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Plutonium disposition in the PBMR-400 High-Temperature Gas-Cooled Reactor

Eben Mulder*, Eberhard Teuchert

Reactor and Radiation Analysis, PBMR (Pty) Ltd, PO Box 9396, Centurion 0046

Abstract

Versatility in application is considered to be one of the major characteristics of a typical Generation IV type reactor. In this paper the opportunities offered by on-line fuelling in a pebble bed reactor concept is demonstrated in a design aimed at the dispositioning of weapons grade or reactor grade plutonium.

The standard PBMR-400 commercial reactor design is chosen. The fuel cycle variations are selected to achieve the inherently safe characteristics that are accepted as standard practice in the PBMR design philosophy. Calculated results of the phenomena of interest are presented, such as the levels of Pu dispositioning achieved and the negative temperature coefficient. Tables are presented displaying the characteristic data of inserted material versus the remaining content in the discharged spent fuel.

1. Introduction

Results are reported of a study performed to establish the feasibility of disposing of reactor grade and weapons grade plutonium in the South African PBMR-400 reactor design. The unique feature of pebble bed reactors is employed, viz. inserting the plutonium in one type of pebble, while simultaneously employing driver fuel in a second one. The advantage of such an approach is recognized in the burnup history and isotopic composition achieved in the respective pebble types. Based on these characteristics each of the different types can be managed individually. A varying number of passes through the core can be selected depending on the required burnup characteristics of the different pebble types.

The driver pebble comprised highly enriched uranium and thorium as mixed oxide thus excluding a major build-up of secondary plutonium.

Together, with the negative reactivity coefficients, this study demonstrates the basic versatility of some fuel cycle designs in the PBMR-400 commercial reactor. This is true, however, for pebble bed reactors in general (see [3], [4], and [5]).

Note: Fuel layout considerations have been employed to ensure that the power generation per fuel sphere would remain within the range of existing thermo-mechanical acceptance.

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* Corresponding author, Tel. (+27) 12 677-9509, Fax. (+27) 12 666-8012, E-mail: eben@wmailbox.net

2. Layout data and calculational model

The PBMR-400 is the 400 MW_{th} South African commercial pebble bed reactor design (see Fig. 1). Reitsma intends to present the design details at this conference in [1]. In Table 1 the general specifications of the design are summarized.

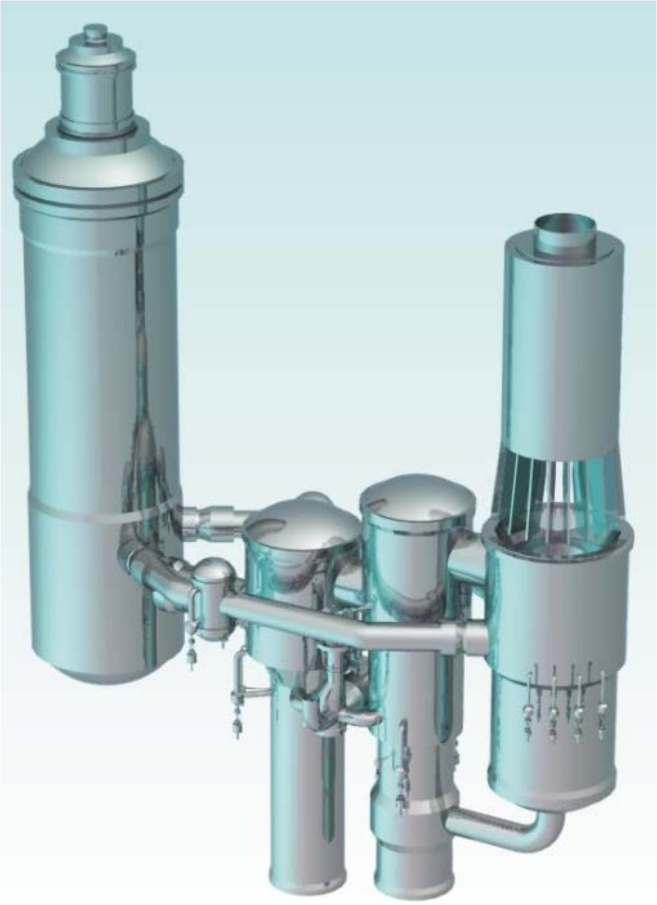


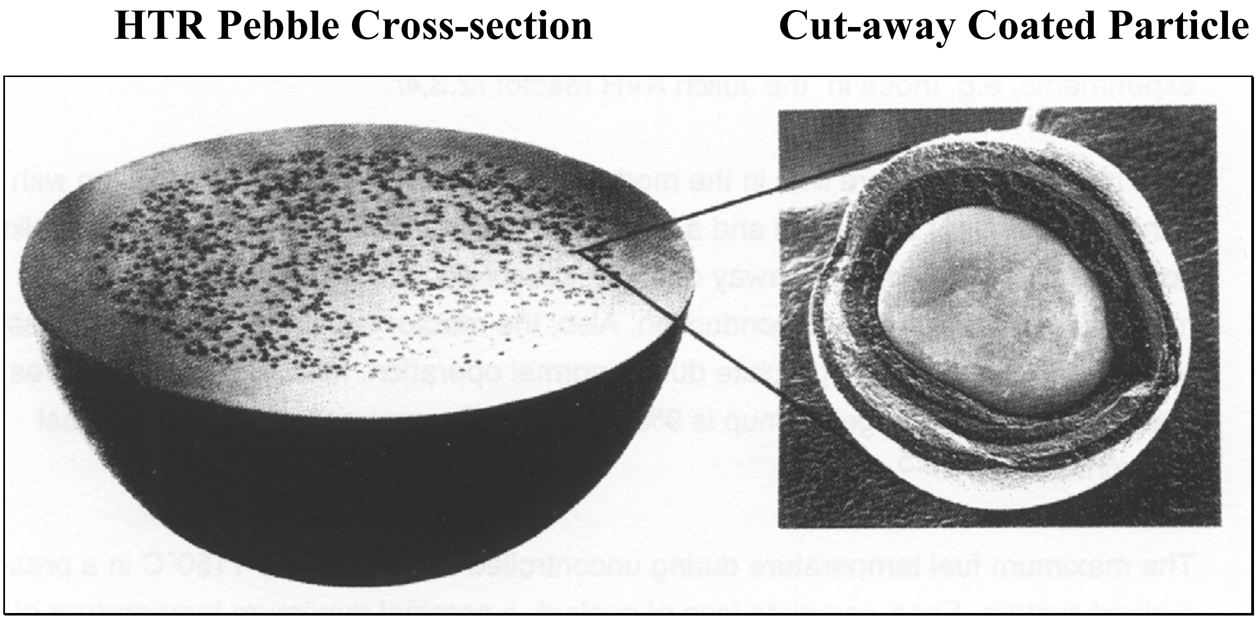
Fig. 1: PBMR-400 plant layout

Table 1: Reactor specifications

Thermal Power	MW_{th}	400
Core height	m	11.0
Core annular thickness	m	0.85
Central reflector diameter	m	2.0
Core power density	MW/m^3	4.8
Helium heat-up: inlet/outlet	°C	500/900

A depiction is provided of the fuel elements and cut-away section of a coated particle in Fig. 2. In Table 2 the specifications of the two cases prepared for the current investigation are summarized. In the first instance a 5-pass cycle design is aimed at disposing of the reactor plutonium. Here 50% of the core contained pebbles charged with 3.0 g Pu with a composition of $70^0/_a$ Pu^{239} and $30^0/_a$ Pu^{240}. The second half of the core contained pebbles with 18.30 g of Th^{232} and $1.58^0/_a$ U^{235} ($93^0/_a$). As driver pebbles in the second case a pebble design for weapons grade Pu is employed with $93^0/_a$ Pu^{239} and $7^0/_a$ Pu^{240}. In Fig. 3 the calculational model depicts the reactor model and the core sub-division for simulating the flow of the pebbles.

Subsequently, a second cycle was designed for the disposing of weapons grade Pu. The dual-pass cycle consists of pebbles containing 1.8 g of plutonium with a composition of $93^0/_a$ Pu^{239} and $7^0/_a$ Pu^{240}. These pebbles pass 4 times through the reactor, while a second pebble type containing 20 g of pure Th^{232} passes 6 times through the reactor. The core inventory comprised 60% of Pu pebbles and 40% of the Th type.



HTR Pebble Cross-section

Cut-away Coated Particle

Fig. 2: Pebble fuel layout

Table 2: Fuel cycle specification

	Reactor-Pu		Weapons-Pu	
	Pu	Th/U	Pu	Th
Coated particle diameter (mm)	0.24	0.50	0.24	0.50
Heavy metal loading (g/pebble)	3	20	1.8	20
U^{235} ($93^0/_a$) loading (g/pebble)	-	1.58	-	-
Pu^{239}/Pu^{240}	70/30	-	93/7	-
Number of passes	5	5	4	6
In-core fuel fraction (%)	50	50	60	40

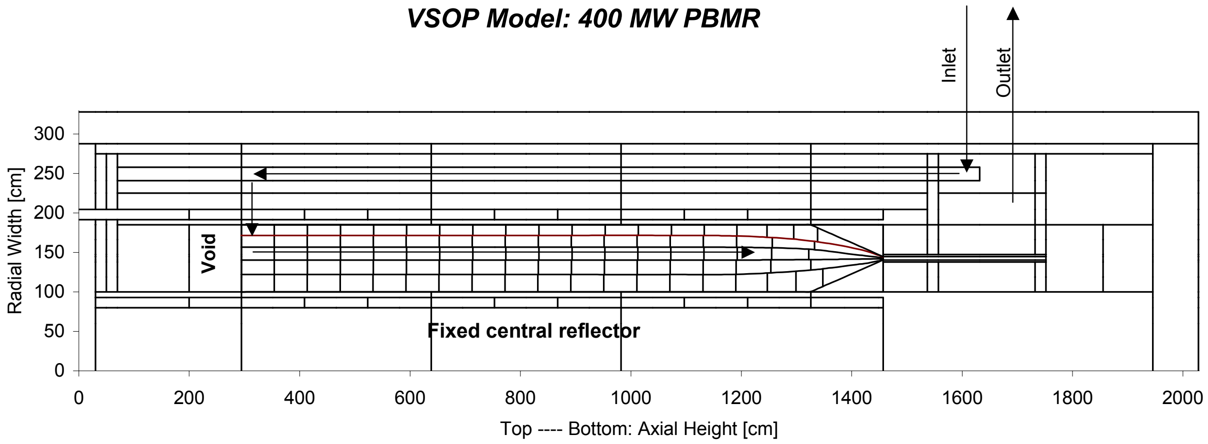


Fig. 3: Calculational model for neutronics and thermal-hydraulics

3. Results and discussion

All calculations have been performed in 2-D with the VSOP-NTC suite of design codes [2].

In Table 3 a comparison of results is provided of the two cases studied. A very high degree of Pu^{239} burning can be observed in both cases.

In the reactor-Pu case 95% of the Pu^{239} is burned, whilst the discharged Pu mainly contains the higher isotopes of which the main contributor is Pu^{241}(48%). Furthermore, this isotope, gradually decays due to its half-life of 14.4 years. The destruction of the inserted Pu and build-up of the higher Pu isotopes is depicted in Fig.4 on the left hand side. On the right hand one may observe the cycle histories of the charged U^{235} and bred U^{233} isotopes in the driver pebbles.

In the weapons-Pu case the small amount of neutron absorbing Pu^{240} leads to the fact that the bred U^{233} in the Th pebbles is sufficient as driver material and U^{235} will be superfluous. Due to the delayed build-up of the U^{233} in the Th pebbles the residence time of these pebbles is increased by 50% compared to that of the Pu pebbles. In Fig. 5 the destruction of Pu is depicted. Here it can be seen that the build-up of higher isotopes is lower than that of the reactor-Pu case. This is due to low amount of Pu^{240} (7%) in the loading.

Temperature coefficients have been calculated for both the cases and results are summarized in Table 4. In general negative values have been found in both cases. It should be noted that the Doppler coefficient refers to temperature variations in the Th pebbles alone. The reactivity response to temperature changes is mainly governed by the moderator coefficient, which is more negative in both cases.

Table 3: Data comparison: Disposition of reactor versus weapons grade plutonium

	Reactor-Pu		**Weapons-Pu**	
	Pu	**Th/U**	**Pu**	**Th**
Fuel residence time (d)	1619	1619	1098	1647
Conversion ratio	0.554		0.472	
Avg. thermal flux (10^{14}/cm^2*s)	0.22		0.44	
Avg. burnup (MWd/t_{HM})	125000		151000	
Burnup (MWd/t_{HM})	657000	45000	763000	26000
Power fraction (%)	69	31	80	20
Pu charged (kg/GWa_{th})	381.8		409.9	
Pu burned (kg/GWa_{th})	282.4		332.0	
U^{235} charged (kg/GWa_{th})		201.1		-
Pu discharged/charged (%) (After decay of Pu1)	26 (13)		19 (12)	
Discharged Pu: Pu9/Pu0/Pu1/Pu2 (%)	13/13/48/26		6/26/38/30	

Table 4: Temperature coefficients

	Reactor-Pu	**Weapons-Pu**
Δk/Δt (10^{-5}/K)		
Doppler coefficient	-1.4	-1.2
Moderator coefficient	-5.4	-2.4
Reflector coefficient	+1.6	+2.4
TOTAL	-5.2	-1.2

4. Conclusions and future prospects

Due to its flexibility in loading the fuel it is shown that the PBMR-400 could be successfully deployed in the disposition of both reactor and weapons grade Pu. The charged Pu was destroyed by 74% and 81% in the respective cases. In the discharged Pu the largest portion comprises the isotope Pu^{241} ($\lambda_{1/2}$=14.4 years), which decays further when finally disposed.

This preliminary study paves the way for continued research into the fuel characteristics required to best meet the ensuing thermo-neutronics and thermo-mechanical conditions that limit performance under operational load. Full 3-D neutronics simulations are required to confirm the shutdown characteristics during equilibrium conditions and during the start-up phase. Based on the equilibrium design a start-up and running-in design of such reactors offer interesting opportunities for further investigation.

Fig.4: Reactor grade plutonium disposition using a dual-pebble composition (5 Passes / 5 Passes)

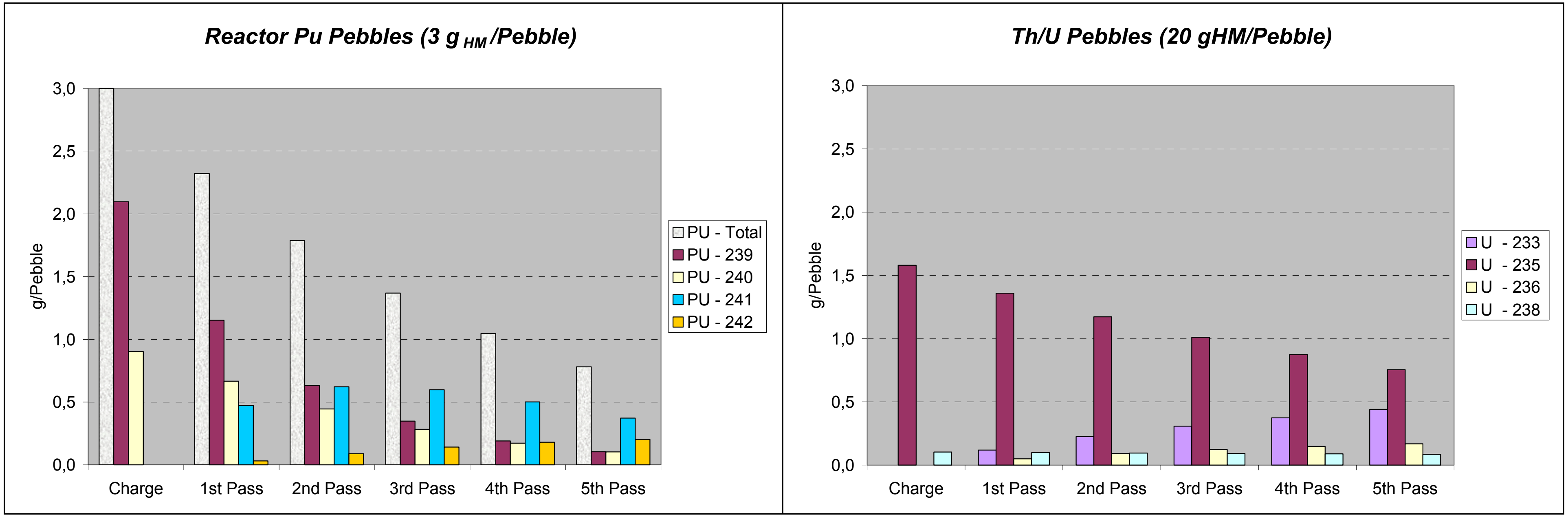
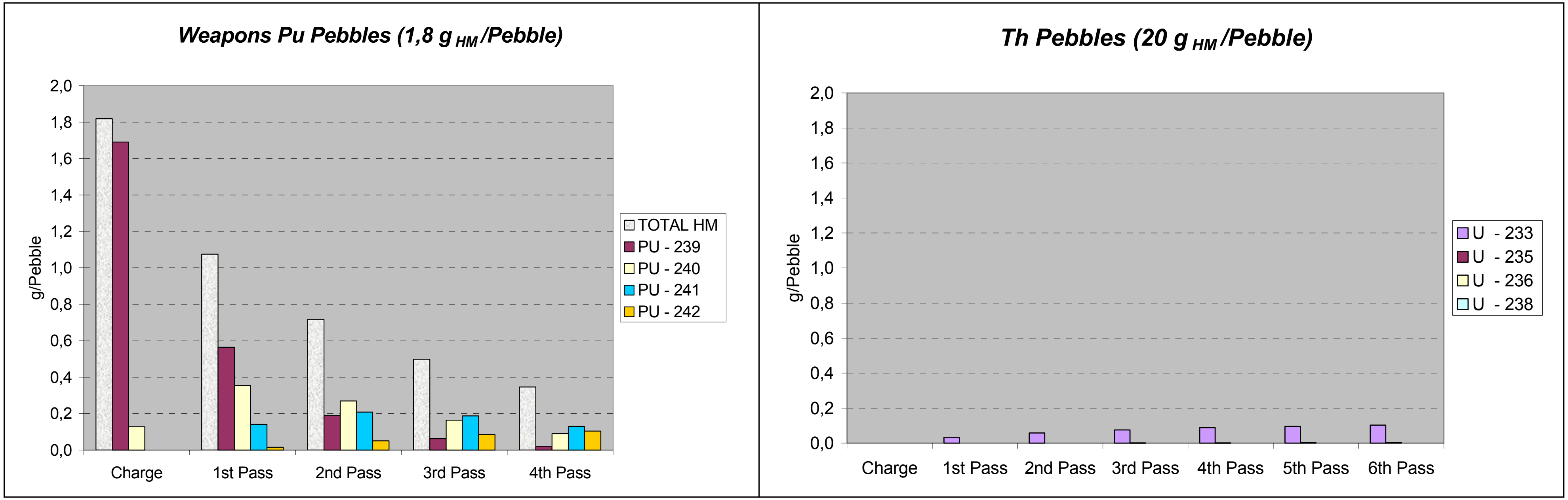


Fig. 5: Weapons grade plutonium disposition using a variable passage, dual-pebble composition (4 Passes / 6 Passes)



Weapons Pu Pebbles (1,8 g_{HM}/Pebble)

Th Pebbles (20 g_{HM}/Pebble)

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