for the control rod, 1 for the void region and the remaining 30 are for the reflector regions. The void region on top of the pebble bed was modeled by directional diffusion coefficients. The control rod was modeled by using an equivalent boron concentration. A simplification to the model was made by modeling the side void (air gap) and reactor pressure vessel as graphite.

It was chosen to perform the PEBBED full core calculation in a high number of energy groups (28), since intermediate calculations between pebble level and full core calculations are omitted. Furthermore, the depletion calculation in PEBBED uses the zone wise energy spectrum of the full core calculation to perform the zone wise depletion. It is therefore attractive to retain in a relatively fine group energy structure, especially, in the case of Pu-fuel with important low-lying resonances.

2.3. Description of the THERMIX code

The thermal-hydraulic feedback is provided by THERMIX-KONVEK, which utilizes the power density profile calculated by PEBBED and computes the average temperature for each material zone. This temperature is then used in the cross section preparation step in SCALE-6 in which each zone is treated separately.

THERMIX is a 2D thermal hydraulics code that consists of a heat conduction (and thermal radiation) part and a part for the fluid convection. In the first, the pressure field of the moving fluid for a two-dimensional cylindrical configuration is solved by linking the equations for conservation of mass and momentum. In the second part of the code the energy conservation equation is solved for steady state or time-dependent cases considering the solid material. The two parts are coupled by a source term that represents the heat transfer between the solid and the fluid.

The pebble bed is treated as a (porous) homogeneous material, having an effective conductivity based on the Zehner-Schlünder relation. In this relation not only conductivity through touching pebbles is taken into account, but also radiation between the pebbles and a convective effect caused by mixing of the helium fluid in the direction perpendicular to the flow direction.

At the boundary of the conduction model a fixed temperature (side) or an adiabatic boundary condition (top and bottom) is prescribed. For the convection model, the coolant inlet temperature and outlet pressure are used as boundary conditions.

3. RESULTS OF THE REFERENCE DEEP-BURN CORE DESIGN

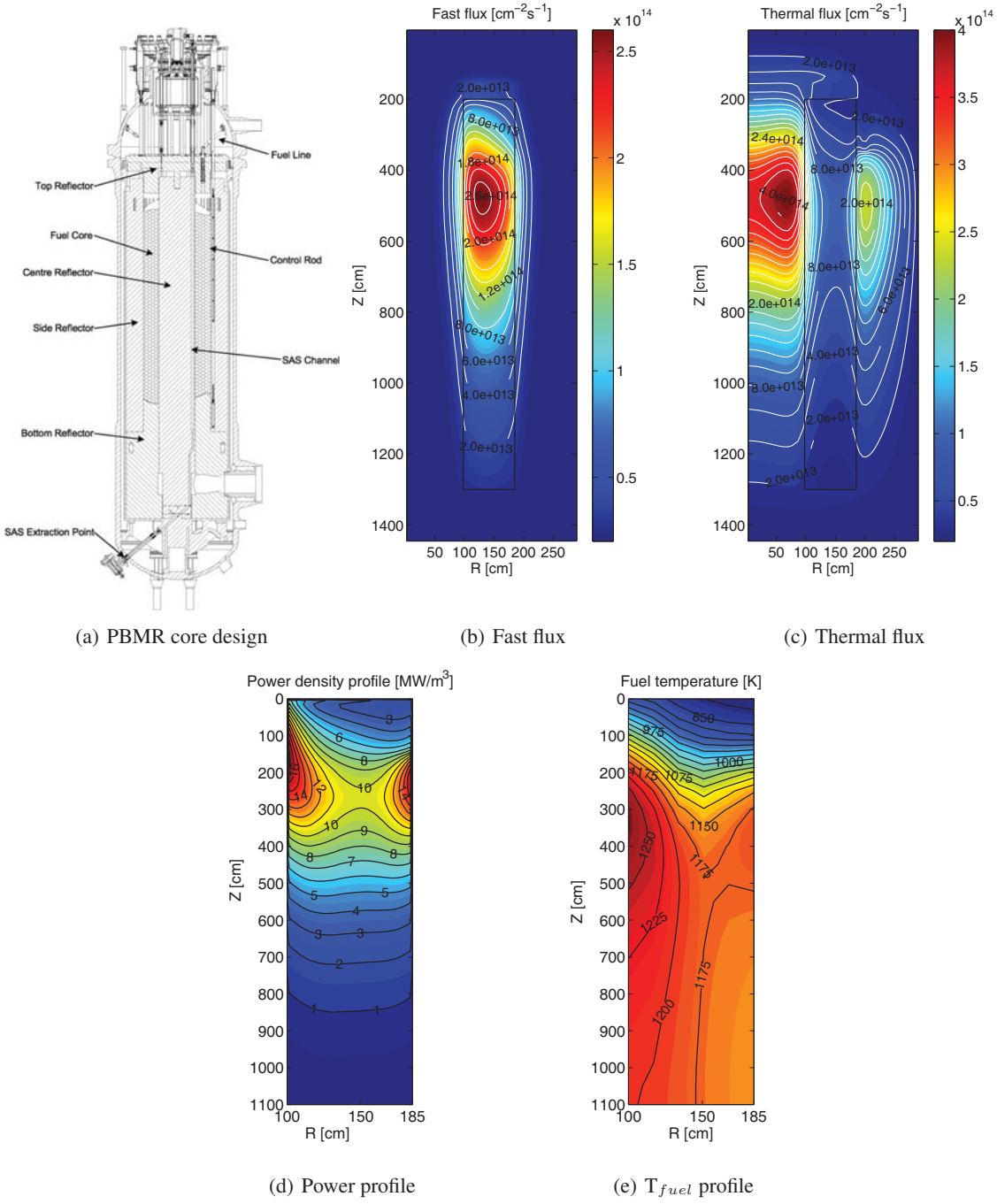
3.1. The reference Deep-Burn pebble bed reactor design and nominal operating conditions

Presently, two commercial pebble bed reactor designs are being considered for future deployment, namely: the 400 MW_{th} PBMR and the Chinese HTR-PM. The first was chosen as the reference design for the present study. A schematic overview of the PBMR design is given in Fig. 2(a). The pebble bed core lies between an inner and outer radius of 1 m and 1.85 m, respectively, and is 11 m in height. The core is surrounded on all sides by graphite reflectors.

The normal operating conditions have been modeled with the code system presented in Sec. 2. Figs. 2(b) and 2(c) present the fast and thermal flux profiles in a Pu-fueled (equilibrium) PBMR core. The peaks in the thermal flux profile in inner and outer reflectors result in peaks in the power density profile (Fig. 2(d)) and fuel temperature (Fig. 2(e)) near the core-reflector interface. Note that the maximum temperature (1276 K) is located below the power peak since the coolant flow direction is downward. The results of the Pu+Ma fueled core are similar but with a fuel temperature peak of 1319 K.

3.2. Pu and MA reduction capability of the Deep-Burn pebble bed reactor

Table II presents the main burnup characteristics of a DB pebble bed reactor. The discharge burnup reached is considerably lower for the Pu + MA fuel than for the Pu-only fuel, 560 MWd/kg compared to 702 MWd/kg, respectively. As a result the amount of heavy metal discharged from the core is considerably larger, 287 g/d compared to 136 g/d, respectively.



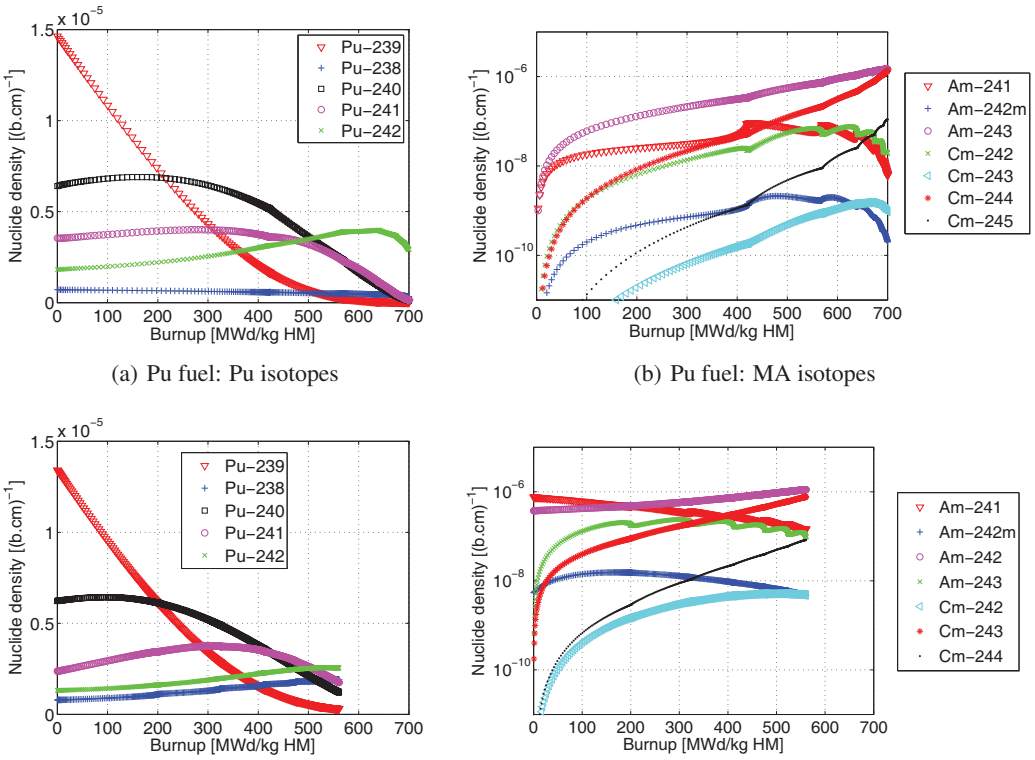
(a) PBMR core design (b) Fast flux (c) Thermal flux

(d) Power profile (e) T_{fuel} profile

Figure 2. The Deep-Burn PBMR; schematic overview of the core design (a); fast (b) and thermal (c) flux profiles; power profile (d); and the fuel temperature profile (e). The thermal flux peak near the reflector results in peaks in the power and temperature profile.

Table II. TRU destruction and burnup characteristics for the DB PBMR.

Item	Pu fuel	Pu + MA fuel
Discharge burnup (average) [MWd/kg]	702.4	560
Discharge burnup in FIMA (average) [%]	74.9	59.71
Total pebble injection rate [#/d]	1712	2172
Fresh pebble injection rate [#/d]	285	362
Heavy metal content introduced [g/pebble]	2.0	2.0
Heavy metal content discharged [g/pebble]	0.479	0.794
Heavy metal destruction rate [g/d]	433	436
Heavy metal discharge rate [g/d]	136	287



(a) Pu fuel: Pu isotopes

(b) Pu fuel: MA isotopes

(c) Pu + MA fuel: Pu isotopes

(d) Pu + MA fuel: MA isotopes

Figure 3. Nuclide (homogeneous core) density histories of Pu and MA isotopes in the two DB fuel types.

Fig. 3 shows the irradiation history of the Pu and MA nuclides. The higher discharge burnup of the Pu fuel results from a large initial content of Pu-239/241. For both fuel types it can be seen that a large part of the initial Pu isotopes is destroyed. This reduction in the amount of initial heavy metals results in a large overall net reduction in the total amount of heavy metals, even as the Am and Cm inventory grows.

3.3. Temperature reactivity feedback coefficients

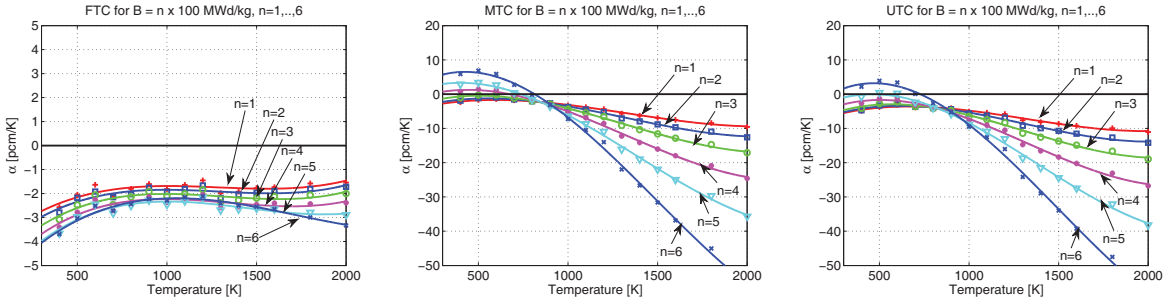
The effect of the fuel kernel, graphite moderator and uniform temperature on the reactivity in the DB core has been investigated.

In general, an increase of the fuel (kernel) temperature results in broadening of the resonances of the absorption cross section. This causes a decrease of the resonance self-shielding and results in an increase of the resonance absorption rate, i.e. a negative fuel temperature coefficient (FTC). This (Doppler) effect occurs instantly after an increase in reactor power, since most of the fission power is deposited locally within the fuel kernel.

In contrast to the fuel temperature effect, the moderator temperature effect is delayed since some time has to elapse to allow for heat transfer from the fuel kernel to the moderator. It is noted that this time is short in general when one considers as the moderator the graphite matrix, in which the fuel particles are embedded. An increase of the moderator temperature leads to a shift of the thermal spectrum to a higher energy. If one considers the resonance of Pu-239, the shift of the neutron spectrum causes two effects acting in opposite directions with regard to the multiplication factor k_∞, [3]. First, a shift of the spectrum towards the resonances causes an increase in the resonance absorption, resulting in a higher thermal utilization factor (the factor f of the four factor formula ($k_\infty = \eta \cdot f \cdot p \cdot \epsilon$). This is, therefore, a positive contribution to the moderator temperature coefficient (MTC). On the other hand, the capture-to-fission ratio of Pu-239 increases toward the 0.3 eV resonance. Therefore, the spectral shift leads to a decreased number of neutrons produced per absorbed neutron (η) resulting in a negative contribution. The moderator-to-fuel ratio, which changes during burnup, and the moderator temperature determine which of the two is the dominating effect.

However, with increased burnup the ratio of absorption in Pu-241 to Pu-239 increases. The capture to fission ratio of Pu-241 decreases first before it starts to increase above 0.1 eV, towards the resonance energy. This leads to a positive contribution to η for low temperatures and a negative contribution at high temperatures. With regard to the four-factor formula, one can verify that the effect on the resonance escape probability is always negative, caused by increased nonthermal resonance absorption in 240-Pu and a decrease of the capture to fission rate in Pu-241 for increased moderator temperature. The contribution of the fast fission factor ϵ is negative at high burnups and low temperatures. It is also noted that a shift of the Maxwell spectrum to higher energies leads to a decrease of the absorption in graphite and the fission product Xe-135, which results in a positive contribution to the MTC. This effect becomes stronger with increased burnup (corresponding to an increased moderator-to-fuel ratio).

To investigate the temperature coefficients as a function of the fuel burnup, a computation of the equilibrium core composition using the code system of Sec. 2 (i.e. PEBBED, SCALE, THERMIX) has been performed first. From the resulting data the composition of the fuel can be



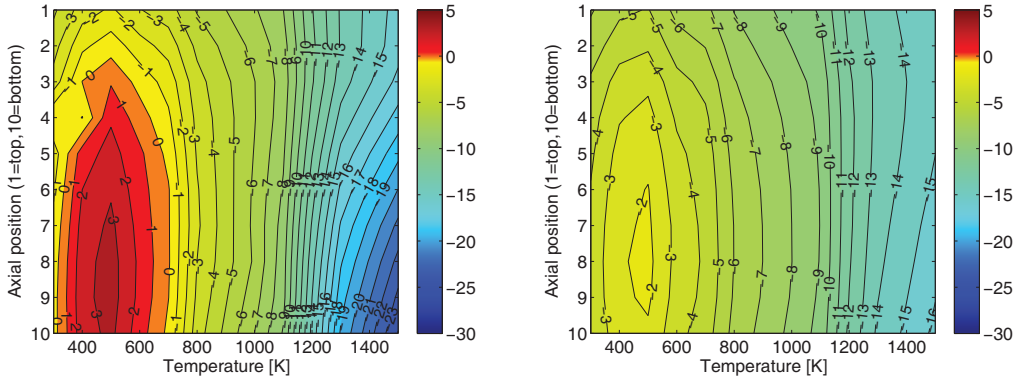
(a) FTC (b) MTC (c) UTC

Figure 4. Temperature reactivity feedback coefficients in the Deep-Burn (Pu-fueled) PBMR as a function of temperature and burnup; for the fuel (a); moderator (b) and uniform (fuel and moderator) temperature (c). The MTC determines the reactivity feedback and is positive for low temperatures and high burnup.

derived at each point in time (i.e. burnup level) during the lifetime of a pebble. These nuclide density data are then used in successive (1D) transport calculations of a TRISO, a pebble and a radial slab of the core using SCALE-6 [6] in order to determine the reactivity coefficients at several burnup levels.

Figs. 4(a), 4(b) and 4(c) show the FTC, MTC and UTC as a function of the temperature with the burnup level as a parameter. It can be seen from Fig. 4(a) that the FTC hardly changes as a function of the burnup level. On the other hand, the MTC decreases in magnitude with increasing burnup level and becomes positive above a burnup level of 300 MWd/kg for low temperatures ($T < 800K$) (see Fig. 4(b)). Furthermore, it becomes more negative with increasing burnup for the high temperature range. It is obvious that the positive MTC at low temperatures is undesirable during the start-up of the reactor. It can be concluded from Figs. 4(b) and 4(c) that the MTC largely determines the UTC, which is only slightly off set by the negative FTC as compared to the MTC.

In practice, the core of a pebble bed reactor is a mix of pebbles with different burnup levels. The previous analysis suggests that zones with a high average burnup could display a positive MTC and/or a positive UTC. Normally the zones with the highest burnup value can be found near the (inner) reflector at the bottom of the core, since the pebbles move down with time (burnup) and the highest thermal flux levels in the pebble bed are found near the inner reflector. The PEBBED code is used to calculate the average nuclide densities, which represents the mixture of pebbles having different burnup levels, for several core zones. These nuclide densities are used to calculate the temperature coefficients as a function of the axial core position in a procedure similar to the one described above. Fig. 5(a) shows the UTC for several axial positions as a function of the temperature. It can be seen that at low temperatures ($T < 800$ K) a significant portion (75%) of the core has a positive UTC.



(a) UTC without Er addition (b) UTC with Er addition

Figure 5. Uniform Temperature Coefficients of reactivity in the Deep-Burn (Pu-fueled) PBMR as a function of the axial core position and the temperature; for the reference case without addition of Er (a) the core has a positive UTC at low temperatures at the bottom region; for a case in which Er was added to the fuel kernel (b) a core-wide negative UTC is found for the entire temperature range.

Similarly to what was found for the Pu-only core, a positive moderator coefficient was found for low temperatures and high burnup values for the Pu + MA fuel case. This renders the UTC positive for temperature below 600 K and burnup values higher than 400 MWd/kg.

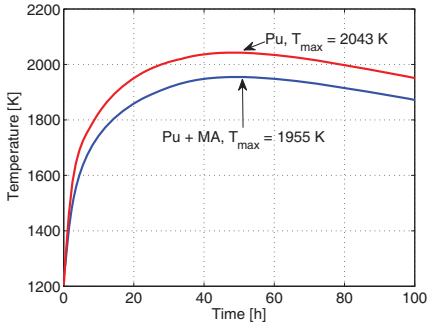


Figure 6. Maximum core temperature history during a DLOFC transient for the two DB fuel loadings in the PBMR design.

3.4. Loss Of Forced Cooling transient conditions

The fuel temperature during a Loss Of Forced Cooling (LOFC) incident has been computed. It was assumed that the helium coolant flow is reduced (instantaneously) to a zero mass flow and that the system pressure is reduced from 9 MPa to 0.1 MPa. It was assumed that a SCRAM is initiated at the beginning of the transient and that the reactor power is determined by the decay

heat only. In the absence of forced cooling and system pressure the removal of the decay heat is determined by the conduction and thermal radiation in the pebble bed and reactor structures to the ultimate heat sink at the outer surface of the reactor pressure vessel (RPV). The absence of the helium coolant in the core results in a reduction of the heat removal capability of the core. Therefore, the local fuel temperature in the core increases in general. Specifically, the core region near the power peak has a relatively large temperature increase.

Fig. 6 shows the core maximum temperature history during the LOFC transient for the two DB fuels. For both fuel types the peak temperature is significantly above the peak temperature ($\sim$1875K) of a UO_2 fueled PBMR, which is a consequence of the larger power peak near the inner reflector (see Fig. 2(d)).

4. DEEP-BURN CORE OPTIMIZATION

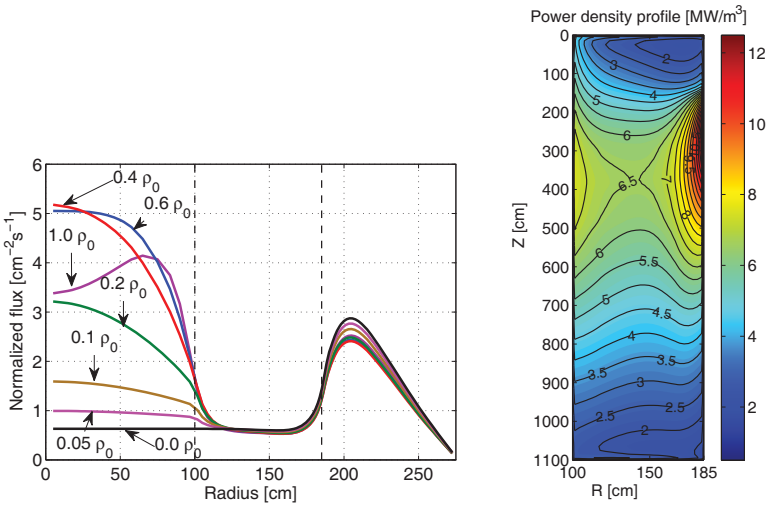
Two problems were found in the performance of the reference DB pebble bed design, namely:

1. The large power peaks (and resulting temperature peaks) near the inner and outer reflectors. This problem results in maximum fuel temperatures of 1276 K and 1319 K at normal operating conditions for the Pu and Pu + MA fuel cases, respectively. The maximum temperatures during a LOFC are 2043 K and 1955 K, respectively. Of special concern are the high temperatures for the LOFC transient, which would be expected to lead to fuel integrity related problems.
2. A large part ($>$ 75 %) of the core has a positive temperature coefficient (UTC) for temperatures below 700 K. Although the core has a strong negative coefficient at (and above) its normal operating temperature the positive temperature coefficient for the low temperatures is unattractive during start-up and shut-down of the plant.

The remainder of this section presents the results of two optimization studies which aim at mitigating the above problems. In the first study the inner reflector graphite density is used as a varying parameter to investigate whether a low density (transparent) reflector can lead to reduced power and temperature peaking. In a second study Erbium poison is added to the fuel kernel in an attempt to improve the UTC. The Er-167 concentration in the fuel is used as a parameter.

4.1. Power peak reduction

In order to reduce the power peak near the inner reflector a reduction of the graphite density of the inner reflector is proposed. Fig. 7(a) shows the effect on the radial profile of the thermal flux for several inner reflector graphite densities. It can be seen that for low graphite densities the inner peak in the thermal flux completely disappears with the result that the power peak also vanishes (see Fig. 7(b)). As a result the maximum temperature during a LOFC transient reduces from 2043 K to 1841 K ($\rho = 0.05\rho_0$). It is noted that the discharge burnup for this latter core design is slightly lower (681 MWd/kg) compared to the 702 MWd/kg of the reference case. Furthermore, due to a reduced thermal capacity of the inner reflector the core reaches the maximum temperature (1841 K) several hours earlier in the transient than the reference core design.



(a) (b)

Figure 7. Radial thermal (normalized) flux profile for several inner reflector graphite densities (a) (ρ_0 = 1.78 g/cm^3) showing that the peak in the flux near the inner reflector edge disappears for low graphite densities. The dashed lines shows the boundaries of the pebble bed. The power profile for a DB core with a 'transparent' ($\rho = 0.05\rho_0$) inner reflector having no power peak near the inner edge of the pebble bed (b).

4.2. Improvement of the MTC

In an attempt to improve the UTC the isotope Er-167 is added to the fuel particles as a burnable poison. Er-167 has a significant resonance near the 0.3 eV resonances of Pu-239 and Pu-241. Therefore, an increase of the moderator temperature resulting in a thermal shift to higher energies will lead to increased absorption in Er-167, which gives a negative contribution to the MTC.

Table III presents the core maximum temperature coefficient for the entire temperature range considered (300 K $<$ T $<$ 1500 K) for several concentrations of initial Er-167. The concentration is normalized to homogeneous pebble bed material. It can be seen that the UTC can be made negative for the entire core. The UTC as a function of the axial core position and temperature for a concentration of $1.5{\cdot}10^{-6}$ (b.cm)$^{-1}$ is shown in Fig. 5(b). The achievable discharge burnup reduces with increased Er-167 concentration, due to increased parasitic absorption. It is noted that although the pebbles with a high burnup level do not contain much Er, which burns off before the end of the irradiation, Er is distributed over the core effectively since the pebbles are (re)loaded in the core for 6 times.

Table III. Effect of Er-167 addition on the temperature coefficient and the discharge burnup.

Er-167 concentration [(b.cm)$^{-1}$]	Maximum UTC [pcm/K]	Discharge burnup [MWd/kg]
0	3.5	695
$5.0{\cdot}10^{-7}$	2.6	689
$1.0{\cdot}10^{-6}$	2.0	684
$1.5{\cdot}10^{-6}$	-1.7	600
$2.0{\cdot}10^{-6}$	-2.4	580

5. CONCLUSIONS

A new code system based on PEBBED and SCALE-6 has been developed for the neutronic, thermal-hydraulic and depletion analysis of the Deep-Burn pebble bed reactor design. The PBMR-400 was chosen as the reference DB pebble bed reactor design. The following conclusions can be drawn:

- It was found that the initial reference design suffers from large power density peaks, which result in high temperatures during a LOFC ($T_{max} = 1955$ K and 2042 K for Pu and Pu + MA fuel, respectively).
- A positive moderator temperature coefficient (MTC) can be expected for off-nominal core conditions ($T < 750$ K) for 75 % of the core. A maximum MTC value of +3.5 pcm/K at the bottom region of the core has been computed for these conditions.
- Analysis shows that the power peak can be reduced by reducing the inner reflector graphite density (below 10 % of the original density), which results in a lower peak fuel temperature (peak reduction of 200 K) for the LOFC transient.
- Adding Er-167 to the fuel kernel improves the UTC. A negative UTC for the entire core and temperature domain can be ensured. This comes with a performance penalty in the form of a reduction of 100 MWd/kg in the achievable discharge burnup.

The presented code system will be further improved in the future and will be used to perform a full optimization analysis of the DB pebble bed reactor in which the maximum temperature (nominal and LOFC), reactivity coefficients (MTC, FTC, UTC) and the fuel discharge burnup will be the criteria.

In order to increase the effectiveness of the Er poison at high fuel burnup levels one could consider shielding the Er by putting it at the center of the fuel kernel or using separate Er kernels that have a larger diameter than the fuel kernel, thus using self-shielding as a mechanism to enhance performance.

ACKNOWLEDGEMENTS

Work supported by the U.S. Department of Energy, Office of Nuclear Energy (NE), under DOE Idaho Operations Office Contract DE-AC07-05ID14517.

REFERENCES

[1] R.M. Versluis, F. Venneri, D. Petti, L. Snead and D. McEachern, "Project Deep-Burn: Development of transuranic fuel for high-temperature helium-cooled reactors", *Proceedings of the 4th International Topical Meeting on High Temperature Reactor Technology (HTR2008)*, Washington DC, USA (2008).

[2] A. Koster., H.D. Matzner, D.R. Nicholsi, "PBMR design for the future", *Nuclear Engineering and Design*, **222**, pp. 231-245, (2003).

[3] E.E. Bende, "Temperature Reactivity Effects in Pebbles of a High-Temperature Reactor Fueled with Plutonium", Nuclear Technology, **131**, pp. 279-296, (1999).

[4] A. Meier, W. Bernnat, K. Hossain and G. Lohnert, "Analysis of High Temperature Pebble Bed Reactors with Plutonium Fuel", International Conference on Mathematics, Computational Methods & Reactor Physics (M&C 2009), ANS, New York, (2009).

[5] J.B.M. de Haas, J.C. Kuijper, J. Oppe, "Burnup and transient analysis of a HTR-400 design loaded with PuO_2", *Proceedings of the 3rd International Topical Meeting on High Temperature Reactor Technology (HTR2006)*, Johannesburg, South Africa, (2006).

[6] *SCALE-6, A Modular Code System for Performing Standardized Computer Analysis for Licensing Evaluations*, RNL/TM2005/39, Version 6.0, Vols I-III, ORNL, (2009).

[7] W.K. Terry, H.D. Gougar and A.M. Ougouag, "Direct Deterministic Method for Neutronics Analysis and Computation of Asymptotic Burnup Distribution in a Recirculating Pebble-Bed Reactor", *Annals of Nuclear Energy*, **29**, pp. 1345-1364 (2002).

[8] E. Teuchert et al, "V.S.O.P. Computer Code System for Reactor Physics and Fuel Cycle Simulation", Forschungszentrum Jülich GmbH Jül-2897, (1994).

[9] S. Goluoglu, "Analysis of a Computational Benchmark for a High-Temperature Reactor Using SCALE", *Proceedings of PHYSOR 2006*, Vancouver, BC, Canada, September 10-14, (2006).