

Reducing fuel temperature during depressurized loss of forced coolant transients, using neutron poisons in the external reflector in a Once-Through-Then-Out PBMR-200 DPP core

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ABSTRACT

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Title of study: **Reducing fuel temperature during depressurized loss of forced coolant transients, using neutron poisons in the external reflector in a Once-Through-Then-Out PBMR-200 DPP core**

Nuclear power plant safety is an important topic worldwide. It is therefore essential to continue to improve the safety of nuclear power plants. HTR technology improves safety and quality through its inherent design, ensuring that no internal or external incident results in the excessive release of radioactive material.

Previous studies have been carried out successfully to reduce maximum Depressurised Loss of Forced Coolant (DLOFC) fuel temperatures for the PBMR-400 MW core to about 300 °C below the chosen safety limit of 1600 °C. Such reductions have been achieved through the introduction of neutron poison into its central reflector, in the centre of its annular fuel core. This strategy was successful both for the standard six-pass fuel pebble recirculation scheme and the Once-Through-Then-Out (OTTO) refuelling schemes. The aim of this study is to extend these gains to pebble bed reactors with cylindrical fuel cores, i.e. cores that does not have a central reflector, such as the PBMR-200. For such cores the only option would be to place the neutron poison in the external reflector, which can be expected to be less effective than placing it in the central reflector. Furthermore, it was decided to opt for the OTTO refuelling scheme, as many recent designs have selected this option. For technical reasons, it was decided to mimic the lack of a central reflector in the PBMR-200 by placing the poison only in the external reflector of the PBMR- 400, with an OTTO refuelling cycle, rather than to develop the required models to test this option for a PBMR-200 core.

In practice, it is normally a DLOFC temperature hotspot in only a relatively small part of the fuel core that results in the upper limit for the maximum DLOFC temperature being exceeded. Therefore, the objective was to optimise the neutron poison placement in the external reflector to suppress DLOFC temperature hotspots by greatly flattening the axial profile of the DLOFC temperature. So, while the average DLOFC temperature might not be reduced substantially, the maximum DLOFC temperature can be expected to be greatly reduced. The value of this strategy was assessed by comparing the results to the case where optimised neutron poison distributions were placed in both the internal and external reflectors of the PBMR-400 core.

The optimisation attempts were greatly frustrated by instabilities in the simulated power distribution, induced by the neutron poisons. From previous studies, it was known that a largely flat axial profile for the DLOFC temperature could be obtained by inducing a large power peak near the top of the core, followed by a suppression in power lower down and then again, a smaller power peak towards the bottom of the core. However, when the poisons were used to induce such a power distribution, the Very Superior Old Program (VSOP) diffusion simulation code apparently experienced instabilities in its calculational algorithm. This resulted in an unstable oscillation, where one refuelling cycle produced a large power peak at the top and almost no power at the bottom, while the alternating cycle produced a large power peak at the bottom and almost no power at the top. After much trial and error, good stable power profiles were obtained for both cases, i.e. where poison was placed only in the external reflector and where it was placed in both the internal and external reflectors.

Switching from the 6-pass to the OTTO refuelling cycle increased the maximum DLOFC temperature for the PBMR-400 from its typical value of 1880 °C to 1979 °C. However, placing a tailored poison distribution in only the external reflector reduced the maximum DLOFC fuel temperature 1584 °C. Placing the poison in both the central and external reflectors reduced the maximum DLOFC temperature substantially to only 1519 °C.

However, the more serious problem was that the poison in the external reflector substantially reduced the thermal neutron flux in the external reflector, which reduced the number of neutrons that were available to be absorbed by the control rods, which were placed in the external reflector. This meant that placing poisons in the external reflector reduced the ability of the control rods to shut the reactor down safely. For this reason, it was concluded that reducing DLOFC temperatures by means of poison placement in the external reflectors of pebble bed reactors with cylindrical cores was not an optimal strategy.

Based on these results, it was concluded that for the future development of this technique it would be best to revert to core designs with a central reflector and to place the bulk of the poison in the central reflector.

Key terms: Nuclear Power Plants (NNP), High-Temperature Reactors (HTR), Once-Through-Then-Out (OTTO), Depressurised Loss of Forced Coolant (DLOFC), Very Superior Old Program (VSOP), Pebble Bed Modular Reactor (PBMR), Neutron Poison (NP), Boron-10 (^{10}B)

ABBREVIATIONS

AVR	Arbeitsgemeinschaft Versuchsreaktor
C	Conversion ratio
DLOFC	Depressurised Loss of Forced Cooling
ENDFB	Nuclear library name: Evaluated Nuclear Data File/B
GWd/THM	Gigawatt days/ton heavy metal
HM	Heavy metal
HTGR	High-Temperature Gas-Cooled Reactor
HTR	High-Temperature Reactor
HTR-PM	High-Temperature Reactor-Pebble-Bed Modules
IAEA	International Atomic Energy Agency
K_{eff}	Neutron multiplication factor of a finite reactor core
K_{∞}	Neutron multiplication factor of an infinite reactor core
LEU	Low Enriched Uranium
NPP	Nuclear Power Plant
NWU	North-West University
NRF	National Research Foundation
OTTO	Once-Through-Then-out
PBMR-DPP	Pebble-Bed Modular Reactor Demonstration Power Plant
Pu	Plutonium
TRISO	Tri-Structural Isotropic
U	Uranium
VSOP	Very Superior Old Programs
VSOP 99/05	VSOP 99, version 5
Th	Thorium

TABLE OF CONTENTS

ACKNOWLEDGEMENTS.....	I
ABSTRACT	II
ABBREVIATIONS	IV
1. INTRODUCTION	1
1.1 Background	1
1.2 Problem statement	3
1.3 General Purpose of study	3
1.3.1 Aim	3
1.3.2 Objectives.....	4
1.4 Methods.....	4
1.5 Structure of the study	6
2. LITERATURE REVIEW.....	7
2.1 High-temperature reactors.....	7
2.1.1 Types of high-temperature gas-cooled reactors.....	7
2.1.1.1 Pebble bed modular reactors.....	7
2.1.1.2 The prismatic block reactor	8
2.1.2 Safety of high-temperature reactors.....	10
2.1.3 Fuel characteristics.....	11
2.1.4 Fuel cycle	13
2.1.4.1 Low enriched uranium fuel cycle.....	13
2.1.4.2 Thorium based fuel cycles	13
2.1.5 Thorium as a nuclear fuel	14
2.1.6 Description of the South African PBMR	16
2.1.7 Previous work Done on PBMR-400 DPP	16
2.2 Multi-pass and Once-Through-Then-Out refuelling schemes	17

2.3	Depressurised loss of forced coolant.....	19
2.4	Neutron poison	19
2.5	Safety shut down margins	20
2.6	General Definitions.....	21
3.	METHODOLOGY	23
3.1	VSOP code	23
3.2	Quality control of the VSOP input file and model for PBMR-400 DPP	27
3.3	Simulations of PBMR-400 DPP	29
3.3.1	PBMR-400 DPP core design	29
3.3.2	Simulation of neutron poison placement into both the internal and external reflectors.....	33
3.3.3	Simulation of neutron poison placement into the external reflector only	35
4.	RESULTS AND DISCUSSION	37
4.1	DLOFC temperature results	37
4.2	Effect of poisons in the reflectors on the cold shutdown margins of the control rods	45
5.	CONCLUSION AND RECOMMENDATIONS	46
5.1	Conclusion.....	46
5.2	Recommendation for future studies	47
6.	REFERENCES	49

LIST OF TABLES

Table 2-1:	Pebble bed adopted safety limits (Tchonang Pokaha, 2018).....	11
Table 3-1:	Description of the fuel and reactor (Tchonang Pokaha, 2018).....	32

LIST OF FIGURES

Figure 2-1: The pebble bed reactor concept (World Nuclear Association).	8
Figure 2-2: Conceptual view of typical prismatic reactor core. www.sciencedirect.com/science/article/pii/S1738573315301042	9
Figure 2-3:TRISO fuel particle diagram (Tchonang Pokaha, 2018).....	12
Figure 2-4:Thorium transmutation chain into ^{233}U https://energyeducation.ca/encyclopedia/Thorium_fuel_cycle	15
Figure 2-5:Comparison of the OTTP and multi-pass refuelling scheme (Hoai Nam Tran,Van Khanh Hoang, 2012)	18
Figure 2-6: Xenon-135 fluctuations during power changes (intergrated Publishing,Inc, 2019).....	20
Figure 3-1:VSOP code flow Chart for HTR core physics calculations (Geringer, 2010).....	26
Figure 3-2: Standard axial profiles of a PBMR-400 DPP fuelled with a 16g heavy metal loading per pebble mixture of thorium and 30 a/o% LEU, with average enrichment of 10.8975 a/o%.	27
Figure 3-3: Standard axial profiles of a PBMR-400 DPP fuelled with a 16g heavy metal loading per pebble mixture of thorium and 20 a/o% LEU, with average enrichment of 7.265 a/o%.	28
Figure 3-4:VSOP reactor geometry (Khoza, 2012).	30
Figure 3-5: Schematic representation of the placement of five different concentrations of ^{10}B in the central and external reflector.....	34
Figure 3-6: Placement of five different concentrations of ^{10}B in the external reflector.	36
Figure 4-1: Standard axial profiles of a PBMR-400 DPP fuelled with a 16g heavy metal loading per pebble mixture of thorium and 20 a/o% LEU, with average enrichment of 7.265 a/o%.	37
Figure 4-2: P, T axial profiles of a double layer of five different concentration of ^{10}B in both the central and external reflectors.	40
Figure 4-3: P, T axial profiles of a double layer of five different concentration of ^{10}B on the external reflector only.	42

Figure 4-4: DLOFC temperatures as a function of time for the two placement strategies of the neutron poison.	44
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1. INTRODUCTION

1.1 Background

Safety in nuclear power plants (NPP) is a major priority due to concerns following past nuclear accidents. Nuclear power plant technology is not fail-proof. Hence research needs to be continually carried out to improve the safety of NPP technology.

High-Temperature Reactors (HTR) are regarded as part of future options for nuclear industries due to their strong inherent safety features. Consideration is given to the fact that they are designed to retain almost all fission products up to roughly 1600 °C fuel temperatures during Depressurised Loss of Forced Coolant (DLOFC) accidents and that these reactors provide online refuelling by allowing fuel pebbles to circulate continuously through the core of the reactor. Online continuous refuelling uses multi-pass or Once-Through-Then-Out (OTTO) refuelling schemes (Marius Tchonang Pokaha & Dawid.E Serfontein, 2017).

There are advantages to both replacing an annular core around a central reflector with a cylindrical core without a central reflector, as well as replacing a multi-pass refuelling cycle with an OTTO cycle:

- The central reflector of the PBMR-400 is about 12 metres high and only 2 metres in diameter. Obviously, this creates the risk of it becoming unstable and falling over, which would bring safety risks. So, getting rid of it will reduce licencing risk as well as accident risks during operation.
- The OTTO refuelling scheme is also cheaper to build than a multi-pass scheme because it eliminates the need for fuel handling systems that assess the integrity and fuel burnup levels on each pass before deciding whether to recirculate an individual fuel sphere to the top of the core or discard it to the spent fuel tank. Because of the OTTO scheme's reduced complexity, licencing risks and thus financial risks are also reduced (Marius Tchonang Pokaha & Dawid.E Serfontein, 2017).

However, cylindrical cores and OTTO refuelling schemes also have disadvantages:

- The annular core of the PBMR-400 is only 85 cm thick. So, if one were to simply remove its central reflector, with a radius of 100 cm, that would increase the distance from the innermost fuel to the inside of the external reflector from 85 cm to 185 cm. This would greatly increase the total thermal resistance of the decay heat that must travel from these inner fuel layers to the external reflector, during a DLOFC accident, which would again greatly increase the temperature difference between these central fuel layers and the inside of the external reflector required to drive the evacuation of a

given outward flux of decay heat. Therefore, replacing an annular core around a central reflector with a cylindrical core without a central reflector would normally greatly increase the maximum DLOFC temperature. To reduce the maximum DLOFC temperature back to the levels where the central reflector was still in place, the maximum thermal power output during normal operation would have to be cut back substantially. This largely explains the reduction in rated thermal power output from 400 MW for the PBMR-400 demonstration power plant (DPP) to only 200 MW for the PBMR-200. Obviously, this also halves the income from power sales, which is problematic.

- Switching from a multi-pass to an OTTO cycle also greatly increases the maximum DLOFC temperature. Different from the multi-pass refuelling scheme that mixes fresher and older fuel spheres throughout the core, the OTTO scheme concentrates all the fresh fuel at the top and progressively older fuel towards the bottom. This results in a much higher infinite neutron multiplication factor (K_{∞}) for the fuel at the top than at the bottom (Marius Tchonang Pokaha & Dawid.E Serfontein, 2017). This results in a very high-power density peak near the top of the core, with much lower power densities towards the bottom. This power hotspot near the top results in a similar hotspot in the DLOFC fuel temperature near the top of the core (Marius Tchonang Pokaha & Dawid.E Serfontein, 2017). Therefore, switching from the standard 6-pass recirculation refuelling scheme of the PBMR-400 leads to an increase in the maximum DLOFC temperature from about 1580 °C to about 1980 °C, as was observed in the present study. 1980 °C greatly exceeds the safety upper limit of 1600 °C that was chosen for the South African pebble bed modular reactor (PBMR) project. It should be noted that some research suggests that with improved fuel design this limit could be increased substantially. However, since such research falls outside the scope of the current research project, the traditional safety limit of 1600 °C has been adopted. To reduce the maximum DLOFC temperatures for OTTO cycles back to the levels for the multi-pass cycles from which they were conceptually derived, their maximum thermal power output during normal power output needs to be reduced greatly, typically of the order of 50%. Several pebble bed reactors with both cylindrical cores and OTTO refuelling cycles have recently been proposed. The arguments stated above would explain why the highest rated thermal power output for these designs is 100 MW only.

Even so, the designers of these commercial reactors claim that pebble bed reactors with cylindrical cores and OTTO cycles would be more profitable than the much higher performing models with annular cores and multi-pass refuelling cycles. Therefore, for this study it was decided to investigate methods for reducing maximum DLOFC temperatures

in a pebble bed reactor with a cylindrical core and OTTO cycle, without having to reduce the power output.

Previous studies have been carried out successfully to reduce maximum DLOFC fuel temperatures for the PBMR-400 MW core to about 300 °C below the chosen safety limit of 1600 °C. Such reductions have been achieved through the introduction of neutron poison into its central reflector (Marius Tchonang Pokaha & Dawid Serfontein, 2018). This strategy was successful both for the standard six-pass and the OTTO refuelling schemes. Therefore, there is a possibility of extending these gains to cylindrical cores such as the PBMR-200. However, since cylindrical cores do not have central reflectors, the only option would be to place the required neutron poison in the external reflector.

Previous studies showed that it is normally only a relatively small DLOFC temperature hotspot that results in the upper limit for the maximum DLOFC temperature being exceeded. Therefore, what is needed is to optimise the neutron poison placement in the external reflector to suppress DLOFC temperature hotspots substantially by flattening the axial profile of the DLOFC temperature. So, while this strategy might not substantially reduce the average DLOFC temperature, it can be expected to greatly reduce the maximum DLOFC temperature.

1.2 Problem statement

The problem to be solved is to change the multi-pass refuelling scheme of a pebble bed reactor with a cylindrical core into an OTTO cycle and to design a neutron poison distribution for its external reflector that will reduce the maximum DLOFC temperature enough to compensate for the increase in the DLOFC temperatures affected by changing from the multi-pass to the OTTO cycle. The nett result must be that it is not necessary to reduce the power output of the reactor and that all its other safety limits will still be adhered to.

1.3 General Purpose of study

1.3.1 Aim

The aim of this study is to change the multi-pass refuelling scheme of the PBMR-200 reactor into an OTTO cycle and to design a neutron poison distribution for its external reflector that will reduce the maximum DLOFC temperature enough to compensate for the increase in the DLOFC temperatures affected by changing from the multi-pass to the OTTO cycle.

1.3.2 Objectives

The objectives of this study are to:

- Design a Once Through Then Out (OTTO) refuelling cycle to replace the standard multi-pass refuelling cycle for a cylindrical core, such as the PBMR-200.
- Determine the increase in the maximum Depressurised Loss of Forced Coolant flow (DLOFC) temperature, affected by changing to the OTTO cycle.
- Design a boron-10 (^{10}B) neutron poison distribution for its external reflector that will reduce the maximum DLOFC temperature to below the level for the standard multi-pass refuelling cycle, without having to reduce the power output and without breaching any of the standard safety limits.

1.4 Methods

VSOP 99_05 is a well-known numerical simulation code for the diffusion approximation for the neutronic core physics of pebble bed Reactors and was also the code used by the design team of the PBMR in South Africa. Therefore, it was selected as the simulation code for this study. It has a reactor imitation setting to perform any combined neutronic and thermal-hydraulic analysis.

Initially the plan was to do all the simulations for the PBMR-200, as stated in the Aims and Objectives above. However, it was later discovered that the required input model to simulate a DLOFC accident for the PBMR-200 was not available. Since all the required VSOP 99_05 models for the PBMR-400 were available and since creating such a model for the PBMR-200 fell outside the scope of this study, it was decided to mimic placement of neutron poisons in the external reflector of the PBMR-200 by using the model for the PBMR-400 DPP. This has both an internal and an external reflector, but the poison would be placed only in the external reflector. The rationale behind this technique was that, although the central reflector in the PBMR-400 DPP substantially changes the neutron energy spectrum and thus the neutron reactions in its central fuel layers, adjacent to the central reflector, the presence of this central reflector will not substantially affect the neutron energy spectrum in its external fuel layers, adjacent to its external reflector, or inside the external reflector itself. Based on this assumption we assumed that the change in the neutron reactions effected by placing neutron poisons in the external reflectors of the PBMR-400 DPP and the PBMR-200 would be similar and thus the one could be used to mimic the other. The increase in temperature of PBMR-200 OTTO cycle also does not differ that much from that of a modified OTTO cycle of PBMR-400 DPP done by (Marius Tchonang Pokaha & Dawid Serfontein, 2018) which resulted in temperatures of 1970°C. The change in temperature from a multi-pass to OTTO cycle in a PBMR-200

reactor is 1940°C this can be seen in (Geringer, 2010) studies. Therefore, the following methods were followed for the simulation of the Low Enriched Uranium/Thorium (LEU/Th) fuel cycle OTTO scheme PBMR-400 DPP by placing ^{10}B in the inner and outer core reflectors:

- An OTTO refuelling cycle for the PBMR-400 DPP, which had been designed by a previous student in the research group (Tchong Pokaha, 2018), was used to replace the standard 6-pass refuelling scheme.
- Since previous studies in the group produced better results with the neutron poison technique for LEU/Th fuel cycles than for the standard 9.6 wt% LEU fuel cycle of the PBMR-400, such a LEU/Th fuel cycle was implemented with a 20 wt% enrichment for the LEU and 16 g heavy metal (HM) per fuel sphere.
- Different ^{10}B concentrations were placed in different regions in the external reflector to improve the reduction in the maximum DLOFC temperature, under the stated restrictions.
- Standard simulations for fully inserting the control rods were carried out to assess their ability to keep the core safely shut down once the core had cooled after shutdown and most of the ^{135}Xe poison had decayed.

1.5 Structure of the study

1. Introduction: The study's motivation and objectives will be described.
2. Literature survey: This will provide the supporting information.
3. Method: The focus will be on the VSOP-99 stable status codes and how to perform the simulation.
4. Results and Discussion: This chapter will cover the results and how they were obtained, as well as a discussion of the findings.
5. Conclusions and recommendations: This chapter will present the conclusions and recommendations for the results obtained and recommendations for future research will be made.
6. References: Sources used in the research will be referenced.

2. LITERATURE REVIEW

2.1 High-temperature reactors

High-Temperature reactors (HTGRs) use ceramic materials that operate at very high temperatures. They are known to good inherent safety features due to their inner core structures which contain pebbles that have fissile and fertile fuel kernels (Tchonang Pokaha, 2018). The fuel kernels are mixed on a graphite matrix, which is known to be a moderator which helps to slow down neutrons in the reactor. HTGRs uses helium as a coolant to cool down the core when the fission reaction is taking place. Helium is the best material to be used due to its inert nature. It does not form any kind of reaction with reactor core materials and it has an effective coolant outlet temperature which is suitable for a closed cycle gas turbine plant (Boyes, 2017). HTGRs are used as part of generation IV reactors due to the advantages they display. Firstly, their net electrical efficiency is increased by the maximum temperature that the reactor can use while in operation, implying that the ratio of MW of electricity sent to the grid to the MW of thermal energy produced can use a direct Brayton helium cycle without the use of heat exchange (tran, 2012). Secondly the low power density and high thermal conductivity that the core structural materials possess aids with removing decay heat faster with conduction, convection and radiation. Lastly the fuel pebbles can withstand high temperatures up to 1600°C and still retain their form without releasing any dangerous levels of radioactive material to the environment (tran, 2012).

2.1.1 Types of high-temperature gas-cooled reactors

There are two types of high-temperature gas-cooled reactors. These are known as pebble bed reactors and prismatic block reactors.

2.1.1.1 Pebble bed modular reactors

Pebble bed reactors are online refuelling reactors which are usually loaded with fuel pebbles at the top of the reactor. The pebbles then flow through the reactor core until they reach the bottom of the core, where they are normally unloaded and evaluated for disposal as spent fuel or for recirculation through the core . The fuel load rate depends on the number of passes and the neutron economy of the reactor (Reitsma, 2012).

The Arbeit gemeinschaft Versuch Reaktor (AVR) is one of the first pebble bed reactors. It is a graphite driven, helium- cooled reactor with a rated power output of 46 MW thermal. The reactor operated from 1967 to 1988 and supported the advances and upgrades of

newer generations of pebble bed reactors by providing a large amount of data on the tasks of pebble beds. The AVR reactor produced a burn-up of up to 100 000 MWd/ T_{HM} (G Longoni ,RO Gates & BK,Mcdowell, 2015).

The HTR-PM commissioned in China is one of the modern pebble bed reactors, consisting of two units with a control output of 250 MW thermal. It is connected to a conventional steam turbine of 210 MW electric. The fuel pebbles contain a 7-g heavy metal load of UO_2 with an enrichment of 8.8%. The core of the reactor can take 520 000 fuel pebbles, expected to burn to 80 000 MWd / T_{HM} (Zhang, 2004).

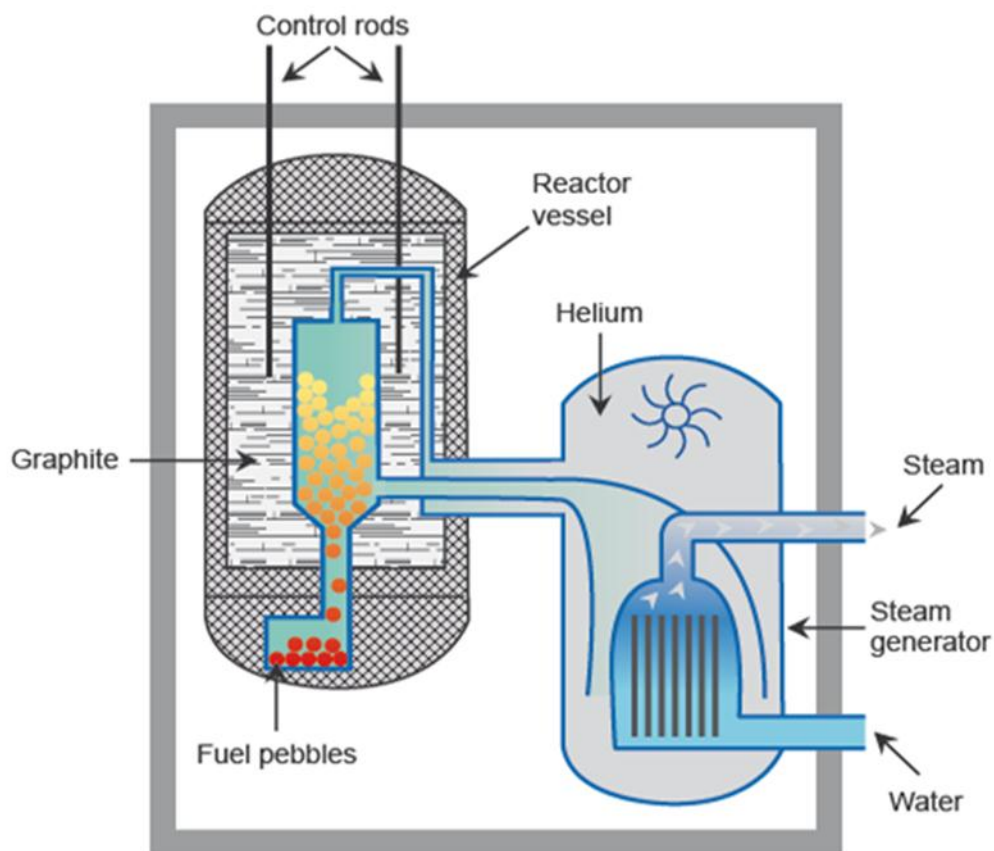


Figure 2-1: The pebble bed reactor concept (World Nuclear Association).

2.1.1.2 The prismatic block reactor

The prismatic block reactor core is made up of hexagonal graphite fuel blocks and reflector components, plenum components, start-up sources, and reactivity control material. The active core consists of hexagonal graphite fuel blocks with 210 visually impaired holes for compact fuel and 102 full- length channels for helium coolant flow. The fuel blocks are stacked to form ten high components of fuel. The fuel segments are packed in an annulus with components of the hexagonal graphite reflector in the internal and external regions.

Six focus reflector blocks and 24 side reflector blocks contain control rod channels (IAEA, 2010).

The DRAGON reactor was one of the first reactors and was operational from 1964 until 1975. It was a 20 MW_{th} graphite-moderated, helium-cooled reactor used for material testing and was used for (Th/U) O₂ and (Th/U) C₂ fuel coated particles. It had a hexagonal arrangement and was in a prism. It gave about 100 000 MWd/T_{HM} of burnup. (G Longoni ,RO Gates & BK,Mcdowell, 2015)

The high-temperature test reactor (HTTR) is a modern prismatic block reactor that has been operational since 1998 and originated in Japan. It is a helium cooled, graphite-moderated UO₂ reactor that produces 30 MW_{th} control power yields. It was primarily intended to demonstrate high temperature reactor technology and to produce hydrogen. (G Longoni ,RO Gates & BK,Mcdowell, 2015).

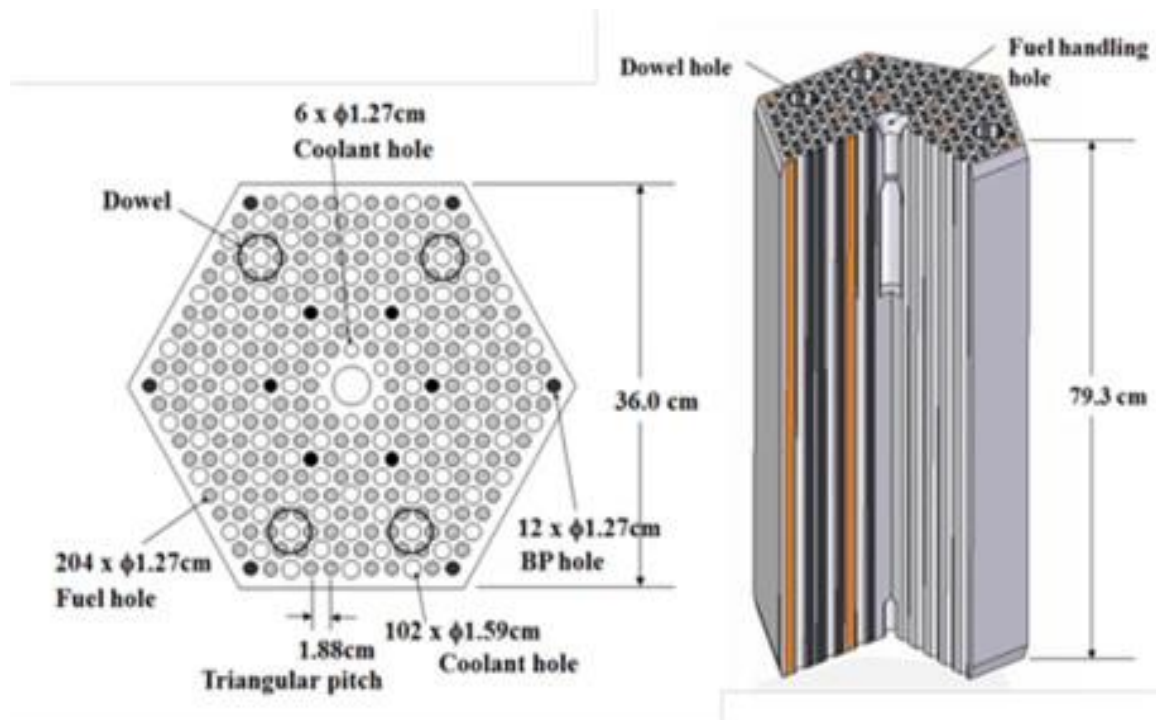


Figure 2-2: Conceptual view of typical prismatic reactor core.

(www.sciencedirect.com/science/article/pii/S1738573315301042)

2.1.2 Safety of high-temperature reactors

HTR technology offers improved safety and quality through its inherent design, ensuring that internal or external incidents will be unlikely to lead to the release of dangerous quantities of radioactive material as verified by many test and demonstration reactors worldwide (AREVA, 2014). The main feature of these inherently safety features is the design of the fuel elements that remain undamaged at very high temperatures, the efficient retention of fission products and the low power density of the core and its self-acting ability to remove decay heat (Kadak, 2005). Silicon carbide, which is one of the materials used in the coated fuel pebble, should be of a good quality to enable it to retain the fission products very well. In safety assessments completed to date, it is standard on these lines that one out of every 10 000 of these microspheres (pebbles) has a disfiguration that would discharge the fission products into the coolant. If this happens the discharge from the core would be very low to the point that no emergency response offsite would be required (Kadak, 2005). The low power density of the reactor suggests that the heat generated are volumetrically low and that there is a regular heat exchanger that removes heat through conduction and radiation, even if no convective core cooling occurs (tran, 2012). It is important to point out that the temperature achieved in the overall loss of coolant transient is below the fuel destruction limit temperature and that it usually takes 40– to 80 hours to reach the peak temperature. In this respect, the assumption that fuel disfiguration will not occur and that the core will not cause an emergency by melting down is demonstrated by tests and simulations carried out in Germany, Japan, China, South Africa and the United States. The safety of HTRs does not depend or rely on engineered systems but on the basic design and the laws of physics (Kadak, 2005).

Parameters	Limit
Maximum equilibrium power density	4.5 kW/fuel sphere. For the 15,000 coated particles in the standard PBMR fuel sphere, this translates to a limit of 300 mW/Coated particle
Maximum temperature during normal operation	1130 °C
Maximum fast fluency on the coated particles of spent fuel elements	8.0 E+21 neutrons/cm ²
Maximum fuel temperature during a DLOFC	1600 °C
Temperature Reactivity Coefficients	Negative under all plausible condition

Table 2-1: Pebble bed adopted safety limits (Tchonang Pokaha, 2018).

2.1.3 Fuel characteristics

The pebble nuclear fuel is designed with improved qualities that are intended to be used at high coolant temperatures and at the high nuclear burn-ups. The pebble nuclear fuel is known as tristructural isotropic (TRISO) fuel components. TRISO fuel was first established and used in Germany for the AVR reactor, the 46 MW thermal, pebble bed reactor and the 750 MW Thorium High-Temperature Reactor (THTR-300) (Jeffrey J Powers & Brian.D Wirth, 2010).

TRISO particles are made of five different coated layers:

- The fuel kernel in the middle of the coated particle can be an oxide, carbide or oxy-carbide mixed with heavy metals such as uranium, plutonium, thorium or a mixture of the heavy metals to make up nuclear fuels (Boyes, 2017).

- A porous carbon buffer surrounds the fuel kernel. This reduces the recoiling fission fragments and gives adequate space for internal gas build up.
- The external layers consist of an internal pyrolytic carbon layer, a silicon carbide layer and an external pyrolytic carbon layer. The pyrolytic carbon layers are relatively dense; their theoretical density is about 90% of 2.2 g/cm^3 (Jeffrey J Powers & Brian.D Wirth, 2010).
- The internal pyrolytic carbon layer shields the fuel kernel during manufacturing from destructive gases used to deposit the silicon carbide layer (IAEA, 2010).
- The silicon carbide layer functions as the primary pressure vessel for the coated particle. It bears the strains and pressures from the build-up of internal gas and it also gives a scattering diffusion barrier to maintain a strategic distance from the release of steam and fission products (Jeffrey J Powers & Brian.D Wirth, 2010).
- The external pyrolytic carbon layers protect the silicon carbide layer from composite flare-up throughout TRISO molecular activity and acts as an additional diffusion barrier to fission products (Jeffrey J Powers & Brian.D Wirth, 2010).

The main advantages of using TRISO particle fuel are improved inherent safety, increased fuel utilisation because of reaching high burn-ups and leading to higher fuel consumption before it is disposed of as nuclear waste (IAEA, 2010). Another advantage is that it creates less carbon monoxide and vaporous fission product load at a high level of burnup (Boyes, 2017). The performance of the TRISO coated particles can reach extremely high burnups that are approximated to be 220 000 MWD/THM) for both uranium and plutonium fuels.

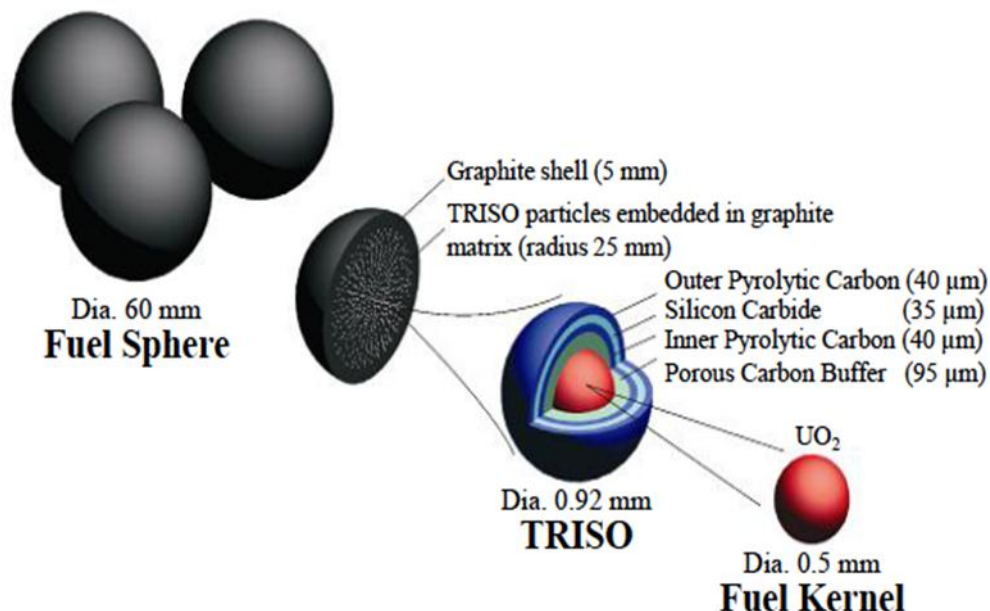


Figure 2-3:TRISO fuel particle diagram (Tchonang Pokaha, 2018).

2.1.4 Fuel cycle

The benefit of HTRs which differentiates them from other reactor types is their fuel. The fuel can be used in different fuel cycles which comprise numerous mixtures of fissile material such as (^{235}U , ^{233}U , ^{239}Pu) and fertile material such as (^{238}U , ^{232}Th) and ^{238}U , which can be fissionable as well (fission due to a fast neutron). The fuel types are classified into four groups, but only two fuel cycles will be investigated in this study, LEU and Th based fuel cycles (International Atomic Energy Agency, 2015).

2.1.4.1 Low enriched uranium fuel cycle

The LEU fuel cycle uses a uranium enrichment of 5% up to 20% in the reactor. These enrichments are higher in HTRs, compared to light water reactors. The LEU cycle was studied in the USA, UK, Germany and France from 1960 to 1970. The LEU fuel, mainly UO_2 has been utilised in HTRs around the globe in reactors from both past and current eras. The benefit is that the LEU fuel cycle will be chosen as the perspective fuel in all future HTR ventures and that globally there is vested interest in LEU fuel (International Atomic Energy Agency, 2015).

2.1.4.2 Thorium based fuel cycles

There are three kinds of thorium-based fuels cycles, the High Enriched Uranium (HEU)-thorium fuel cycle, the LEU-thorium fuel cycle and the thorium-plutonium (Th/Pu) fuel cycle. This study will consider the LEU-thorium fuel cycle only.

In the late 1970s, research on this cycle was conducted in the United States because of the Non-Proliferation arrangement (Boyes, 2017). The idea was to explore fuel cycles suitable for reducing the dangers of proliferation associated with the use of fissile materials that could be used to produce atomic weapons. The HEU fuel cycle investigated the use of cycles with limited enrichment levels of 20% ^{235}U or 12% ^{233}U with a specific amount of thorium (IAEA, 2010). This cycle made it challenging to manage the large nuclei of uranium and thorium. The thorium- based ^{233}U has a high neutron multiplication factor in contrast to the ^{238}U formed by ^{239}Pu (International Atomic Energy Agency, 2015). ^{232}Th has an epithermal capture cross-section which is four times smaller than ^{238}U , which prompts fewer captures. This leaves more neutrons accessible to fission the fissile fuel, which will then deliver more fission neutrons, which will increase the neutron multiplication factor of a finite reactor core (K_{eff}). This thorium is converted to ^{233}U , the best HTR thermal fuel. In thermal neutron energy spectra, ^{233}U has a significantly improved neutron economy and a much-improved conversion ratio compared to ^{239}Pu , which is produced from ^{238}U (Marius Tchonang Pokaha & Dawid E. Serfontein, 2016). This explains why the

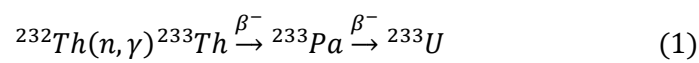
replacement of ^{238}U with ^{232}Th results in fewer neutron captures in the ^{232}Th than in the ^{238}U and more fission neutrons from the ^{233}U than in the ^{239}Pu (M Lung & O Gremm, 1997).

2.1.5 Thorium as a nuclear fuel

Thorium, like iron and uranium, is an essential element of nature. Like uranium, its properties enable it to fuel a nuclear chain reaction that can fission and generate power in a nuclear plant. Thorium is more abundant in the crust of the earth than uranium with a concentration of 0.0006% vs 0.00018% for uranium. This is often cited as a significant advantage, but only if the reserves are deductible economically (Whatisnuclear.com, 2018).

Thorium cycles only allow thermal reactors to breed. More neutrons are discharged into a thermal reactor per neutron absorbed into the fuel. This implies that reactors could be fuelled without mining any new ^{235}U for reactivity boosts if the fuel is reprocessed, which means that nuclear fuel resources can be stretched by two requests for size without a portion of the complexities of fast reactors (Tchonang Pokaha, 2018). The Th-U fuel cycle does not radiate ^{238}U and thus does not produce transuranic particles such as plutonium, americium, curium, etc. These transuranic products are the real concern for long-term nuclear waste. Th-U waste will thus be less poisonous in the multi-year time frame (Whatisnuclear.com, 2018).

Thorium itself will not cause fission and discharge energy because it is known to be fertile. When bombarded with neutrons, it will transition to a fissile uranium isotope called ^{233}U , which will soon fission and discharge energy when it absorbs a neutron. ^{232}Th neutron absorption changes to ^{233}Th with a half-life of about 22 minutes and a beta-decay (β^- decay) to protactinium-233 (^{233}Pa), with a half-life of 27 days and it beta- decay to ^{233}U . (Tchonang Pokaha, 2018)



A portion of the reproduced ^{233}U is replaced by additional neutron absorption with ^{234}U . ^{234}U is an unwanted parasite absorber of neutrons. It changes to the fissile ^{235}U , a commonly occurring uranium isotope, and this compensates for this neutronic disadvantage. The development of ^{234}U may be apparent in fuel cycles such as the multi-use of Th- ^{233}U fuels. A core ^{233}U generally produces more neutrons when splitting than either the ^{235}U or the ^{239}Pu . A greater number of neutrons is created and discharged into the surrounding fuel for each thermal neutron consumed in a ^{233}U fuel. This gives a better reactor neutron economy (Marius Tchonang Pokaha & Dawid.E Serfontein, 2017).

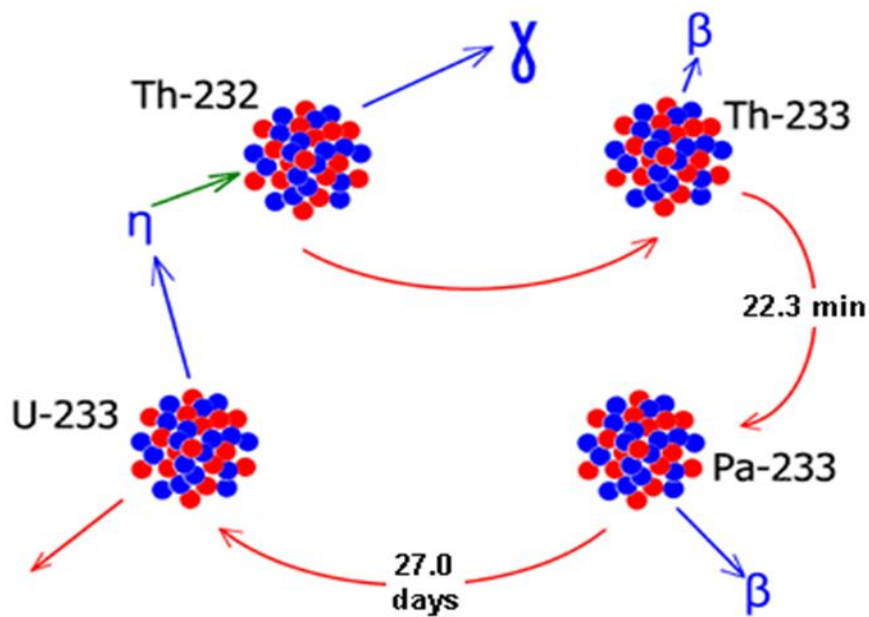


Figure 2-4: Thorium transmutation chain into ^{233}U

(https://energyeducation.ca/encyclopedia/Thorium_fuel_cycle)

Thorium is recognised as safe to proliferate and contrasts with U-Pu cycles. The problem with plutonium is that it can be artificially isolated from the waste and used to create nuclear weapons (Tchonang Pokaha, 2018). Even reactor-grade plutonium can be transformed into a nuclear weapon if carefully done. Apart from Pu, thorium cycles are superior in this respect and thorium has extra self-shielding from the hard gamma beams released due to ^{232}U , making it more challenging to steal thorium-based fuels (Tchonang Pokaha, 2018). The heat from these gammas makes the creation of weapons difficult, as it is difficult to prevent the pit from melting due to the heat. The gammas come from the ^{232}U decay chain, not from the ^{232}U itself. This implies that the contaminants can be isolated artificially and that the material would be much easier to work with. ^{232}U has a multi-year half-life, so it takes a long time to return to these gammas.

2.1.6 Description of the South African PBMR

The South African PBMR has been described as modular with integrated groups of up to eight independent units at the same site. The ability to increase the number of units was expected to create a more appropriate plan for small national power frameworks and frameworks where the request was isolated (Thomas, 2011). The South African PBMR has slight differences from the German reactor. The PBMR was initially proposed in the 1990s, with the objective of planning and commissioning a demonstration thermal 400 MW power plant. The significant advancement compared to previous pebble bed designs was that the helium coolant would be fed directly to a gas turbine rather than through a conventional steam turbine steam generator (Khoza, 2012). It was anticipated that the efficiency with which the reactor energy would be used would be increased, but this would reduce the capital collected through a toll per installed kW electric (Thomas, 2011). The PBMR nuclear power plant is a graphite-moderated, helium-cooled reactor that uses nuclear fission to generate heat and a direct cycle power conversion unit in which heat is converted into electricity using a turbine-driven generator. The reactor to be evaluated in this study is the PBMR-400 DPP, and the PBMR-200 MW core is mimicked with the 400 MW reactor. The discrepancy between the two plants is that the PBMR-200 DPP has a cylindrical core that does not have a central reflector but an external reflector and has a thermal power output of 200 MW. On the other hand, the PBMR-400 DPP has an annular core that includes both internal and external reflectors and thermal power output of 400 MW.

2.1.7 Previous work Done on PBMR-400 DPP

Several studies have been conducted on coupling neutronic and thermal hydraulics on the PBMR DPP-400 to reduce the most extreme DLOFC temperatures in transient conditions. The main difference between the PBMR-200 DPP and the PBMR-400 DPP is that the PBMR-200 DPP has no internal reflector and the PBMR-400 DPP has an internal reflector. The studies show compelling methods for reducing DLOFC temperatures by improving the reactor power profiles and reducing peaking factors. In 2014, Serfontein used ^{10}B neutron poison in a 400 MW PBMR core internal reflector, which uses a six-pass refuelling system. He suppressed the axial power peak near the centre of the core while increasing the power density close to the top and bottom of the core. In order to increase the heat leakage during transient DLOFC, the DLOFC temperature hotspot was spread across the reactor core. The fuel temperature of the DLOFC improved from 1581 °C to 1297.6 °C (Serfontein D. E., 2014). Tchonang Pokaha and Serfontein led more research by placing the neutron poison, ^{10}B in the central reflector of Th-LEU fuelled OTTO PBMR DPP-400 core. It was seen that bringing down the most extreme DLOFC temperatures

can be accomplished by expanding the neutron poison concentrations in various regions of the inner reflectors. However, the enrichment of the fuel ought to likewise be expanded with the goal that it can repay the loss of burn-up. The results showed a significant reduction in DLOFC temperatures in the symmetric core, from 1925 °C to 1509 °C (Marius Tchonang Pokaha & Dawid Serfontein, 2018). The fundamental purpose of placing the neutron poison in the internal reflector is that if coolant is lost in the core, the fuel pebbles cannot generally evacuate heat by convection because there is not any helium gas circulation to carry out the heat. Heat can only be evacuated by conduction and radiation. The neutron poison placement shortens the distance required to evacuate the heat to the external reflector in the reactor.

2.2 Multi-pass and Once-Through-Then-Out refuelling schemes

Pebble bed reactors are reactors that refuel online; they do not need to be shut down to load fresh pebbles. The fresh fuel is loaded at the top of the core during operation while depleted pebbles are removed from the bottom of the core. In a multi-pass refuelling scheme, fuel pebbles circulate more than once in the core, then the fuel integrity is checked before moderately burnt out pebbles are placed back into the top of the reactor core for recirculation. When target burn-up is reached, pebbles are disposed of as nuclear waste and sent to final storage. A multi-pass refuelling system has a flatter distribution of power in its core (Hoai Nam Tran, Van Khanh Hoang, 2012). However, the complex fuel handling system is expensive and produces enormous amounts of graphite dust caused by the recirculation of the spheres. In a multi-pass refuelling scheme, the pebbles cannot be followed and due to the recirculation, some pebbles can be burned to higher qualities than intended. In the OTTO refuelling system, pebbles pass through the core at a slower rate, and once they reach the bottom of the core, are disposed of as nuclear waste. An OTTO refuelling system has a higher power peaking factor, and in the case of an accident the system would have a higher fuel temperature. However, the complex fuel management system required for a multi-pass refuelling scheme is eliminated. The fuel spheres can be effectively followed in an OTTO cycle, which means that the exact location of the sphere is known during its entire lifetime (Boyes, 2017).

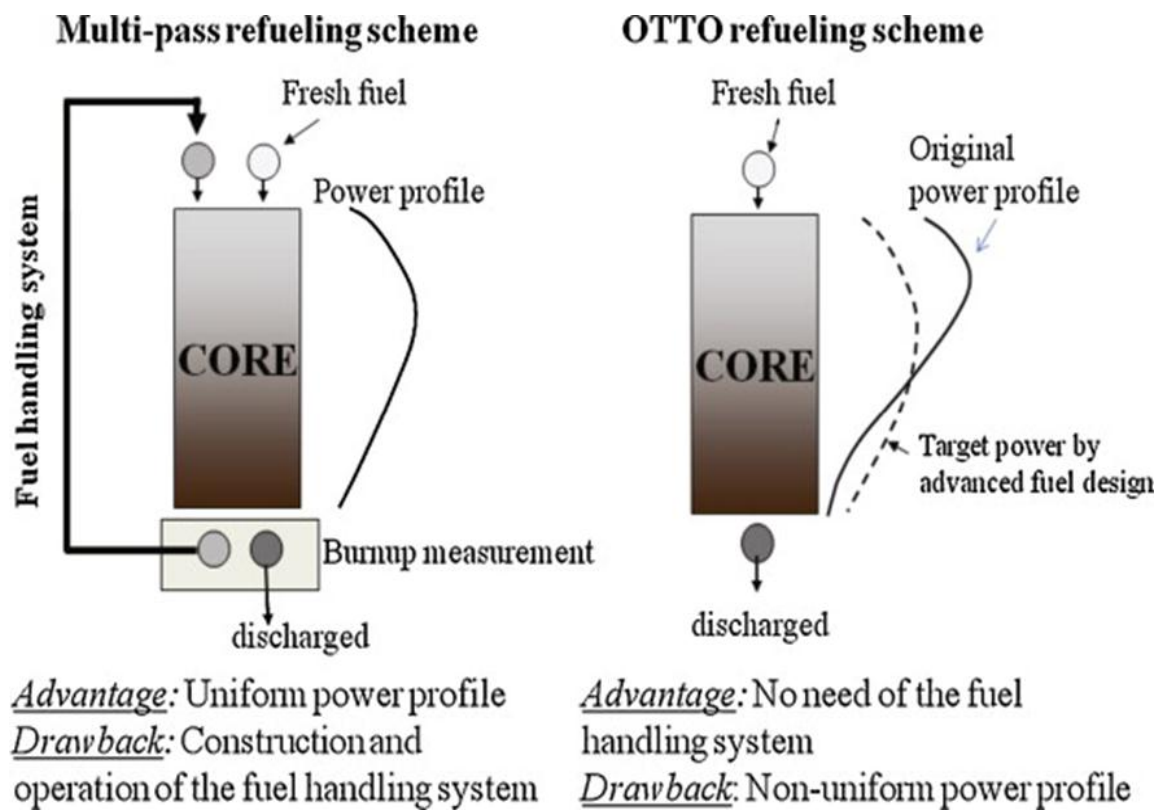


Figure 2-5: Comparison of the OTTP and multi-pass refuelling scheme (Hoai Nam Tran, Van Khanh Hoang, 2012) .

2.3 Depressurised loss of forced coolant

A depressurised loss of forced coolant (DLOFC) incident is an extreme planned transient for a high temperature reactor. In a DLOFC incident study, the coolant flow is expected to stop due to a coolant pipe break. The fission chain reaction is shut down in a few seconds when the control rods are embedded. The model expectations are that the depression and the addition of the control rods happen at zero time. Because of the broken coolant pipe, it is expected that there will be no air ingress, and this will lead to the core heating up. Helium pressure is normally at 7000 KPa under typical operating conditions (Graafland, 2014). The helium pressure falls to 100 KPa during a DLOFC transient. Therefore, the common transport mechanism under stable conditions, heat exchange by convection, is unimportant. The active approach to evacuating decay heat through conduction and radiation becomes a heat exchange process. These procedures remove the heat slower than with convection, and the temperatures of the reactor components, especially the fuel, will increase significantly along these lines (Graafland, 2014).

2.4 Neutron poison

Neutron poisons are elements with a high cross-section of neutron absorption and are intended to reduce the high reactivity of their different fresh fuel loads in a few reactors (Tchonang Pokaha, 2018). Due to the burning of the poisoning material, the negative reactivity of the combustible poison mass decreases over the lifetime of the core. ^{10}B is used for this study. Burnable neutron poison can also be loaded separately in the reactor core in desired positions to form or control flux profiles to maintain a strategic distance from aggressive flux and power peaks near specific reactor regions.

Boron is by far the most commonly used neutron poison in nuclear reactors due to the high cross-section of ^{10}B isotopes. ^{10}B has a high (n, α) cross-section of reaction across the whole neutron energy range. The (n, α) cross-section of reaction for thermal neutrons is around 3840 barns in slow energy regions of 0.025 eV (Nuclear Power, 2018). The cross-section of ^{10}B reduces monotonically with energy. Boron decays into helium and lithium which are stable isotopes. Therefore, there will be fewer difficulties with decay heat of burnable poisons used in the reactor core (Nuclear Power, 2018).

Although in pebble bed reactors the continuous online refuelling provides a low excess reactivity, neutron poisons have also been used to reduce the peaking factor of the axial power profile, which is very pronounced in the OTTO refuelling scheme (van Dam, 2000).

2.5 Safety shut down margins

The shutdown margin is the prompt amount of reactivity by which a reactor is sub-critical or would be sub-critical from its current condition if all control rods are fully embedded, other than the single rod with the highest integral worth, which is supposed to be completely withdrawn. (DOE, 1993).

It is necessary to have a continuous shutdown margin even when the reactor is critical. It is imperative that the control rods insert adequate negative reactivity to ensure complete and continuous shutdown during the core lifetime. A margin of shutdown between 1% and 5% is generally required (DOE, 1993). The stuck rod criterion refers to the fact that for the insertion of the highest worth control rod, the shutdown margin does not take credit. The application of the stuck rod criterion ensures that the failure of one control rod does not prevent the reactor from being shut down by the control rod system. After shutdown, Xenon quickly builds up in the reactor, reaching a peak within 10 to 11 hours of shutdown, as shown in Figure 2.6 below.

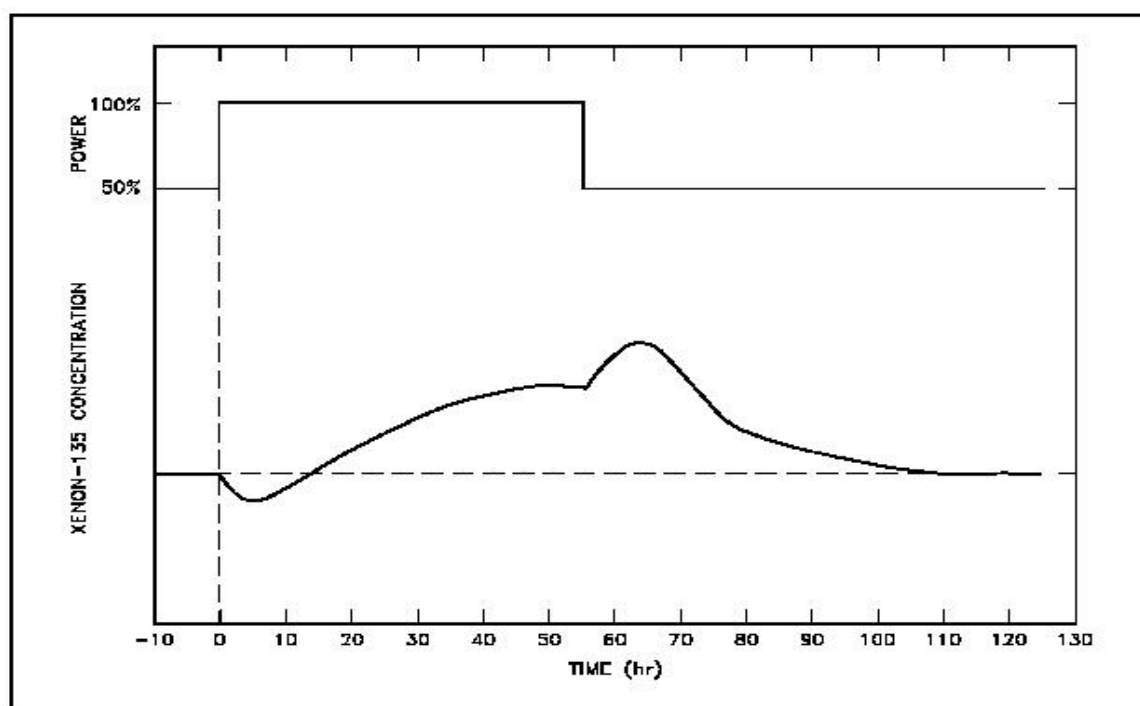
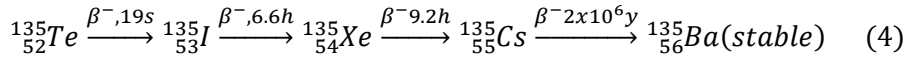


Figure 2-6: Xenon-135 fluctuations during power changes (integrated Publishing,Inc, 2019)

The peak occurs due to the heat of ^{135}I decay that creates ^{135}Xe that cannot burn out as the flux of neutrons is zero. Because it has a half-life of 9.2 hours, the ^{135}Xe build-up rate is much higher than the xenon decay rate. Half-life suggests an unstable isotope's decay rate (DOE, 1993).



${}^{135}\text{Xe}$ build-up after shutdown depends on pre-shutdown operating neutron flux. The higher the operating neutron flux, the higher the xenon peak. A higher operating neutron flux produces higher ${}^{135}\text{Xe}$ peaks that can cause problems when starting a reactor for operation. The reverse effect occurs when power increases, say from 50% to 100%, after a steady low power operation. Xenon burns rapidly while the production of iodine decay remains low (canteach, 2018). Reactivity increases and negative reactivity must be compensated by the system. This is complemented by adding poison as needed to the moderator. A transient xenon peak is generated by any reduction in power (intergrated Publishing, Inc, 2019). The lower the power, the lower the peak, and the sooner it takes place. A power reduction from 100% to 50%, for example, still results in an initial production excess over the loss, but the xenon remains burnt out by significant neutron flux. The height and duration of the peak are reduced, and the peak occurs earlier (canteach, 2018).

2.6 General Definitions

2.6.1 Criticality

Criticality occurs when the active multiplication factor K_{eff} is equal to one. When k_{eff} is below one, the reactor is known to be sub-critical, meaning that the nuclear reaction chain would not be sustainable. When it is above one the reactor is known to be supercritical, meaning that the nuclear reaction chain will be uncontrollable. K_{eff} describes the reactor's ability to sustain a nuclear reaction. In the following equation $v \sum_f \phi$ is the production rate of neutrons and $DB^2 + \sum_a \phi$ is the leakage rate added with the absorption rate for the next fission to occur (Geringer, 2010).

$$k = \frac{v \sum_f \phi}{DB^2 \phi + \sum_a \phi} \quad (5)$$

2.6.2 Reactivity

Reactivity is a measure of the state of a reactor in relation to where it would be in a critical state. If reactivity is positive, the reactor is known to be super-critical and when it is negative, the reactor is known to be sub-critical, and when the reactivity is zero, the reactor is critical.

For a finite reactor, the reactivity can be described by the following equation:

$$\rho = \frac{k_{\text{eff}} - 1}{k_{\text{eff}}} \quad (6)$$

The reactivity unit is pcm, and 1 pcm is equal to a reactivity of 10^{-5} .

2.6.3 Power density

In the centre of the reactor, the maximum flux value in a uniform bare reactor is always found. The centre of the core has a higher power density in the reactor because it is a function of the neutron flux (Geringer, 2010). It is described as:

$$P = E_R \sum_f \int_{-a/2}^{a/2} \phi(x) dx \quad (7)$$

Where P is the power in units of W/cm², E_R is the recoverable energy of 200 MeV or 3.2x10¹¹ Joules and , $\sum_f \phi(x)$ is the reaction rate, where Σ_f is the macroscopic cross-section in *neutrons/cm* and where $\phi(x)$ is the flux in *neutrons/cm².sec*

The maximum flux ratio over the average flux throughout the reactor indicates to what extent the maximum power density exceeds the average power density. The maximum power density thus occurs when the maximum neutron flux in the fuel element is positioned. The peak factor in the assembly is the ratio of the peak to the average power density (John R. Lamarsh, Anthony J. Baratta, 2001).

$$F_{pp} \equiv \frac{\sum_{fF} \phi_F(a)}{\sum_{fF}^{eff} \phi_{av}} \quad (8)$$

Where F_{pp} is the power peaking factor in units of W/cm², $\sum_{fF} \phi_f(a)$ is the reaction rate for the maximum flux (*fission/sec*) and $\sum_{fF}^{eff} \phi_{av}$ is the reaction rate of the average flux(*fission/sec*).

2.6.4 Burnup

Burnup is the energy produced in the fuel during the core residence period for the total mass of the fuel (Geringer, 2010). Burn-up (B) can be described by:

$$B = \frac{1}{\rho} \int_0^\rho \bar{E}_{f(t)} \cdot \phi(t) \sum_{f(t)} \cdot \phi(t) \cdot dt \quad (9)$$

Burnup is the total energy released by a certain amount of nuclear fuel (MWd) in fission, while specific burning is the burning of heavy metal originally contained in the fuel (MWd/t) per metric ton.

3. METHODOLOGY

3.1 VSOP code

Very Superior Old Programs, (VSOP) is an arrangement of related codes for the simulation of reactor life histories. VSOP includes codes like DATA-2, BIRGIT, TRIGIT, ZUT- DGL, GAM-1, THERMOS, THERMIX, FEVER. The code framework uses thermal information from a THERMALIZATION/GATHER library, using THERMALIZATION code generated spectrum (Nuclear Energy Agency, 2018). It enables users to follow the reactor lifespan from the beginning of the core to the core equilibrium state and the transient temperature is achieved through a quasi - static nuclear assessment. It includes neutron cross-section libraries and processing routines; repeated neutron spectrum assessment; calculation of 2-D and 3-D diffusion, depletion, and shutdown; in- core and out- of- quantity fuel management; analysis of fuel cycle costs; and thermal hydraulics in both stable and transient scenarios. Repeated calculations of different core physics structures guarantee the reliability of their feedback throughout the burning process, fuel shuffling simulation and differences in the core power rating (H.J. Rütten,K.A. Haas,H.Brockmann,W.Scherer, 2007). Different procedures were used to speed up iterative processes and improve internal data exchange. The code framework has been widely used for comparing thermal reactors, their fuel cycles, thermal transients and safety evaluations. In addition to its use in innovative work for the gas - cooled reactor at high temperatures, the framework was closely connected to the light water and heavy water reactors MAGNOX and RBMK. (Nuclear Energy Agency, 2018).

There are two libraries containing nuclear data for 184 isotopes. Fast and epithermal information in a GAM- I structure of 68 groups was arranged from ENDF / B- V and JEF- 1. Cross-section resonance information is given as input. Thermal information in a 30-groupstructure of THERMOS was extracted from a 96-group library of THERMALIZATION/GATHER by a significant neutron energy spectrum produced by the THERMALIZATION code. The matrices of graphite dispersion depend on the spectrum of young graphite phonons. A mixture of GAM and THERMOS codes calculates the neutron spectrum. In some core regions, they can also be used with different temperatures, burns and fuel component layouts (Nuclear Energy Agency, 2018).

The hot cell code THERMOS has been stretched out to treat the grain structure of the coated particles inside the fuel components, and the epithermal GAM code utilises changed cross sections for the resonance absorbers arranged from double heterogeneous ZUT-DGL counts (H.J. Rütten,K.A. Haas,H.Brockmann,W.Scherer, 2007).

The diffusion portion of the code is CITATION with 2 to 8 energy groups. It gives the neutron flux for 1515 compositions in 2-D cases, r-z (9999 combinations in 3-D cases, x-y-z). The burnup design has been created from the FEVER code. The build-up history of up to 49 fission product nuclides in the compositions is pursued explicitly. The diffusion portion of the program framework can be repeated at many short burnup time steps, and the spectrum portion can be repeated at more significant time steps when some considerable change in the spectrum is regular (Nuclear Energy Agency, 2018). The fuel management and cost portion perform the fuel shuffling and general assessments of the reactor and fuel component life history. The fuel management simulates the presently known shuffling and out of quantity progressions for different reactors. It has additionally been stretched out to incorporate the standard features of the pebble bed reactor, for example, burnup subordinate dependent optional reloading of components, isolated treatment of various fuel streams, and reusing in new fuel component types as indicated by a predictable mass balance and timing (Nuclear Energy Agency, 2018). Alternatively, a few unique kinds of data files can be set up with the characteristic data of the reactor life. These are utilised for more detailed examinations and display programs.

The restart choice permits the investigation of different periods of the reactor life, for example changes of the fuelling plan, of the burnup, of the power yield, of the coolant temperature, and of the reactivity impacts. The fuel cycle cost informational index is made for the present worth KPD code (Nuclear Energy Agency, 2018). Two-dimensional thermal hydraulic investigations for operating and transient conditions can be performed with the THERMIX code. This is a suite in VSOP that analyses the thermal hydraulics and safety of pebble bed reactors both in normal operation and accident situations (Yang Tang, Yangping Zhou and Zhiwei Zhou, 2013). The code consists of a steady-state or transient heat conduction module for general purposes and a quasi-stationary gas convection module. The finite-difference method is used by both modules with the successive point-wise over - relaxation solution. The THERMIX heat conduction module consists of a solid material two-dimensional transient temperature model and a one-dimensional transient temperature model of spherical fuel elements. It solves the general equation of time-dependent heat conduction with temperature-dependent material properties (Fubing CHEN , Yujie DONG , Yanhua ZHENG , Lei SHI & Zuoyi ZHANG, 2009).

In (Cleveland J.C. and Greene S.R., 1986), the elementary equations and numerical solution technique were discussed in full detail.

To calculate the temperatures through a DLOFC transient, THERMIX is notified that all helium coolant flow and pressure is missing, and that the fission reaction has ceased immediately, as described in section 2.3. The heat generation rate at that point reduces

to just around 7% of full power decay heat generation, which likewise diminishes exponentially after some time (Tchonang Pokaha, 2018). In any case, since all active cooling will be lost, the small amount of heat generation should now be taken out by conduction and radiation processes. The outcome is that heat creation surpasses heat evacuation, and in this manner, the core begins to heat up. As time advances the decay heat generation collapses to less than 1% and the heat evacuation rate increases as the core heats up (Tchonang Pokaha, 2018). Eventually, heat evacuation at that point begins to surpass heat generation, where after the core gradually begins to cool off. This tipping point ordinarily comes somewhere in the range of 24 to 48 hours into the transient. The point is to create a core in such a manner that the tipping point will be reached before the maximum temperature limit of 1600 °C is reached (Tchonang Pokaha, 2018)

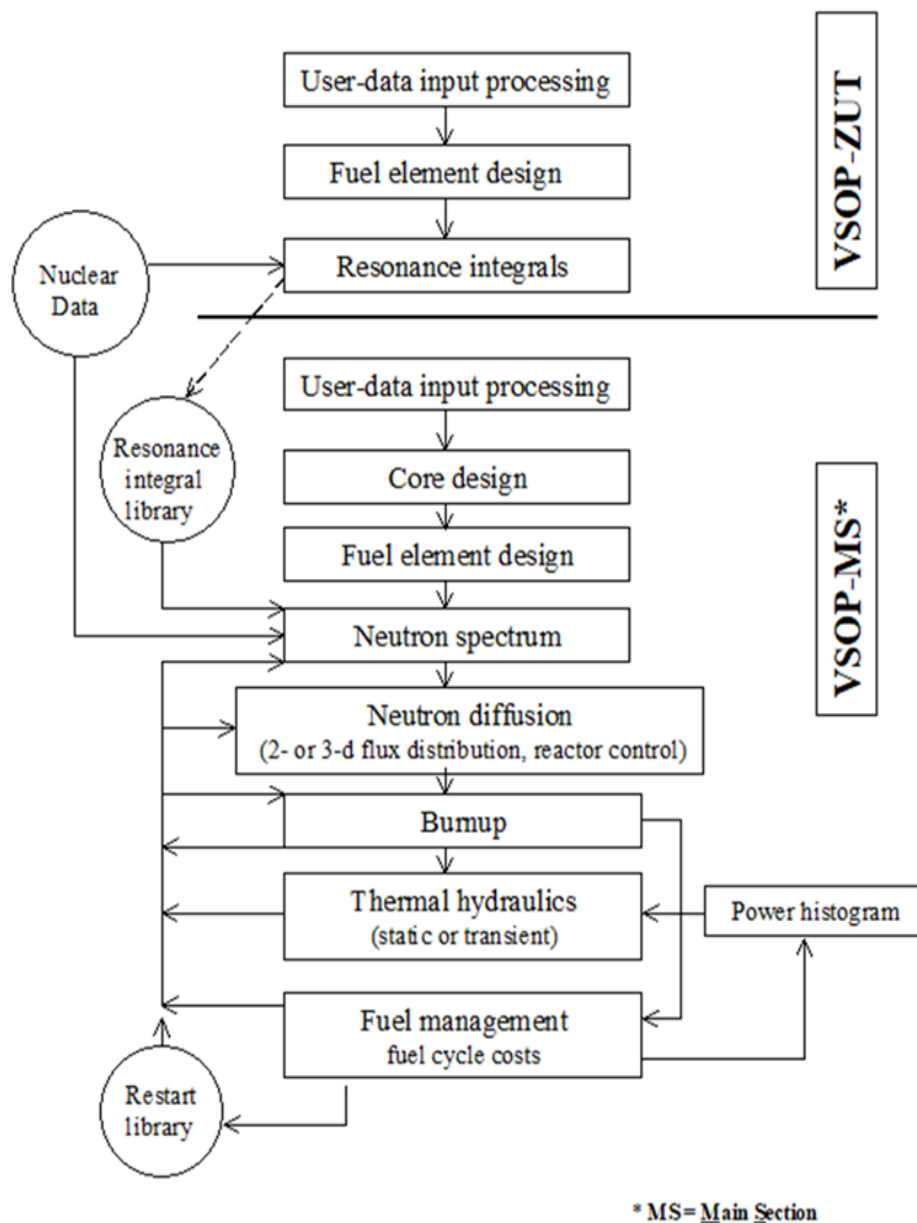


Figure 3-1:VSOP code flow Chart for HTR core physics calculations (Geringer, 2010).

3.2 Quality control of the VSOP input file and model for PBMR-400 DPP

The input of VSOP-99/05 was verified in three ways to demonstrate similarities and non-similarities in the results.

The first input method was simulated to change the fuel enrichment from the core that was simulated by Tchonang Pokaha and Serfontein by increasing the fuel enrichment by a factor of 1.5 from 16 g heavy metal loading per pebble thorium mixture and 20 a/o% LEU, with an average enrichment of 7.265 a/o%. The 1.5 factor led to 30 a/o% LEU, mixed with the Thorium to give an average enrichment of 10.8975 a/o%. The results showed a difference from those of Tchonang Pokaha and Serfontein.

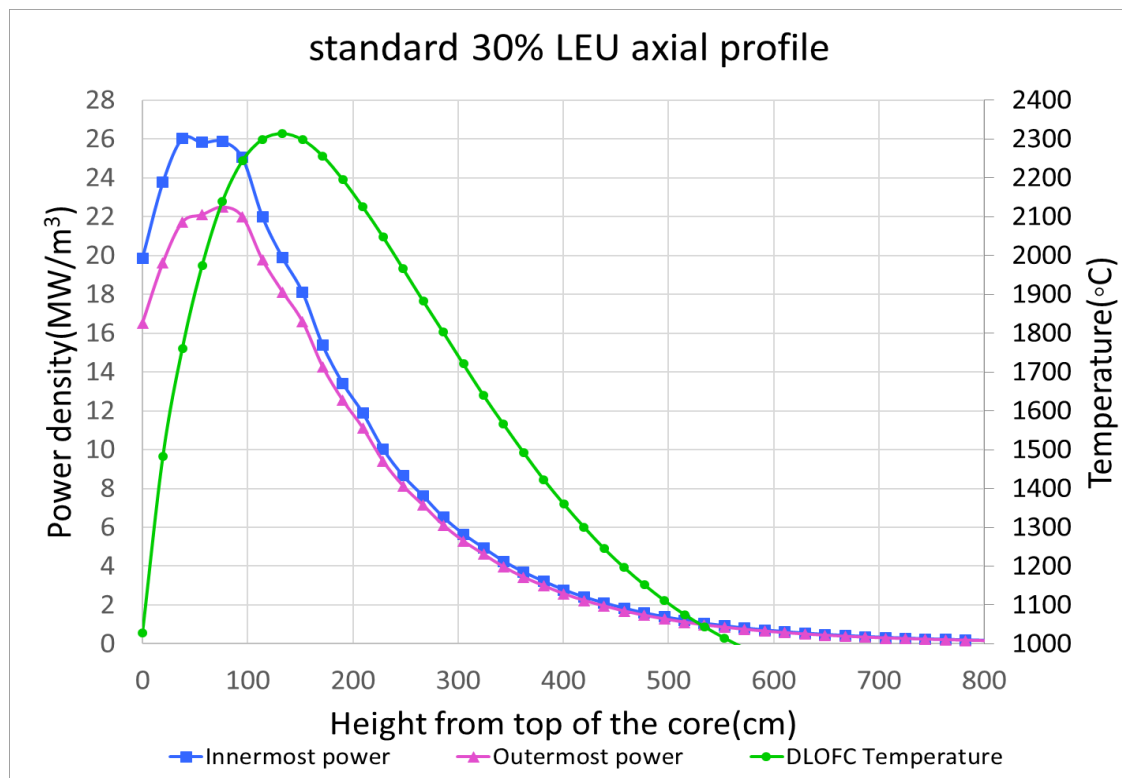


Figure 3-2: Standard axial profiles of a PBMR-400 DPP fuelled with a 16g heavy metal loading per pebble mixture of thorium and 30 a/o% LEU, with average enrichment of 10.8975 a/o%.

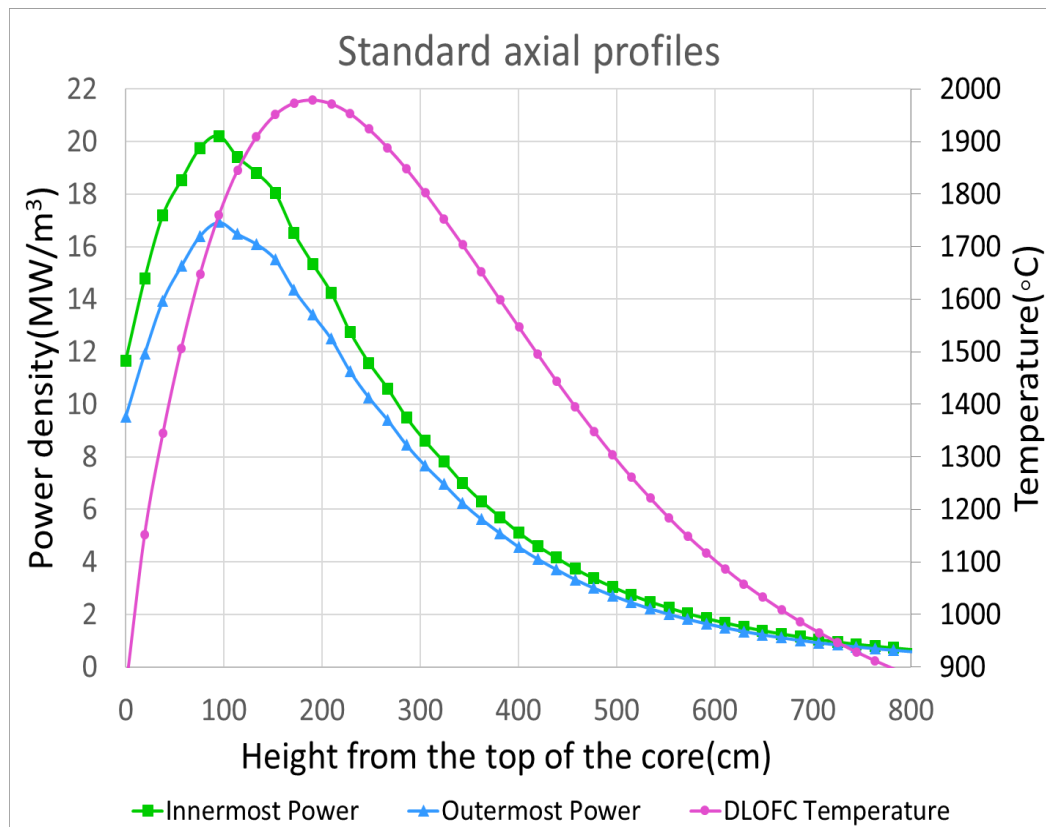


Figure 3-3: Standard axial profiles of a PBMR-400 DPP fuelled with a 16g heavy metal loading per pebble mixture of thorium and 20 a/o% LEU, with average enrichment of 7.265 a/o%.

In the second simulation poison was placed in the central reflector at 16 g heavy metal loading per pebble. This consisted of thorium mixed with 20 a/o% LEU, with an average enrichment of 7.265 a/o% and in the central reflector of 16 g heavy metal loading per pebble thorium mixture and 30 a/o% LEU, with an average enrichment of 10.8975 a/o%. The accuracy of the input model was compared to the 20 a/o% LEU model that produced the same results as those of Tchonang Pokaha and Serfontein and the 30 a/o% LEU model that yielded different results from those of Tchonang Pokaha and Serfontein.

Once the input models were verified, optimisation of the PBMR-400 DPP core was carried out. by placing neutron poison in the reflectors

3.3 Simulations of PBMR-400 DPP

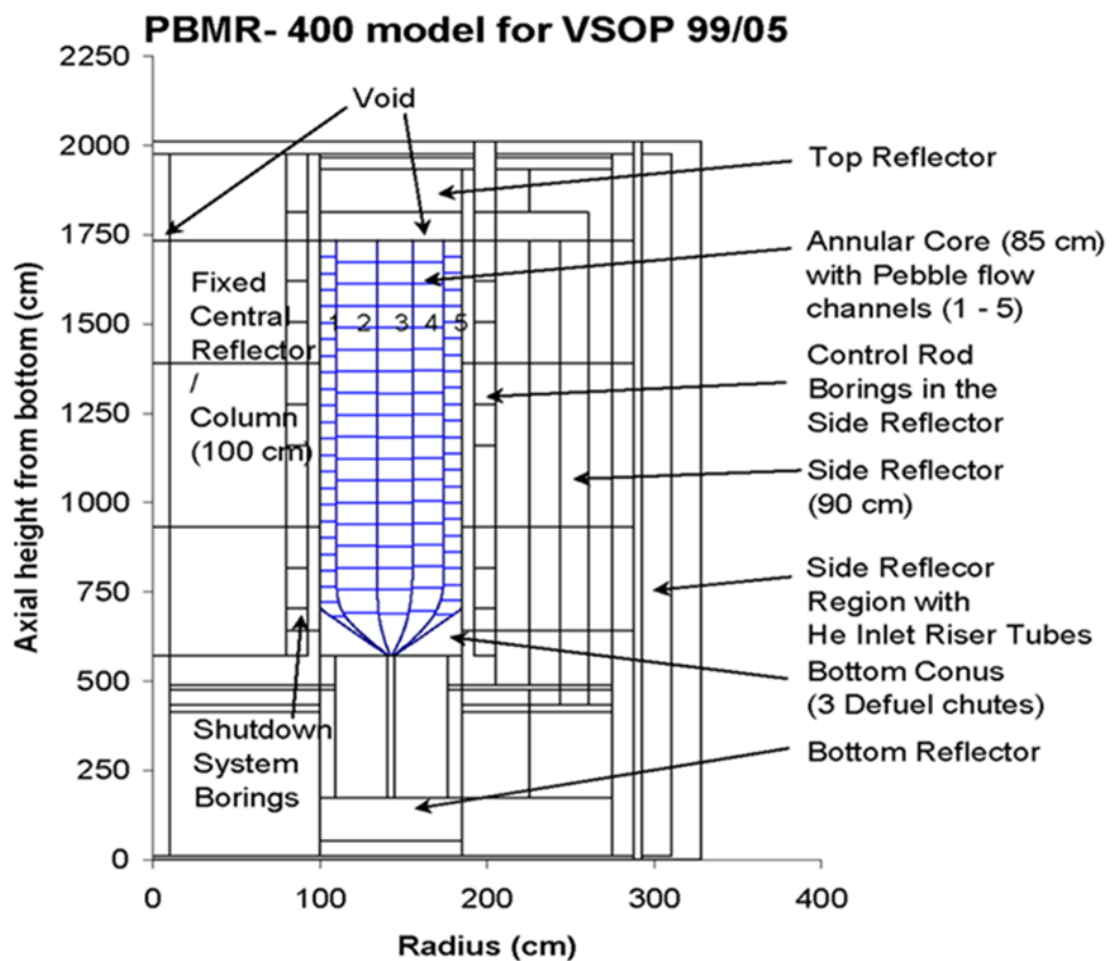
3.3.1 PBMR-400 DPP core design

The current study will focus on the PBMR-400 DPP that was redesigned to have an OTTO refuelling scheme core (Marius Tchonang Pokaha & Dawid Serfontein, 2018). The modified PBMR-400 DPP consists of an annular core, where the radius of the central graphite reflector is 100 cm, which is also the inner radius of the fuel annulus. Since the fuel annulus is 85 cm thick, the outer radius of the fuel annulus is 185 cm. The fuel annulus is surrounded by a 95-cm thick external graphite reflector, which also takes the shape of an annulus. The actual cylindrical core height is 11.625 m as described in Table 3.1 below. Since the core is modified to an OTTO refuelling scheme, the fuel will only be circulated once through the core at a much slower speed so that it can reach the burnup target in a similar timespan to the six-pass fuelling scheme (Marius Tchonang Pokaha & Dawid.E Serfontein, 2017). The reactor operates at a pressure of 90 bar. The core is divided into the standard five vertical fuel flow channels, as shown in Figure 3.2. The numbers of axial layers in each fuel flow channel are simulated to contain all the fuel inserted at the top during a single refuelling time step. With each refuelling step, the fuel layer at the bottom of each fuel flow channel is discarded to the spent fuel tank (Geringer, 2010). Each fuel layer then moves one position down to replace the discarded fuel layer and the top layer is then replaced by a layer of fresh fuel. The number of fuel layers in each fuel flow channel is 24, 18, 18, 18 and 24, respectively, with Channel (1) being the innermost one and Channel (5) the outermost. Since the lengths of all the channels are identical, the layers of Channel (1) and Channel (5) are shorter than those in the three central channels, by a ratio of 18/24. Since the refuelling time steps are identical for all channels, and since the fuel flow speed = layer length / refuelling time step, the flow speed in Channel (1) and Channel (5) is only 18/24 times that of the flow speed in the three central channels. This is to simulate the fact that the graphite fuel spheres in reality experience substantial friction against the graphite reflectors and therefore flow substantially slower than the fuel spheres further away from the reflectors.

One problem with this method is that it simulates actual continuous refuelling and thus continuous fuel flow, both in time and space, in rather coarse discrete time steps and spatial meshes. This results in the reactivity of the fuel and thus the power density of adjacent fuel layers changing in significantly coarse steps. The same applies to different concentrations of neutron poison in adjacent material regions in the reflectors. The long refuelling intervals also lead to a somewhat abrupt increase in reactivity each time refuelling takes place and each time fuel temperatures are recalculated and used to recalculate the cross-sections for the different nuclear reactions. Since it is known that the

neutron diffusion approximation is inaccurate at sharp boundaries between layers of substantially differing nuclear fuel or neutron poison concentrations, it is to be expected that these factors introduce instabilities and inaccuracies into the simulation results that are not present in an actual reactor. These might explain the instabilities in the simulated results that are reported later in the results section.

With this specific mesh pattern, the simulations of this reactor will give relevant data on the fuel costs, fuel shuffling, decay heat production and other core constraints during steady-state operations and during transient situations which are relevant to this study (Geringer, 2010). An online refuelling scheme warrants low excess reactivity of the core. It also eliminates the need to shut the reactor down for refuelling, which increases the availability factor of the plant.



Our modified fuel spheres for the PBMR-400 DPP use heavy metal loading of 16 g/sphere with enrichments of 20 a/o% for LEU/Th mixtures where the fuel particles are a homogeneous mix of LEU and Th. The reasoning behind this modification is that given a mass of ^{235}U , expanding the enrichment of the LEU decreases the mass of ^{238}U , which makes space for more Th. Essentially, for a given mass of LEU per pebble, expanding the heavy metal substance per pebble makes space for more Th (Marius Tchonang Pokaha & Dawid.E Serfontein, 2017). The inner fuel matrix has a radius of 2.5 cm and the outer graphite shell has a radius of 3 cm. Each fuel kernel has a diameter of 0.05 cm and fuel density of 10.4 g/cm^3 . As mentioned above, there are five fuel flow channels inside the core and 24 axial fuel layers in the two-external fuel pebble flow channels and 18 layers in the three internal channels. Every layer comprises six fuel batches. For the 6-pass refuelling scheme, one batch of the top layer is filled with fresh fuel, the next one with recirculated fuel that has passed through the core once, the next batch with recirculated fuel that has passed through the core twice, etc. However, for the OTTO cycle, all the batches are filled with fresh fuel. A tiny seventh batch was added to represent round-off errors in the calculated volumes of these layers (Khoza, 2012).

Parameter	Unit	Value
The volume of the fuel core	m^3	83.7
Packing fraction of fuel spheres		0.6
Height of core	m	11.625
Radii of fuel core annulus: inner/outer	m	1.00/1.85
Fuel recirculation		1
Number of fuel flow channels	No. of passes	5
Flow pattern	Steps/channel	24/18/18/18/24
Pressure of helium coolant	Bar	90
Heating of helium	$^{\circ}\text{C}$	500→944
Helium mass flow after reduction for cold bypass	kg/s	173.4

Cold bypass	%	10
Fuel sphere geometry:		
Outer radius of zones: Inner fuel matrix / outer graphite shell	cm	2.5 / 3.0
Heavy Metal per fuel sphere	g	16.0
Coated particles:		
Diameter of fuel kernels	cm	0.05
Fuel composition		ThO ₂ /UO ₂
Fuel density	g/cm ³	10.4

Table 3-1: Description of the fuel and reactor (Tchonang Pokaha, 2018).

During a DLOFC incident, rapid depressurisation of the core causes a complete loss of cooling. The VSOP code is a steady-state code. Therefore, for thermal hydraulics calculations, the reactor is assumed to be at a proper steady-state set-up, and the DLOFC begins immediately when the power of the reactor is changed from 400 MW to 0 MW (Tchonang Pokaha, 2018). As mentioned above, THERMIX will be notified immediately that all helium coolant movement and pressure is lost, and that the fission reaction chain has stopped. As soon as the helium gas is lost in the reactor, the decay heat will heat the core, and heat can only be evacuated using conduction or thermal radiation between the fuel spheres and lastly to the reflectors and from the external reflector outwards, through the core conditioning system and the steel pressure vessel, through the building to the atmosphere (Marius Tchonang Pokaha & Dawid.E Serfontein, 2017).

In this study, shaping and flattening of the power profiles will be achieved by placing neutron poisons in the reflectors of the core to suppress maximum DLOFC temperature. The most challenging problem of the OTTO scheme is that the fresh fuel pebbles are concentrated at the core top and the irradiated fuel pebbles are concentrated at the core bottom (Tchonang Pokaha, 2018). This results in a non-uniform axial power profile with an excessively high-power peak at the core top. By introducing neutron poison (NP) in the core reflectors to suppress the axial power profile near the top, the problem of the high-power peak at the top can be resolved. However, neutron poisons will increase fuel consumption (van Dam, 2000).

3.3.2 Simulation of neutron poison placement into both the internal and external reflectors

The process was as follows:

- The first simulations conducted in this study were to use enrichment values of 20 a/o% for LEU and 7265 a / o% for the thorium mixture.
- Five different concentrations of ^{10}B poison were then placed in the double layer of the central reflector and the external reflector based on the poison strength from the strongest to the weakest.
- The neutron poison was placed in the central reflector from the 57.3 cm of the core, and the most potent concentration of ^{10}B was between 172 cm and 345 cm and in the external reflector with the potent poison being placed at 171.9 cm along the reflector length.
- The concentration of ^{10}B was then adjusted to reduce the maximum DLOFC temperature to below 1600 °C.
- The refuelling interval was also varied until criticality was achieved, i.e. $k_{\text{eff}} = 1.0000$.
- The criticality was achieved at the following ^{10}B concentrations in the following material regions, as shown schematically in Fig. 3.5 below:

56 = 2.200×10^{-6} atoms/(barn.cm)

57 = 1.500×10^{-6} atoms/(barn.cm)

58 = 1.000×10^{-6} atoms/(barn.cm)

59 = 0.250×10^{-6} atoms/(barn.cm)

60 = 0.125×10^{-6} atoms/(barn.cm)

To follow how the placement of ^{10}B , refer to different shades of blue in Figure 3.5 below, where the dark blue and lightest shade of blue represent high concentration and lowest concentration of ^{10}B respectively. The double layer is where columns of poison is shown. The zeros represent the fuel in the core, and different numbers represent reactor materials.

62	62	62	62	62	62	62	62	62	62	62	62	62	62	62	16	63	63	63	63	63	64	95	95	
89	2	76	1	66	66	66	66	66	66	66	66	66	66	66	16	67	67	67	67	43	64	94	95	
89	2	76	1	55	55	55	55	55	55	55	55	55	55	55	16	54	54	54	54	43	64	94	95	
89	2	76	1	3	3	3	3	3	3	3	3	3	3	11	16	28	33	33	33	43	64	94	95	Top reflector
89	2	77	1	4	4	4	4	4	4	4	4	4	4	11	17	38	38	38	33	43	64	94	95	Void above core and below top reflector
90	61	61	61	0	0	0	0	0	0	0	0	0	0	12	18	29	34	39	96	44	64	94	95	20.3 cm Start of fuel core: Splitted for Thermix: (15)=18=First batch of CR next to fuel core.
90	61	61	60	0	0	0	0	0	0	0	0	0	0	61	18	29	34	39	96	44	64	94	95	37cm Splitted for Thermix
90	61	59	58	0	0	0	0	0	0	0	0	0	0	61	18	29	34	39	96	44	64	94	95	57.3 cm
90	61	58	56	0	0	0	0	0	0	0	0	0	0	59	19	29	34	39	96	44	64	94	95	"
90	61	58	56	0	0	0	0	0	0	0	0	0	0	59	19	29	34	39	96	44	64	94	95	"
90	61	57	56	0	0	0	0	0	0	0	0	0	0	57	20	29	34	39	96	44	64	94	95	
90	61	58	57	0	0	0	0	0	0	0	0	0	0	58	20	29	34	39	96	44	64	94	95	Use for poisons, from strong to weak: 56, 57, 58, 59, 60
91	61	59	58	0	0	0	0	0	0	0	0	0	0	59	21	30	35	40	97	45	64	94	95	
91	61	60	59	0	0	0	0	0	0	0	0	0	0	59	21	30	35	40	97	45	64	94	95	
91	61	60	59	0	0	0	0	0	0	0	0	0	0	59	22	30	35	40	97	45	64	94	95	
91	61	60	59	0	0	0	0	0	0	0	0	0	0	60	22	30	35	40	97	45	64	94	95	
91	61	83	59	0	0	0	0	0	0	0	0	0	0	61	23	30	35	40	97	45	64	94	95	
91	61	83	59	0	0	0	0	0	0	0	0	0	0	13	23	30	35	40	97	45	64	94	95	
91	61	83	59	0	0	0	0	0	0	0	0	0	0	13	23	30	35	40	97	45	64	94	95	
91	61	78	59	0	0	0	0	0	0	0	0	0	0	13	23	30	35	40	97	45	64	94	95	
92	61	79	60	0	0	0	0	0	0	0	0	0	0	13	24	31	36	41	98	46	64	94	95	
92	61	80	61	0	0	0	0	0	0	0	0	0	0	13	24	31	36	41	98	46	64	94	95	
92	61	81	61	0	0	0	0	0	0	0	0	0	0	14	25	31	36	41	98	46	64	94	95	
92	61	82	88	0	0	0	0	0	0	0	0	0	0	14	25	31	36	41	98	46	64	94	95	
92	61	83	88	0	0	0	0	0	0	0	0	0	0	14	26	31	36	41	98	46	64	94	95	
92	61	84	88	0	0	0	0	0	0	0	0	0	0	14	26	31	36	41	98	46	64	94	95	
92	61	85	88	0	0	0	0	0	0	0	0	0	0	15	27	32	37	42	99	47	64	94	95	
92	61	86	88	0	0	0	0	0	0	0	0	0	0	15	27	32	37	42	99	47	64	94	95	
93	61	87	88	6	10	10	10	5	10	10	10	10	7	15	15	32	37	42	99	47	64	94	95	
93	72	72	72	68	10	10	10	5	10	10	10	10	69	70	70	70	70	71	70	47	64	94	95	
93	72	72	72	8	10	10	10	5	10	10	10	10	9	48	48	48	49	52	49	47	64	94	95	
93	73	73	73	8	10	10	10	5	10	10	10	10	9	74	74	74	75	75	75	47	64	94	95	
93	73	73	73	8	10	10	10	5	10	10	10	10	9	48	48	48	49	49	49	47	64	94	95	
93	73	73	73	53	53	53	53	53	53	53	53	53	50	50	50	50	50	50	50	47	64	94	95	
93	73	73	73	51	51	51	51	51	51	51	51	51	50	50	50	50	50	50	50	47	64	94	95	
65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	64	95	95	Figure

Figure

3-5: Schematic representation of the placement of five different concentrations of ^{10}B in the central and external reflector.

3.3.3 Simulation of neutron poison placement into the external reflector only

The process was as follows:

- Second simulations were done on the external reflector of the PBMR-400 MW core.
- The ^{10}B was placed on the external reflector of the PBMR-400 to mimic the PBMR-200 DPP.
- The neutron poison was placed in the external reflector from 37.3 cm inside the core, and the most potent concentration of ^{10}B was between 57.3 cm and 343.8cm along the reflector length.
- By placing it in the external reflector, it also helped to see how it would have affected the core when it could have been placed in a PBMR-200 core since it had only the external reflector.
- The delay day was also varied until a perfect k_{eff} of 1. k_{eff} represented the critical reactor.
- The k_{eff} of one occurred at a ^{10}B concentration of:
 - 56 = 5.000×10^{-6} atoms/(barn.cm)
 - 57 = 2.400×10^{-6} atoms/(barn.cm)
 - 58 = 1.000×10^{-6} atoms/(barn.cm)
 - 59 = 0.500×10^{-6} atoms/(barn.cm)
 - 60 = 0.250×10^{-6} atoms/(barn.cm)

To follow the placement of ^{10}B , refer to different shades of blue in Figure 3.6 below, where the dark blue and lightest shade of blue represent high concentration and lowest concentration of ^{10}B respectively. The zeros represent the fuel in the core, and different numbers represent reactor materials.

62	62	62	62	62	62	62	62	62	62	62	62	62	62	62	16	63	63	63	63	63	64	95	95	
89	2	76	1	66	66	66	66	66	66	66	66	66	66	66	16	67	67	67	67	43	64	94	95	
89	2	76	1	55	55	55	55	55	55	55	55	55	55	55	16	54	54	54	54	43	64	94	95	
89	2	76	1	3	3	3	3	3	3	3	3	3	3	11	16	28	33	33	33	43	64	94	95	Top reflector
89	2	77	1	4	4	4	4	4	4	4	4	4	4	11	17	38	38	38	33	43	64	94	95	Void above core and below top reflector
90	61	61	61	0	0	0	0	0	0	0	0	0	0	12	18	29	34	39	96	44	64	94	95	20.3 cm Start of fuel core: Splitted for Thermix: (15)=18=First bath of CR next to fuel core.
90	61	61	61	0	0	0	0	0	0	0	0	0	0	57	18	29	34	39	96	44	64	94	95	37cm Splitted for Thermix
90	61	61	61	0	0	0	0	0	0	0	0	0	0	56	18	29	34	39	96	44	64	94	95	57.3 cm
90	61	61	61	0	0	0	0	0	0	0	0	0	0	56	19	29	34	39	96	44	64	94	95	"
90	61	61	61	0	0	0	0	0	0	0	0	0	0	56	19	29	34	39	96	44	64	94	95	"
90	61	61	61	0	0	0	0	0	0	0	0	0	0	56	20	29	34	39	96	44	64	94	95	
90	61	61	61	0	0	0	0	0	0	0	0	0	0	56	20	29	34	39	96	44	64	94	95	Use for poisons, from strong to weak: 56, 57, 58, 59, 60
91	61	61	61	0	0	0	0	0	0	0	0	0	0	56	21	30	35	40	97	45	64	94	95	
91	61	61	61	0	0	0	0	0	0	0	0	0	0	57	21	30	35	40	97	45	64	94	95	
91	61	61	61	0	0	0	0	0	0	0	0	0	0	58	22	30	35	40	97	45	64	94	95	
91	61	61	61	0	0	0	0	0	0	0	0	0	0	59	22	30	35	40	97	45	64	94	95	
91	61	83	61	0	0	0	0	0	0	0	0	0	0	60	23	30	35	40	97	45	64	94	95	
91	61	83	61	0	0	0	0	0	0	0	0	0	0	13	23	30	35	40	97	45	64	94	95	
91	61	83	61	0	0	0	0	0	0	0	0	0	0	13	23	30	35	40	97	45	64	94	95	
91	61	78	61	0	0	0	0	0	0	0	0	0	0	13	23	30	35	40	97	45	64	94	95	
92	61	79	60	0	0	0	0	0	0	0	0	0	0	13	24	31	36	41	98	46	64	94	95	
92	61	80	61	0	0	0	0	0	0	0	0	0	0	13	24	31	36	41	98	46	64	94	95	
92	61	81	61	0	0	0	0	0	0	0	0	0	0	14	25	31	36	41	98	46	64	94	95	
92	61	82	88	0	0	0	0	0	0	0	0	0	0	14	25	31	36	41	98	46	64	94	95	
92	61	83	88	0	0	0	0	0	0	0	0	0	0	14	26	31	36	41	98	46	64	94	95	
92	61	84	88	0	0	0	0	0	0	0	0	0	0	14	26	31	36	41	98	46	64	94	95	
92	61	85	88	0	0	0	0	0	0	0	0	0	0	15	27	32	37	42	99	47	64	94	95	
92	61	86	88	0	0	0	0	0	0	0	0	0	0	15	27	32	37	42	99	47	64	94	95	
93	61	87	88	6	10	10	10	5	10	10	10	10	7	15	15	32	37	42	99	47	64	94	95	
93	72	72	72	68	10	10	10	5	10	10	10	10	69	70	70	70	70	71	70	47	64	94	95	
93	72	72	72	8	10	10	10	5	10	10	10	10	9	48	48	48	49	52	49	47	64	94	95	
93	73	73	73	8	10	10	10	5	10	10	10	10	9	74	74	74	75	75	75	47	64	94	95	
93	73	73	73	8	10	10	10	5	10	10	10	10	9	48	48	48	49	49	49	47	64	94	95	
93	73	73	73	53	53	53	53	53	53	53	53	53	50	50	50	50	50	50	50	47	64	94	95	
93	73	73	73	51	51	51	51	51	51	51	51	51	50	50	50	50	50	50	50	47	64	94	95	
65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	64	95	95	

Figure 3-6: Placement of five different concentrations of ¹⁰B in the external reflector.

4. RESULTS AND DISCUSSION

4.1 DLOFC temperature results

The standard axial power and maximum DLOFC temperature profile of the PBMR-400 DPP powered by an OTTO refuelling cycle can be seen in Figure 4-1 below. It uses 16 g heavy metal loading per fuel sphere. The fuel consists of a mixture of thorium mixture and 20 a/o% LEU, with an average enrichment of 7,265 a/o %.

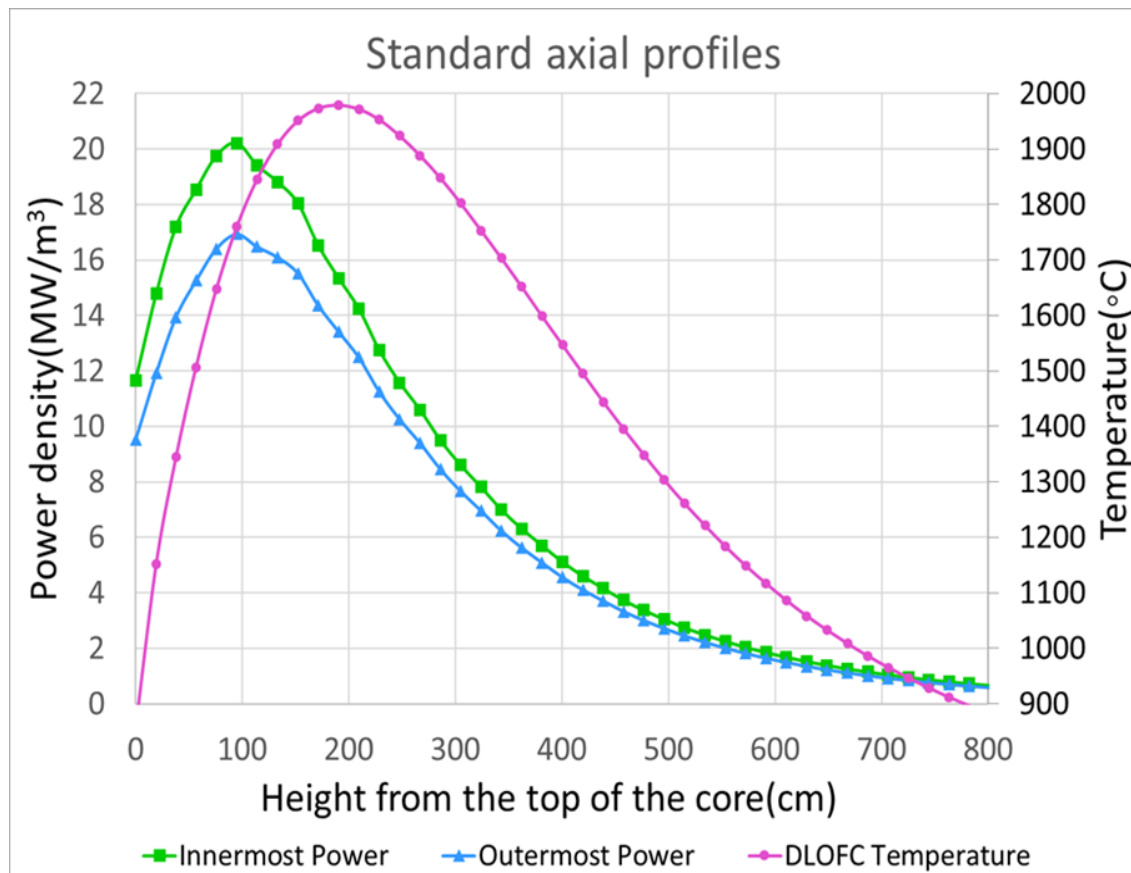


Figure 4-1: Standard axial profiles of a PBMR-400 DPP fuelled with a 16g heavy metal loading per pebble mixture of thorium and 20 a/o% LEU, with average enrichment of 7.265 a/o%.

The figure above shows that switching from the standard 6-pass refuelling cycle for the PBMR-400 caused the maximum DLOFC temperature to jump from a typical value of 1580 °C for the PBMR-400 to 1979 °C, which greatly exceeds the chosen safety limit of 1600 °C. The innermost axial power density profile is substantially higher than the outermost profile, due to the cylindrical effect in an annular core that focuses the neutron

flux near the inner layers of the core (Serfontein D. E., 2014). The presence of the control rods in the external reflector, which were inserted to the level of the top of the fuel core, probably also played a role in suppressing the power density directly adjacent to the external reflector. The inner and outer power density profiles peak intensely at the top of the core, reaching a maximum of approximately 100 cm into the core, and then abruptly decrease with increasing depth into the fuel core.

The DLOFC peaks at approximately 200 cm into the fuel core, i.e. about 100 cm below the power density profiles. The probable reasons for the shapes of the power density peaks have been described in detail by (Marius Tchonang Pokaha & Dawid.E Serfontein, 2017). In short, the downward flow of the coolant gas causes the coolant gas to heat up cumulatively as it flows down. Therefore, the lower parts of the fuel core are cooled less effectively and are thus at higher normal operating temperatures. Due to the strong negative Doppler fuel temperature reactivity coefficient, these increases in temperature and thus reduce the reactivity of the fuel lower down, which again suppresses the power density. Furthermore, the increasing burnup of the fuel as it flows down depletes its enrichment and thus its reactivity and power density. This peak occurred in the axial profile directly adjacent to the central reflector. Due to the said increases in coolant gas and fuel temperatures, as the fuel flows down the lower parts of the graphite reflectors are also heated up. This means that at the start of a DLOFC accident, the hotter reflector blocks lower down will absorb less of the decay heat and will therefore cool the fuel less effectively. This explains why the profile for the DLOFC temperature peaks lower down than the axial power density profiles.

The reason why axial power profiles can be flattened by adding thorium to the fuel is that Th/²³³U fuel cycles in HTRs deliver higher fissile fuel conversion ratios than the standard LEU fuel cycles. Radiative neutron capture by ²³²Th causes fissile ²³³U to fission in thermal reactors with a significantly improved neutron economy, compared to both ²³⁹Pu reproduced by ²³⁸U and ²³⁵U in the LEU (Marius Tchonang Pokaha & Dawid.E Serfontein, 2017). Since more fissile fuel is bred by the Th, the enrichment of Th/²³³U fuel cycles decreases slower with increasing burnup, leading to higher enrichments at the bottom of the core and thus higher power densities lower down and correspondingly lower power densities near the top, which results in a flattening of the axial power density profile.

Even so, thorium cycles often deliver higher DLOFC temperatures due to its high inventory of bred protactinium-233 (²³³Pa). The ²³³Pa generation is a common isotope in the ²³³U breeding process. It emits substantial amounts of decay heat in the form of β -particles and gamma rays as it decays radioactively to produce the desired ²³³U (Boyes, 2017).

Unfortunately, ^{233}Pa has a half-life of 27 days, compared to only nine hours for the equivalent ^{239}Np in the transmutation chain from ^{238}U to ^{239}Pu (M Lung & O Gremm, 1997). Therefore, while the decay heat emitted by ^{239}Np will halve after nine hours into a DLOFC incident for a LEU/Pu fuel cycle, the same reduction will take 27 days for the ^{233}Pa in Th-based fuel cycles. Since the maximum DLOFC temperature normally occurs about two to three days into the accident, the decay heat from ^{239}Np will have decayed to insignificant levels by that time, while it will still be at almost full power for the ^{233}Pa , which explains the elevated maximum DLOFC temperatures of Th-based fuel cycles (Tchonang Pokaha, 2018). Therefore, to get the benefit of the ability of the bred ^{233}U to flatten the axial power profile, additional neutron poison must be used to suppress the power peak near the top and to use the bred ^{233}U to create a larger power peak towards the bottom, that might have been the case for LEU/Pu fuel cycles (Serfontein, 2014).

Figure 4-2 below shows such an attempt to suppress the power profile near the top of the core by means of neutron poison placement, both in the central and external reflectors of the PBMR-400 DPP core. When five different concentrations of ^{10}B are placed in the inner and outer reflector, the inner and outer density profile is suppressed at approximately 270 cm from the top of the core, although the suppression of the outer profile suppression is not so pronounced as the inner profile. It can be seen, however, that the outer power profile is higher than the inner power profile. The aim was to design the double layer of neutron poison in the inner reflector and to lift the outermost profile by using five different concentrations of poison. The improvement of the outer profile shows a beneficial modification of the decay heat, which is mainly evacuated through the external reflector. By manipulating the power profiles in such a manner that the outer profile is higher than the inner one, the power hotspot occurs to a greater extent against the external reflector, which shortens the average distance from the point of release of the decay heat to the outer reflector (Tchonang Pokaha, 2018).

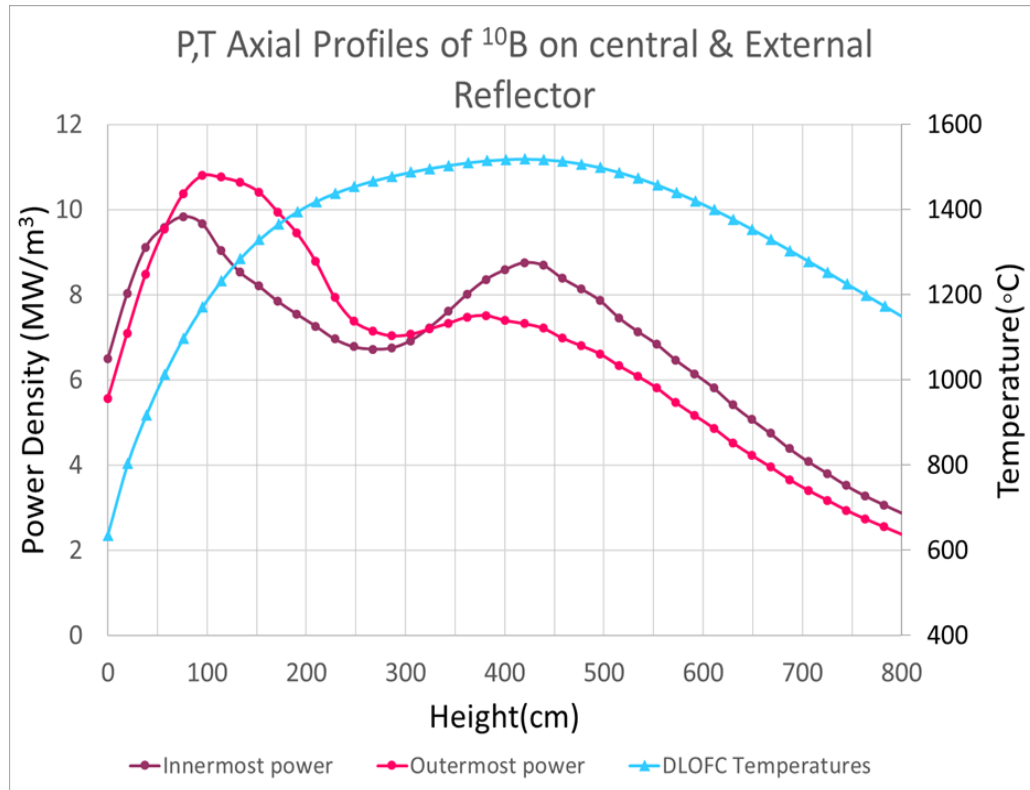


Figure 4-2: P, T axial profiles of a double layer of five different concentration of ^{10}B in both the central and external reflectors.

When the DLOFC begins, the fuel evacuates heat both inward and outward, since both the central and external reflectors are initially cooler than the fuel that is continuously heating up due to the release of decay heat and the lack of coolant flow (Serfontein, 2014). However, the heat that is evacuated from the inner fuel layers into the central reflector largely becomes “trapped” in there as only the top and bottom of the central reflector are connected to the top and bottom reflector respectively, while the central part of the central reflector is isolated from any heat sinks. The decay heat in the central reflector will thus accumulate to the point that the temperature in the central part of the central reflector will within a few hours increase to similar levels to the fuel in the inner fuel layers (Serfontein, 2014). At this point the inward evacuation of decay heat will slow to a halt so that cooling of the inner fuel layers will become very ineffective and therefore these fuel layers will start to heat up at elevated rates. The situation for the external reflector is substantially different as it can not only leak out heat through the top and bottom parts of the steel pressure vessel, but also radially through the large surface area of the cylindrical side wall of the pressure vessel. Due to this, there is much more effective cooling of the external reflector.

Its temperature always remains substantially lower than that of the heated outer fuel layers and therefore it acts as an effective heat sink for the fuel. Therefore, the DLOFC temperatures of the external fuel layers are consistently substantially lower than for the internal fuel layers. This explains why it would be beneficial for the outermost power profile to have the highest power (Serfontein D. E., 2014).

In previous studies, placement of the neutron poison in the inner and outer reflector achieved the most effective flattening of the axial DLOFC temperature peak when the axial power peak was divided into a relatively high but short peak very close to the top of the core, a subsequent longer power suppression zone and a smaller peak near the bottom of the core (Serfontein D. E., 2014). In Figure 4.2 above, this strategy reduced the internal power density from 20 MW/m³ to 9.69 MW/m³ and the external power density from 16 MW/m³ to 10.65 MW/m³, which reduced DLOFC temperatures from 1979 °C to 1519 °C.

Although the figure above shows excellent results, the optimisation attempts were frustrated by instabilities in the simulated power distribution, induced by the neutron poisons.

The VSOP diffusion simulation code apparently experienced instabilities in its calculational algorithm:

On the one hand this meant that small changes in the poison concentrations led to large changes in the shapes of the power density profiles and thus in the maximum DLOFC temperature profiles. This is clearly undesirable as it implies that small deviations between the planned core design and the actual one could lead to large and unpredictable changes, which could compromise the design of the intended reductions in the maximum DLOFC temperature, which would have obvious negative safety implications.

On the other hand, the instabilities came in the form of an unstable oscillation, where one refuelling cycle produced a large power peak at the top and almost no power at the bottom, while the alternating cycle produced a large power peak at the bottom and almost no power at the top. This oscillation went on indefinitely. After much trial and error, a few good stable power profiles were obtained for both the case where poison was placed only in the external reflector and the case where it was placed in both the internal and external reflectors. However, even a small change in the poison concentrations would set these oscillations in motion again.

The observed unstable oscillation can possibly be explained as follows:

If after one refuelling cycle the power profile makes a large peak at the top of the core, with very little power lower down, the normal operating temperature at the top will go up,

while the temperature lower down will be lower than normal. After the next refuelling cycle, the neutron flux distribution is recalculated. Since the fuel has a strong negative Doppler fuel reactivity coefficient, the simulated temperature increases at the top will decrease the reactivity of the fuel at the top, while the reduced temperatures at the bottom will increase the reactivity towards the bottom. This could result in the algorithm favouring the bottom during the recalculation, so that the power is then concentrated at the bottom with very little power at the top. With the refuelling cycle after that, the situation will reverse. Due to the lower temperatures at the top, the reactivity at the top will increase and it will decrease at the bottom, so that in that cycle the power will once again be concentrated at the top. This can then continue indefinitely in alternating cycles, which is exactly what was observed in this study.

Figure 4-3 below shows the power density and DLOFC temperature profiles for the case where the neutron poison concentrations were placed in the external reflector only.

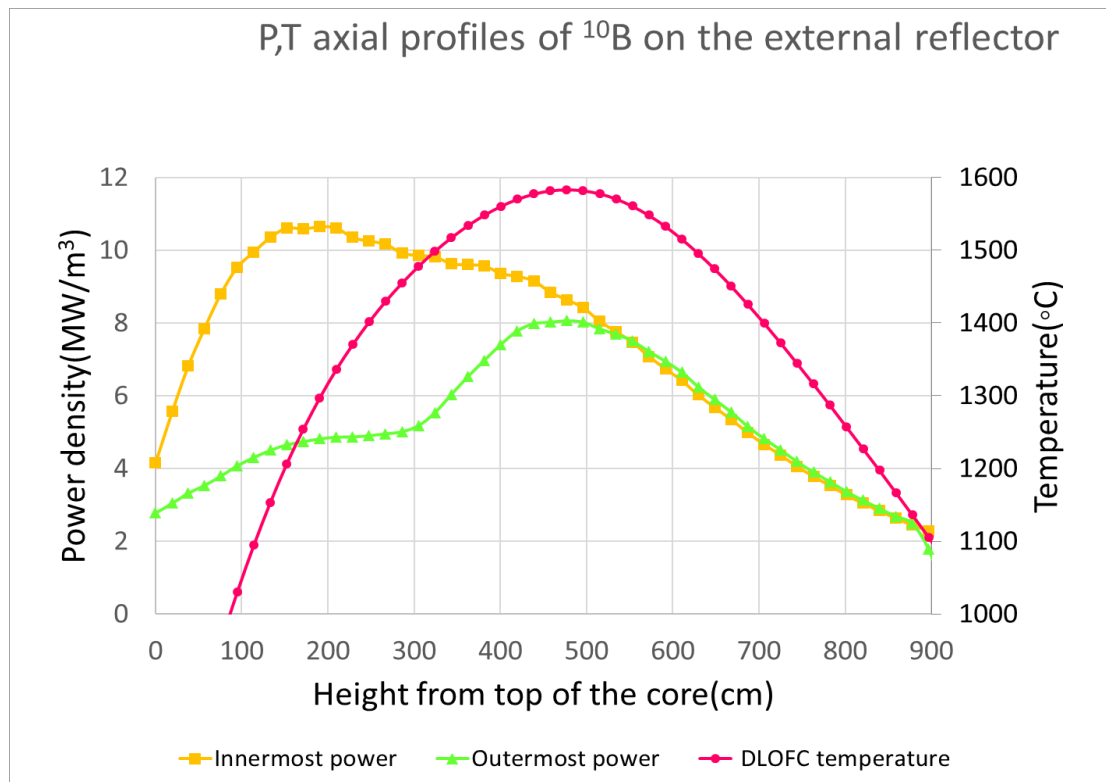


Figure 4-3: P, T axial profiles of a double layer of five different concentration of ^{10}B on the external reflector only.

The placement in the external reflector of the PBMR-400 MW core of five different concentrations of ^{10}B has a similar effect as the ^{10}B in the both the central and external reflectors. The placement of ^{10}B in the external reflector was expected to have the same effect of suppressing the axial power as in the profiles above, at the top and in the suppression zone in the centre of the core and at the bottom of the core. Although the optimisation did not occur as planned as in figure 4-2, the peaked profile of the standard axial profile in figure 4-1 was suppressed. The axial power profiles were suppressed, where the fuel in the innermost regions of the core started burning first closer to the top of the core around 170 cm, where after the fuel in the outermost power regions peaked lower down the core around 470 cm. The decay heat would be evacuated efficiently to the external reflector because the outer fuel regions have more power than the internal fuel regions. However, the outer profile peak is lower than the central peak, the modification has the advantage that the internal fuel first burns at the top of the core, and the burning begins to burn the outer fuel. The time taken to evacuate heat from the reactor by conduction and radiation would, therefore, be significantly lower.

The placement of neutron poison in the outer reflector shows the sharp flattening of the highest risk DLOFC temperature peak, although the axial power peak was not divided into the desired shape of a peak near the top of the core, a subsequent depression zone and a lower peak near the bottom of the core as suggested (Serfontein D. E., 2014) study. The change reduced the internal power density from 20 MW/m³ to 10.64 MW/m³ and the external power density from 16 MW/m³ to 8.02 MW/m³, from 1979°C to 1585°C.

Figure 4-4 below shows, for the same cases as above, maximum DLOFC temperatures as a function of time into the DLOFC accident, for the two neutron poison placement strategies.

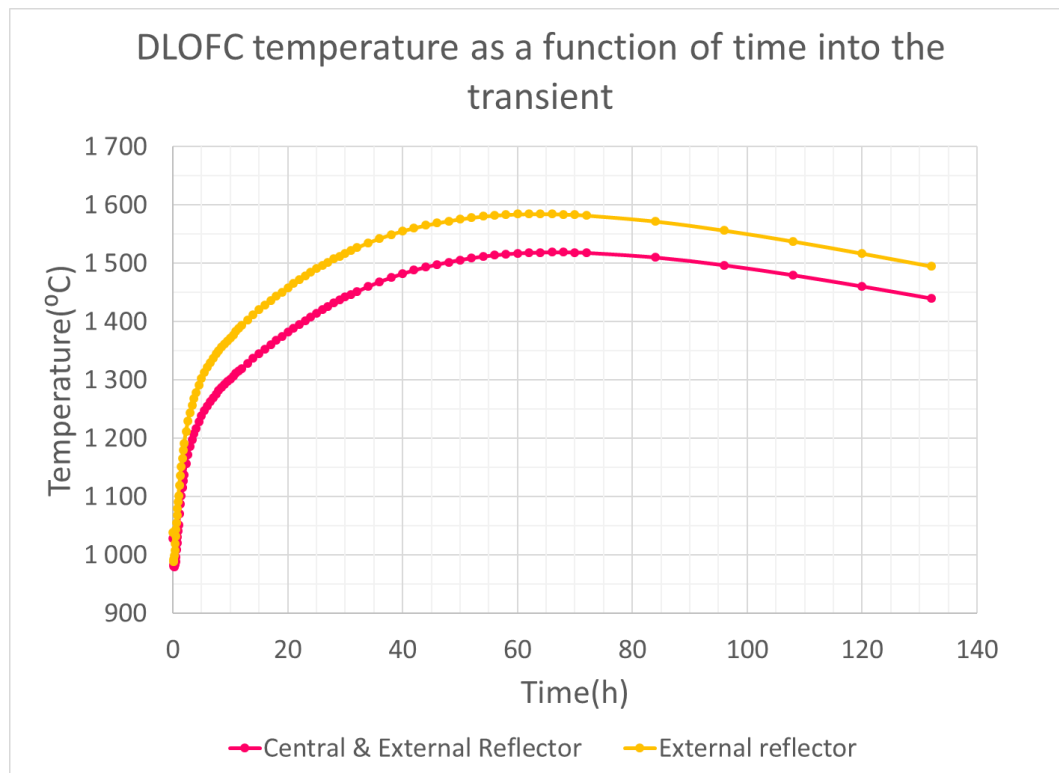


Figure 4-4: DLOFC temperatures as a function of time for the two placement strategies of the neutron poison.

The maximum DLOFC temperature of optimised neutron poisons in both the reflectors and the external reflector is 62 and 60 hours in the transients, respectively. The main benefit is that the spread of the high temperature peak over an extended period allows the evacuation of a large total amount of decay heat, with lower heat fluxes, leading to lower fuel temperatures. This is also a benefit because it gives more time for possible corrective actions to avoid damage to the fuel and ultimate release of radioactivity to the environment (Marius Tchonang Pokaha & Dawid E. Serfontein, 2016).

4.2 Effect of poisons in the reflectors on the cold shutdown margins of the control rods

The method used in the PhD of (Serfontein, D.E., 2011) was repeated to calculate the ability of full-length insertion of all the control rods to maintain the reactor in cold shutdown, but without recalibrating the methods for the Th-based fuel cycle, as opposed to the LEU fuel cycle used by Serfontein. Therefore, these results are not correct in absolute terms. However, they do give a relative indication of the effect of the poison placement strategies on the ability to maintain cold shutdown. The following results were obtained. Both cores started out at criticality.

- For the case where the neutron poisons were placed both in the central and external reflector, cold shutdown resulted in $k_{\text{eff}} = 0.9654$.
- For the case where the neutron poisons were placed in the external reflector only, cold shutdown resulted in $k_{\text{eff}} = 1.014$.

This means that when the poisons were placed mainly in the central reflector, with a lesser concentration in the external reflector, the core was shut down safely with a large safety margin. Placing the poison in only the external reflector left the control rod unable to maintain cold shutdown, by a large margin.

Placement of poisons in the external reflector reduces the thermal neutron flux available there for absorption by the control rods and thus it renders the control rods largely ineffective.

Since the ability to maintain cold shutdown is a critical safety issue, this is a serious blow to the method of placing the poisons in the external reflector.

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

With the OTTO cycle, the power density is very high towards the top of the core where all the fresh fuel is located, and very low lower down where only older and thus depleted fuel is present. This resulted in a similarly sharp peak in the axial profile of the DLOFC temperature. The resulting DLOFC temperature hotspot led to greatly elevated maximum DLOFC temperatures for the OTTO cycle compared to the standard 6-pass refuelling cycle of the PBMR-400. Switching from the 6-pass to the OTTO refuelling cycle increased the maximum DLOFC temperature for the PBMR-400 from its typical value of 1880 °C to 1979 °C. However, placing a tailored poison distribution in only the external reflector reduced the maximum DLOFC fuel temperature to 1584 °C. However, placing the poison in both the central and external reflectors reduced the maximum DLOFC temperature substantially to only 1519 °C.

The optimisation attempts were greatly frustrated by instabilities in the simulated power distribution, induced by the neutron poisons. From previous studies, it was known that a largely flat axial profile for the DLOFC temperature can be obtained by inducing a large power peak near the top of the core, followed by a suppression in power lower down and then again, a smaller power peak towards the bottom of the core. However, when the poisons were used to induce such a power distribution, the VSOP diffusion simulation code apparently experienced instabilities in its calculational algorithm. This resulted in an unstable oscillation where one refuelling cycle produced a large power peak at the top and almost no power at the bottom, while the alternating cycle would produce a large power peak at the bottom and almost no power at the top. After much trial and error, good stable power profiles were obtained for both cases where poison was placed only in the external reflector and where it was placed in both the internal and external reflectors.

However, the more serious problem is that the poison in the external reflector reduces the thermal neutron flux in the external reflector, which reduces the number of neutrons that are available to be absorbed by the control rods which are placed in the external reflector. In this study placing poisons in the external reflector greatly reduced the ability of the control rods to safely shut the reactor down. For this reason, it was concluded that reducing DLOFC temperatures by means of poison placement in the external reflectors of pebble bed reactors with cylindrical cores is not an optimal strategy.

Based on these results, it was concluded that for the future development of this technique it would be best to revert to core designs with a central reflector and to place the bulk of the poison in the central reflector.

5.2 Recommendation for future studies

This study set out to find a way to use neutron poison placement in the external reflector to reduce the DLOFC temperatures for cylindrical cores with OTTO refuelling cycles to a similar level as for annular cores with multi-pass cycles. However, the two serious problems that were induced by these strategies, namely instabilities in the calculational algorithms of VSOP 99_05 and the reduction of the effectiveness of the control rods in the external reflector, due to the placement of additional poisons in the external reflector, suggest that the tested strategy is not a good one. Nonetheless it is clear that neutron poison placement in the central reflector is a very effective strategy to reduce the maximum DLOFC temperature. Therefore, the following strategy is proposed for future studies:

- Revert to annular cores and place the poison mostly in the central reflector.
- Switch to non-burnable poisons, as the use of ^{10}B is not sustainable as it will burn away too quickly.
- Since it was the high poison concentrations, used to flatten the axial DLOFC temperature profiles, that caused the calculational instabilities, reduce the need for high poison concentrations by redesigning the core to flatten the power profiles in a more natural way, without poisons, and then add the poisons for extra effect. This could be attempted by:
 - Reverting to a multi-pass refuelling cycle, as that automatically flattens the axial power profiles,
 - Reducing the diameter of the central reflector, thereby reducing neutron leakage and thus increasing the conversion ratio.
 - Using this improved core to re-optimize a thorium-based fuel cycle in order to obtain the maximum possible conversion ratio, which will naturally lead to higher power densities at the bottom of the core and thus flatter power profiles.

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DISCLAIMER:

"Any opinion, finding and conclusion or recommendation expressed in this material is that of the author(s) and the NRF does not accept any liability in this regard"

This dissertation is dedicated to my late grandmother 'Mma Ruta' for all her hard work, support and love.

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