Using thorium to decrease maximum DLOFC temperatures and increase total power output in Pebble-Bed High Temperature Reactors

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Declaration

I, Marius Tchonang Pokaha, hereby declare the thesis titled:

Using thorium to decrease maximum DLOFC temperature and increase total power output in Pebble-Bed High Temperature Reactors

is my own work and has not been submitted to any university before. Where publications involving co-authors were used, the necessary permission from these authors had been obtained in writing. Relative contributions by the different authors are acknowledged in the relevant chapters.

Signed at Potchefstroom on..

Preface

- This is to state that I, Marius TCHONANG POKAHA have chosen the article format for submitting my thesis.
- This thesis is written in South African English. All articles are written in American English because of submitting to international journals.
- All articles were written by:

M. Tchonang Pokaha, and D.E. Serfontein
DST Chair in Nuclear Engineering, School of Mechanical and Nuclear Engineering, North-West University, Potchefstroom 2520, South Africa

D.E Serfontein acted as study leader during the whole study with the task to provide guidance and support to M. Tchonang Pokaha whilst also evaluating the academic soundness and strength of the research. All research was conducted and documented by M. Tchonang Pokaha.

Format of the thesis

The format of the thesis is in accordance with academic rule 5.4.2.7 which states: "Where a candidate is permitted to submit a thesis in the form of a published research article or articles or as an unpublished manuscript or manuscripts in article format and more than one such article or manuscript is used, the thesis must still be presented as a unit, supplemented with an inclusive problem statement, a focused literature analysis and integration and with a synoptic conclusion, and the guidelines of the journal concerned must also be included."

Rule 5.4.2.8 states: "Where any research article or manuscript and/or internationally examined patent is used for the purpose of a thesis in article format to which other authors and/or inventors than the candidate contributed, the candidate must obtain a written statement from each co-author and/or inventor in which it is stated that such co-author and/or co-inventor grants permission that the research article or manuscript and/or patent may be used for the stated purpose and in which it is further indicated what each co-author's and/or co-inventor's share in the relevant research article or manuscript and/or patent was."

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Furthermore, from the minutes of the post graduate faculty management committee meeting held on 13 June 2012:

"The proposal was approved that three accredited journal articles of which 2 are already accepted for publication and a third already submitted, is considered sufficient for an article based PhD to hand in for examination."

For clarity, all references used in all of the papers were listed again at the end of the thesis in the correct style, according to the guidelines of this University.

Statement from co-author

Contribution from Prof D.E. Serfontein, co-author is recognised, and his statement follows: As promoter of M. Tchonang Pokaha's PhD, I gave guidance throughout the study. Since Mr Tchonang Pokaha did his Masters in a different field of physics than Nuclear Engineering, I had to give him strong guidance at the beginning of his study. For instance, the broad concept for the study came from me. However, as the study progressed and Mr Tchonang Pokaha's experience and confidence grew, I gradually withdrew in order to make room for him to take the lead, which indeed he did. Therefore I declare that, although I gave strong guidance, Mr Tchonang Pokaha is rightfully the prime author of the articles contained in this PhD, as well as of this thesis that binds these articles together.

Yours sincerely.

Dawid E. Serfontein,
Associate Professor in the School of Mechanical and Nuclear Engineering,
North-West University
South Africa

Statement of consent: D.E. Serfontein

To whom it may concern,

I, Dawid Edward Serfontein, give my consent to Marius Tchonang Pokaha, candidate for the degree Philosophiae Doctor in Nuclear Engineering at the North-West University, to include in his thesis titled “Using thorium to decrease maximum DLOFC temperature and increase total power output in Pebble-Bed High Temperature Reactors”, the following publications, of which I am the co-author.

.

Signed at Potchefstroom on ____.

D.E. Serfontein

List of Publications

The publications presented in this thesis are:

Tchonang Pokaha, M. & Serfontein, D.E. 2016. REDUCING DLOFC FUEL TEMPERATURES BY MIXING THORIUM WITH LEU IN A SINGLE-ZONE SIX-PASS FUEL CYCLE IN A PBMR-DPP-400 CORE. HTR 2016, Las Vegas, NV, November 6-10, 2016.

Tchonang Pokaha, M. & Serfontein, D.E. 2017. Using thorium to reduce the maximum fuel temperatures during depressurized loss of coolant accidents in a once-through-then-out (OTTO) PBMR DPP-400 core. *Journal of NUCLEAR SCIENCE and TECHNOLOGY,* 54(5):589-599.

Tchonang Pokaha, M. & Serfontein, D.E. 2018. Neutron poison distribution in the central reflector to reduce the DLOFC temperature of a Th-LEU fueled OTTO PBMR DPP-400 core. *Journal of NUCLEAR SCIENCE and TECHNOLOGY*.

Tchonang Pokaha, M. & Serfontein, D.E. 2018. DIFFERENT TECHNIQUES FOR REDUCING DLOFC FUEL TEMPERATURES IN A PBMR-DPP-400 CORE. Nuclear Engineering and Design, 33, 210-218

Guidelines for papers

The first article "Tchonang Pokaha, M. & Serfontein, D.E. 2016. REDUCING DLOFC FUEL TEMPERATURES BY MIXING THORIUM WITH LEU IN A SINGLE-ZONE SIX-PASS FUEL CYCLE IN A PBMR-DPP-400 CORE. HTR 2016, Las Vegas, NV, November 6-10, 2016" was published by the American Nuclear Society after presentation at the International Topical Meeting on High Temperature Reactor Technology (HTR 2016). It is therefore formatted accordingly. Guidelines for authors available at:

www2.ans.org/pubs/proceedings/docs/guidelines.pdf

The second article "Tchonang Pokaha, M. & Serfontein, D.E. 2017. Using thorium to reduce the maximum fuel temperatures during depressurized loss of coolant accidents in a once-through-then-out (OTTO) PBMR DPP-400 core. *Journal of NUCLEAR SCIENCE and TECHNOLOGY,* 54(5):589-599." was published in the Journal of Nuclear Science and Technology.

The third article "Tchonang Pokaha, M. & Serfontein, D.E. 2017. Neutron poison distribution in the central reflector to reduce the DLOFC temperature of a Th-LEU fueled OTTO PBMR DPP-400 core. *Journal of NUCLEAR SCIENCE and TECHNOLOGY"* is under review by the Journal of Nuclear Science and Technology.

These two are then formatted accordingly. Guidelines for authors available at
www.tandfonline.com/action/authorSubmission?journalCode=tnst20&page=instructions

The fourth article "Tchonang Pokaha, M. & Serfontein, D.E. 2017. DIFFERENT TECHNIQUES FOR REDUCING DLOFC FUEL TEMPERATURES IN A PBMR-DPP-400 CORE." is under review by Nuclear Engineering and Design. Guidelines for authors available at
www.elsevier.com/wps/find/journaldescription.cws_home/505661?generatepdf=true

The following acknowledgement applies to all four articles mentioned above, as well as to this thesis:
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Any opinion, finding, conclusion or recommendations expressed in this material are those of the author(s) and the NRF does not accept any liability in this regard.

Abbreviations

α: Capture-to-fission ratio

AVR: Arbeitsgemeinschafts versuchsreaktor

BISO: Bi-structural Isotropic

C: Conversion ratio

DLOFC: Depressurised Loss of Forced Cooling

η: Number of fission neutrons produced per neutron absorbed in the fissile fuel nuclides.

ENDFB: Nuclear library name: Evaluated Nuclear Data File/B

FZJ: Research Centre Jülich

GWd: Gigawatt days

GWd/t_{HM}: 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

LEU: Low Enriched Uranium

LWR: Light water reactor

NWU: North-West University

NNR: National Nuclear Regulator

NRF: National Research Foundation

OECD: Organisation for Economic Co-operation and Development

OTTO: Once Through Then Out

Pa: Protactinium

PBR: Pebble Bed Reactor

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 – Developed by FZJ

VSOP-A: VSOP-Advanced

Th: Thorium

WW2: Wold War 2

ABSTRACT

Using thorium to decrease maximum DLOFC temperature and increase total power output in Pebble-Bed High Temperature Reactors

Key words: HTGR, Pebble-bed, Thorium, DLOFC, Power profile

This is a study on the topic of modifying the fuel cycles of Pebble-Bed Reactors in order to reduce their maximum fuel temperatures during Depressurised Loss of Forced Coolant (DLOFC) accidents, in order to prevent unacceptable levels of release of radioactive fission products from the fuel into the environment. It therefore reviews the literature on the subject, with a special focus on possible solutions to the identified problems. It discusses the lessons learnt in the preceding papers, identifies gaps in them and adds new research in order to fill these gaps.

The principle strategies used for reducing the maximum DLOFC temperatures were (a) flattening the peaks in the axial profiles of the maximum DLOFC temperature, which increases the surface areas over which effective evacuation of decay heat takes place and thus reduces the resulting heat fluxes and temperatures and (b) "pushing" the radial profiles of the equilibrium power density outward towards the external reflector, thereby decreasing the distance, and thus the thermal resistance, over which the decay heat has to be evacuated towards the external reflector.

These strategies were applied for both 6-pass recirculation fuelling schemes and Once Through Then Out (OTTO) fuelling schemes. The techniques used for flattening the peaks in the axial profiles of the maximum DLOFC temperature were (a) flattening of the peaks in the axial profiles of the equilibrium power density by adding thorium to the Low Enriched Uranium (LEU) fuel in order to improve the breeding and conversion ratios, which slowed the depletion of the enrichment of the fuel with increasing burn-up, and (b) placing purposely designed distributions of neutron poison in the central reflector in order to supress the standard peaks in the axial profiles of the equilibrium power density.

The poison in the central reflector simultaneously served the purpose of pushing the power densities outward from the central towards the external reflector. This strategy was further targeted by creating asymmetric cores in which the enrichment of the fuel in the outer fuel flow channels are higher than in the inner ones, which automatically shifts the power out to these higher enriched outer fuel zones.

The result was a substantial reduction in the maximum DLOFC temperatures from 1536 °C to 1488 °C for the multi-pass. This is small compared to the 1298 °C achieved in a different study with the same reactor. Our strategy was more effective with a large reduction in the maximum DLOFC temperature from 2273 °C to 1448 °C for the OTTO. Using neutron poison in the central reflector to flatten the peaks in the axial profiles of the maximum DLOFC temperatures reduced the maximum DLOFC temperature much more effectively than any of the other techniques. The effectiveness of pushing the power out by creating asymmetric cores was disappointingly low. As this technique adds design complexity which might create new accident risks and thus licencing risks, it was recommended that this technique should not be pursued in commercial Pebble-Bed Reactors, although it might be more useful in Prismatic Block Reactors.

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1. PROBLEM STATEMENT AND AIMS

1.1 Problem Statement

The 400 MW_{th} Pebble-Bed Modular Reactor Demonstration Power Plant (PBMR-DPP-400) was developed in South Africa from the middle of the 1990s. However, uncertainty about some technical issues regarding the safety case of this reactor led to the South African National Nuclear Regulator (NNR) postponing the final decision to grant it a licence. This delay was a substantial contributing factor to the eventual demise of the project.

Since limiting the maximum fuel temperature during a Depressurised Loss of Forced Coolant (DLOFC) accident is one of the main pillars of the safety case for most High Temperature Gas-Cooled Reactors (HTGR), reducing these maximum temperatures even further was the focus of this study. In the PBMR-DPP-400, the axial and radial powers peak at about a third from the top of the core and directly adjacent to the central reflector. This unnecessarily increases the maximum fuel temperatures during a DLOFC accident, as this peak in the equilibrium power density creates a DLOFC temperature hot-spot: the decay heat power density during a DLOFC accident is directly proportional to the equilibrium thermal fission power density that preceded the accident. Therefore the peak in the equilibrium power density also produces a similar peak in the DLOFC decay heat power density, which leads to a DLOFC temperature hot-spot some distance below the power hot-spot. This hot-spot causes a safety issue in that it causes the DLOFC fuel temperatures in this hot-spot to increase to just below the upper limit of 1600 °C: if the simulations contain a calculational error, or there is for instance a material or geometry error in the manufacturing of the reactor or of the fuel, the actual maximum DLOFC temperature might then exceed the safety limit. It would therefore be beneficial to reduce the maximum DLOFC temperature to well below the safety limit, in order to create a substantial safety margin. If, however, the equilibrium power output were to be reduced in order to also reduce the maximum DLOFC temperature, it will reduce the revenues from power sales and thus the profitability of the plant.

In view of the above, **the problem to be solved is to design a fuelling scheme for the PBMR-DPP-400 that will substantially reduce the maximum DLOFC fuel temperature,**

while maintaining the power output and without substantially reducing the fuel economy.

1.2 Knowledge gap to be filled

The concept of using thorium in High Temperature Gas-cooled Reactors is not new:

1. Pebble-Bed Reactors have also been operated successfully for more than 20 years in Germany and have been tested with a large number of fuel compositions, including a mixture of thorium and High Enriched Uranium (HEU). Therefore, the knowledge base regarding their operation and optimisation is well developed. More recently, Wols et al. (Wols *et al.*, 2014:1) published simulation results for the conceptual design studies of a passively safe thorium breeder Pebble-Bed Reactor.
   However, these studies focused mainly on using thorium for breeding U-233, with a view to reducing the consumption of natural uranium. Therefore there exists a knowledge gap regarding the optimisation of the use of thorium in order to reduce the maximum DLOFC fuel temperature.

2. Several techniques have been used to suppress the peaks in the equilibrium power density profiles. A standard approach is to flatten the axial power profile by increasing the number of fuel recirculation passes, as was done using 10 passes in an indirect Rankine steam cycle for the HTR-PM (Boer *et al.*, 2009:1049). Another approach is the use of burnable neutron poisons in the fuel in order to reduce the reactivity at the beginning of life of the fuel and thus to reduce the peaking factor of the axial power profiles (Kloosterman, 2003:1807; van Dam, 2000:733).
   However, a recent study by Serfontein (Serfontein, 2014:492) showed that the maximum DLOFC fuel temperature is not minimised when the axial power density profiles are flattened maximally, but rather when the axial profiles of the maximum DLOFC fuel temperatures are flattened maximally.
   Since there are large differences between the shapes of the axial equilibrium power density profiles and the axial maximum DLOFC temperature profiles, this means that the optimisation studies that were aimed at flattening the equilibrium power density profiles are not optimal and therefore their prevalence creates a knowledge gap for studies, such as the present one, which focuses on flattening the maximum axial DLOFC temperature profiles.

3. Most of the previous studies that used neutron poisons to reduce maximum DLOFC fuel temperatures of Pebble-Bed Reactors simulated insertion of the poisons directly into the fresh fuel (Mulder, 1998). However, putting the poisons in the fuel is sub-optimal as one loses all control over the poison concentration in the fuel spheres once they are inserted at the top of the fuel core. Thereafter poison gradually burns away as the fuel sphere travels slowly from top to bottom, without any possibility to adjust these poison concentrations lower down in the core.

   This creates a knowledge gap for studies, such as the present one, that optimises the reduction of the maximum DLOFC temperatures by inserting the poisons into the internal and/or external reflectors of the core. It allows the optimisation of the axial equilibrium axial power density profiles by continuously manipulating the poison concentration in the reflectors, from top to bottom. Furthermore the radial power density profiles can be optimised by varying the poison concentrations between the internal and external reflectors. This shifts the neutron flux and thus the fission power density in the radial direction, which allows an additional degree of freedom for optimisation.

4. Many previous studies focused on using the said techniques for reducing the maximum DLOFC temperatures for multi-pass recirculation fuel cores. Whenever these cores were redesigned for OTTO cycles, it was mostly assumed that a substantial drop in equilibrium power output is inevitable. Therefore the maximum equilibrium thermal power output for the OTTO cores that are currently being proposed are 200 MW (X-energy, October 2014), compared to 250 MW for cores that have multi-pass fuel recirculation (Zhang *et al.*, 2009:1212). Therefore, this tendency created a knowledge gap regarding the optimisation of OTTO cores with a view to obtaining the same power output as for the multi-pass refuelling schemes. The present study aims to fill this gap.

5. Since the cancellation of the PBMR-DPP-400 construction project, most Pebble-Bed Reactor studies focused on simplified designs in which the central reflector was removed in order to create a cylindrical fuel core. Since the central reflector of the PBMR-DPP-400 created a significant additional licensing risk and therefore a commercial risk, the move to cylindrical cores might make commercial sense.

However, due to its central reflector, the PBMR-DPP-400 was technically superior in that it could produce 400 MW thermal power, compared to only 250 MW of the Chinese HTR-PM. It also produced substantially less neutron leakage and thus a substantially higher conversion ratio and higher average fuel burn-up. Since the cost of Pebble-Bed fuel is currently much higher than that of water cooled reactors, this is an important advantage. Especially if the aim is to conserve natural uranium by breeding U-233 from thorium. It is therefore likely that once the nuclear industry has made good progress in overcoming its licensing risks, annular cores with central reflectors will once again become a favourite design option. Therefore, the current practice to shun central reflector designs is creating a knowledge gap regarding the optimisation of cores with central reflectors. The present study aims to fill this gap.

6. Most of the existing studies either use thorium in combination with HEU or the "direct" Th/U-233 fuel cycle, with their associated proliferation risks.
   Therefore, there exists a knowledge gap regarding the optimisation of the use of Low Enriched Uranium (LEU) as driver fuel for thorium cycles, with a view to reducing the maximum DLOFC temperatures, while maintaining the high nuclear weapons proliferation resistance of LEU fuel cycles.

This study is thus the first attempt to mix LEU with thorium in order to improve the power profiles, which will better the safety features of the PBMR-DPP-400, and by extension any commercial sized Pebble-Bed Reactor, with or without the central graphite reflector. If this optimisation is achieved successfully, it may open up on one hand a major additional niche market for PBRs in terms of the inherent safety, and on the other hand a more realistic market for thorium which will now be seen as complementary rather than as a competitor to the well-established uranium fuel cycle. This study will therefore make a unique research contribution which may have a significant positive impact on the future commercial success of PBRs and thorium.

1.3 Explicit formulation of the research problem

The problem to be solved is the improvement of a Th/LEU fuel cycle for Pebble-Bed Reactors with a view to substantially lowering the maximum fuel temperature during a DLOFC accident. During this process all safety standards should be adhered to, including the prevention of nuclear weapons proliferation by means of denaturation of the bred U-233 by U-238 from LEU.

1.4 General aims

- To simulate and evaluate a Th/LEU fuel cycle for a Pebble-Bed Reactor with an annular core around a central reflector, with and without neutron poisons in the central reflector, for both a multi-pass recirculation and an OTTO refuelling cycle, aimed at reducing the maximum DLOFC fuel temperature. This will entail fuel and core optimisations and the determination of an operational regime for the practical implementation of the Th/LEU fuel cycle.
- To investigate the technical viability of the use of thorium together with LEU in the current design the PBMR-DPP-400 reactor.
- To create guidelines for a follow-up study to address challenges identified in this study.

1.5 Specific objectives

1. To reduce the maximum DLOFC fuel temperatures in the PBMR-DPP-400 core, for both the 6-pass recirculation and the OTTO refuelling scheme, by:
    a. flattening the axial profiles of the DLOFC fuel temperature, at the time into the DLOFC accident at which this temperature peaks and by
    b. "pushing" the equilibrium power density radially outwards by inserting neutron poisons into the central reflector and/or by placing higher enriched fuel in the outer fuel layers of the core.

2. To investigate the suitability of the Th/LEU mixture in the current PBMR-DPP-400 reactor layout for the purpose of decreasing the maximum DLOFC fuel temperature.

3. To investigate the composition of thorium-based fuel to be employed in the investigation.

4. To investigate the neutronics core distribution in the PBMR-DPP-400 due to the new fuel cycle layout, in comparison to the reference layout, for the following fuel configurations:

- Homogeneous fuel sphere distribution for OTTO and multi-pass Th/LEU.
- Asymmetric fuel sphere distribution for OTTO and multi-pass Th/LEU that is with lower enriched fuel spheres in the inner layers of the core and higher enriched spheres in the outer layers.

5. Evaluate the decay heat distribution and temperature distribution.

6. Evaluate the proliferation resistance of this fuel cycle.

The progress of the project has been reported from time to time as required. The results of this investigation have been presented at international conferences and the findings published in peer reviewed journals.

The main method of investigation will be computer simulations using the VSOP-99/05 neutron diffusion code.

1.6 Chapters division

The heart of this thesis is one conference paper and three journal articles, of which the candidate is the prime author, as this is an article based PhD. The thesis will consist of the following chapters:

1) Problem statement and aims.
2) Introduction and literature survey.
3) Article 1: Reducing DLOFC fuel temperatures by mixing thorium with LEU in a six-pass fuelling scheme of a PBMR-DPP-400 core.
4) Article 2: Using Thorium to reduce the maximum fuel temperatures during Depressurised Loss of Forced Coolant (DLOFC) accidents in a Once-through-then-out (OTTO) PBMR-DPP-400 Core.
5) Article 3: Neutron poison distribution in the central reflector to reduce the DLOFC temperature of a Th-LEU fueled OTTO PBMR-DPP-400 core.
6) Article 4: Different techniques for reducing DLOFC fuel temperatures in a PBMR-DPP-400 core.
7) Discussion of study and conclusion

2 INTRODUCTION AND LITERATURE SURVEY

Each article contains its own literature survey, aimed at the specific topics that the article addresses. However, this is a more general overview, aimed at founding the whole narrative of the thesis on the relevant literature.

2.1 Introduction

The global energy consumption has drastically increased in the last half of the twentieth century and is generally expected to continue to do so, even if it were to happen at a slower pace. The increase in the last century was due to the increased level of industrialisation in North America, Europe and part of Asia. The current century increase will be driven by the increase in energy use in developing countries like China, India and Africa. 80 % of the current energy consumption of the world is produced by the relatively "cheap" fossil fuels (oil, coal and natural gas), around 10 % by nuclear and the remaining by renewable sources. The use of these fossil fuels comes with a hidden cost due to air pollution, acid rain and a potential contribution to global warming with the associated risk to the global climate, economy and the wellbeing of society in general. Despite massive investment and on-going research, large-scale economic viability of renewable energy sources like wind and solar electricity remains challenging, mainly due to low availability and high variability of wind and solar power (Crossland, 2012:3). The challenges posed with renewable energies, combined with large fluctuations in fossil fuel prices, led to the hope of a strong "nuclear renaissance" in which expanding nuclear power production would be seen as an essential component of the fight against pollution and global warming (Zoran, 2007:14.1). The external cost of nuclear power in Europe, is estimated to be more than a factor 10 lower than for coal fired power stations (European, 2003:13). Therefore nuclear power could play a substantial role in supplying base-load electricity at lower external cost than coal for the twenty-first century.

However, the high capital cost of nuclear power plants, delays in their construction and questions regarding the safe and economical disposal of nuclear waste, combined with a recent sharp decline in the price of oil and natural gas, due to amongst others cheap exploitation of shale gas in the USA, the lifting of sanctions against Iran, as well as a sharp deterioration of the public's perception of the safety of nuclear power plants, due to the Fukushima Daiichi nuclear disaster, are currently threatening the "nuclear renaissance". Added to this is sharp decreases in the cost of wind power and especially solar-PV power.

The nuclear industry may thus have to reduce the cost of nuclear power if the expected "nuclear renaissance" is to be accomplished. It should, however, be noted that the current fleet of nuclear reactors, even when the Three Mile Island nuclear accident and Fukushima Daiichi and Chernobyl nuclear disasters are included, has an excellent safety record. After the Chernobyl disaster the designs of all susceptible reactors in the remaining fleet of mainly Generation II reactors have been corrected in order to make a Chernobyl-style explosion impossible in all currently operating commercial reactors. Furthermore new nuclear reactors, i.e. Generations III, III+ and IV, are several orders of magnitude safer than the remaining Generation II reactors. The other set-back is the belief by the general public that there is no solution for the final disposal of high level nuclear waste. This is due to the constant association in the public mind of nuclear power plants with the horrors of the atomic bomb explosions at Hiroshima and Nagasaki. This brings the issue of proliferation of nuclear weapons. The main, serious and unresolved problems for the nuclear power industry are:

1. The perception amongst the general public that nuclear reactors are not safe (Three-Mile Island, Chernobyl and Fukushima Daiichi)

2. The public perception that nuclear waste cannot be disposed of safely.

3. Nuclear weapons proliferation.

The Fukushima Daiichi nuclear disaster demonstrated that the problem of reactor safety has already been solved on a technical level, to the extent that the real risk to the public is very small.

The safety concern with the current reactor designs is caused by the reliance on active systems to remove the decay heat from the core. A nuclear reactor continues to produce heat (up to 1 % of the nominal power) even after a scram. With large Light Water Reactors (LWR), this represents a significant amount of heat, and will cause a core meltdown if the active cooling system loses power, as was the case at Fukushima Daiichi. The European Pressurised Reactor (EPR) attempts to solve this problem by increasing the redundancy of the system (Leverenz, 2006). Although the problem of exaggerated safety fears might need to be addressed mainly on a political and public relations level, the design of reactors with a fully passive emergency cooling system would help in many regards. The AP1000 has such passive cooling system (Abram & Elshahat, 2012:41) but ultimately, we need reactors which are inherently safe by their design. High Temperature Gas-cooled Reactors (HTR), built in a modular way are currently the closest to achieving inherent safety (Reutler & Lohnert, 1984:129).

For the two other issues, namely nuclear waste management and nuclear weapons proliferation, the total radio-toxicity of the nuclear waste of the spent fuel, as well as the risk of nuclear weapons proliferation resistance, could be reduced by the use of a modified thorium fuel cycle in a Pebble-Bed HTR. This study will investigate such use of thorium in the PBMR-DPP-400.

The development of Gas-cooled Reactor started in the early days of the nuclear age. After the use of these reactors to convert U-238 into Pu-239 for military purposes during the WW2 by the USA, other countries continued this after the war. They used natural uranium as fuel, graphite moderator and air coolant. The 1960s saw a boom in the development of High Temperatures Gas-cooled Reactors (HTGR) which went on to become one of the most mature nuclear reactor technologies with a fully passive emergency cooling system. These reactors take advantage of the gaseous coolant to produce very high outlet temperatures (750 - 950 ^{o}C), leading to high thermal efficiency. Many gases have been used in the pass but because helium is chemically inert, has good heat-exchange properties and does not get activated by neutrons, it is the only currently used coolant for HTRs. To accommodate these high temperatures, the reactor and the fuel are all graphite in different forms. The fuel consists of a spherical kernel of oxides or carbides of uranium, thorium, plutonium or a mixture of these heavy metals. This kernel whose diameter varies between 200 and 800 µm is coated in layers of pyrolytic carbon to form a fuel coated particle. A layer of silicon carbide can be sandwiched between the low and the high density pyrolytic carbon forming the "TRISO" coated particle. "BISO" particles have also been used in the pass: these are coated particles without silicon carbide, which proved not to retain metallic fission products. The coating has a thickness of 150 to 200 µm. These particles are dispersed within a graphite matrix which is shaped either as a hollow cylinder for the prismatic block HTRs or a sphere for the Pebble-Bed type; Figure 1 shows the schematic description of a fuel pebble. In Pebble-Bed Reactors, the fuel is continuously inserted at the top of the core and discharged from the bottom; the integrity and the burn-up level is then checked and the pebble reinserted at the top of the core if the target burn-up is not yet reached: this is the recirculation fuelling scheme. Another fuelling scheme is the one in which the speed of the fuel elements is slowed down to reach the desired burn-up level in one pass: this is the "Once-Through-Then-Out"

(OTTO) fuelling scheme (Hansen *et al.*, 1972:132). The online refuelling, together with the passive safety features of PBR constitute their main advantage.

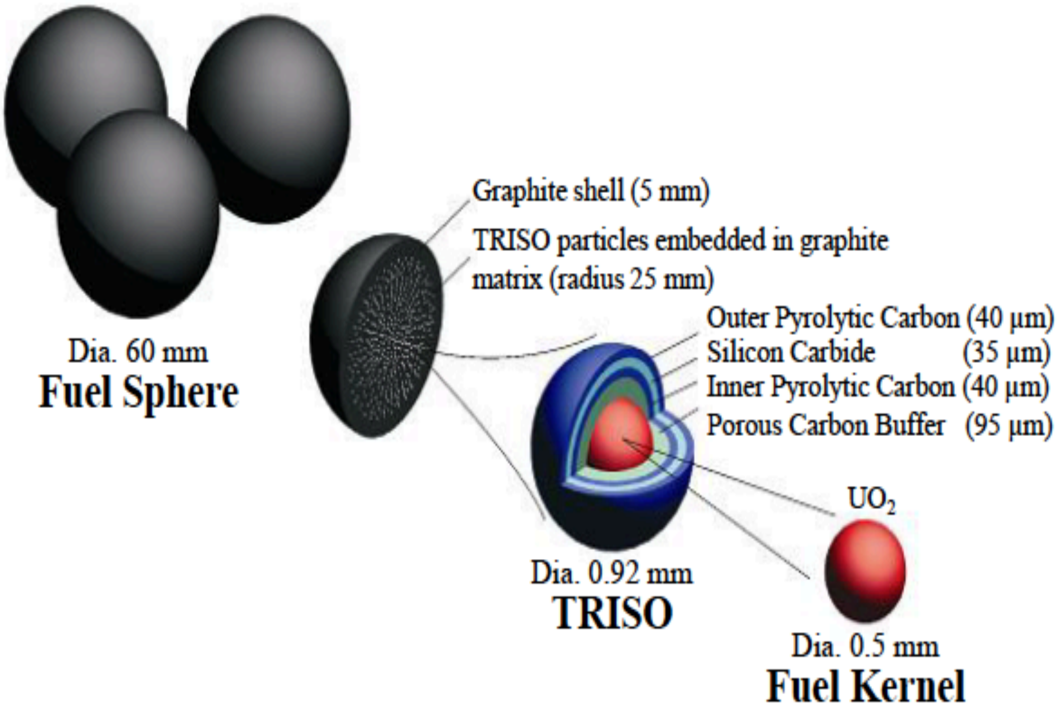

Figure 1: Schematic of a fuel kernel, TRISO particle and fuel pebble

2.2 Thorium fuel cycle for Pebble-Bed Reactors

2.2.1 Pebble-Bed Reactors

Pebble-Bed Reactors (PBR) originates from Germany where they have been operated at an experimental level with the 46 MW_{th} German Arbeidsgemeinschaft Versuchsreaktor (AVR) in Jülich from 1967. For more than 20 years of operation, this cylindrical (2.8 m high and 3 m diameter) core was cooled by helium and produced outlet temperatures of 850 and then 950 ^oC, using different fuel types (Ding *et al.*, 2009:3105; Krüger & Ivens, 1985:61). The AVR experienced releases of radioactive fission products from the fuel spheres into the cooling system that was much higher than the designed values. This appears to be due to errors, in the form of oversimplifications, in the input models of the simulation models for the AVR. The result was that the actual maximum equilibrium temperatures were substantially higher than those predicted by the simulation model. Therefore the fuel leaked substantially more radioactivity than was predicted by the model. In response, the German nuclear regulator ordered the equilibrium fuel temperatures to be reduced substantially for the remainder of the plant's life. The end result was that the internal structures of the plant was seriously contaminated. Therefore the regulator ordered the internal structures of the plant to be filled with concrete, in order to contain the radioactivity. Due to these unfortunate events, the decommissioning of the AVR has not yet been completed.

The experience gained with the AVR, in terms of fuel elements testing and safety features, led to the construction and operation of the commercial Thorium High Temperature Reactor (THTR-300). This 6 m high, 5.6 m diameter cylindrical core produced 750 MW of thermal power from 675000 pebbles made of a mixture of thorium and highly enriched uranium oxides fuel. With a 250 ^{o}C inlet and 750 ^{o}C outlet temperatures, it was cooled by a 40 bar helium flow (Baumer *et al.*, 1990:155; Baumer & Kalinowski, 1991:59). Due to its large core and high power density, the THTR did not have the important inherent safety feature of being by design able to limit the maximum fuel temperatures during a DLOFC accident to below 1600 °C. Due to financial and political difficulties and fears about the safety of nuclear reactors, after the Chernobyl accident, the THTR-300 was closed down after generating 2.9 million MWh and 423 full power days in roughly 3 years with good plant availability. The specific incident that led to the closure of the THTR was the crushing of a few fuel spheres, due to insertion of control rods directly into the fuel bed, which resulted in the release of some radioactivity into the atmosphere.

The claim to fame of HTRs, beside their higher temperatures allowing for process heat application and higher efficiency in producing electricity compared to light water reactors, has always been their advanced safety features. However, the anticipated bright future of HTRs was doomed by the design philosophy of the time: the continuous increase of the power output of reactors in order to match that of the fossil fuelled power plants (Reutler & Lohnert, 1984:129).

The Chernobyl accident triggered a shift in the design philosophy of nuclear reactors, with researchers focusing more on passively safe reactors. Work by Reutler and Lohnert (Reutler & Lohnert, 1983:22; Reutler & Lohnert, 1984:129) suggested new designs combining large surface-to-volume ratio and low core power. This would ensure that in all operating and accident conditions, the decay heat can be removed by conduction and natural convection only to avoid fuel temperatures from exceeding 1600 ^{o}C. The result was the so-called HTR-module, with a power output in the region of 200 MW_{th}, so that a plant of any size could be constructed by combining several of these modular reactors in parallel.

In the mid-1990s, China adhered strictly to that philosophy with the development of the HTR-10 (Wu *et al.*, 2002:25); in operation since 2000 near Beijing. This reactor has produced enough experimental data that led to the development of the 250 MW_{th} High Temperature Reactor Pebble-Bed Modular (HTR-PM). A prototype 210 MW_e power plant, formed by twin HTR-PM units driving a single steam turbine, is currently under construction and should come online in the near future. The success of this prototype could lead to the construction of 18 more HTR-PMs on the same site (Zhang *et al.*, 2009:1212). In South Africa, the design of the HTR-module was substantially modified in the development of the 400 MW_{th} Pebble Bed Modular Reactor (PBMR-400), which is another example of that modular concept (Reitsma, 2004). The present study will focus on the use of thorium in the PBMR-DPP-400 for the standard six-pass recirculation and for the OTTO refuelling schemes.

2.2.2 Thorium fuel cycle

The interest in thorium as a nuclear fuel, mostly as a supplement to the known uranium reserves, which were initially thought to be quite limited, started in the early days of nuclear energy. After the success of burner reactors in the sixties, breeding reactors was demonstrated in the seventies and eighties in both water-cooled and gas-cooled reactors. The discovery of new uranium reserves and the slow-down in the nuclear industry in the eighties after the Three Mile Island and Chernobyl accidents reduced the interest in thorium, except for countries with large thorium deposits, such as India. The enthusiasm in alternative fuel cycles further declined with the introduction into the market of down-blended uranium from nuclear weapon disarmament programs such as the USA collaboration with Russia in the "Megatons to Megawatts" program. Thorium was mainly deployed with HEU in the early days of this fuel cycle. However, this raised concern about the nuclear weapons proliferation risk of the HEU.

The new millennium, however, came with renewed interest in thorium-based fuels, due to factors such as its low production of plutonium and minor actinides, the possibility of burning plutonium in a plutonium/thorium fuel in a thermal reactor and the possibility of breeding fissile isotopes in a thermal reactor. It is impossible in this work to provide a detailed history of the thorium fuel cycle. Instead, we shall focus here on the use of thorium in High Temperature Gas-cooled Pebble-Bed Reactors which is more relevant to this work. As stated earlier, the use of thorium in PBRs was mainly developed in Germany with the experimental AVR (Ding *et al.*, 2009:3105; Krüger & Ivens, 1985:61) which gave rise to the commercial THTR-300 (Baumer *et al.*, 1990:155; Baumer & Kalinowski, 1991:59). Although high operational costs and an operational incident which resulted in the release of radioactive materials are the official grounds for the shutdown of the THTR-300, there are suggestions that the actual reason was political (probably the proliferation issue).

2.2.3 Proliferation risk of thorium fuel cycles in PBRs

The proliferation resistance is the capacity of a nuclear energy system to inhibit, impede, or prevent the diversion of associated fuel-cycle materials or facilities from civilian to military use. As such, there must be a clear distinction between institutional risk from governments harbouring nuclear weapon ambitions and technical nuclear weapons proliferation risk. The former is more a political matter than a scientific one as many nuclear powers developed their military program before the civilian (USA, Israel), others only signed the Non-Proliferation Treaty (NPT) after successful test of their nuclear weapons (France) and others even signed the NPT but still went ahead and developed nuclear weapons (North Korea). Iran is another example but the government of Iran has denied allegations that they harbour a nuclear weapons ambition. In this section, we will only look at the technical proliferation resistance as it is the most effective against sub-national threats (terrorist activities) (Kang, 2005:672).

The proliferation resistance is defined in terms of the resources required (personnel, technological base and financial), time required and the risk of detection for a proliferation activity in light of their inherent difficulty. Highly Enriched Uranium and weapons-grade plutonium are very well known as potential nuclear weapon fuels. The determination of the isotopic barrier of a nuclear material will be based on the critical mass, the heat generation rate, the spontaneous neutron generation and the gamma radiation. In terms of all these criteria, U-233 which is the main fissile isotope of the thorium fuel cycle is comparable with Pu-239 with the same Bare Critical Mass (BCM). The Proliferation Resistance enrichment threshold for U-233 is therefore at 12 a/o %, compared to 20 a/o % for U-235-based LEU (Artisyuk *et al.*, 2008:647; Ezoubtchenko *et al.*, 2005:701; Kang & von Hippel, 2001:1).

2.3 Influence of the neutron spectrum on reactor safety and conversion ratio

2.3.1 Pebble-Bed Reactors spectra

Simulations with VSOP-99/05 showed that the conversion ratio for the standard 6-pass recirculation scheme with 9.6 wt% enriched, 9 g per fuel sphere low-enriched uranium (LEU) fuel cycle of the PBMR-DPP-400 is in the range of 0.45, which is substantially lower than the approximately 0.6 for standard LEU fuelled pressurised light water reactors (PWRs) and very much lower than the approximately 0.8 for pressurised heavy water reactors such as the CANDU reactors fuelled with natural uranium (Lamarsh & Barata, 2001:119).

In light water reactors, the conversion ratio is raised by reducing the lattice pitch, thereby decreasing the moderation ratio. This leads to a less moderated neutron spectrum and thus to more fast fissions and more neutron captures in the epithermal resonances of U-238, i.e. to more breeding of Pu-239. A further contributing factor to more breeding is less thermal neutron captures in the water. However, this does not apply to Pebble-Bed Reactors: the reduced lumping, due to the tiny fuel particles, reduces the fraction of fast fissions in Pebble-Bed Reactors to insignificant levels, irrespective of the moderation ratio. Since the capture cross section of graphite is much smaller than for light water, neutron captures in the graphite moderator inside the fuel spheres are insignificant and therefore reducing the moderation ratio will not significantly reduce these captures.

A key towards a higher conversion ratio is the use of a breeder fertile fuel blanket around a driver core which produces the majority of the fissions and thus the fission neutrons, as has been implemented in Core Design and Fuel Management Studies of a Thorium-Breeder Pebble-Bed High-Temperature Reactor (Wols *et al.*, 2014:1). However, this in practice raises a problem of realistic applicability, together with proliferation concerns because of the recycling of the fuel.

Another possible key towards improving the conversion ratio for the PBMR may be reducing the neutron leakage. The current PBMR design unnecessarily loses neutrons in the central reflector. This 2 metre diameter graphite cylinder is so thick that many neutrons cannot migrate all the way through it. As the fast and epithermal neutrons enter the reflector, they quickly get moderated down to thermal energies and therefore the fast and epithermal fluxes approach zero somewhere between 20 to 50 cm into the central reflector (Reitsma, 2004). At this depth the task of thermalising the neutrons are essentially completed and the rest of the reflector does not contribute to the moderation, but unfortunately contributes strongly to the capture of these thermal neutrons. This is because the microscopic cross-section for radiative capture by C-12 increases sharply with decreasing neutron energy in the thermal energy window. These losses can be reduced by reducing the diameter of the central reflector to the point where most neutrons will pass through and exit the reflector just after they have been properly moderated. However, this will mean a deep redesign of the reactor with all the challenges that come with it.

A way of improving the neutron economy in PBMRs without touching the design parameters is improving the number of neutrons emitted/neutron absorbed ($\eta = \nu\sigma_f /(\sigma_f + \sigma_c)$) in the fissile fuel. As shown in Figure 2, η is well above 2 for almost the entire spectrum of ^{233}U, and substantially higher than that of the other fissile isotopes (U-235 and Pu-239). So if the PBMR were to be fuelled with the Th/U-233 fuel cycle, breeding or at least a very good conversion ratio would theoretically be possible.

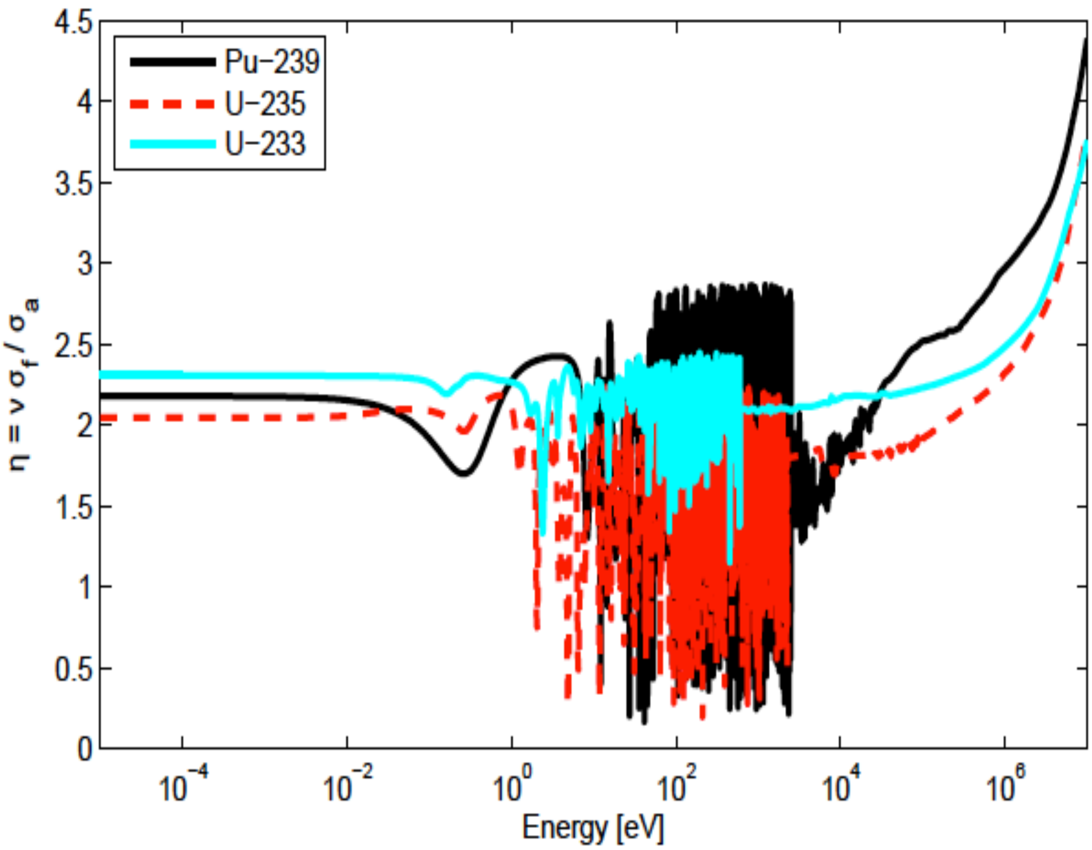

Figure 2: The number of fission neutrons produced/neutron absorbed (η), as a function of energy (eV) for U-233, U-235 and Pu-239

2.3.2 The transmutation chain of Thorium

Fissile ^{233}U does not occur naturally like the 0.72 wt% of U-235 in natural uranium. It is rather produced from natural thorium (almost 100% ^{232}Th) via the following nuclear reaction:

$$^{232}Th(n,\gamma)^{233}Th \xrightarrow{\beta^-} {}^{233}Pa \xrightarrow{\beta^-} {}^{233}U$$

A neutron capture by Th-232 produces Th-233, which undergoes a β-decay with a half-life of 22.3 minutes to produce protactinium (Pa-233). Pa-233, which is also radioactive with a half-life of roughly 27 days, undergoes another β-decay to become U-233. Therefore to start the process, it is merely necessary to introduce thorium into a critical reactor where it is irradiated by neutrons. After a reasonably short irradiation time, at which point the U-233 has built up to the desired level, the fuel can be withdrawn from the reactor and the U-233 can be extracted chemically from the thorium, since they are two completely different chemical elements. The purpose here is to introduce this U-233 into the fresh fuel of a second reactor.

This, however, carries a proliferation risk as such U-233 could potentially be used to fuel nuclear weapons (Serfontein & Mulder, 2014:106). Otherwise the bred U-233 can be kept inside the Th-based fuel in the first reactor for as long as possible, with a view to countering the enrichment depletion of the fuel with increased burn-up. The aim is then to burn as much of the U-233 *in situ*. This substantially reduces the proliferation risk as the fuel then remains in the reactor until it is extremely radioactive and thus very difficult and risky to work with, for would-be nuclear weapon proliferators. Furthermore the fact that the bred U-233 is irradiated inside the reactor for a much longer time leads to a much higher accumulation of U-232. U-232 has a very radioactive decay chain, which could help to deter would-be proliferators. Therefore this last approach of *in situ* fissioning of the U-233 was taken in this study.

2.3.3 Neutron poisons in Pebble-Bed Reactors

Neutron poisons are neutron-absorbing materials, or nuclides with a high absorption cross-section for neutrons. In light water and block type reactors, some of these neutron poisons (B-10, Gadolinium, Hafnium ...) are used to control the excess reactivity of the start-up core, while others (Xe-135, Sm-149 ...) are produced in the core as fission products (Lamarsh & Barata, 2001:119). 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, 2000:733)

2.3.4 Depressurised Loss of Force Coolant (DLOFC) accidents in HTRs

A DLOFC accident occurs when due to a pipe break in the primary coolant loop, a fast depressurisation of the core causes a complete loss of cooling. This results in a sharp rise in the fuel temperature, which in turn with the very strong negative reactivity coefficient will quickly drop the multiplication factor and stop the chain fission reaction, resulting in a reactor scram (Serfontein, 2011). This is considered the worst design condition as the decay heat has to be evacuated from the core by natural means in order to maintain the integrity of the fuel and prevent the release of radioactive material in the environment. During a DLOFC accident, the reactor loses the helium flow through a large break and rapid depressurization. For the thermal hydraulic calculations, the reactor is considered at its nominal steady-state conditions, and the loss of coolant happens immediately and the power is taken from 400 to 0 MW instantaneously. The decay heat in the absence of helium cooling will heat up the core.

This decay heat is dissipated by conduction between pebbles, from pebbles to reflectors or by thermal radiation in the gaps between pebbles.

More literature on the topic of the DLOFC, which is the focus of this work, will follow at the beginning of each article.

2.3.5 V.S.O.P. (99/05) computer code system (Rütten, 2007)

VSOP which stands for Very Superior Old Programs is a system of computer codes linked together for the numerical simulation of the physics of thermal reactors. The code processes cross sections, sets up the reactor and fuel elements, evaluates neutron spectra, and calculates neutron diffusion, fuel burn-up, fuel shuffling, reactor control and thermal hydraulics in steady state and transients. While the neutronics calculations can be performed in up to three dimensions, thermal hydraulics is restricted to HTRs in two spatial dimensions. The code allows following the reactor from initial core towards the equilibrium core and the temperature transients are obtained by doing a quasi-static nuclear evaluation. The code has been extensively used in the development of HTRs with spherical fuel elements. It requires as input the geometry of the reactor fuel core, as well as the atomic number densities for each isotope that the core consists of, together with other physical attributes such as the temperatures of different regions, the helium coolant gas flow rates and inlet temperature and pressure. It then iteratively solve the diffusion equation which produces the neutron flux in four discrete energy groups together with all the required nuclear reaction cross-sections for each energy group. From this it calculates all the important reaction rates, such as the fission rate of ^{235}U, the rate of radiative capture in ^{238}U, which simultaneously yields the depletion rate of ^{238}U and the production rate of ^{239}Pu. From this the depletion, breeding and transmutation evolution of all important isotopes, as a function of burn time, are calculated for the present fuel loading in the core. After a stipulated burn cycle the core is refuelled: All fuel layers move one position down, at pre-specified fuel flow speeds, five in designated fuel flow channels. The layer at the bottom of each channel falls out of the core. For a Once-Through-Then-Out refuelling scheme, this whole fuel layer is sent to the spent fuel tank. For the six-pass recirculation-refuelling scheme of the PBMR-400, only the oldest fuel batch (Pass (6)) is sent to the spent fuel tank. Pass (1) then becomes Pass (2) and is sent back to the top of the core and reintroduced into the first fuel layer at the top, which became vacant when the fuel moved down. Similarly the old Pass (2) becomes the new Pass (3), etc. The space for

Pass (1) fuel in each top layer is then filled with fresh fuel from the fresh fuel tank. This process repeats itself throughout the while life of the core.

From the reaction rates the neutron multiplication factor (k_{eff}) and all other important parameters regarding the neutron economy of the core is calculated. Once the neutronic calculations have converged, the fission heat production rates are calculated from the fission rates and are sent to the THERMIX thermo-hydraulics code, which use them to iteratively recalculate the heat flow and from that temperature distribution throughout the core, including the temperature of the coolant gas. THERMIX then send the updated temperature distribution back to VSOP.

Since most neutronic reaction rates are temperature sensitive, VSOP uses the new temperatures to iteratively recalculate the neutron fluxes, cross-sections, reaction rates and the evolution of the atomic number densities of the isotopes. This is repeated after each burn and refuelling session. It then uses this new data to recalculate the heat production rates, where after it again send it to THERMIX, so that the whole process repeats iteratively until the whole burn history of the core has been calculated for the life of the plant and all relevant results are then summarised in an output file.

In order to calculate the temperatures during a DLOFC accident, THERMIX is informed that all helium coolant flow and pressure has been lost and that the fission reaction has stopped instantaneously, as described above. The heat production rate then decreases to only about 7% of full power decay heat production, which also decreases exponentially over time. However, since all active cooling has been lost, this small heat production must now be evacuated by means of only conduction and radiation. The result is that heat production exceeds heat evacuation and thus the core starts to heat up. As time progresses the decay heat production falls to below 1% and the heat evacuation rate increases as the core heats up. At some point heat evacuation then starts to exceed heat production, where after the core slowly starts to cool down. This tipping point is normally reached between 24 and 48 hours into the accident. The aim is to design the core such that this tipping point will be reached before the maximum industry guideline fuel temperature 1600°C is reached. Experimental measurements suggests that if this temperature is not breached, no large leakages of radioactive decay products will occur through the coating layers around the fuel particles. The 99/05 version of the code used in this study was developed in collaboration with PBMR/ESKOM specifically for the Pebble-Bed Modular Reactor (PBMR) for which a review of neutron spectrum calculation methods was performed in the frame of validation and verification. Some experiments were conducted at the High Temperature Test Unit (HTTU) facility of the North-West University. Validation of the code will prove very difficult as no pebble-bed reactor has operated at burnup equilibrium.

References

Abram, T. & Elshahat, A., E. 2012. Advanced nuclear reactors and passive safety. (In G. & et al., eds. In: Nuclear power plants. Nova Science Publishers, Inc. p. 41-68).

Artisyuk, V.V., Saito, M. & Ezoubtchenko, A. 2008. Development of methodology to assess proliferation resistance of nuclear heavy metals. *Progress in nuclear energy,* 50647-653.

Baumer, R. & Kalinowski, I. 1991. THTR commissioning and operating experience. *Energy,* 16(1-2):59-70.

Baumer, R., Kalinowski, I., Röhler, I., Schöning, J. & Wachholz, W. 1990. Construction and operating experience with the 300-MW THTR nuclear power plant. *Nuclear engineering and design,* 121(2):155-166.

Boer, B., Kloosterman, J.L., Lathouwers, D. & Van Der Hagen, T.H.J.J. 2009. In-core fuel management optimization of pebble-bed reactors. *Annals of nuclear energy,* 361049-1058.

Boer, B., Lathouwers, D., Kloosterman, J.L. & Van Der Hagen, T.H.J.J. 2010. Optimization of a radially cooled pebble bed reactor. *Nuclear engineering and design,* 2402384-2391.

Ding, M., Boer, B., Kloosterman, J.L. & Lathouwers, D. 2009. Evaluation of experiments in the AVR with the DALTON-THERMIX coupled code system. *Nuclear engineering and design,* 2393105-3115.

European, C. 2003. External costs: Research results on socio-environmental damages due to electricity and transport. http://www.extern.info/externpr.pdf Date accessed: 04 Feb. 2016: Directorate-General for Research. ExternE project. (nr. EUR 20198).

Ezoubtchenko, A., Saito, M., Artisyuk, V.V. & Sagara, H. 2005. Proliferation resistance properties of U and Pu isotopes. *Progress in nuclear energy,* 47(1-4):701-707.

Hansen, U., Schulten, R. & Teuchert, E. 1972. Physical properties of the "once through then out" pebble-bed reactor. *Nuclear science and engineering,* 47132-139.

Kang, J. 2005. Analysis of nuclear proliferation resistance. *Progress in nuclear energy,* 47(1-4):672-684.

Kang, J. & von Hippel, F.N. 2001. U-232 and the proliferation-resistance of U-233 in spent fuel. *Science & global security,* 91-32.

Krüger, K.J. & Ivens, G.P. 1985. Safety-related experiences with the AYR reactor. PROCEEDINGS OF A SPECIALISTS' MEETING ON SAFETY AND ACCIDENT ANALYSIS FOR GAS-COOLED REACTORS, OAK RIDGE NATIONAL LABORATORY, OAK RIDGE, 13-15 May, 1985.

Lamarsh, J.R. & Barata, A.J. 2001. Nuclear reactor fuels. (In Anon. Introduction to nuclear engineering. 3rd ed. p. 119).

Leverenz, R. 2006. The EPR- A safe and competitive solution for future energy needs. Nuclear energy for new Europe, Portoroz, Slovenia, September 18-21, 2006.

Reitsma, F. 2004. The pebble bed modular reactor layout and neutronics design of the equilibrium cycle. PHYSOR 2004 -the physics of fuel cycles and advanced nuclear systems:

Global developments, on CD-ROM, American nuclear society, Lagrange Park, IL. Chicago,

Illinois, April 25-29, 2004.

Reutler, H. & Lohnert, G.H. 1984. Advantages of going modular in HTRs, *Nuclear engineering and design,* 78(2):129-136.

Reutler, H. & Lohnert, G.H. 1983. The modular high-temperature reactor. *Nuclear technology,* 62:22-30.

Rütten HJ, Haas KA, Brockmann H et al V.S.O.P. (99/05) (release 2): Computer code system for reactor physics and fuel cycle simulation. 2007, Jülich: Institut für Sicherheitsforschung und Reaktortechnik [Software]

Serfontein, D.E. 2014. Sharp reduction in maximum fuel temperatures during loss of coolant accidents in a PBMR-400 core, by means of optimised placement of neutron poisons. *Nuclear engineering and design,* 271:492-498.

van Dam, H. 2000. Long-term control of excess reactivity by burnable particles. *Annals of nuclear energy,* 27(8):733-743.

Wols, F.J., Kloosterman, J.L., Lathouwers, D. & Van Der Hagen, T.H.J.J. 2014. Core design and fuel management studies of a thorium-breeder pebble bed high-temperature reactor. *Nuclear technology,* 186:11-16.

Wu, Z., Lin, D. & Zhong, D. 2002. The design features of the HTR-10. *Nuclear engineering and design,* 218:25-32.

Zhang, Z., Wu, Z., Wang, D., Xu, Y., Sun, Y., Li, F. & Dong, Y. 2009. Current status and technical description of Chinese 2 x 250MWth HTR-PM demonstration plant, *Nuclear engineering and design,* 239:1212-1219.

Zoran, V.s. 2007. The nuclear renaissance and AREVA's reactor designs for the 21th Century: EPR and SWR-1000. Nuclear energy for new Europe 2007, Portoroz, Slovenia, September 10-13, 2007. Date of access: 04 Feb 2016.

3 REDUCING DLOFC FUEL TEMPERATURES BY MIXING THORIUM WITH LEU IN A TWO-ZONE SIX-PASS FUEL CYCLE IN A PBMR-DPP-400 CORE

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3.1 Motivation and Relative contributions of authors

3.1.1 Motivation

The main motivation for this work came from the ground work done during the PBMR years in developing a South African design of an inherently safe nuclear reactor. Further motivation was the whole myth and unsubstantiated claims of many possibilities of thorium replacing uranium as the primary fuel for the nuclear industry.

3.1.2 Relative contribution of authors

Prof. D.E. Serfontein was the study leader during this stage of the research with the task to provide guidance and support to M. Tchonang Pokaha whilst also evaluating the academic soundness and strength of the research. The initial broad concept for the study came from Prof. Serfontein. However, as the study progressed Tchonang Pokaha took the lead. All research was conducted and documented by M. Tchonang Pokaha.

3.2 Article1: REDUCING DLOFC FUEL TEMPERATURES BY MIXING THORIUM WITH LEU IN A TWO-ZONE SIX-PASS FUEL CYCLE IN A PBMR-DPP-400 CORE

Abstract: Many studies have been done in neutronics and thermal-hydraulic simulation of the standard 6-pass fuel recirculation scheme for the standard 9.6 wt % enriched, 9 g per fuel sphere low-enriched uranium (LEU) fuel in the PBMR-DPP-400, using different versions of the VSOP diffusion codes. Maximum DLOFC temperatures were all below the upper limit of 1600 °C. The DLOFC temperature is highly dependent on the peaking factor of the power; meaning a lower maximum DLOFC temperature can be obtained by supressing the axial power peak and by moving the radial power peak towards the external reflector. In this study the standard 6-pass fuel recirculation was retained. The improvement strategy was thus attempted by means of flattening the axial power profile by mixing substantial amounts of thorium into the LEU fuel. The addition of thorium led to breeding of substantial amounts of 233U. This led to slower depletion of enrichment with burn-up, which increased fuel reactivity and power densities near the bottom of the core and thus flattened the axial power profile. The effect was a reduction in maximum DLOFC temperature by 44 °C. The simulations were made using the VSOP-99/05 diffusion code. It was further shown that the results obtained are also applicable to the Chinese HTR-PM and the proposed strategies for further improvement can be expected to produce even much better results in Block Reactors than in Pebble Bed Reactors.

I. Introduction

The HTR-PM currently under construction in China marks a revolution in the nuclear industry in general and the Pebble Bed Reactors (PBR) in particular. It combines two 200 MW_{th} reactors to drive a single 210 MW_e turbine, each reactor having a cylindrical core of 3 m diameter and 11 m height[1]. The 400 MW_{th} Pebble-Bed Modular Reactor Demonstration Power Plant (PBMR-DPP-400) was also developed in South Africa from the middle of the 1990s. However, uncertainty about some technical issues regarding the safety case of this reactor led to the South African National Nuclear Regulator (NNR) postponing the final decision to grant it a licence. This delay was a substantial contributing factor to the eventual demise of the project. Except for the nominal power output, the main difference between these two reactors is the use of a central graphite reflector in the PBMR-DPP-400 in addition to the external reflector. This central reflector, by pushing the fuel spheres outwards toward the external reflector, allows for a higher power output[2]. However, these reflectors very effectively moderate the neutrons that enter them and thus reflect an abundance of thermal neutrons back into the fuel. This causes fission power peaks in the fuel directly adjacent to both reflectors. Unfortunately the peak against the central reflector is substantially higher than against the external reflector.

The slow rate at which fuel spheres flow from the top to the bottom of the core results in burn-up levels at the bottom of the core which are substantially higher than at the top. The top-to-bottom gas flow direction also produces much higher fuel temperatures at the bottom than at the top. Together these factors result in fuel reactivity and thus in power densities that are substantially lower at the bottom than at the top of the core, resulting in a sharp peak in the axial power profiles of most PBRs.

In the case of the PBMR-400 DPP, the combined axial and radial peak is situated about a third from the top of the core and directly adjacent to the central reflector[3]. This becomes a problem in the case of a Depressurized Loss of forced Coolant (DLOFC) accident, as this peak in the equilibrium power profile creates a DLOFC temperature hotspot: the decay heat power during a Depressurized Loss of Forced Coolant (DLOFC) accident is directly proportional to the equilibrium thermal fission power density that preceded the accident. Therefore the peak in the equilibrium power density also produces a similar peak in the DLOFC decay heat power density, which leads to DLOFC temperature hot-spot some distance below the power hot-spot. This hot-spot causes a safety issue in that it causes the DLOFC fuel temperatures in this hotspot to approach the upper limit of 1600 °C at normal equilibrium power output. If, however, the equilibrium power output is reduced in order to reduce the maximum DLOFC temperature, it reduces the revenues from power sales and thus the profitability of the plant.

Many studies have been done in neutronics and thermal-hydraulic simulation of the standard 6-pass recirculation scheme for the standard 9.6 wt % enriched, 9 g per fuel sphere low-enriched uranium (LEU) fuel in the PBMR DPP-400, using the VSOP-A and different versions of the VSOP-99 diffusion codes. Maximum temperatures during a DLOFC incident were all below the upper limit of 1600 °C, which ensures that the leakage of radioactive fission products through the TRISO coatings around the fuel kernels will remain below the acceptable limits[2,3].

Substantial reductions of this DLOFC temperature can be obtained by manipulating the axial and radial power profiles. A standard approach is to flatten the axial power profile by increasing the number of fuel recirculation passes, as has been done for the indirect Rankine steam cycle of HTR-PM. However the designers of the PBMR-400 rejected more passes as they were concerned that this would grind too much graphite dust particles of the fuel spheres, which could damage the helium turbine blades of the direct Brayton cycle, and that the shorter out-of-core time available for measuring the burn-up of the fuel spheres could jeopardise these measurements. Therefore more passes were also not explored in this study. An improvement of the power profiles with the use of a neutron poison distribution in the central reflector produced a maximum DLOFC temperature of 1297.6 °C (Ref.4). However, since the use of neutron poison in the central reflector limits this technique to cores that have a central reflector, this option will not be explored in the present study. Another optimisation study combined the multi-pass scheme with a multi-zone refuelling: the fresher fuel was placed in the outer fuel zones and the more depleted fuel in the inner fuel region[5], together with a radial outer-to-inner gas flow and smaller pebbles reported maximum DLOFC temperatures of 1369 °C (Ref.6). However, since changing the coolant flow pattern is a major modification to the original design, this option will not be explored here.

On the other end of the spectrum the number of recirculation passes can be reduced to one, the so-called Once-Through-Then-Out (OTTO) refuelling scheme. This is done to simplify the design of the reactor and thus to reduce its construction cost. However, by the logic explained above this makes the peak in the axial power profile much sharper and thus sharply increases the maximum DLOFC temperature, which then necessitates a sharp reduction in the power output, which reduces the revenue from power sales. OTTO cycles also produce a substantially lower maximum burn-up of the fuel spheres, which increases fuel cost. Therefore this option will not be explored here.

The aim of this study is to design a fuel sphere content for the standard fuel sphere geometry in the standard six-pass fuel recirculation scheme in the standard PBMR-DPP-400 which will reduce the maximum DLOFC fuel temperature by flattening the axial power profile, while maintaining the power output and without substantially increasing the fuel cost. Also, we want to come up with a solution that will also be applicable to the HTR-PM and for Prismatic Block fuelled HTRs. This will be attempted by breeding ^{233}U by adding thorium to the LEU fuel. It is well known that ^{233}U fissions with a better neutron economy in thermal reactors than ^{235}U, ^{239}Pu or ^{241}Pu and that therefore adding thorium to LEU fuel improves its breeding ratio. In the present case that will mean that the rate at which the fissile enrichment decreases with increasing burn-up will be reduced. Therefore the rate at which the enrichment and thus the reactivity and power density of the fuel decreases as it flows down from the top towards the bottom of the core should also decrease. Therefore the addition of thorium should increase the power densities below the axial power peak, which will by definition smooth this peak.

II. Simulation methods

A. Reactor and Fuel Geometry and Safety Limits

This study will be based on the design of the PBMR-DPP-400 as described by Reitsma[2] and by Serfontein and Mulder[7]. The safety limits are from Serfontein's PhD dissertation and its follow-up studies[3,7,8] and are given in Table 1. The simulation parameters for the annular core of the PBMR DPP-400 are from (Ref.6) except that the Heavy Metal content for the Th/LEU mixture fuel spheres will be increased from 9 to 20 g, the enrichment of its LEU will be increased from 10 to 20 a/o %. Different fractions of thorium will be mixed with this LEU in order to manipulate overall enrichment of the fuel. These parameters are given in Figure 1 and Table 2 below, and more details are discussed further down.

Table 1: Adopted safety limits for Pebble Bed Reactor fuel

Parameter	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 conditions.

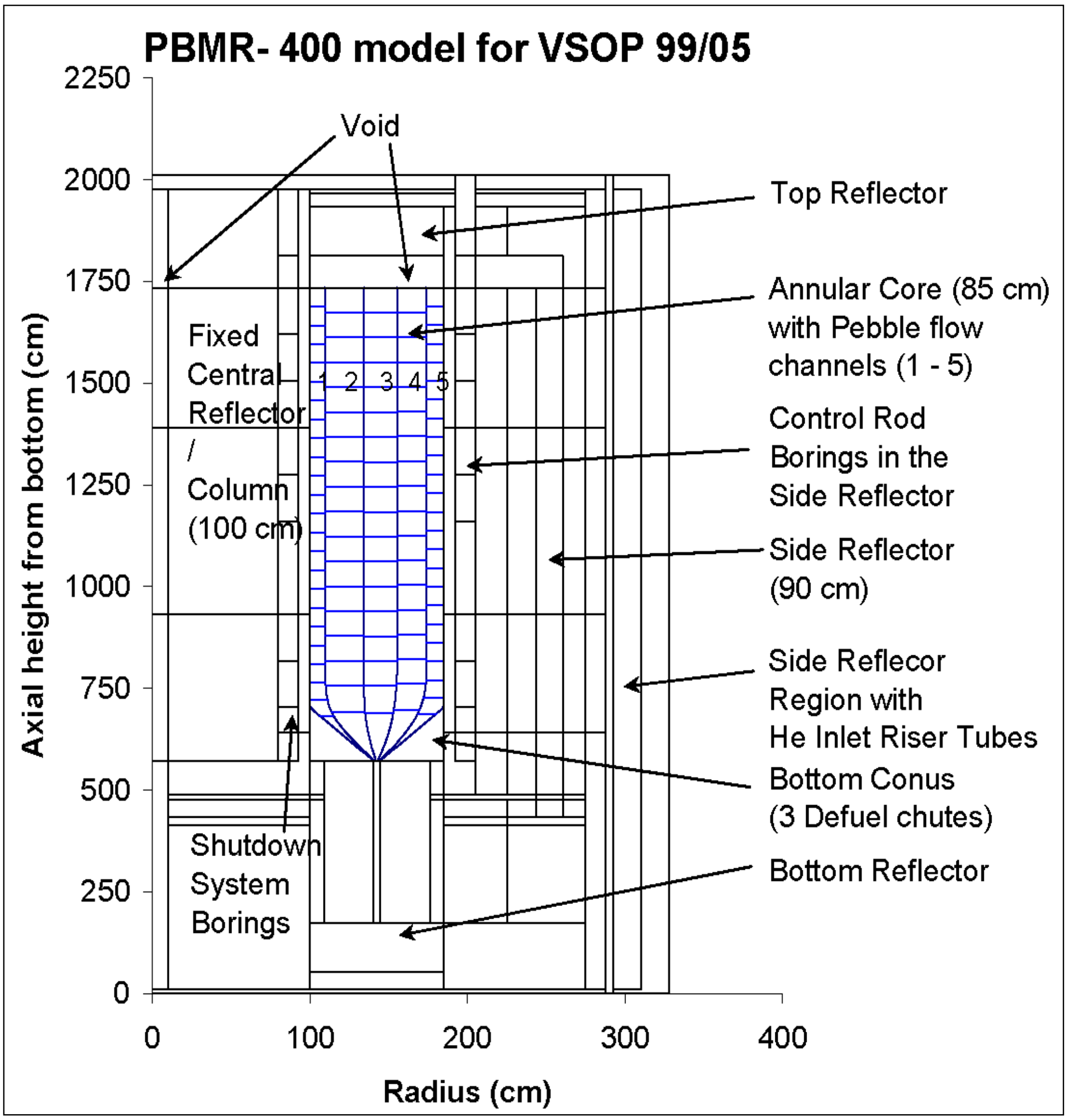

Figure 1: Reactor geometry used for VSOP simulations

Table 2: Simulation parameters for the annular PBMR DPP-400 reactor core

Parameter	Unit	Value
Volume of fuel core	m^3	83.73
Packing fraction of fuel spheres		0.61
Height of core	m	11.625
Radii of fuel core annulus: inner / outer	m	1.00 / 1.85
Fuel recirculation	Nr. of passes	6
Number of fuel flow channels		5
Flow pattern	Steps / channel	24 / 18 / 18 / 18 / 24
Pressure of helium	Bar	90
Heating of helium	°C	500 → 944
Helium mass flow, after reduction for cold bypass	kg/s	173.4
Cold bypass	%	10.0
Fuel sphere geometry:		
Outer radius of zones: Inner fuel matrix / outer graphite shell	cm	2.5 / 3.0
Heavy Metal per fuel sphere	g	9 for LEU, 9-20 for Th+LEU
Coated particles:		
Diameter of fuel kernels	cm	0.05
Fuel composition		ThO_2/UO_2
Fuel density	g/cm^3	10.4

B. **Theoretical approach to optimization of the axial power profile**

Figure 2 shows the axial equilibrium fission power density profiles in the inner and outer-most fuel flow channels of the PBMR DPP-400 core, fuelled by the standard 10 a/o % LEU with a six-pass recirculation fuelling scheme. The resulting maximum axial DLOFC temperature profile is also shown on a different scale

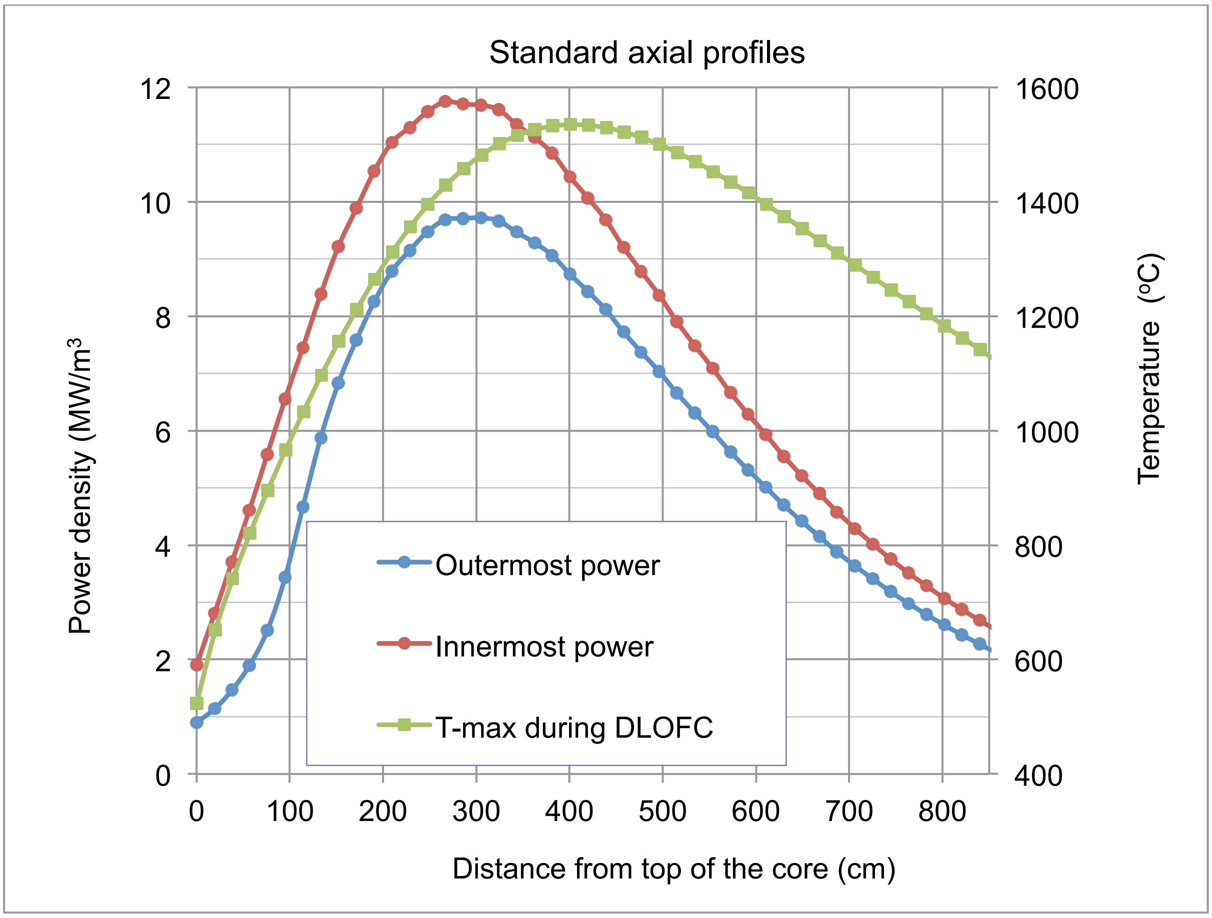

Figure 2: Axial equilibrium power density profiles for the standard six-pass cycle core and the maximum DLOFC temperature profile, shown on a separate scale.

Understanding of these profiles from Figure 2 could facilitate improving strategies to reduce the maximum DLOFC temperature without compromising the other performance parameters of the system:

- The axial equilibrium power density profiles peak at ±280 cm from the top of the core, where after they decrease quickly with the continuous depletion of the fissile ^{235}U in the fuel and the build-up of fission product poisons with increased burn-up from the top towards the bottom of the core[9]. The drop in power density can further be explained by the fact that the helium coolant temperature and thus the fuel temperature rise substantially from top towards the bottom, reduces the reactivity of the fuel[4].

- The power in the innermost channel is substantially higher than in the outermost channel. This is due to the fact that the thermal neutron flux is focused near the centre of a cylindrical core and that the control rods in the outer reflector absorbs substantial numbers of neutrons near the top of the core and thus suppresses fission in the top part of the outer fuel layers[4]. This power peak adjacent to the central reflector increases the distance over which the high power decay heat, produced in these inner layers of the fuel core, has to be conducted out towards the external reflector and then outwards towards the ultimate heat sink. This increases the temperature difference between the inner and outer fuel layers, required to drive this increased conduction requirement. This increases the DLOFC temperatures near the inner part of the fuel core, as is observed.
- The maximum DLOFC temperature profile also peaks near the top of the core at about 400 cm from the top, with the higher temperatures (>1300°C) concentrated in the region between 200 and 700 cm from the top. It should be noted that the DLOFC temperature peaks about 100 cm below the power density peaks and then drops off much slower that the power peaks. This substantial displacement of the DLOFC temperature peak towards the bottom of the core can be explained as follows:

  It has already been explained that the DLOFC decay heat power density is directly proportional to the equilibrium power and thus the shape of the axial profile of the decay heat power density should be virtually identical to that of the equilibrium power. The differences between the equilibrium power profiles and the DLOFC temperature profile should therefore be explained by heat evacuation, rather than heat production. Due to the accumulation of heat in the coolant gas the equilibrium coolant temperature increases monotonously as the gas flows from the top to the bottom. Therefore the equilibrium fuel temperature as well as the temperature of the reflectors increases in a similar fashion. At the beginning of the DLOFC accident, all the structures are still at their equilibrium values. Therefore the temperatures of the fuel and reflectors below the equilibrium power peaks are much higher than above it. Therefore the decay heat produced in the fuel above the equilibrium power peaks will be conducted out towards the top and the external reflectors at a high rate, as these reflectors are much cooler than the fuel. By the same logic the decay heat produced below these power peaks will be evacuated out towards the outer and the bottom reflectors at a much slower pace as the temperatures of these reflectors are much higher than was the case above the power peaks. Therefore the DLOFC temperatures below the power peaks will start off higher, will then rise during the accident and stabilise at higher values, compared to positions above the equilibrium power peaks.

- The peak in DLOFC temperatures are confined in the narrow region between about 200 and 700 cm from the top. Thus the conduction of the decay heat power from the inner layers towards the external reflector and to the ultimate heat sink will also be concentrated in this thin hotspot region. This leads to a high outward heat flux in this thin region, resulting in unnecessarily high DLOFC temperatures.

These observations show that the DLOFC temperature is highly coupled with the equilibrium power profiles. In order to reduce the maximum DLOFC temperature, the axial equilibrium power profiles has to be manipulated such that the maximum DLOFC temperature profile is flattened as much as possible. This has been done very successfully by Serfontein[4] by placing an optimised distribution of neutron poison in the central reflector. Unfortunately all these poisons absorbed a lot of neutrons and thus reduced the achieved burn-up of the fuel substantially. Therefore, in the present study no poison will be used. Rather, the flattening of the DLOFC temperature profile will be attempted by only adding thorium to the LEU fuel.

C. Modification of the fuel for optimization of the axial power profile

In the quest to flatten the axial power profile, the Heavy Metal content of the standard 9 g/fuel sphere 10 a/o % LEU fuel was replaced by a mixture of thorium and 20 a/o % LEU. The motivation for the fuel choice comes from the fact that radiative capture of neutrons by ^{232}Th breeds fissile ^{233}U, which fissions in thermal reactors with a much better neutron economy than both the ^{239}Pu bred from ^{238}U and the original ^{235}U in the LEU. This is because the number of fission neutrons released per neutron absorbed in the fissile fuel (η) is much higher for ^{233}U than for ^{239}Pu, which is in turn caused by the fact that the capture-to-fission ratio (α) in thermal and especially in epithermal neutron spectra is much higher for ^{239}Pu than for ^{233}U (Ref.10).

Unfortunately ^{232}Th is a less effective neutron capturer than ^{238}U: The microscopic cross-section for radiative capture of thermal neutrons by ^{232}Th (7.4 barns) is about 3 times higher than that of ^{238}U (2.7 barns) (Ref.11&12). However, the epithermal capture resonances of ^{238}U is much stronger than that of ^{232}Th and therefore the resonance integrals for these captures are about four times as high for ^{238}U-based fuel spheres than for ^{232}Th-based ones. Epithermal captures dominate over thermal ones, since thermal captures by the fertile materials have to compete for the available thermal neutrons with absorptions for thermal fission in the fissile fuels, for which the microscopic cross-sections are about two orders of magnitude higher. Therefore, for fuel spheres containing similar number densities of ^{232}Th and ^{238}U, the number of ^{239}Pu nuclei bred from captures in the ^{238}U will be much higher than the number of ^{233}U bred from ^{232}Th.

On top of that, the microscopic thermal fission cross-section of ^{233}U is only about half that of ^{239}Pu. Therefore, not only will ^{239}Pu be bred faster, but it will then also fission at a much higher rate than the ^{233}U. Therefore, for similar number densities of ^{238}U and ^{232}Th, fissioning of ^{239}Pu will strongly dominate over fissioning of ^{233}U and therefore the poor neutron economy of ^{239}Pu will dominate over the good neutron economy of ^{233}U.

Therefore the ratio of ^{238}U/^{232}Th were reduced by increasing the enrichment of the LEU from 10 a/o% to its legal upper limit of 20 a/o% and by increasing the Heavy Metal content progressively from 9 g up to 20 g/sphere, where all of this extra mass was taken up by ^{232}Th. This is similar to the approach taken by Wols *et al*[13].

The improved neutron economy from the bred ^{233}U produces more excess neutrons that can be used for more breeding and thus Th-based thermal energy fuel cycles generally have higher conversion ratios than LEU-based ones. Higher conversion ratios result in faster build-up of ^{233}U, which slows the rate of depletion of the enrichment with increasing burn-up. This leads to slower loss of reactivity and power density as the fuel flows down, which translate into smoothed axial power profiles.

The addition of extra Th to the fresh fuel immediately reduces the enrichment and thus also the reactivity and power density at the top of the core. Breeding of ^{233}U has a much longer time-delay than that of ^{239}Pu. This is due to the unusually long half-life of 26.975 days for the decay of ^{233}Pa to ^{233}U (ENDF/B-VII.-1: Radioactive Decay Data[14]) in the nuclear chain reaction: (Ref.15)

$$^{232}Th(n,\gamma)^{233}Th \xrightarrow{\beta^-} {}^{233}Pa \xrightarrow{\beta^-} {}^{233}U$$

This means that it will take substantially longer than 27 days for the production rate of ^{233}U to approach its equilibrium value. This accumulated ^{233}U will also fission much slower than the accumulated ^{239}Pu, due to the much smaller microscopic fission cross-section of ^{233}U. The ^{233}U concentration will take much longer to rise to close to its equilibrium value than ^{239}Pu would. Therefore the boost in fission power from bred ^{233}U will kick in much lower down in the core. All of this implies an additional suppression of the fission rate at the top and an additional elevation thereof towards the bottom of the core and thus an additional smoothing of the axial power profiles.

III. Results

A. Effects of the Heavy Metal Loading on Temperature and the Conversion Ratio

The table below presents the fissile conversion ratio (C), the maximum equilibrium fuel temperature (T_{Eq}) and the maximum DLOFC temperature (T-DLOFC) for different heavy metal (HM) loadings. The first line deals with the standard 10 a/o % LEU, 9 g/fuel sphere heavy metal loading; which is the reference case and all the subsequent lines represent Th/LEU mixtures.

Table 3:Fuel performance for different heavy metal loadings

HM content (g)	C	T_{Eq} (°C)	T-DLOFC (°C)
9 LEU	0.447	1050	1536
9 Th-LEU	0.433	1056	1557
11 Th-LEU	0.485	1030	1547
13 Th-LEU	0.527	1023	1537
15 Th-LEU	0.559	1027	1533
16 Th-LEU	0.560	1030	1526
17 Th-LEU	0.585	1050	1516
18 Th-LEU	0.595	1067	1510
19 Th-LEU	0.604	1085	1502
20 Th-LEU	0.611	1107	1492
21 Th-LEU	0.617	1132	1482

This table shows that at 9 gram heavy metal per fuel sphere, the LEU has a higher conversion ratio, a lower equilibrium fuel temperature and also a lower DLOFC temperature than the Th-LEU mixture. This is due to the fact that the amount of added thorium was so small that it bred only a small amount of ^{233}U. On the other hand, the same decrease in the mass of ^{238}U caused a larger decrease the breeding of ^{239}Pu. This is because ^{238}U has a much higher microscopic cross-section for radiative capture of neutrons, compared to ^{232}Th. As the ^{232}Th concentration was increased by using higher heavy metal loading, the conversion ratio increased and the DLOFC temperature decreased. This is due to the desired flattening of the axial power profile as was predicted. However, the equilibrium fuel temperature shows that the heavy metal content cannot be increased indefinitely: the increase in heavy metal drops the equilibrium fuel temperature until a HM loading of 13g/sphere is reached. Thereafter the equilibrium fuel temperature increases continuously to reach a value above the safety limit at 21g/sphere heavy metal loading. The increase of the equilibrium fuel temperature for the higher HM contents could be explained by the fact that more heavy metal in a fuel sphere means the mean free path for the neutrons between collisions with fuel particles becomes smaller and therefore the core becomes more under-moderated, i.e. the more neutrons will be captured in the epithermal resonances of ^{232}Th and thus more ^{233}U will be bred. However the fission rate in the centre of the core will be supressed due to lack of thermal neutrons. Only the fuel close to the reflectors will burn well due to the abundance of thermal neutrons that stream in from the reflectors. Due to more breeding and less fissions the fuel in the central flow channel will reach the exit cone at the bottom of the core with a substantially higher enrichment than that of the fuel in the outer flow channels, next to the reflectors. However, upon entering the exit cone, all the fuel channels are squeezed and thus become much thinner. The fuel in the central fuel channel thus now move close enough to the reflector cones that they are for the first time also bathed in the influx of thermal neutrons. Therefore the power in this central fuel channel suddenly spikes, as is shown in Figure 3 below in which the axial power and equilibrium fuel temperature profiles for the 13 and 20 g/sphere cores are compared, at the radius of maximum fuel equilibrium temperature for the 20 g/sphere case. For the reasons given above, this maximum temperature occurred in the central fuel flow channel. Note that this power spike happens at the bottom of the core where the coolant gas is already so hot that it loses much of its heat removal capability, and this small spike in power translates into a substantial spike in the equilibrium fuel temperature. As can be seen this power spike is not present for the 13 g/sphere case. This power spike for the high MH content can probably be eliminated easily by putting neutron poison in the graphite of the exit cones, which would probably reduce the maximum equilibrium temperature.

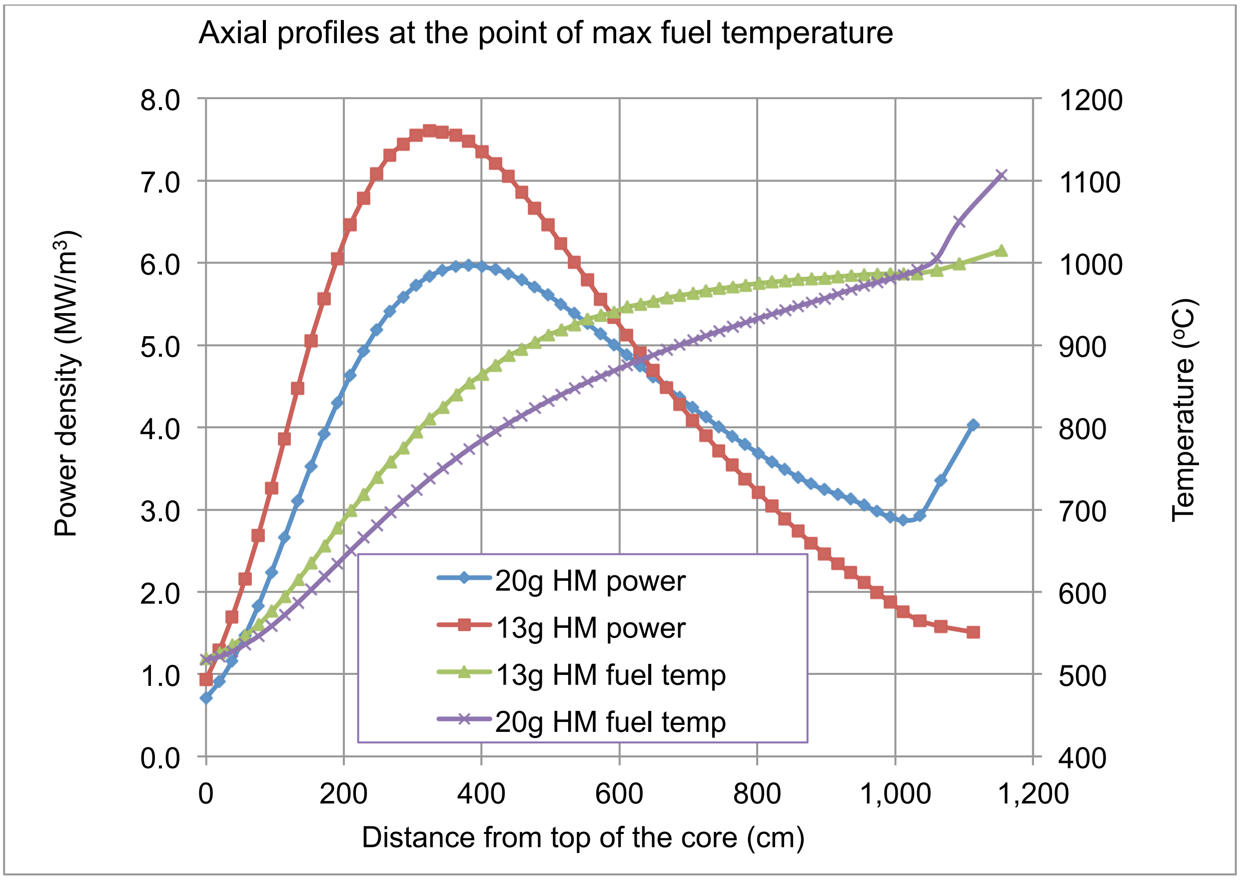

Figure 3: Axial equilibrium power density and equilibrium fuel temperature profiles comparison for 13g/sphere and 20g/sphere Th-LEU mixture for the central fuel flow channel.

B. Effects of the Heavy Metal Loading on Axial Profiles

The results presented in table 3 of the previous section impose 20g/sphere as our maximum permissible heavy metal loading because 21g/spheres produce an equilibrium fuel temperature of 1132°C, which is just above the safety limit of 1130°C. In this section, a comparison of the axial profiles of the standard 9g/sphere LEU and those of a 20g/sphere Th-LEU is made. Figure 4 shows the axial equilibrium fission power density profiles in the innermost fuel flow channel for the LEU 9g/fuel sphere (i.e. the pure LEU fuel cycle) and for the Th-LEU 20g/fuel sphere mixture.

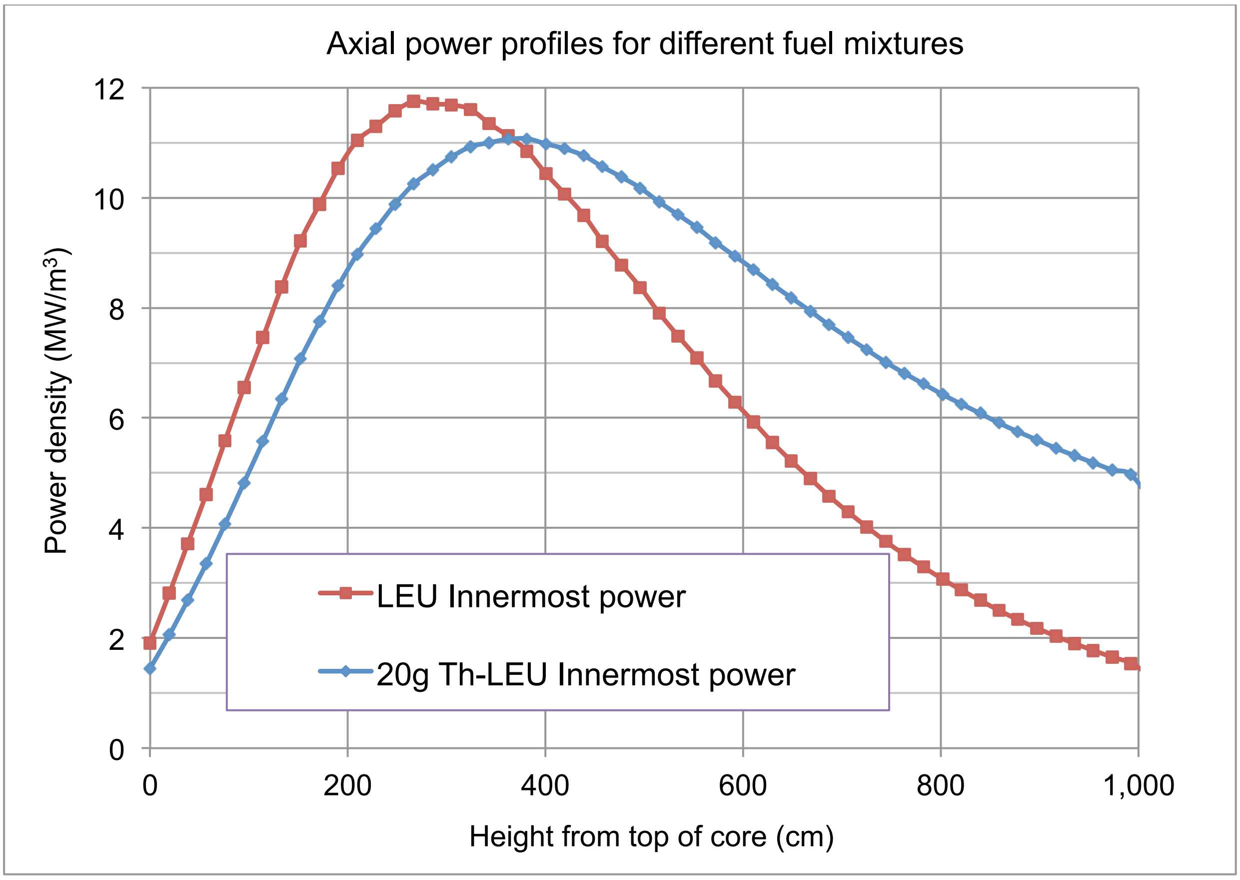

Figure 4: Axial equilibrium power density profiles comparison for LEU and Th-LEU mixture in the innermost channel.

The two profiles show the same features, peaking near the top of the core (285.6 cm for LEU and 381.4 cm for the Th-LEU mixture) before dropping off sharply. The LEU profile peaks at 11.73 MW/m^3 compare to only 11.13MW/m^3 for Th-LEU. However, the drop in the Th-LEU mixture's profile below the peak is much slower so that the power density below 800 cm is more than double that of the LEU core. At 1000 cm into the core (this is almost the entire height of the core), the power of the mixture is about 5 MW/m^3, compared to less than 2 MW/m^3 for the LEU core. As was explained above, this flattening of the axial power profile is due to the higher conversion ratio and the better neutron economy of the ^{233}U fuel cycle, which kicked in below about 4 m into the core. The effects of this flattened peak in the axial power profile for the Th-LEU can be observed in the DLOFC temperature profiles in Figure 5 below. Figure 5 shows that, as was expected, the flattening of the peak in the axial equilibrium fission power profile also produced a flattening of the axial DLOFC temperature profile for the Th-LEU, which reduced the maximum DLOFC temperature from 1536 ^{o}C for the LEU to 1492 ^{o}C for the TH-LEU.

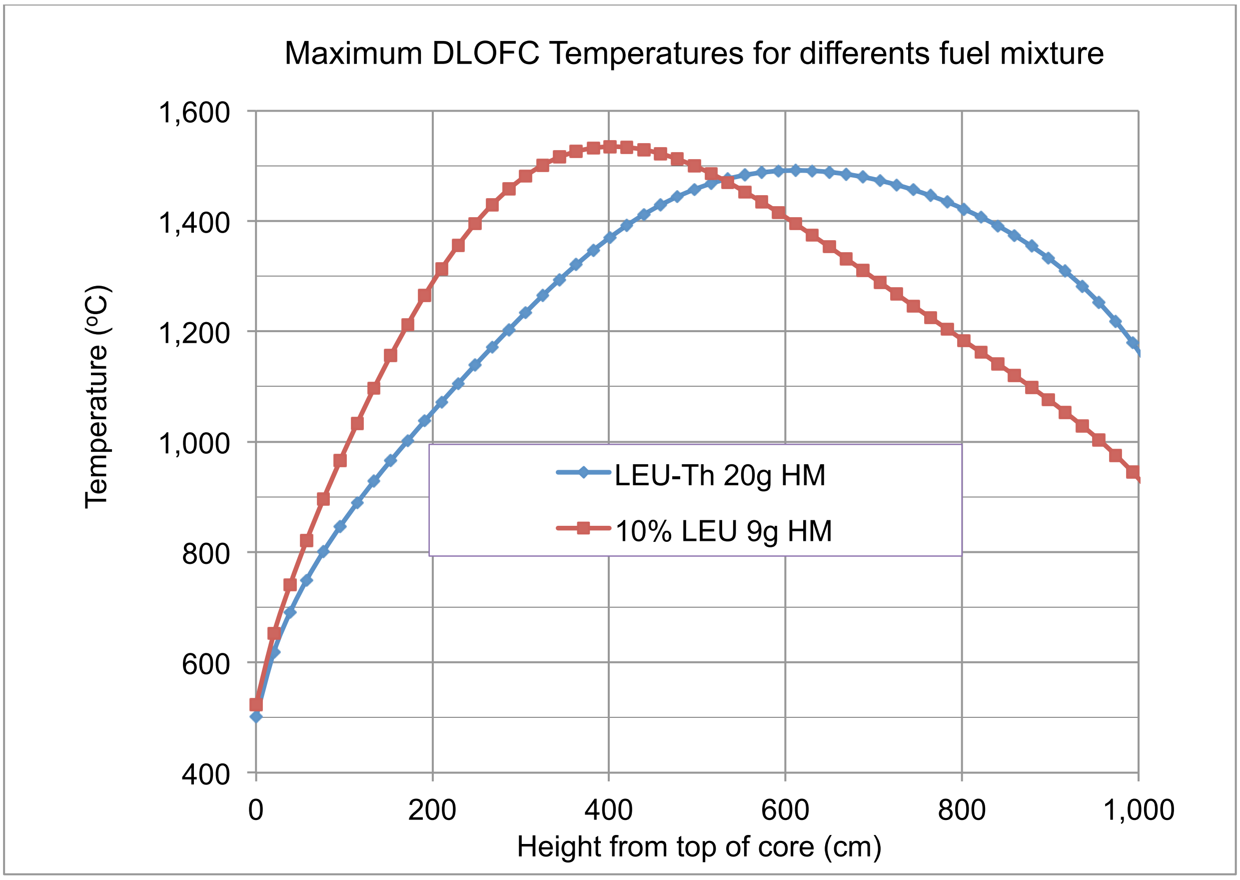

Figure 5: Axial DLOFC temperature profile comparison for the two fuel cycles.

It is noteworthy to mention that the maximum DLOFC temperature with the optimised approach is only reached after 62 hours into the accident, compared to the 50 hours into the accident for the LEU, as is shown in Figure 6, which shows the different DLOFC temperatures as a function of time. This is a major advantage because the spreading out of the high temperature peak over a longer period, allows for the evacuation of a large total amount of decay heat, with lower heat fluxes, which led to decreased temperatures. This is also an advantage as it gives more time for possible remedial actions to be taken in order to prevent fuel damage and eventual radioactivity release into the environment.

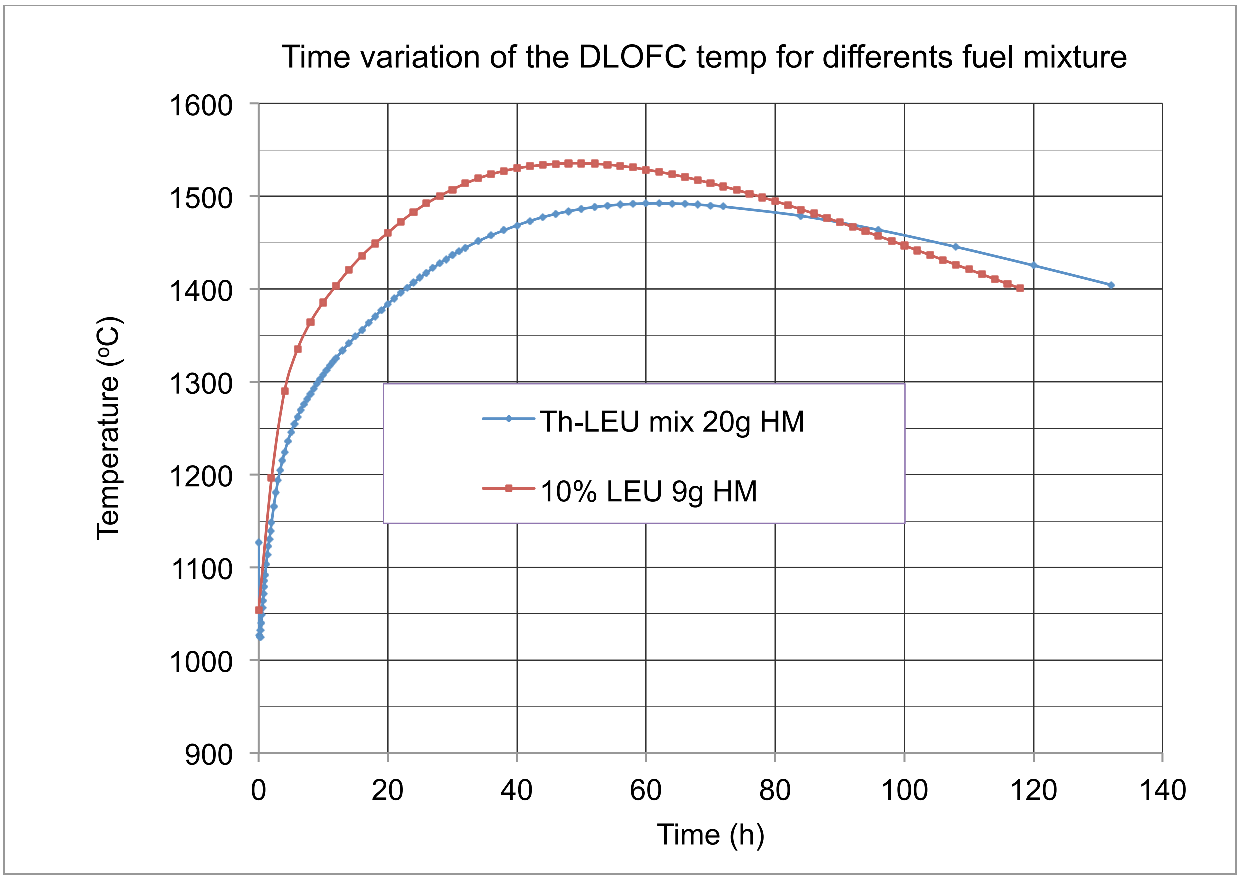

Figure 6: DLOFC temperature as a function of time into the accident for the two fuel types.

IV. Discussion

The maximum DLOFC temperature of 1492 °C for the Th-LEU mixture was 44 ^{o}C lower than the 1536 °C for the LEU fuel. However, this improvement is relatively small. The upper limit in the equilibrium temperature of 1130°C is due to the use of a direct cycle and the fear of highly radioactive ^{110m}Ag being released and platting out on the cold surface of the turbine blades, thus making the maintenance difficult[2]. However, the industry accepted equilibrium temperature is 1200°C; with such temperature, the Heavy metal content could have been increased even further, which would increase the equilibrium fuel temperature but reduce the maximum DLOFC temperature even further.

V. Conclusion

- The optimisation of the axial power profile, aimed at substantially reducing the maximum DLOFC temperatures by means of using a mixture of LEU and thorium in optimum enrichments resulted in a reduction of the maximum DLOFC temperature by 44^{o}C. As the leakage rate of radioactive fission products through the coating layers around the fuel particles increase exponentially with increasing temperature, such a small decrease in temperature could produce a substantial reduction in this leakage rate and could thus contribute to the expansion of thorium-based fuel cycles.

- Even so, this small reduction in the maximum DLOFC temperature was disappointing. Therefore the following follow-up studies are proposed to reduce this temperature much further by combing the use of thorium with:
  - designing an asymmetric core in which the fresh fuel is loaded in the external flow channels first, and only go through the inner flow channels after reaching a certain burn-up in order to reduce the maximum DLOFC temperature even further
  - Obtaining even larger temperature reductions by also putting an optimised neutron poison distribution in the central reflector.
- It should be noted that while the present study was conducted for the PBMR-400 DPP, the results and proposed studies are also applicable to other HTRs:
  - Since the technique of putting neutron poison in the central reflector was not used in the present study, its results for the Th-LEU mixture can be expected to also apply directly to PBRs that do not use a central reflector, such as the Chinese HTR-PM.
  - All the improvements achieved and proposed can be expected to give even better results in in Prismatic Block type HTRs. In PBRs manipulating the fuel distribution is difficult, since this can only be done once, i.e. when inserting the fuel at the top of the core the composition or placement in different radial zones can be manipulated. Thereafter the fuel flows down without any opportunity for further manipulation in the axial fuel distribution. However, in Prismatic Block reactors, manipulations of both the fuel and poison distributions can be carried out in the radial and axial directions. Using burnable poisons distributions to maintain the reactivity of the core with increasing burn-up is already a standard feature of prismatic block cores. However the improved neutron economy and thus more breeding that comes with introducing large quantities of Th into the core will slow the rate of decrease of the reactivity of the core with increasing burn-up. Therefore less burnable poisons will be required to maintain the reactivity. This will result in

less parasitic absorption of neutrons and thus even more neutrons will become available for even more breeding. Therefore the opportunity for fine-tuning the core for reduction of both equilibrium and DLOFC temperatures should produce even much better results in Block Reactors.

References

1. Zhang, Z., Wu, Z., Wang, D., Xu, Y., Sun, Y., Li, F. & Dong, Y. 2009. Current status and technical description of Chinese 2 x 250MWth HTR-PM demonstration plant, *Nuclear engineering and design,* 239:1212-1219

2. Reitsma, F. 2004. The pebble bed modular reactor layout and neutronics design of the equilibrium cycle. PHYSOR 2004 -the physics of fuel cycles and advanced nuclear systems: Global developments, on CD-ROM, American nuclear society, Lagrange park, IL. Chicago, Illinois, April 25-29, 2004.

3. Serfontein, D.E., Mulder, E.J. & Reitsma, F. 2014. Optimisation of deep burn incineration of reactor waste plutonium in a PBMR DPP-400 core. *Nuclear engineering and design,* 271:99-105.

4. Serfontein, D.E. 2014. Sharp reduction in maximum fuel temperatures during loss of coolant accidents in a PBMR-400 core, by means of optimised placement of neutron poisons. *Nuclear engineering and design,* 271:492-498.

5. Boer, B., Kloosterman, J.L., Lathouwers, D. & Van Der Hagen, T.H.J.J. 2009. In-core fuel management optimization of pebble-bed reactors. *Annals of nuclear energy,* 36:1049-1058.

6. Boer, B., Lathouwers, D., Kloosterman, J.L. & Van Der Hagen, T.H.J.J. 2010. Optimization of a radially cooled pebble bed reactor. *Nuclear engineering and design,* 240:2384-2391.

7. D.E.SERFONTEIN*,* *"*Deep burn strategy for the optimized incineration of reactor waste plutonium in pebble bed high temperature gas-cooled reactors", PhD Theses, North-West University, South Africa (2011)

8. Serfontein, D.E. & Mulder, E.J. 2014. Thorium-based fuel cycles: Reassessment of fuel economics and proliferation risk. *Nuclear engineering and design,* 271:106-113.

9. Hansen, U., Schulten, R. & Teuchert, E. 1972. Physical properties of the "once through then out" pebble-bed reactor. *Nuclear science and engineering,* 47:132-139.

10. J.R.LAMARSH & A.J.BARATA, *Introduction to Nuclear Engineering 3rd Ed,* p.119, Prentice Hall, New Jersey (2001)

11. J.J.DUDERSTADT & L.J.HAMILTON, *Nuclear Reactor Analysis*, JOHN WILEY & SONS, New York (1976)

12. IAEA-TECDOC-1450, Thorium fuel cycle - potential benefits and challenges, Vienna (2005)

13. Wols, F.J., Kloosterman, J.L. & Lathouwers, D. October 2012. Fuel pebble design studies of a high temperature reactor using thorium, *Proceedings of the HTR 2012 (Tokyo, japan)*.

14. ENDF/B-VII.-1. 2013. JANIS database 4.0, OECD nuclear energy agency. http://www.oecd-nea.org/janis/ Date of access: September 3, 2015.

15. Wols, F.J., Kloosterman, J.L., Lathouwers, D. & Van Der Hagen, T.H.J.J. 2014. Core design and fuel management studies of a thorium-breeder pebble bed high-temperature reactor. *Nuclear technology,* 186:11-16.

4 Using thorium to reduce the maximum fuel temperatures during Depressurized Loss of Coolant Accidents in a Once-through-then-out (OTTO) PBMR DPP-400 Core

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4.1 Motivation and relative contribution of authors

4.1.1 Motivation

The motivation for this study comes from the results of the previous one in which thorium was mixed with LEU in a multi-pass fuelling scheme. Although good conversion ratio was achieved, the effect on reducing the maximum DLOFC temperature was disappointing. It was identified that the low reduction of the DLOFC temperature is due to the fact that the bred ^{233}U is loaded back to the top of the core, thereby not balancing the difference in depletion levels between the top and the bottom of the core. Furthermore an OTTO fuelling scheme has the advantage of discarding the fuel handling system thus reducing the complexity of the system.

4.1.2 Relative contribution of authors

Prof. D.E. Serfontein was the study leader during this stage of the research with the task to provide guidance and support to M. Tchonang Pokaha whilst also evaluating the academic soundness and strength of the research. All research was conducted and documented by M. Tchonang Pokaha.

4.2 Article 2 :Using thorium to reduce the maximum fuel temperatures during Depressurized Loss of Coolant Accidents in a Once-through-then-out (OTTO) PBMR DPP-400 Core

Abstract This article presents the results for the PBMR-DPP-400, but for a Once-Through-Then-Out (OTTO) refueling scheme. An optimization attempt of the axial and radial power profiles is reported. The main aim was to reduce the maximum DLOFC temperature by adding thorium to the fuel and making the fuel layout radially asymmetric by placing lower enriched fuel in the inner and higher enriched fuel in the outer fuel flow regions. These measures (1) flattened the peaks in the axial power profiles and thus suppressed the hotspots in the axial DLOFC temperature profiles and (2) 'pushed' the power radially outwards, so as to reduce the distance that the decay heat must be evacuated towards the outside of the fuel core. This resulted in a huge reduction in the maximum DLOFC temperature for the OTTO cycle from 2273°C to 1811°C, which is still above the 1600°C limit but represents a remarkable result. Maximum DLOFC temperature below the 1600°C limit was obtained by reducing the power output. The results obtained and the proposed strategies for further improvement are applicable to the Chinese HTR-PM and could produce even better results in Prismatic Block Reactors such as the Japanese HTTR.

1. Introduction

The claim to fame of most High-Temperature Gas-cooled Reactors (HTGRs) is their strong passively safety features, which makes a catastrophic release of radioactivity during a nuclear accident highly improbable. This is due to the fact that they are designed such that, during a depressurized loss of forced coolant (DLOFC) accident, they will, by the passive means of radiation and conduction only, evacuate their decay heat so effectively to the ultimate heat sink that the maximum fuel temperature will not exceed the safety limit of 1600 °C, above which the leakage of radioactive fission products through the TRISO coatings around the fuel kernels may become unacceptable [1].

Different from the 250 MW_{th} HTR-PM [2], the 400MWth Pebble Bed Modular Reactor Demonstration Power Plant (PBMR DPP-400) [1,3,4] not only makes use of an external, but also of a central graphite reflector. This central reflector was introduced for the sake of increasing the power output of the reactor by pushing the fuel outwards towards the external reflector. This reduces the maximum distance over which the decay heat would have to be evacuated from the inner fuel layers towards the external reflector, during a DLOFC accident. This then reduces the thermal resistance against this outward flow of heat, which reduces the temperature increase in the inner fuel layers and thus the maximum fuel temperature during such an accident.

The fuel spheres in the six-pass recirculation refuelling scheme flows down slowly from the top and actually takes several months to reach the bottom of the fuel core. Therefore, the burn-up level of the fuel increases quickly with distance from the top, causing fast continuous depletion of the fissile enrichment and build-up of fission product poisons with increasing burn-up [5]. The continuous increase of the helium coolant temperature and thus of the fuel temperature with distance from the top increases the Doppler effect and thus the radiative capture of neutrons in the capture resonances of ^{238}U[6]. The combined effect is that the reactivity of the fuel decreases quickly with distance from the top. Therefore, after the axial power density profile peaked close to the top of the core, it decreases quickly with distance from the top.

On the other hand, the fuel spheres in a once-through-then-out (OTTO) refuelling scheme flow down from top to bottom once only and then goes out to the spent fuel storage facility for final storage [5]. Therefore, the fuel spheres flow down roughly six times slower, as they have to traverse this distance once only during their lifetime, compared to six times for the standard six-pass recirculation scheme. Therefore, the reactivity of the fuel decreases roughly six times faster with distance from the top and therefore this axial power peak is much higher and appears much closer to the top of the core and is then followed by a much faster decline towards the bottom in OTTO refuelling schemes, which is the topic of the present paper.

Both the two graphite reflectors are very effective neutron moderators and, due to the absence of fuel to absorb these neutrons, a much higher thermal neutron flux accumulates in these reflectors than in the fuel. In accordance with Fick's law of diffusion a strong current of these thermal neutrons are therefore continuously injected into the fuel, where they are promptly absorbed, causing a sharp increase in fissions in the fuel layers directly adjacent to the reflectors. This causes peaks in the radial power density profiles directly adjacent to the reflectors. However the peak in the innermost fuel channel is much higher and sharper than in the outermost one. This is due to the fact that the control rods are positioned only in the external reflector and is normally inserted to about 1 meter below the top of the fuel core. The absorption by these control rods thus strongly increase the neutron leakage in the top part of the external reflector, which suppresses fission in the top part of the in the outer fuel flow channels. Secondly the cylindrical effect focuses the neutron flux towards the centre of any cylindrical core, which results in higher neutron flux in the inner fuel flow channels [6]. While in reality fuel flow is continuous, the VSOP 99/05 diffusion code model subdivides the fuel core into five discrete fuel flow channels, which are each again subdivided into discrete fuel layers (Figure 1) in order to simulate the fact that the fuel spheres flow slower in the regions directly adjacent to the reflectors, due to friction against these reflectors.

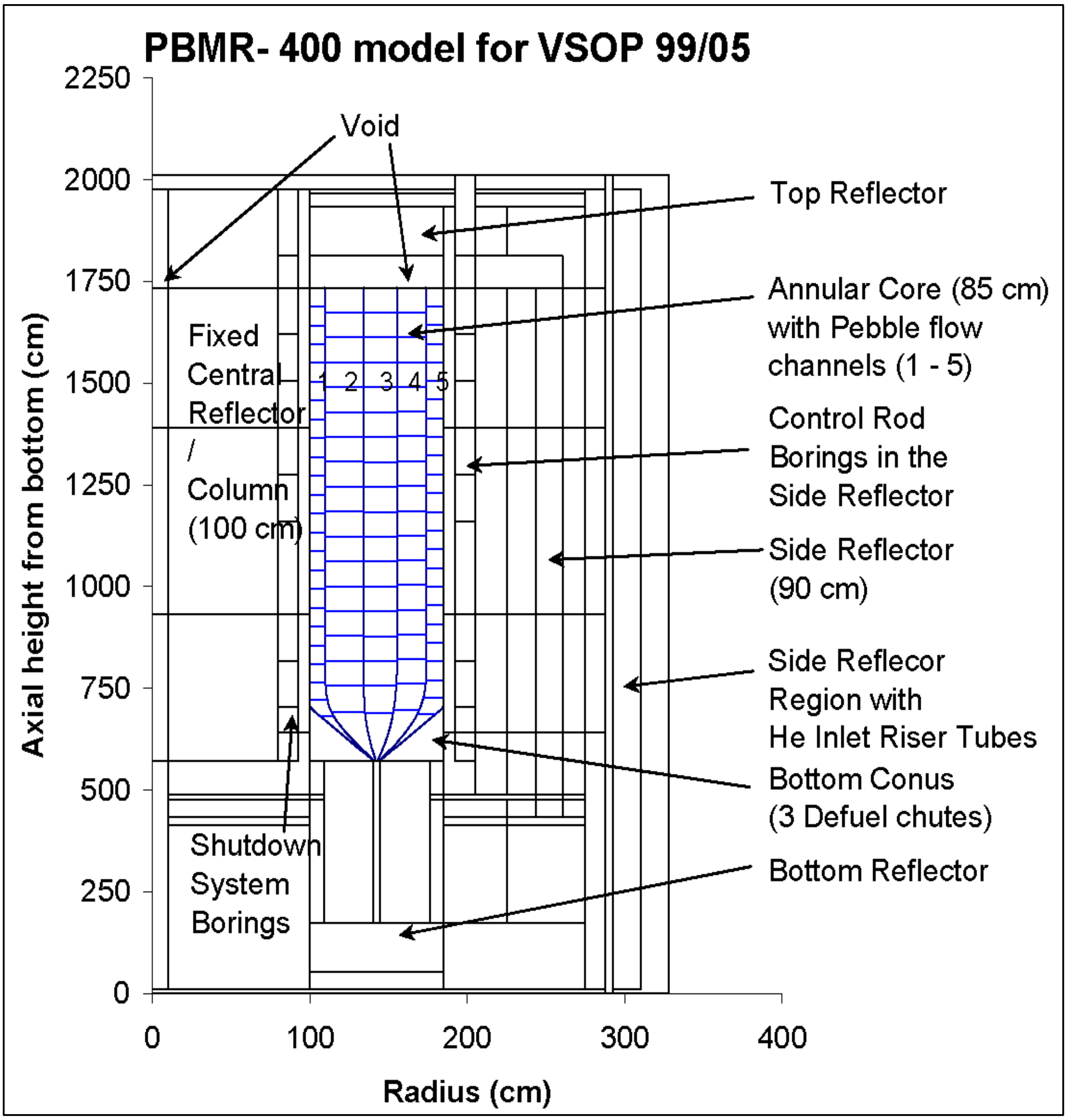

Figure 1: Reactor geometry used for VSOP simulations

The said sharp equilibrium power peak for the OTTO core, very close to the top of the core and directly adjacent to the central reflector, is disadvantageous in the case of a DLOFC accident, for the following reasons:

Since the decay heat power density during a DLOFC is directly proportional to the equilibrium thermal fission power density that preceded the DLOFC, the DLOFC decay heat power density displays a similar peak at the same position. The fact that this peak occurs in the inner-most fuel layer increases the distance and thus the thermal resistance over which the decay heat has to be evacuated radially outwards to the external reflector. This sharply increases the DLOFC temperature generated in this inner fuel layer, i.e. it produces a sharp peak in the radial DLOFC temperature profile, directly adjacent to the central reflector.

The sharp peak in the axial decay heat power profile concentrates the production of decay heat in this narrow axial region and thus sharply concentrates the outward heat flux during a DLOFC accident around this region, which leads to a DLOFC temperature hotspot and thus to unnecessarily high maximum DLOFC temperatures, as will be shown below.

This causes a safety issue in that the maximum DLOFC fuel temperature limit of 1600°C might be exceeded at high power outputs. Normally this problem is mitigated by substantially reducing the power output in order to reduce the maximum DLOFC temperature. However this reduces the revenues from power sales and thus the profitability of the plant. OTTO cycles also achieve substantially lower burn-ups than multi-pass schemes, which will also reduce the fuel economy.

Therefore switching from an OTTO to a multi-pass fuel recirculation scheme is a standard and valid strategy for reducing the maximum DLOFC temperature and increasing the burn-up. However, this requires a complex fuel handling system to check the integrity and the burn-up level of each fuel sphere before reloading it into the core. Since this is a critical safety system, it will be subject to extra regulatory requirements, which will drive up capital costs. So while sticking to an OTTO cycle would reduce the power output and fuel economy, its lower capital cost could possibly lead to higher profitability and therefore this is the route that will be explored in this paper.

2. Problem statement

In view of the above, the problem to be solved is to redesign the standard OTTO fuelling scheme for the PBMR DPP-400 in order to substantially reduce the maximum DLOFC fuel temperature, while maintaining the high 400MW power output of the standard six-pass fuelling scheme and its resistance against nuclear weapons proliferation, without substantially reducing the fuel economy by reducing the total amount of energy produced per fuel sphere.

3. Literature review

Coupled neutronics and thermal-hydraulic simulation results for the PBMR DPP-400 for the standard uranium (U)/plutonium (Pu) fuel cycle (U/Pu(LEU)) (Table 2), fuelled with 9.6 wt% enriched Low Enriched Uranium (LEU), were reported for the VSOP 99 diffusion code by Reitsma [3] and for both VSOP-A and VSOP 99/05 by Serfontein [1] and in Serfontein *et al.*[4]. Serfontein obtained a maximum DLOFC fuel temperature of 1577°C.

Several attempts have been made to reduce the maximum DLOFC temperature. Serfontein [6] suppressed the standard peak in the axial power profile and pushed the radial power outwards towards the external reflector by placing an optimised distribution of ^{10}B neutron poison in the central reflector of the PBMR-400 DPP. This resulted in a large reduction of the maximum DLOFC temperature from 1577 to 1297°C. Unfortunately the poison reduced the neutron economy and thus resulted in a 22% reduction in the average discharge burn-up of the fuel. Since pebble fuel is currently still much more expensive than light water reactor nuclear fuel, fuel cost is a big issue in Pebble Bed Reactors and therefore this 22% decrease in burn-up might add substantially to the power production cost. Therefore the present study shall attempt to circumvent this problem by not adding neutron poisons to the reactor.

Boer *et al.* [7,8] retained a multi-pass refuelling scheme in a PBMR-400 MW core, but replaced the single fuelling zone with multiple radial fuelling zones where fresher fuel was placed in the outer fuel zones and more depleted fuel in the inner fuel regions. The diameter of the fuel spheres was also reduced and the top-down coolant flow pattern was replaced with radial outer-to-inner coolant flow. As a result the maximum DLOFC temperature dropped to 1369°C.

Li & Jing compared the DLOFC temperature of three different radial fuel loading patterns for the multi-pass refuelling scheme in the HTR-PM: the first was a one-zone core, the second, a two-zone core with the inner zone made of higher burn-up fuel, and the third, a two-zone core with the inner zone made of pure graphite balls. The best result was obtained with the third fuelling pattern, followed by the second [9]. The present study differs substantially from theirs in that the present PBMR-400 has a central reflector, an OTTO fuel cycle is used and thorium is added to the fuel.

However, changing the axial to a radial coolant flow pattern is a major deviation from the PBMR DPP-400 design and thus will not be explored in the present paper.

Using multiple radial fuelling zones is also a substantial deviation from the standard design, as it requires multiple refuelling pipes and partitions at the top of the fuel core in order to confine the different fuels to their respective radial zones. However, in view of its potential to push the radial power profile outwards, this approach will be explored here.

When it comes to OTTO fuel cycles, one successful approach to reducing axial power peaking and thus maximum DLOFC temperatures has been to simulate the addition of burnable poisons to the fuel [5, 10-12]. While this method delivered good results, it has a drawback in the sense that the poison distribution cannot be manipulated in detail, for the sake of optimizing the performance: once the fuel spheres containing the poison has been loaded into the top of the core, the poison concentration will decrease with burn-up as the fuel flows down, without the designer being able to control specific poison concentrations at specific positions in the core. As has been discussed above and in Par. 5.3.1 below, Serfontein [6] showed that the ideal axial power profile is not a flat one and that it is therefore advantageous to tailor the vertical poison distribution in detail, for the sake of optimizing the axial power profile. Furthermore that it is advantageous to place all the poison in the central reflector or in the inner fuel layers and none in the outer regions of the core, so that the peak in the radial power profile can be pushed outwards from the central towards the external reflector. However this possibility is lost when the poison is distributed evenly in the fresh fuel at the top of the core. Such a sub-optimal poison distribution will either decrease the magnitude of the resulting reduction in the maximum DLOFC temperature or increase the magnitude of the undesirable reduction in burn-up. Therefore that approach will not be explored here.

4. Research aims

1) To substantially reduce the maximum DLOFC fuel temperature for the standard OTTO fuelling scheme for the PBMR DPP-400 by flattening the axial and radial profiles of the decay heat power density during a DLOFC.
For lack of better tools, this will in practice be attempted by (a) flatting the normal equilibrium operation axial power density profiles and by (b) "pushing" this power production radially outwards towards the external reflector.

2) To avoid losses in fuel burn-up by not adding neutron poisons to the fuel or reflectors.

3) Therefore to rather use a multi radial fuelling zone scheme to push the peak in the radial power profile from a position directly adjacent to the central reflector outwards towards the external reflector by inserting lower enriched fuel in the inner and higher enriched fuel in the outer fuel flow channels.

4) To maintain the high 400 MW power output and resistance against nuclear weapons proliferation of the standard 6-pass fuelling scheme.

5. Simulation Methods

The basis for this study is the design of the PBMR DPP-400, simulated using the VSOP 99/05 diffusion code [1,3,4], but with the standard six-pass refuelling scheme replaced by an OTTO scheme.

5.1 Safety limits

The adopted safety limits from Serfontein's PhD and its follow-up studies were retained [1,4,13] and are given in Table 1.

Table 1: Adopted safety limits for Pebble Bed Reactor fuel

Parameter	Limit
Maximum equilibrium power density	4.5 kW/fuel sphere, which translates to i.e. 300 mW for each of the 15,000 coated particles in the standard 9g LEU PBMR fuel sphere.
Maximum fuel 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 conditions.

5.2 Reactor and Fuel geometry

Simulation parameters for the standard 9g LEU fuel spheres were retained [6]. For the LEU/Th mixtures the addition of large amounts of Th was facilitated by increasing the

Heavy Metal (HM) content from 9 g/sphere (i.e. a coated fuel particle packing fraction of 10.0%) to 16 g/sphere (i.e. a packing fraction of 17.8%) and by increasing the enrichment of the LEU from 10 a/o% to its legal upper limit of 20 a/o%. The logic is that for a given mass of ^{235}U, increasing the enrichment of the LEU reduces the mass of ^{238}U, which frees up space for more Th. Similarly, for a given mass of LEU per sphere, increasing the Heavy Metal content per sphere creates space for more Th. For the LEU/Th mixtures the fuel kernels consisted of homogeneous mixtures of LEU and Th, as opposed to separate LEU and Th particles. This was essential in order to ensure an instantaneous Doppler effect for the Th as the Th was now in direct contact with the LEU so that in increase of fission power in the ^{235}U would also immediately increase the temperature of the Th, thus triggering the Doppler Effect. Homogeneous mixing also ensured that the ^{233}U that is produced from the Th is immediately diluted and thus denatured by the ^{238}U in the LEU, in order to mitigate the proliferation risk.

The logic for the 16 g/sphere HM loading is as follows: The German simulation studies for the THTR have shown that the conversion ratio increases strongly with increasing HM loading [1]. However, at some point, increasing HM loading leads to a packing fraction that is so high that many coated fuel particles touch and thus crack each other during the pressing of the fuel spheres. Unfortunately the safety envelope of the German fuel design is not well defined and therefore the precise upper limit of the HM loading is not known [1,13]. However it is known that the German fuel performed very well up to a HM loading of 16 g/sphere, but started to give problems at roughly 20 g/sphere. Therefore 16 g/sphere was chosen as the upper limit for this study.

The fuel geometry parameters are given in Table 2 below, except for the enrichments that will be discussed in more detail further down. Different enrichments for the LEU/Th mixture were created by dilution of the LEU with different fractions of Th.

Table 2: Simulation parameters for the annular PBMR DPP-400 reactor core

Parameter	Unit	Value
Volume of fuel core	m^3	83.73
Packing fraction of fuel spheres		0.61
Height of core	m	11.625
Radii of fuel core annulus: inner / outer	m	1.00 / 1.85
Fuel recirculation	No. of passes	1
Number of fuel flow channels		5
Flow pattern	Steps/ channel	24/ 18/ 18/ 18/ 24
Pressure of helium coolant	Bar	90
Heating of helium	°C	500 → 944
Helium mass flow after reduction for cold bypass	kg/s	173.4
Cold bypass	%	10.0
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

5.3 Theoretical Approach to Optimisation of Power Profiles

Figure 2 shows the axial equilibrium fission power density profiles in the inner and outer-most fuel flow channels of the PBMR DPP-400 core, fuelled by 9g/sphere 10 a/o% LEU in an OTTO refuelling scheme. In order to emphasize the details, only the top 500 cm is shown. The resulting axial maximum DLOFC fuel temperature profile is also shown on a separate scale.

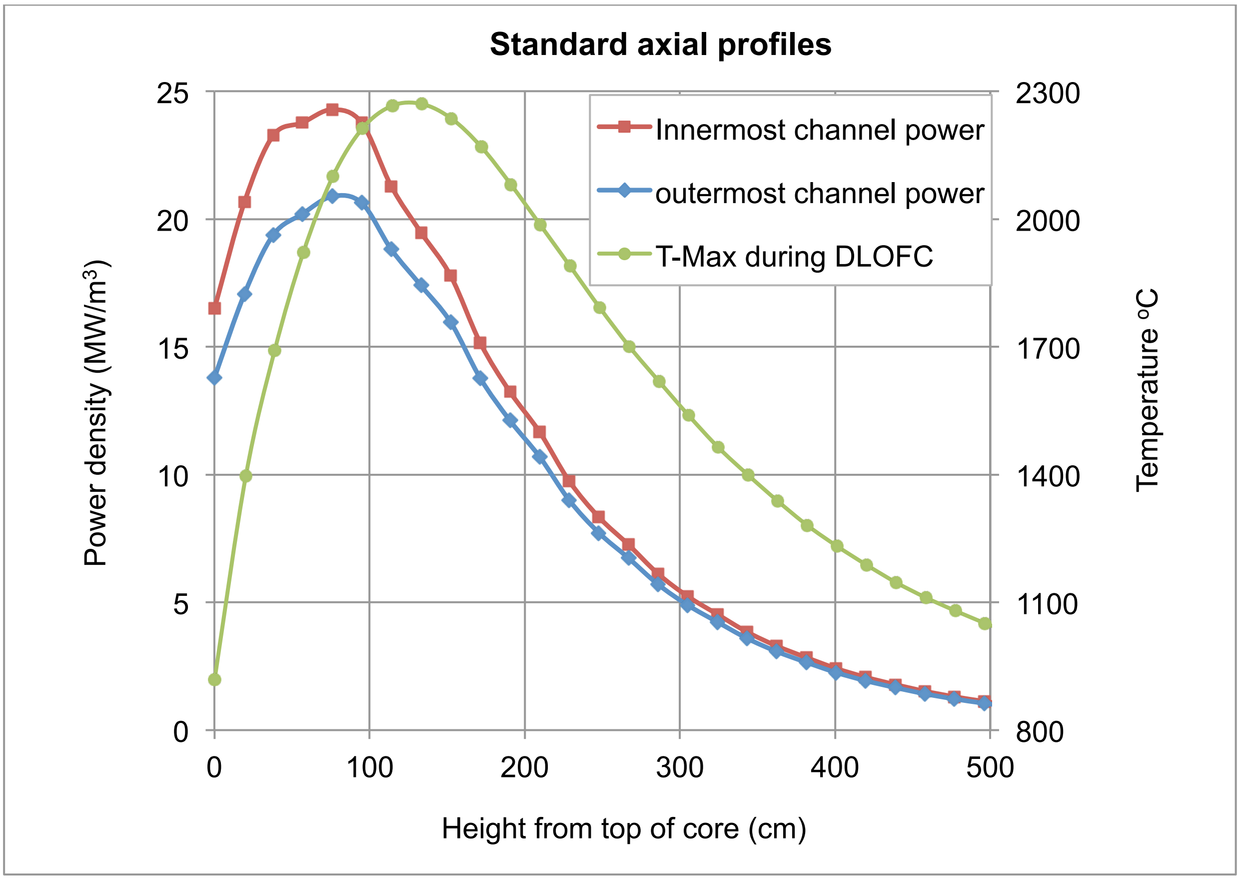

Figure 2: Axial equilibrium power density profiles for the upper part of the standard OTTO cycle core and the maximum DLOFC temperature profile, shown on a separate scale

The axial temperature profile was drawn through the radius containing the point with the maximum DLOFC temperature. These profiles provided us with the following insights for reducing the maximum DLOFC temperature:

- The power in the innermost fuel channel is substantially higher than in the outermost channel, as has been explained above. Since a DLOFC always involves a radial net outward flow of heat, higher temperatures in the inner layers are always required to drive this outward flow and therefore the maximum DLOFC temperature always occurs in the innermost axial fuel layer.

- The axial equilibrium power density profiles are strongly peaked at ±75 cm from the top of the fuel core. The power decreases quickly with distance below this peak.

- The maximum DLOFC temperature profile is also strongly peaked. The high DLOFC temperatures (above 1400°C) in this peak were concentrated in the small axial peak between 20 and 340 cm from the top, reaching a maximum of 2273°C at about 134 cm from the top. This reduced the effectivity of evacuation of decay heat and thus unnecessarily increased DLOFC temperatures, as was explained above.
- The DLOFC temperature peak occurs about 60 cm below the power density peaks and then dropped off much slower than the power peaks. Serfontein [6] explained this downward displacement of the DLOFC temperature peak by stating that the accumulation of heat in the coolant gas causes the equilibrium coolant temperature to increases monotonously as the gas flows towards the bottom. This causes the equilibrium fuel temperatures and the reflector temperatures and thus the amount of heat stored in these structures to increase similarly towards the bottom. This stored heat formed the basis onto which the decay heat generated during the DLOFC accident was added and therefore it lifted the DLOFC temperatures, much more so in the lower than in the upper parts of the core. This resulted in the observed downward displacement of the DLOFC temperature peak.

5.3.1 Optimisation of the axial power profile

The large two meter thick central reflector runs relatively cool (i.e. far below 1600°C) and thus has a substantial ability to absorb and store decay heat at the beginning of the DLOFC. At the beginning of the DLOFC the fuel thus evacuates heat both inwards and outwards. However, since the central reflector is connected only to the top and bottom reflectors, its middle part has nowhere to evacuate this heat to. Therefore this middle part will “fill up” with decay heat after a few hours, i.e. its temperature will increase to almost the same as that of the fuel layer directly adjacent to it, at which point the influx of decay heat will cease almost completely. From this point onwards the decay heat can only flow up into the top reflector, down into the bottom reflector and radially outwards into the external reflector and then from these reflectors out through the pressure vessel and the containment building into the ultimate heat sink, i.e. the atmosphere.

- Due to the increase in equilibrium temperatures from top to bottom, the top reflector starts the DLOFC off at a substantially lower temperature and therefore has the capacity to absorb and store substantially more decay heat per unit mass than the external or bottom reflectors.

  Therefore the DLOFC temperature will not be minimized if the axial equilibrium power profile were to be perfectly flat, but rather when it has a large peak close to the top reflector, a smaller peak close to the bottom reflector and a depression in-between, as has been achieved by Serfontein [6] by inserting high concentrations of neutron poison into the central reflector at the intermediate heights, with no poison at the very top or bottom.
- Since the poison option has been excluded from the present study, forcing a power depressing at the intermediate heights was not a possibility. Therefore we aimed at the next best thing, i.e. to flattening the axial power profiles by adding thorium to the fuel. The logic is that thorium/^{233}U fuel cycles in HTRs are known to produce higher fissile fuel conversion ratios than any other fuel combination [1,13]. Therefore, adding thorium to the fuel slows the rate of depletion of the fissile enrichment of the fuel with increasing burn-up, as the fuel flows down. This higher enrichment of the fuel at the bottom of the core increases the fission power towards the bottom, which by definition flattens the axial power density profiles. The process is that radiative capture of neutrons by ^{232}Th breeds fissile ^{233}U, which fissions in thermal reactors with a much better neutron economy than both the ^{239}Pu bred from ^{238}U and the original ^{235}U in the LEU.
- The improved neutron economy is due to the higher number of fission neutrons released per neutron absorbed in the ^{233}U (η), which is caused by the much lower capture-to-fission ratio (α) in thermal and especially in epithermal neutron spectra [14].
- Unfortunately ^{232}Th is a less effective neutron capturer than ^{238}U: The microscopic cross-section for radiative capture of thermal neutrons by ^{232}Th (7.4 barns) is about 3 times higher than that of ^{238}U (2.7 barns) [15,16]. However, the epithermal capture resonances of ^{232}Th is much weaker than that of and ^{238}U and therefore the resonance integrals for these captures are about four times as high for ^{238}U-based fuel spheres than for ^{232}Th-based ones. Unfortunately epithermal captures dominate, since thermal neutron captures by the fertile materials have to compete with absorption for thermal fission in the fissile fuels, for which the microscopic cross-sections are about two orders of magnitude higher. Therefore, for fuel spheres containing similar number densities of ^{232}Th and ^{238}U, the number of ^{239}Pu nuclei bred from captures in the ^{238}U will be much higher than the

number of ^{233}U bred from ^{232}Th.

On top of that, the microscopic thermal fission cross-section of ^{233}U is only about half that of ^{239}Pu. Therefore, not only will ^{239}Pu be bred faster, but it will thereafter also fission at a much higher rate than the bred ^{233}U. Therefore, for similar number densities of ^{238}U and ^{232}Th, fissioning of ^{239}Pu will dominate that of ^{233}U and therefore the poor neutron economy of ^{239}Pu will dominate the good neutron economy of ^{233}U.

Therefore the ratio of $^{238}U/^{232}Th$ were reduced greatly by increasing the enrichment of the LEU from 10 a/o% to its legal upper limit of 20 a/o% and by increasing the Heavy metal content from 9 g to 16 g/sphere, as explained above. This is similar to the approach taken by Wols et *al* [17].

- The improved neutron economy from fissioning the bred ^{233}U produces more excess neutrons that can be used for breeding even more ^{233}U and thus Th-based fuel cycles, in thermal neutron spectra, generally have substantially higher conversion ratios than LEU-based ones. Higher conversion ratios result in faster build-up of ^{233}U, which slows the rate of depletion of the enrichment with increasing burn-up. This leads to slower loss of reactivity as the fuel flows down, which translate into higher power densities in the bottom parts of the core.
- The addition of extra Th to the fresh fuel immediately reduces the enrichment and thus also the reactivity and power density at the top of the core. However the breeding of ^{233}U has a much longer time-delay than that of ^{239}Pu. This is due to the unusually long half-life of 26.975 days for the decay of ^{233}Pa to ^{233}U [18] in the nuclear chain reaction:

$$^{232}Th(n,\gamma)^{233}Th \xrightarrow{\beta^-} {}^{233}Pa \xrightarrow{\beta^-} {}^{233}U$$

This means that it will take substantially longer than 27 days for the production rate of ^{233}U to approach its equilibrium value, after which the slow build-up of ^{233}U will commence [19]. Since this accumulated ^{233}U will also fission much slower than the accumulated ^{239}Pu, the ^{233}U concentration will take even much longer to approach its equilibrium value, compared to ^{239}Pu. Therefore the boost in fission power from bred ^{233}U will kick in much lower down in the core.

- All of the above implies an additional suppression of the fission rate at the top and an additional elevation thereof towards the bottom of the core and thus an additional flattening of the axial power profiles.

5.3.2 Optimisation of the radial power profile

Radially the optimal power density should be lower in the inner fuel layers and higher in the outer layers, as explained above. This was attempted by putting lower enrichment fuel in the inner layers and higher in the outer layers.

6. Results

6.1 Resulting Fuel Loading Strategies

Figure 3 shows the axial equilibrium fission power density profiles in the innermost fuel flow channel for a single homogeneous radial fuel zone. The fuels were 9g/fuel sphere pure LEU and 16g/fuel sphere LEU-Th mixture respectively. The two profiles show the same features, peaking near the top of the core (76 cm for LEU and 95 cm for the mixture) before quickly dropping. The LEU profile peaks at 24.3 MW/m^3 compare to 18.8 MW/m^3 for Th-LEU, but the drop in the mixture's profile is slower making the power density in the mixture's core higher than that of the LEU core below 2m from the top of the core. The power decreases to below 1 MW/m^3 below 5m from the top for the LEU core, compared to below 7.5 m for the Th-LEU mixture.

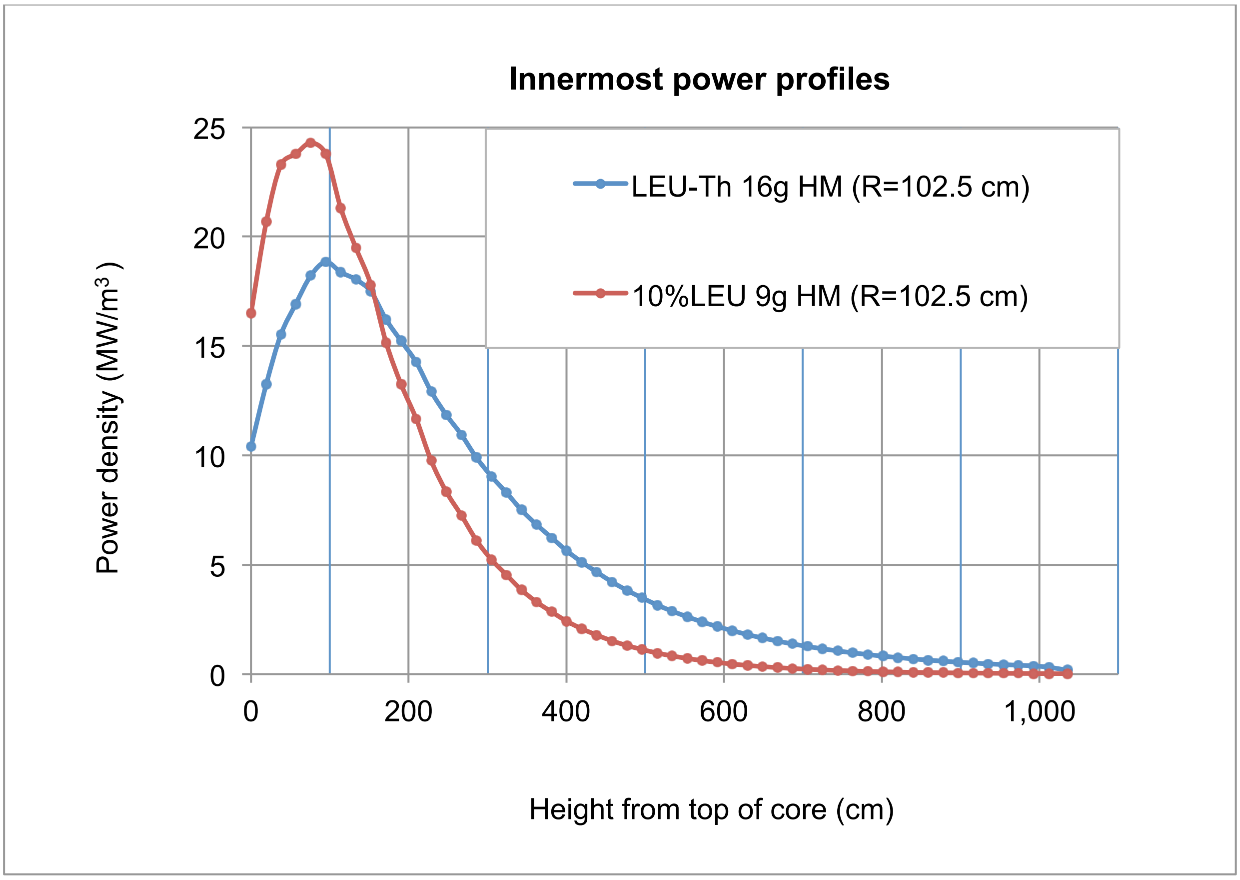

Figure 3: Axial equilibrium power density profiles comparison for LEU and Th-LEU mixture in the innermost channel, for a single homogeneous radial fuel zone

Figure 4 shows the radial power profiles at their respective heights of maximum power density. The small peak in the third point from the left and from the right of the LEU profile is due to the fact that the fuel in the two outer Fuel Flow simulation Channels flow slower than in the three central Channels. The fuel in the inner channels is thus substantially fresher and thus has higher enrichments than in the outer channels. The fresh fuel therefore burns at a higher power density. This, together with a resulting disturbance in the thermal neutron flux, causes these spikes. However, in real life the fuel flow speeds vary continuously and therefore these discontinuous effects do not occur. Figure 3 and Figure 4 show that despite the large drop in power density achieved with the Th/LEU mixture, its power still peaks close to the central reflector, making the distance to be travelled by the heat to reach the external reflector and thus the ultimate heat sink high. Therefore the maximum DLOFC temperature remained high at 1925°C.

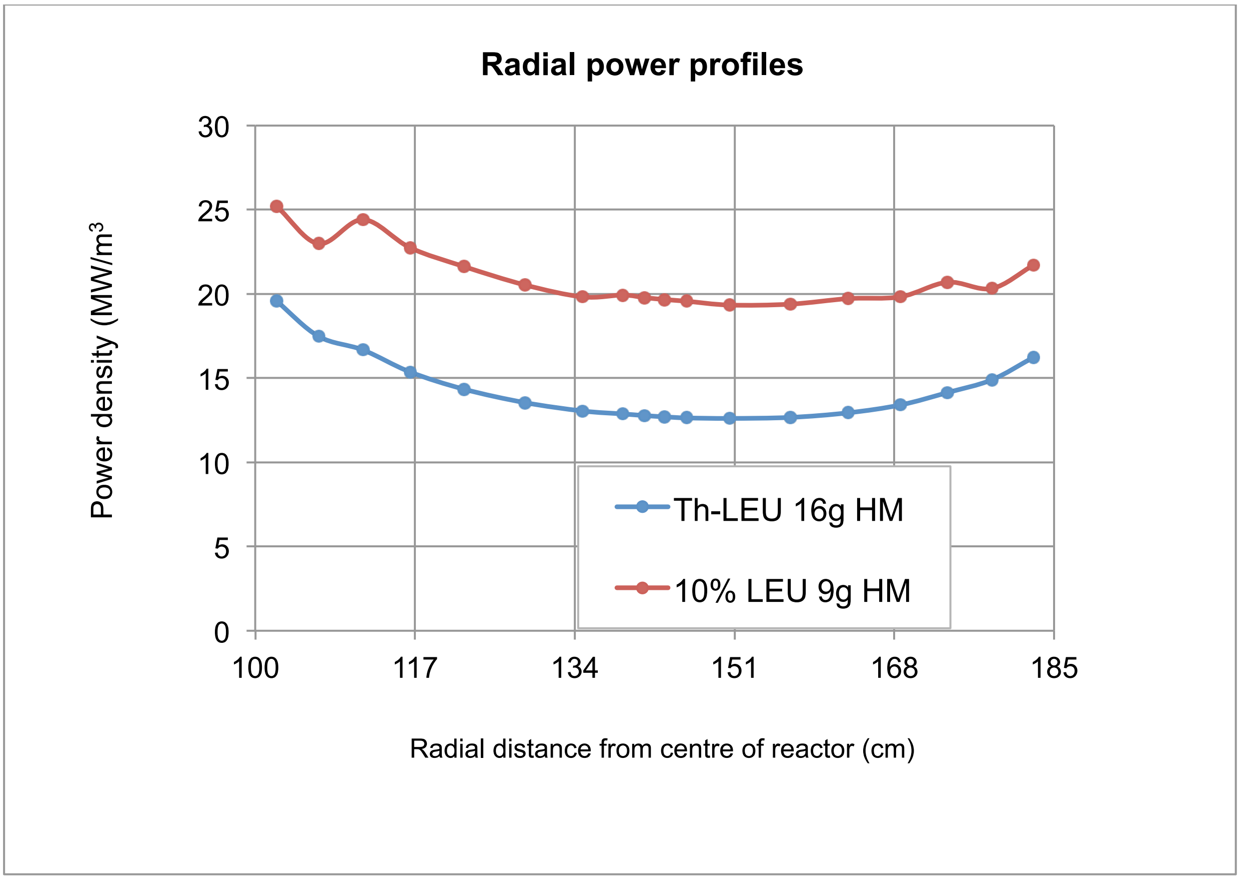

Figure 4: Radial equilibrium power density profiles comparison for LEU and Th-LEU mixture at the height of maximum power.

In order to get rid of the peak in the innermost channel and thereby further reduce the DLOFC temperature, the core was divided in two radial fuelling regions: flow channels 1 and 2 constituted the inner Region 1 while flow channels 3, 4 and 5 constituted the outer Region 2 [9]. The power density profiles were modified by reducing the fuel enrichment of Region 1 by a certain amount while increasing the enrichment of Region 2 by half that amount, so that the total amount of fissile material at every loading remained the same as in the homogeneous symmetric core. This is because Region 1 represents 1/3 of the core volume while Region 2 represents 2/3 thereof.

The objective here was to reach a maximum DLOFC temperature < 1600°C and an equilibrium fuel temperature < 1130°C. At first, the fuel enrichment was changed with a focus only on the equilibrium and the DLOFC temperatures. With an enrichment of 0.435 a/o% and 10.035 a/o% in Region1 and Region 2 respectively, maximum temperatures of 1128°C and 1582°C were obtained at equilibrium and during the DLOFC respectively. However, the price to obtain these low temperatures with the OTTO cycle was that the average burn-up dropped from 45 GWD/ton Heavy Metal for the symmetric core to 34 GWD/ton Heavy Metal. This is due to the fact that an OTTO core has a higher leakage factor than a multi-pass core. The very low enrichment in the inner Region 1 also means that these fuel spheres burn at a much lower average power than the much higher enriched ones in the outer Region 2. They then reduce the average burn-up obtained. The enrichment of the different regions was therefore adjusted to values that retained the same total energy produced per fuel sphere as for the 9g LEU OTTO cycle in the PBMR-400, which translated to a burn-up of 46,339 MWd/ton HM. This was achieved for an enrichment of 1.555 a/o% and 10.595 a/o% respectively, giving temperatures of 1127°C and 1765°C for the equilibrium and DLOFC respectively.

Mitigating proliferation risk

Because Th can easily be chemically separated from U, the enrichment of U in the spent fuel had to be kept below the upper-limit for classification as LEU, in order to mitigate proliferation risk of this fuel cycle. ^{233}U, being a better nuclear weapons fuel than ^{235}U, by law has an upper limit for classification as LEU of only 12 a/o%, compared to 20 a/o% for ^{235}U [13] Therefore the decision was taken to limit the enrichment of the U in the spent fuel to less than 12 a/o%. This would be impossible for pure Th fuel, as it would produce pure ^{233}U, contaminated by only a very small fraction of ^{232}U and its highly radioactive daughter products [13]. Therefore a substantial amount of ^{238}U had to be added to the fresh Th fuel, in order to denature the ^{233}U that would be bred during the life of the fuel. If the enrichment of the LEU in the fresh fuel is fixed at 20 a/o% and a very low enrichment of the fresh LEU/Th fuel were to be selected, too little ^{238}U would be added to the fuel to dilute the bred ^{233}U to below 12 a/o%. Therefore the enrichment of the fresh LEU had to be reduced for the lowest enrichment LEU/Th cases. The final fuel choices thus were 2.575 a/o% enrichment of the LEU/Th mixture in the inner Fuel Region 1, where the LEU enrichment was reduced to 15.0 a/o%, and 9.864 a/o% enrichment for the LEU/Th mixture in the outer Fuel Region 2, where the enrichment of the LEU was retained at 20 a/o%. This was called the radially asymmetric LEU-Th fuel cycle.

6.2 Core-Physics results

The axial and radial equilibrium fission power density profiles are shown in Figures 5 and 6:

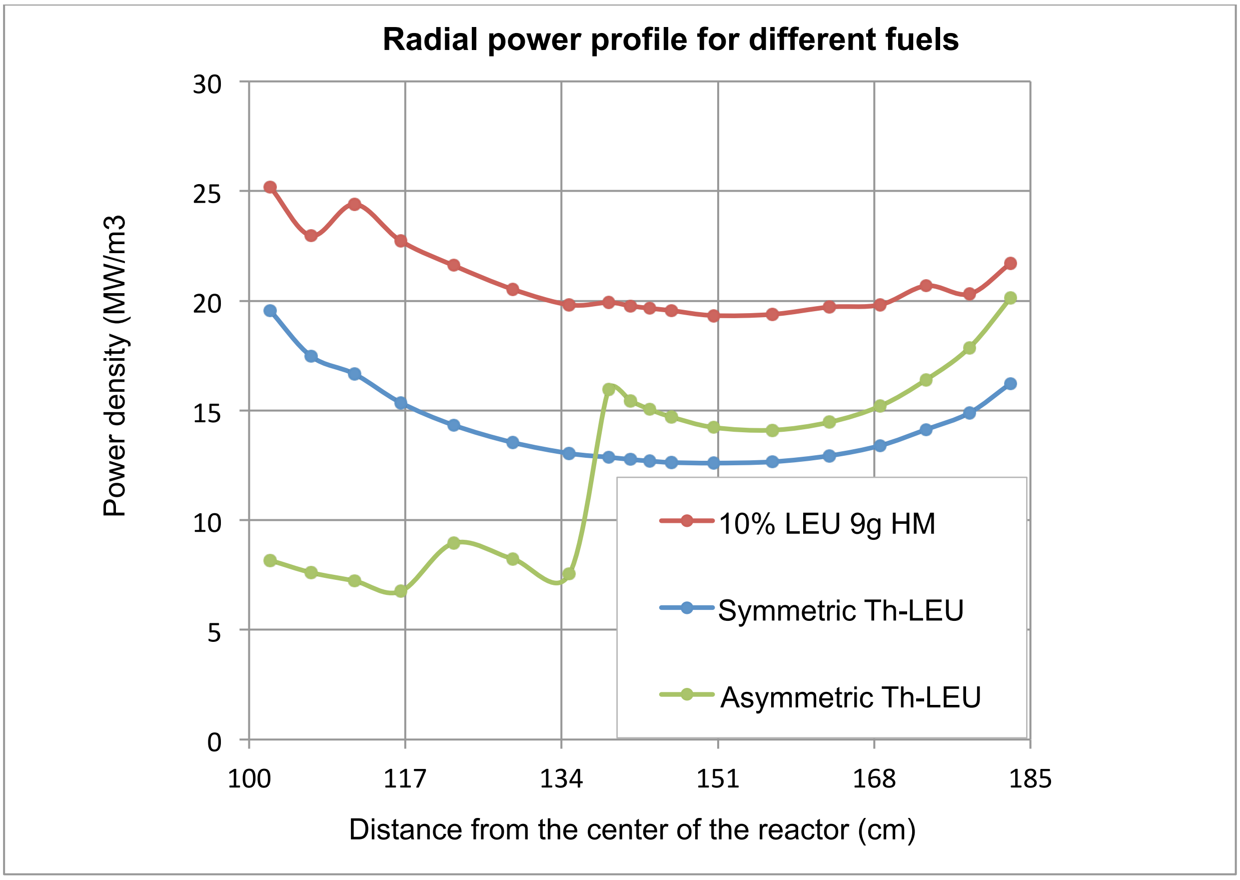

Figure 5: Radial power profile comparison for the three fuel cycles

- The pure LEU radial profile in Figure 5 had a substantially higher power density peak, directly adjacent to the central reflector, compared to the symmetrical and the asymmetrical LEU/Th fuel cycles.
- The symmetrical (i.e. homogeneous) LEU/Th radial profile had a much lower maximum power density than the pure LEU (Figure 5). This was the desired result of the flattening of its axial power profiles by the addition of Th, as discussed above.

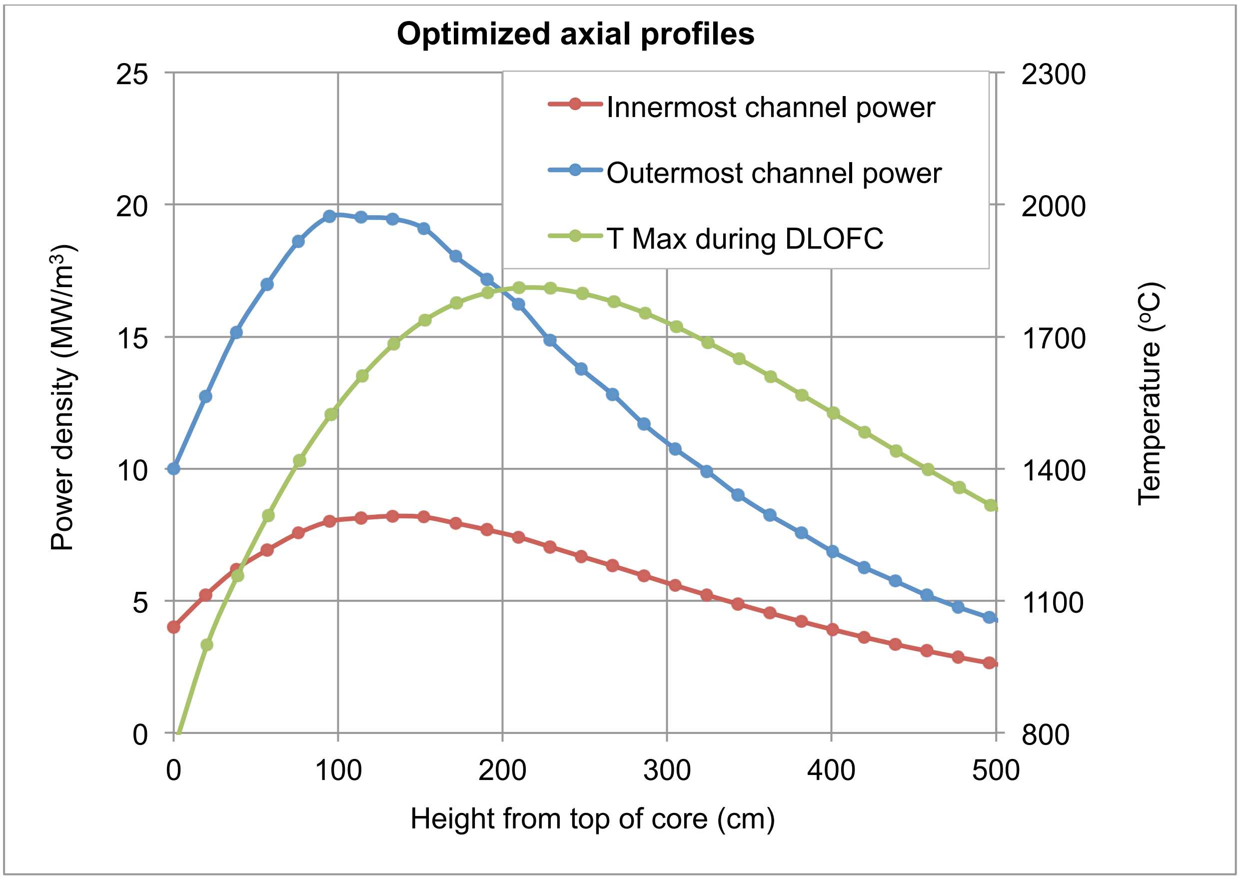

Figure 6: Modified Power and Temperature profiles for producing a lower maximum DLOFC temperature, shown on a separate scale, for the radially asymmetric LEU-Th fuel cycle.

- The radially asymmetric LEU-Th profile had a very small power density in the two innermost fuel channels (Figure 5 and Figure 6), due to the much lower enrichment of this fuel. The profile then makes a local peak at the start of channel (3), i.e. at a radius of just less than 140 cm (Figure 5), then dips down and then increases again to its highest peak at the outer edge of channel (5), directly adjacent to the external reflector.

  It should be noted that at the interface between channels (2) and (3), the outermost data point of channel (2) forms a local minimum and the innermost point of channel (3) a local maximum (Figure 5). This is a standard feature at the interface between lower and higher enriched fuel layers. Due to the low enrichment in the inner channels, thermal neutrons are absorbed for fission by the fissile fuel at a slower rate and therefore their flux increases. By the same logic the thermal flux is lower in the higher enriched layer. At the interface the differential in fluxes causes a net diffusion of thermal neutrons from the lower into the higher enriched layer. When this net influx of thermal neutrons hits the higher enriched fuel, they are quickly absorbed for fission and thus produce a local power peak in the first few centimetres of the higher enriched layer. By the same logic, the net outflow of thermal neutrons from the lower enriched layer depletes the thermal neutrons and thus creates a local power minimum in the last few centimetres of the lower enriched layer.

- It is also noteworthy that, while the symmetrical LEU/Th profile had its highest peak against the central reflector, the asymmetric LEU/Th case peaked against the external reflector, due to the higher enrichment of the fuel in this outer region and due to the influx of thermal neutrons from the external reflector explains the radial peak directly adjacent to the external reflector.
- Figure 6 shows that, as intended, the sharp peak, which was observed in the axial power density profile in the inner fuel channel of the standard 9g LEU/fuel sphere in Figure 3, has now been flattened substantially by replacing the pure LEU with the much less enrichment LEU/Th mixture in the two inner fuel channels. Both Figure 5 and Figure 6 show that this move has successfully displaced the high power density region away from the central reflector towards the external reflector, thereby substantially reducing the distance over which the decay heat has to be transported from the hot-spot to the external reflector. The combined effect of these two achievements was to flatten the axial profile for the maximum DLOFC temperature, as is compared for the different fuel cycles in Figure 7 below, and to thereby reduce the maximum DLOFC temperature by 461°C, from 2273°C to 1811°C. This approach also pushed the DLOFC temperature peak a little bit further downwards from ±125 to ±220 cm below the top of the fuel core.

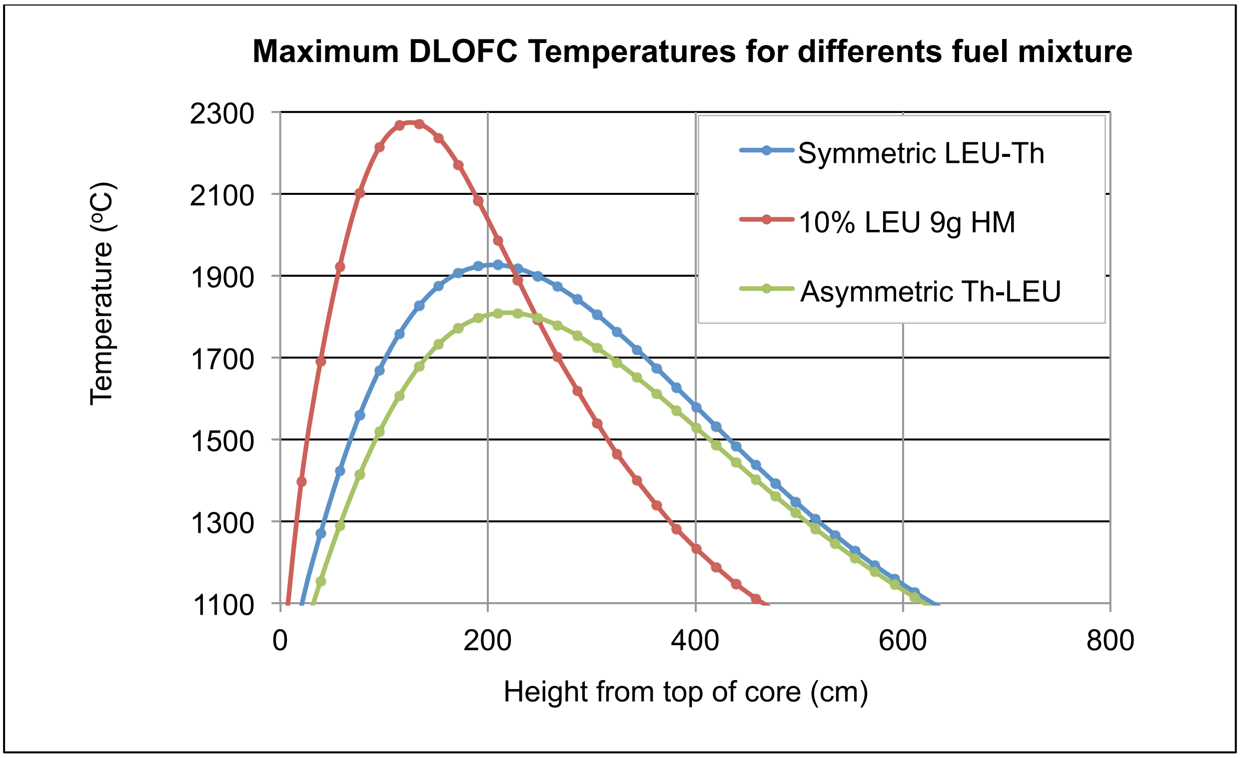

Figure 7: Axial maximum DLOFC temperature profile comparisons for the three fuel cycles.

It is also noteworthy to mention that the maximum DLOFC temperature for the best case is only reached 52 hours into the accident, compared to the 15 hours into the accident for the pure LEU, as is shown in Figure 8, which shows the maximum DLOFC temperatures for the different fuel cycles as a function of time. This partly explains the much lower maximum DLOFC temperature obtained with the Asymmetric LEU/Th case: the spreading out of the high temperature peak over a longer period reduced the outward heat flux required during any one time during the DLOFC, thereby decreasing the fuel temperatures

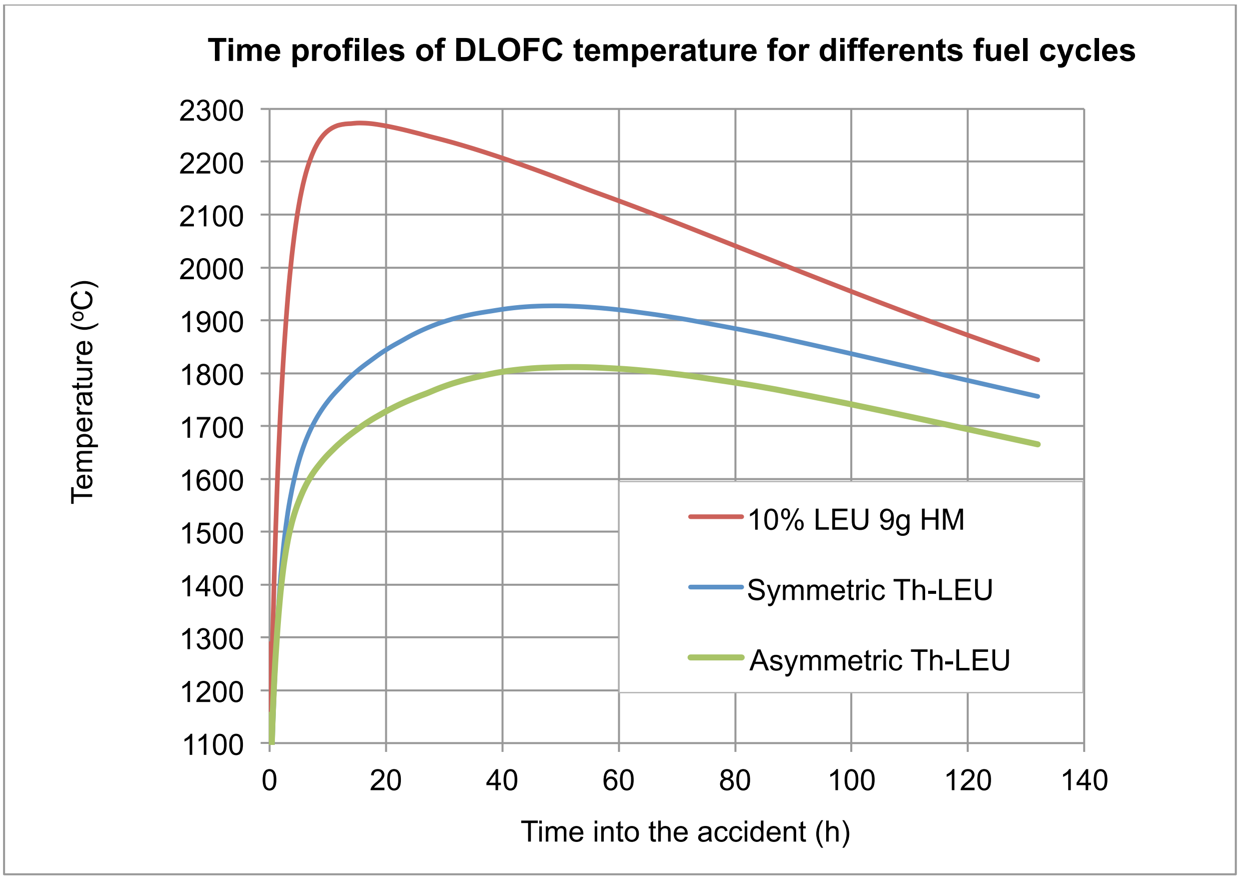

Figure 8: Time profiles for the maximum DLOFC temperatures for different fuel cycles.

6.3 Results for Reduced Power

Although the optimization exercise led to a large reduction in the maximum DLOFC temperature, none of the three fuel cycles achieved the target of remaining below 1600°C. Therefore a second round of simulations were conducted, for each of these fuel cycles, in which the nominal equilibrium power was reduced until the maximum DLOFC temperature was within the range 1595 ± 2 °C. This resulted in nominal powers of 243, 275 and 320 MW for the LEU, Symmetric Th-LEU and Asymmetric Th-LEU respectively. This quantifies the power output and thus the profitability achieved with each of these optimization methods.

7. Discussion

During the optimization attempt it was found that the following dynamics had to be borne in mind: if the enrichment in the inner fuel channels were lowered even further than the 2.575 a/o%, which was selected as the best case for this study, the DLOFC could be reduced much further than was achieved here. However, the following challenges then became apparent:

- In order to maintain $k_{eff} = 1$, lower enrichments in the inner fuel layers had to be compensated for by higher enrichments in the outer layers.
- Higher enrichments in the outer fuel layers mean more LEU and less Th, i.e. less ^{233}U bred from Th and thus less of all the good properties of ^{233}U. Therefore the higher enriched fuel in the outer layers bred less ^{233}U and therefore less of the desired flattening of the axial power profiles.
- By the same logic, the lower enriched fuel in the inner layers bred much more ^{233}U and thus produced much more flattening of the axial power profiles. However, when the enrichment in the inner layers became too low, the enrichment in the outer layers had to be made so high that a power and thus an equilibrium fuel temperature hotspot developed in the outer layers, which sometimes violated the equilibrium power and temperature safety limits.
- When the enrichment in the inner layers was reduced drastically by reducing the fraction of LEU in the mixture, the mixture composition approached pure Th. This meant that almost pure ^{233}U was bred, without sufficient ^{238}U to denature it, which created a proliferation risk. Therefore the desired reduction in enrichment then rather had to be achieved by lowering the enrichment of the LEU, rather than reducing the fraction of LEU.
- Reducing the enrichment in the inner layers below 2.75 a/o% also meant that the power densities and thus the total burn-up produced became much lower in the inner than in the outer fuel layers. Therefore the fuel in the inner layers would be underutilized, or alternatively the burn-up in the outer layers could exceed the maximum safety limit. Therefore reducing the enrichment in the inner layers too much was not a good option.
- It was also found that the radial position of the border between the inner lower enriched and outer higher enriched fuel layers is important. If the inner layer was made thinner than the inner two fuel flow channels, the fraction of the core that operated at a lower power was too small to reduce the DLOFC temperatures substantially. However if the inner layer was made thicker than these two channels, the higher enriched fuel and thus the higher power densities became confined to a thin layer directly adjacent to the external reflector. This increased the fraction of fission neutrons that leaked in the external reflector, i.e. it increased the core leakage, which damaged the overall neutron economy.

  Therefore using the two inner fuel flow channels for the lower and the remaining three outer channels for the higher enriched fuel was found to be a good compromise.

8. Conclusion

- The reduced DLOFC temperature of 1811°C for the best case Asymmetric Th-LEU 400 MW_{th} OTTO fuel cycle was much lower than the 2273°C obtained with the pure LEU fuel. However, this temperature is still substantially higher than the 1600°C required to contain the fission products inside the TRISO particles.
- The current upper limit of 1130°C for the equilibrium temperature is due to the use of a direct cycle and the fear of highly radioactive ^{110m}Ag being released and plating out on the cold surface of the turbine blades, thus making the maintenance difficult [3]. However, the industry accepted equilibrium temperature is 1200°C, which would allow a higher enrichment and thus power density in the outer fuel zone. This would imply an even lower enrichment in the inner fuel zone and thus a further reduction in the maximum DLOFC temperature.
- However, with the current upper limit of 1130°C for the equilibrium temperature, it was shown that the DLOFC temperature could be reduced to below 1600°C by reducing the power output from 400 MW to 320 MW. Unfortunately this will also reduce the profitability. Therefore a follow-up study is proposed in which this DLOFC temperature reduction will rather be attempted by placing an optimised distribution of neutron poisons in the central reflector.
- It should be noted that while the present study was conducted for the PBMR-400 DPP, the results and proposed studies are also applicable to other HTRs:
    - Since the technique of putting neutron poison in the central reflector was not used in the present study, its results for the Th-LEU mixture can be expected to also apply directly to PBRs that do not use a central reflector, such as the Chinese HTR-PM.
    - Prismatic Block type HTRs, such as the Japanese HTTR, could potentially provide much more scope than Pebble Bed Reactors for reducing the maximum fuel temperatures, during both equilibrium operation and during a DLOFC, by means of optimizing the fuel core layout and reshuffling strategies. In Pebble Bed Reactors manipulating the fuel distribution is difficult since this can only be done once when inserting the fuel spheres at the top of the core and only by placing it in different radial zones. Thereafter the fuel flows down without any opportunity for further manipulation, which is severely limiting. For instance, from the combination of [6] and the present article, it is clear that the optimal fuel layout is lower enrichments in the radially inner fuel regions and higher in the outer regions, combined with high enrichment near the top, low in the middle and medium at the bottom. In an OTTO

cycle, the only way to achieve lower enrichment in the inner regions is to start with separate low and higher enriched fresh fuel types, as has been done in the present article, which is an undesirable complication. However, the continuous decrease in enrichment with downward flow makes the requirement of high enrichment at the top, low in the middle and medium at the bottom impossible.

However, Prismatic Block reactors allow the added degrees of freedom of both radial and axial fuel shuffling in multi-batch fuel management [20], which could possibly achieve all of this with a single fuel type: radial shuffling could allow fresh fuel to burn first in the outer regions and in the inner regions in subsequent fuel cycles. Axial fuel shuffling could allow fresh fuel to first burn at the top with a high enrichment, then move down to the bottom for medium enrichment burn and lastly up to the middle for low enrichment burn. However, constraints related to cycle length, discharge burn-up, maximum temperature (gradient) during normal operation; the maximum number of fuel types that can be used etc. might complicate such an optimization.

References

[1] Serfontein DE. Deep burn strategy for the optimized incineration of reactor waste plutonium in pebble bed high temperature gas-cooled reactors. Potchefstroom: North-West University; 2011.

[2] Wang Y, Yanhua Z, Fu L, et al. Analysis on blow-down transient in water ingress accident of high temperature gas-cooled reactor. Nucl. Eng. Des. 2014;271:404–410.

[3] Reitsma F. The pebble bed modular reactor layout and neutronics design of the equilibrium cycle. Proceedings of PHYSOR 2004 – The Physics of Fuel Cycles and Advanced Nuclear Systems: Global Developments; 2004 April 25–29; Chicago (IL) [CD-ROM].

[4] Serfontein DE, Mulder EJ, Reitsma F. Optimisation of deep burn incineration of reactor waste plutonium in a PBMR DPP-400 core. Nucl Eng Des. 2014;271:99–105.

[5] Hansen U, Schulten R, Teuchert E. Physical properties of the "once through then out" pebble-bed reactor. Nucl. Sci. Eng. 1972;47:132–139.

[6] Serfontein DE. Sharp reduction in maximum fuel temperatures during loss of coolant accidents in a PBMR-400 core, by means of optimised placement of neutron poisons. Nucl. Eng. Des. 2014; 271:492–498.

[7] Boer B, Kloosterman JL, Lathouwers D, et al. In-core fuel management optimization of pebble-bed reactors. Ann Nucl Energy. 2009; 36:1049–1058.
[8] Boer B, Lathouwers D, Kloosterman JL, et al. Optimization of a radially cooled pebble bed reactor. Nucl. Eng. Des. 2010; 240:2384–2391.
[9] Li F, Jing X. Comparison of fuel loading pattern in HTR-PM. 2nd International Topical Meeting on High Temperature Reactor Technology; 2004 Sept 22–24; Beijing, China.
[10] Mulder EJ. Pebble bed reactor with equalised core power distribution - inherently safe and simple. Aachen: Faculty of Mechanical Engineering, University of North-Rhine Westfalia; 1998.
[11] Tran HN, Kato Y, Muto Y. Optimization of burnable poison loading for HTGR cores with OTTO refueling. Nucl. Sci. Eng. 2008;158:264–271.
[12] Tran HN,KatoY.An optimal loading principle of burnable poisons for an OTTO refueling scheme in pebble bed HTGR cores. Nucl. Eng. Des. 2009; 239:2357–2364.
[13] Serfontein DE, Mulder EJ. Thorium-based fuel cycles: Reassessment of fuel economics and proliferation risk. Nucl. Eng. Des. 2014; 271:106–113.
[14] Lamarsh JR, Barata AJ. Nuclear reactor fuels. Introduction to nuclear engineering. 3rd ed. Upper Saddle River (NJ): Prentice Hall; 2001. p.119.
[15] IAEA-TECDOC-1450, IAEA VIENNA. Thorium fuel cycle – potential benefits and challenges. Vienna: IAEA; 2005.
[16] Duderstadt JJ, Hamilton LJ. Nuclear reactor analysis. New York (NY): John Wiley and Sons Inc.; 1976.
[17] Wols FJ, Kloosterman JL, Lathouwers D. Fuel pebble design studies of a high temperature reactor using thorium. Proceedings of the HTR 2012; October; Tokyo (Japan); 2012.
[18] ENDF/B-VII.-1. JANIS Database 4.0, build 5.4.647, 1 Nov 2013. OECD Nuclear Energy Agency; 2013. Available from: http://www.oecd-nea.org/janis/. Accessed September/3, 2015.
[19] Wols FJ, Kloosterman JL, Lathouwers D, et al. Core design and fuel management studies of a thorium breeder pebble bed high-temperature reactor. Nucl Technol. 2014; 186(1):1–16.
[20] Yonghee K, Cho C, Venneri F. Long-cycle and High-burnup fuel assembly for the VHTR. J. Nucl. Sci. Technol. 2007; 44(3):294–302.

5 Neutron poison distribution in the central reflector to reduce the DLOFC temperature of a Th-LEU fueled OTTO PBMR DPP-400 core

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5.1 Motivation and relative contribution of authors

5.1.1 Motivation

The previous chapter presented an optimization of the axial and radial power profiles of PBMR DPP-400 in a Once-Through-Then-Out (OTTO) refuelling scheme. The maximum DLOFC temperature was reduced by adding thorium to the fuel and making the fuel layout radially asymmetric by placing lower enriched fuel in the inner parts, and higher enriched fuel in the outer parts of the core. These measures resulted in a reduction in the height of the peaks in the axial power profiles and thus resulted in suppressing the hotspots in the axial DLOFC temperature profiles and 'pushing' the power radially outwards, which in turn reduces the distance that the decay heat must be evacuated towards the outside of the fuel core and thus the thermal resistance against this heat flow. These two mechanisms resulted in a reduction in the maximum DLOFC temperature for the OTTO cycle from 2273°C to 1927°C and to 1812°C for the symmetric and asymmetric cores respectively. However, these temperatures were still above the 1600°C limit. Maximum DLOFC temperatures below 1600°C were thus obtained by reducing the power output. This chapter is a follow-up.

5.1.2 Relative contribution of authors

Prof. D.E. Serfontein was the study leader during this stage of the research with the task to provide guidance and support to M. Tchonang Pokaha whilst also evaluating the academic soundness and strength of the research. All research was conducted and documented by M. Tchonang Pokaha

5.2 Article 3: Neutron poison distribution in the central reflector to reduce the DLOFC temperature of a Th-LEU fueled OTTO PBMR DPP-400 core

Abstract: In a previous study using a mixture of thorium and 20 a/o % LEU at 16 gram per fuel sphere heavy metal loading and adjusting the effective fuel enrichment to produce the same amount of cumulative energy per fuel sphere as with the 10 a/o% LEU, the maximum DLOFC temperature was reduced from 2273 °C to 1925°C and 1811°C for a symmetric and asymmetric core respectively using an OTTO fueling scheme. This article presents an additional strategy for reducing the maximum DLOFC temperature by placing an optimized distribution of neutron poisons in the central reflector. This strategy produced maximum DLOFC temperatures of 1509°C and 1448°C for the symmetric and the asymmetric cores respectively. These results are impressive as it means that the less complicated OTTO cycle with its lower capital cost achieved the same cumulative energy produced per fuel sphere than the standard six-pass refueling scheme and that at substantially lower maximum DLOFC temperatures. Both the addition of the neutron poisons to the central reflector and the creation of a radially asymmetric core resulted in lower burn-ups that had to be reversed by increasing the enrichment of the fuel. However, enriched uranium comprises only a modest fraction of total fuel cost and the thorium that was added to the mix comes at a lower cost than uranium.

Keywords: fuel cycle; HTGR; DLOFC; pebble bed reactor; power density profile; neutron poison; simulation; thorium

1. Introduction

High Temperature Gas-cooled Reactors (HTGRs) are regarded at as one of the sound future options of the nuclear industry because of their strong passive safety features, which render the release of radioactive material in the environment highly improbable. This is due to the use of TRISO coated fuel particles in HTR fuel, allowing high burn-up and almost complete retention of all fission products up to a fuel temperature of 1600°C [1]. In order to make these reactors inherently safe by design, Reutler and Lohnert presented idea of modular HTRs to restrict the power output and the dimensions of the reactor in order to limit the maximum fuel temperature in all operating and severe accident conditions below 1600°C in the early 1980's [2,3]. Since the 1990's, this modular philosophy has been embraced by China with the development of the 250 MW_{th} HTR-PM [4], and in South Africa with the 400 MWth Pebble Bed Modular Reactor Demonstration Power Plant (PBMR DPP-400) [5]. However, uncertainty about some technical issues regarding the safety case of this reactor led to the South African National Nuclear Regulator (NNR) postponing the final decision to grant it a licence. This delay was a substantial contributing factor to the eventual demise of the project. Despite this, the PBMR-400 has some very good features such as low neutron leakages which is very important for increasing the conversion ratio and thus favour the use of thorium as it is the case in this study.

In pebble bed reactors, the continuous online refueling provides low excess reactivity and high load factors. Continuous refueling can use a multi-pass scheme in which the fuel passes through the core several times to reach the target burn-up, or a Once-Through-Then-Out (OTTO) scheme in which the speed of the fuel loading is reduced in order to achieve the target burn-up in only one passage in the core [6]. The main advantage of the OTTO scheme is that it negates the need of the fuel handling system which checks the integrity and the burn-up level of the fuel in the multi-pass scheme. Its drawback is the fact that the difference in multiplication factor between the fresh fuel at the top of the core and the much-depleted fuel at the bottom causes a sharp power peak near the top in the axial power profile, and thus a high peaking factor. The presence of a central graphite reflector in the PBMR DPP-400 causes the radial power profiles to peak directly adjacent to this central reflector [7]. Tchonang Pokaha & Serfontein [8] presented an optimization of the axial and radial power profiles of PBMR DPP-400 in a Once-Through-Then-Out (OTTO) refueling scheme. The maximum DLOFC temperature was reduced by adding thorium to the fuel and making the fuel layout radially asymmetric by placing lower enriched fuel in the inner parts, and higher enriched fuel in the outer parts of the core. These measures resulted in a reduction in the height of the peaks in the axial power profiles and thus resulted in suppressing the hotspots in the axial DLOFC temperature profiles and 'pushing' the power radially outwards, which in turn reduces the distance that the decay heat must be evacuated towards the outside of the fuel core and thus the thermal resistance against this heat flow. These two mechanisms, which were explained in detail in [8], resulted in a reduction in the maximum DLOFC temperature for the OTTO cycle from 2273°C to 1927°C and to 1812°C for the symmetric and asymmetric cores respectively. However, these temperatures were still above the 1600°C limit. Maximum DLOFC temperatures below 1600°C were thus obtained by reducing the power output [8]. In the present follow-up study, the aim is to reduce the maximum DLOFC temperature to below 1600°C while keeping the nominal power of the reactor at 400 MW_{th} by a distribution of neutron poisons in the central reflector. All the simulation work is conducted with the VSOP-99/05 [9], according to the methods described as in the previous work mentioned above [8].

2. Literature review

Neutron poisons are neutron-absorbing materials, or nuclides, with a high absorption cross-section for neutrons. In light water and block type reactors, some of these neutron poisons, such as Boron-10, Gadolinium and Hafnium are used to control the excess reactivity of the start-up core, while others (^{135}Xe, ^{149}Sm...) are produced in the core as fission products [10]. Burnable poison particles (BPPs) in homogeneous, spherical and cylindrical forms were used by Van Dam [11] for long-term reactivity control in a pebble bed reactor. This resulted in a small loss in reactivity and still a highly peaked axial power profile. The heterogeneous spherical BPP produced the best results and gave more flexibility in the choice of burnable poison nuclides. These results were confirmed by Kloosterman *et al.* [12] who reported a reactivity swing of 2% at a k_∞ of 1.1 using either 1070 or 740 BPPs made of B_4C with a radius of 75 and 90 micron respectively in an 8% enriched UO_2, 3 cm radius fuel sphere. Similar results were obtained using 9 BPPs of Gd_2O_3 of 840 micron radius in each fuel sphere. The larger size of gadolinium has the advantage of simplifying the manufacturing process [12]. The problem of excess reactivity is more pronounced at the top of cores using an OTTO refueling scheme. Many extant studies that made use of burnable poisons in the fresh fuel in order to reduce the axial power peaking factor have focused on B_4C and Gd_2O_3. Tran and Kato [13] compared different burnable poison materials (Sm_2O_3, Eu_2O_3, Er_2O_3, CdO, Dy_2O_3 and HfO_2). The main requirement when using burnable poison in the fresh fuel is the virtually complete depletion of the burnable poison when the fuel reaches its target burn-up so that the reactivity loss caused by burn-up and fission product poisoning can be balanced by the disappearance of burnable poison. This requirement, together with the neutron absorption cross-section and the composition of the absorbing isotopes in the compound, suggests that the best BPP should be B_4C, Gd_2O_3, Er_2O_3 and CdO [13].

^{177}Hf, which is the most abundant isotope and thus the main absorber in natural hafnium, has a smaller cross-section than all the other isotopes, and has a very long burn-up chain as shown in the nuclear transmutation reaction below.

$$^{176}\text{Hf} \xrightarrow{(n,\gamma)} {}^{177}\text{Hf} \xrightarrow{(n,\gamma)} {}^{178}\text{Hf} \xrightarrow{(n,\gamma)} {}^{179}\text{Hf} \xrightarrow{(n,\gamma)} {}^{180}\text{Hf}$$

This makes hafnium the worst burnable poison if introduced into fresh fuel, but it could arguably be the most suitable non-burnable poison for long-term use in the reflectors, as it will not readily get depleted.

Serfontein [7] found the best results for a six-pass recirculation core of the PBMR DPP-400 by distribution of ^{10}B neutron poison in the central reflector in such a manner that the high axial power peak right at the top of the core was retained, followed by a power depression zone toward the middle of the core, where after no poison was placed towards the bottom. This resulted in the power density to recover, and to form a smaller power peak near the bottom of the core. The process reduced the maximum DLOFC temperature by 283°C [7]. Although the poison distribution is modified for the present OTTO fueling scheme, the lessons learnt from that study are deployed in the current case

3. Simulation methods

The basis of the present study is the design of the PBMR DPP-400, simulated using the VSOP 99/05 diffusion code, but modified to an OTTO fueling scheme and using a 16 g heavy metal (HM) per fuel sphere Th-LEU mixture, while retaining the standard safety limits [8]. In the six-pass recirculation scheme, each of the five fuel flow channels presented in Figure 3 is divided into six sub-channels: the fuel will then move from sub-channel one to sub-channel two and so on, after going through sub-channel six will be discarded as spent fuel. The modification from six-pass to OTTO scheme was made by filling all the six sub-channels with fresh fuel and discarding the fuel after a single passage in the core. During a DLOFC accident, the reactor loses the helium flow through a large break and rapid depressurization. For the thermal hydraulic calculations, the reactor is considered at its nominal steady-state conditions, and the loss of coolant happens immediately and the power is taken from 400 to 0 MW instantaneously. The decay heat in the absence of helium cooling will heat up the core. This decay heat is dissipated by conduction between pebbles, from pebbles to reflectors or by thermal radiation in the gaps between pebbles. In the previous study [8], the main objective was to attempt to reduce the maximum DLOFC temperature to below 1600°C without placing neutron poisons in the central reflector in order to find a generic solution that would also apply to cores without central reflectors. An asymmetric core was then created by placing low enrichment in the innermost region of the core and higher enrichment in the outer region. This procedure shifted the peaks in the radial power profiles toward the external reflector, reducing the maximum DLOFC temperature from 2273°C to 1812°C. However, this temperature was still above the critical 1600°C. In the present new study, the same objective is pursued but with the addition of an homogeneous distribution of neutron poison in the region of the central reflector directly adjacent to the core to shift the radial power distributions towards the external reflector and to suppress the peak in the axial profile of the maximum DLOFC temperature. This is done in order to reduce the maximum DLOFC temperature without reducing the power output of the reactor.

A. Theoretical approach towards creating the neutron poison distribution

Figure 1 shows the axial equilibrium fission power density profiles for the inner and the outer-most fuel flow channels of a symmetric PBMR DPP-400 core, fueled with a 16g/pebble mixture of thorium and 20 a/o% LEU, with effective enrichment of 6.841 a/o%, in an OTTO fueling scheme. The resulting axial DLOFC temperature is also presented on the right-hand scale. The power densities represent the average power density in each fueling region in the axial fuel flow channel, which is relatively large, as opposed to the temperatures that represent discrete points in the material.

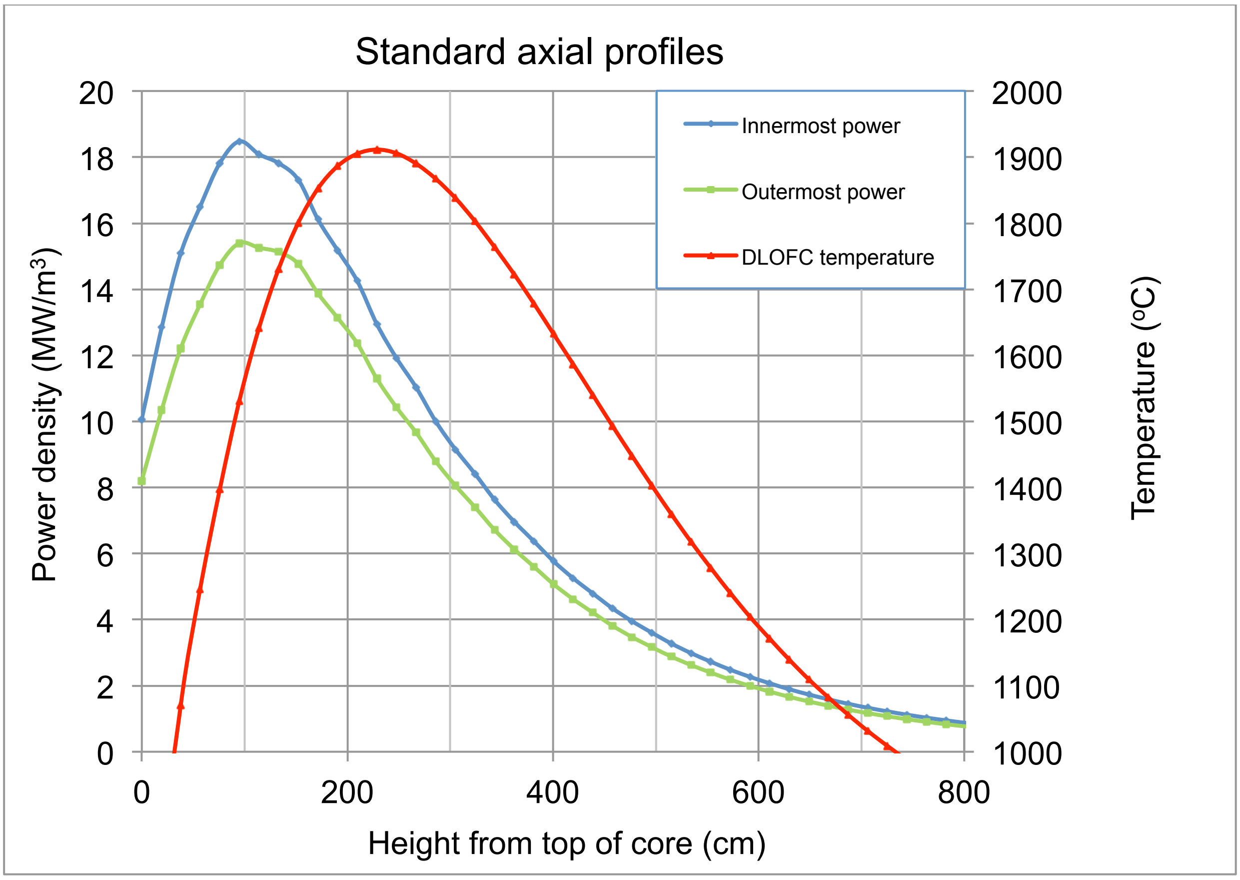

Figure 1: Standard axial power and maximum DLOFC temperature profiles for a PBMR-400 core, fueled with a 16 g/sphere LEU-Th in an OTTO fueling scheme

The following observations can be made from the above figure:

- As expected, the power in the innermost fuel flow channel is substantially higher than in the outermost fuel flow channel. This is a typical result of the cylindrical effect in an annular core with good neutron moderation in both the central and the external reflector and with control rods in the external reflector, as was explained in detail in [8].
- Both equilibrium power density profiles strongly peak at the top of the core to reach a maximum at 95 cm into the core, and then decrease sharply with increasing depth into the core.
- The maximum DLOFC temperature profile, driven by the axial power profiles, also peaks strongly near the top of the core to reach a maximum of 1911°C at 229 cm into the core.
- The DLOFC temperature peaks about 100 cm below the power density peaks, and also dropped off much more slowly. This position of the DLOFC temperature peak

below that of the power profile can be explained by the downward transfer of the heat by the coolant as it flows toward the bottom of the core. The mechanisms by means of which this phenomenon (together with the tendency for higher power densities adjacent to the central reflector) increases the maximum DLOFC temperature were explained in greater detail by Tchonang Pokaha and Serfontein [8].

B. Optimal placement of ^{10}B in the central reflector

Figure 1 shows that the axial power density profiles peak close to the top of the core, resulting in a maximum DLOFC temperature profile with all the very high temperatures (>1400°C) in the region between 76 cm and 500 cm into the core. The lower half of the core thus experiences only medium-high DLOFC temperatures and therefore contributes sub-optimally to the burden of evacuating the decay heat during a DLOFC. This suggests that it would be beneficial to suppress the power peak by placing a high ^{10}B concentration in the central reflector, near to height the top of fuel core. In the first attempt, the ^{10}B was placed right at the top of the core (i.e. height = 0 cm, down to 115 cm). However, this resulted in shifting the power peaks further down towards the middle of the core rather than suppressing these peaks. Therefore the procedure shifted the maximum DLOFC temperature peak downwards, without flattening it substantially. Since Serfontein [7] showed that for a six-pass core, excellent flattening of the maximum DLOFC temperature peak is obtained when the axial power peak is split into a peak near the very top of the core, a subsequent depression zone and a smaller peak lower down, as discussed above, the uniform ^{10}B concentration was then shifted down to the region between 115 cm and 287 cm. This resulted in in a small power peak in the innermost axial profile at 57 cm, followed by a much larger peak at 380 cm, as shown in Figure 2 below, for a ^{10}B concentration of 6.75×10^{-5} atoms/(barn.cm). This procedure reduced the maximum DLOFC temperature to 1745°C, but nonetheless, this temperature is still much higher than the target of 1600°C.

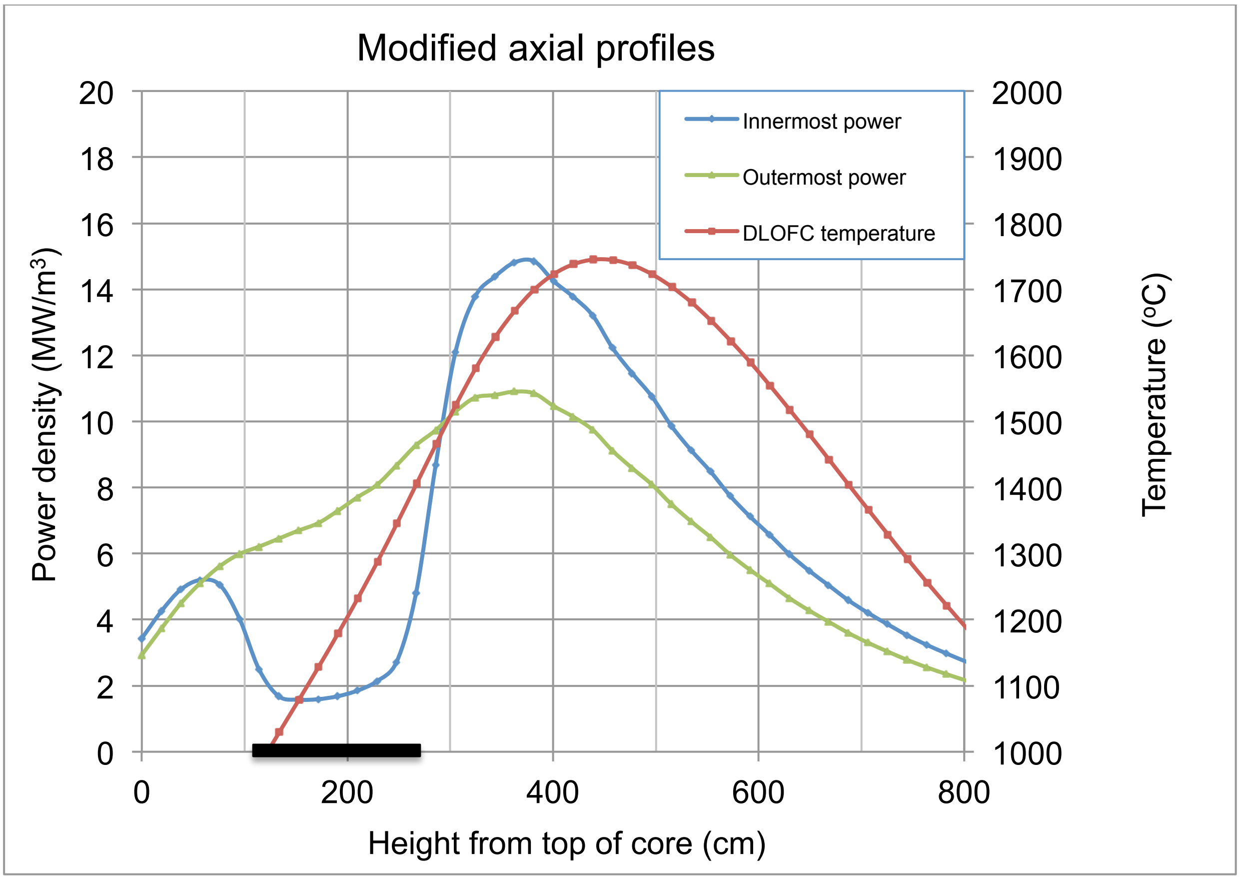

Figure 2: Modified axial power and DLOFC temperature profiles with ^{10}B in the region 115-287cm of the central reflector.

The ^{10}B region was then shifted half a meter further down to the between 172 cm and 345 cm, as shown on the core model in Figure 3 below, in order to create the desired larger power peak at the top end smaller peak lower down. The B-10 concentration was then varied until the maximum DLOFC temperature was reduced to below 1600°C, as shown in Figure 3. This occurred at a ^{10}B concentration of 6.75×10^{-6} atoms/(barn.cm).

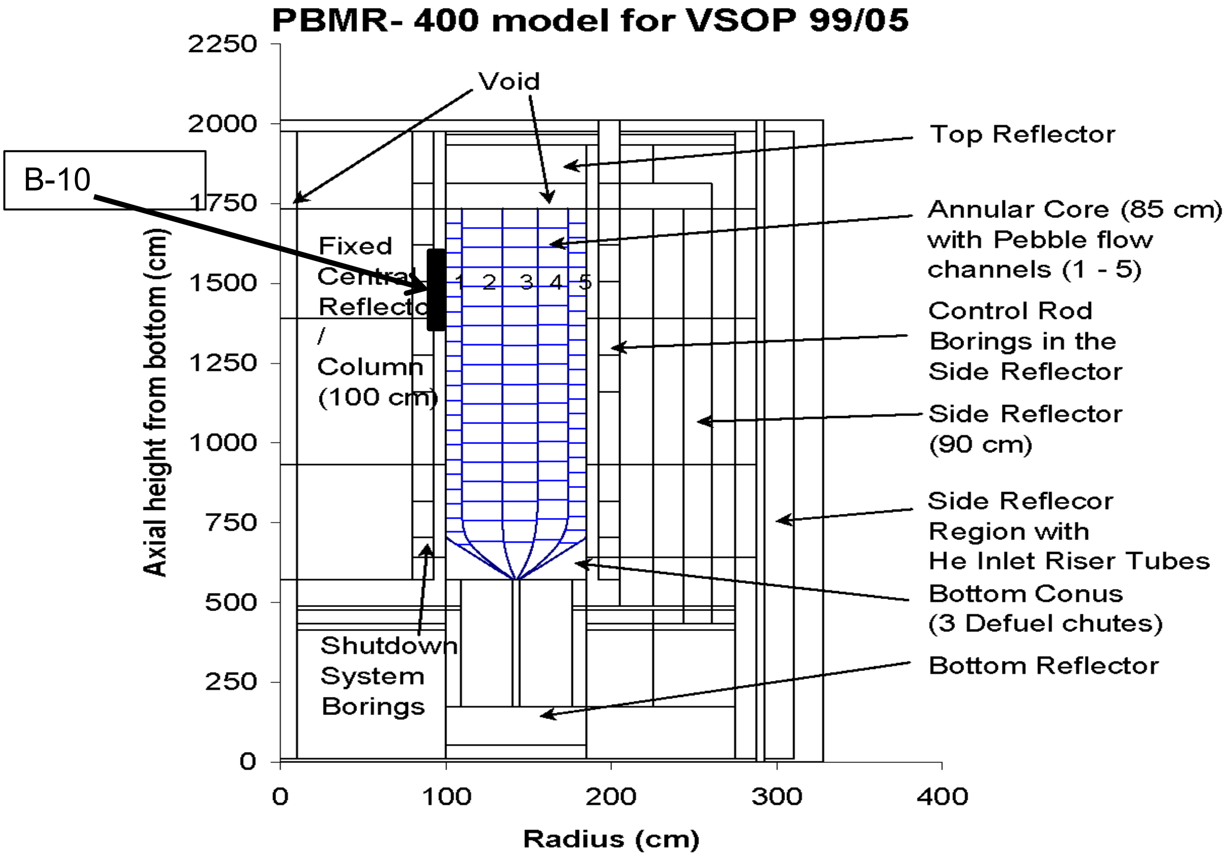

Figure 3: Reactor geometry used for VSOP simulation with the B-10 placement

4. Results

Figure 4 below presents the results for the first ^{10}B distribution that managed to reduce the maximum DLOFC temperature to below 1600°C. It presents both the inner and the outermost axial power profiles, and also the DLOFC temperature profile on a different scale for a ^{10}B concentration of 6.75×10^{-6} atoms/(barn.cm) in the region of between 172 cm and 345 cm below the top of the fuel core. A deeper than usual depression zone and a more pronounced second peak can be seen in the innermost power profile. When compared to the base case (Figure 1) where no poison was inserted in the central reflector, it is clear from Figure 4 that the poison in the central reflector also modulated the outermost power profile in the sense that the first peak near the top of the core is suppressed and the drop in power density, at the height of the second peak in the innermost profile, is also slower. However, this effect was not sufficient to actually create a second peak in the outermost profile. It follows that while the poison distribution in the central reflector also affects the power density in the outermost profile, its effect is limited. This was to be expected as the effect of the neutron poison is reduced with increasing distance from the poison.

The net result of manipulating the axial power profiles in this manner was an almost complete flattening of the DLOFC temperature peak, reaching a maximum value to 1548°C after 56 hours into the accident. These results were obtained at the cost of a loss in burn-up, which had to be compensated for by increasing the fuel enrichment from 6.841wt% to 7.293wt%, in order to restore the original burn-up.

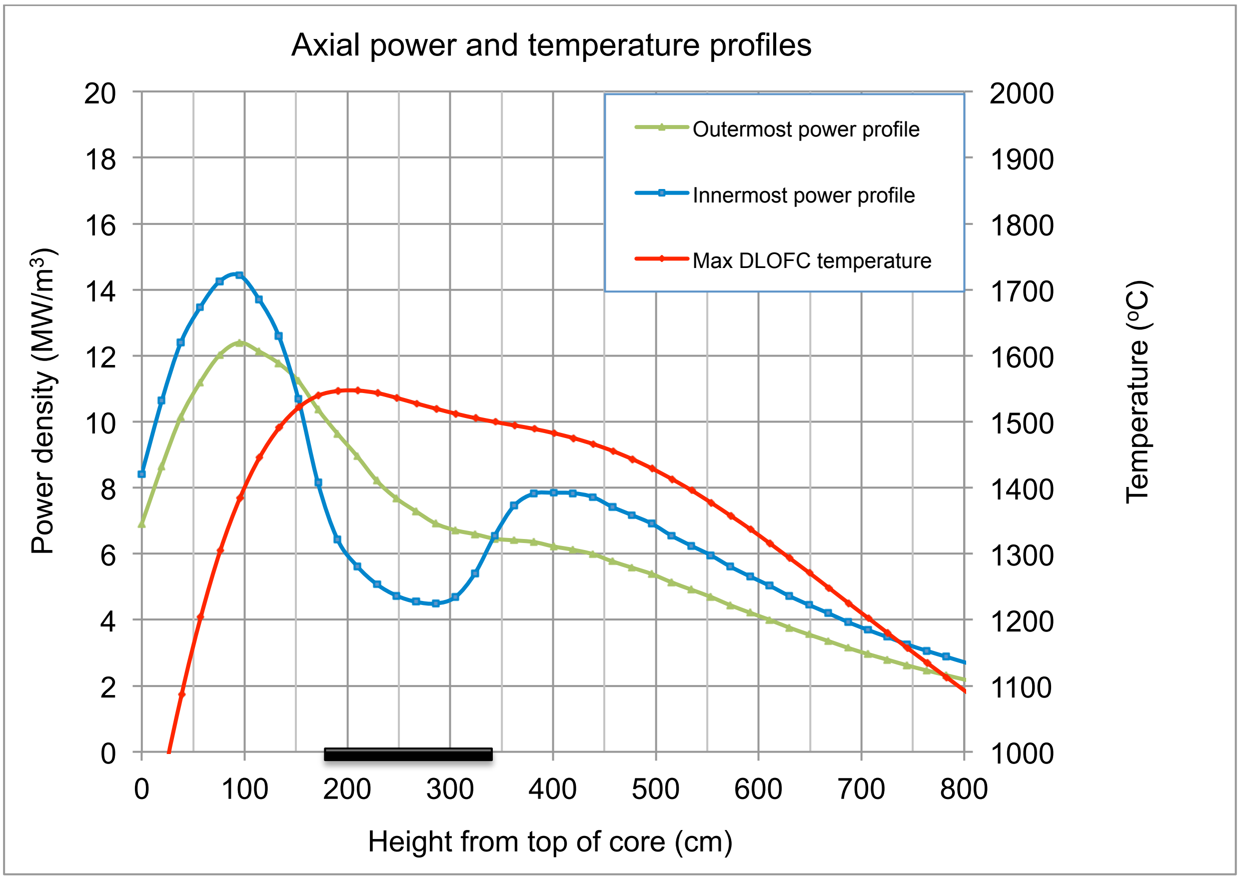

Figure 4: Modified power and maximum DLOFC temperature profiles with a ^{10}B concentration of 6.75×10^{-6} atoms/(barn.cm) in the central reflector in the height-range of 172 cm and 345 cm below the top of the fuel core in order to reduce the maximum DLOFC temperature of the symmetric core.

Although these results are impressive, the first peak in the innermost power profile still appears to be too high, resulting in a maximum DLOFC temperature profile peak, which does not have the desired flat top, but is rather skewed with an unnecessary high bump at 200 cm. In an attempt to further flatten the DLOFC temperature profile, some ^{10}B was introduced in a 57 cm thickness above the initial suppression zone. This strategy seemed to produce positive results (reduction in the height of the first power peak, compensated by a slight increase in that of the second power peak) up to a ^{10}B concentration of 0.544×10^{-6} atoms/(barn.cm) in the 57 cm region, producing a maximum DLOFC temperature of 1509°C after 62 hours into the accident. The results for this configuration are shown in Figure 5 below. It indicates the axial power density and maximum DLOFC temperature profiles for a ^{10}B concentration of 0.544×10^{-6} atoms/(barn.cm) in a 57 cm region above the suppression zone and 6.75×10^{-6} atoms/(barn.cm) in the suppression zone. This resulted in a slight increase in burn-up, which was removed by reducing the enrichment from 7.293wt% to 7.265wt%.

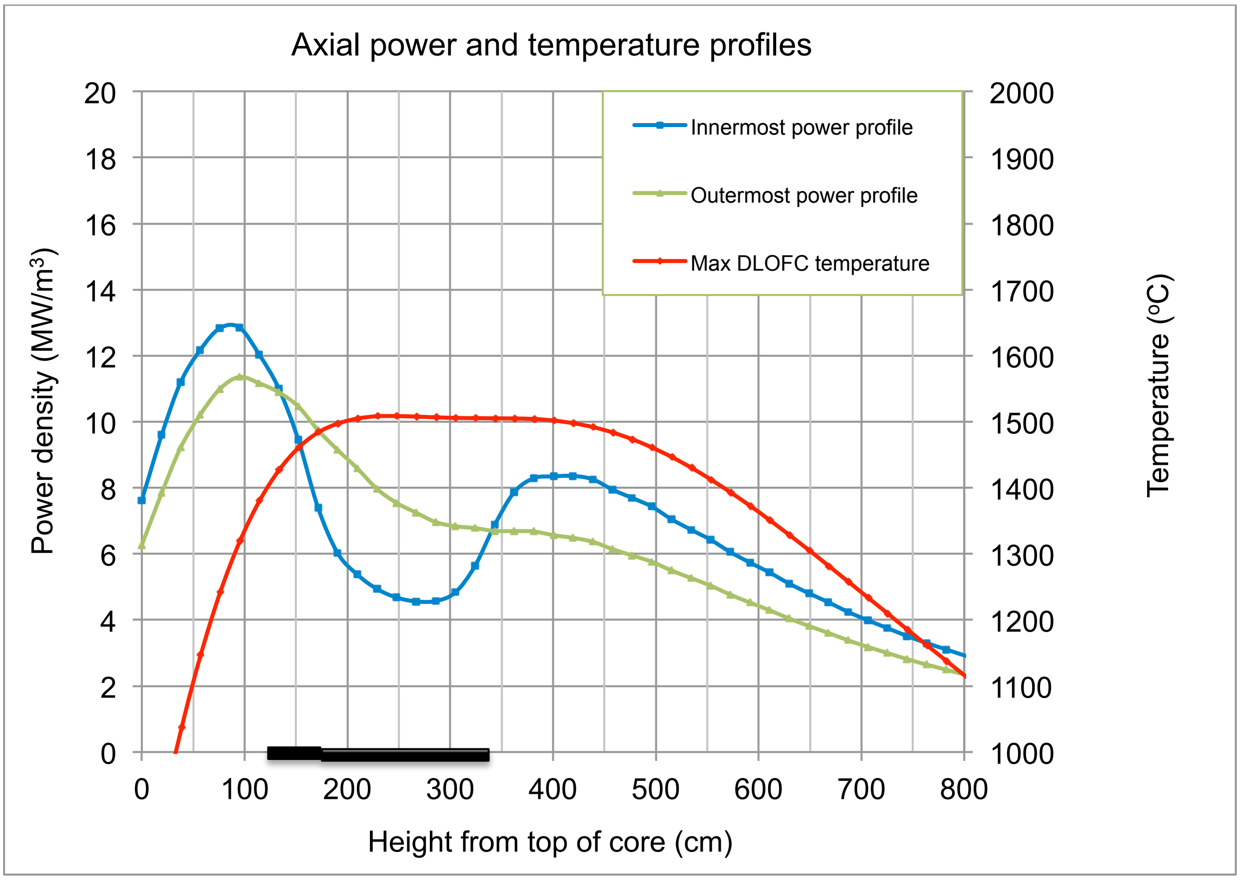

Figure 5: A symmetric maximum DLOFC temperature peak, achieved by modifying the power profiles with a ^{10}B concentration of 6.75×10^{-6} atoms/(barn.cm) in the suppression region of the central

reflector and a ^{10}B concentration of 0.544×10^{-6} atoms/(barn.cm) in a 57cm region above the suppression zone, in order to further reduce the maximum DLOFC temperature of the symmetric core.

The main objective of a previous article [8] was to reduce the maximum DLOFC temperature to below 1600°C, without adding poison to the central reflector, so that the solution would also be applicable to cores that do not have a central reflector. However, having failed in that endeavor, it was decided to place an appropriate ^{10}B concentration in the central reflector for the current study, which unfortunately restricts the current solution to annular cores.

In order to compare the results obtained for both the symmetric and asymmetric cores as in the previous study, another study was added with the same ^{10}B concentrations at the same positions, but for an asymmetric core. The asymmetric core was created by having a mixture of thorium and 15 a/o% LEU with effective enrichment of 2.575 a/o% in the inner two fuel flow channels of the core and a mixture of thorium and 20 a/o% LEU with effective enrichment of 9.864 a/o% in the outer three fuel flow channels. It must be noted that an asymmetric core adds an extra level of complexity to the system, because the two types of fuel types to be separated physically by some engineered means, and to some extent need to be prevented from mixing for their entire journey through the core. This can only be achieved by having extra structures in the core, which would have an influence on the neutron economy and could create added safety risks, for instance the risk that these structures could break, in which case the two fuel streams will no longer flow as designed. Figure 6 below shows the axial power density and maximum DLOFC temperature profiles for the asymmetric core without B-10 in the central reflector [8], together with the corresponding data for the radially symmetric core from

Figure above.

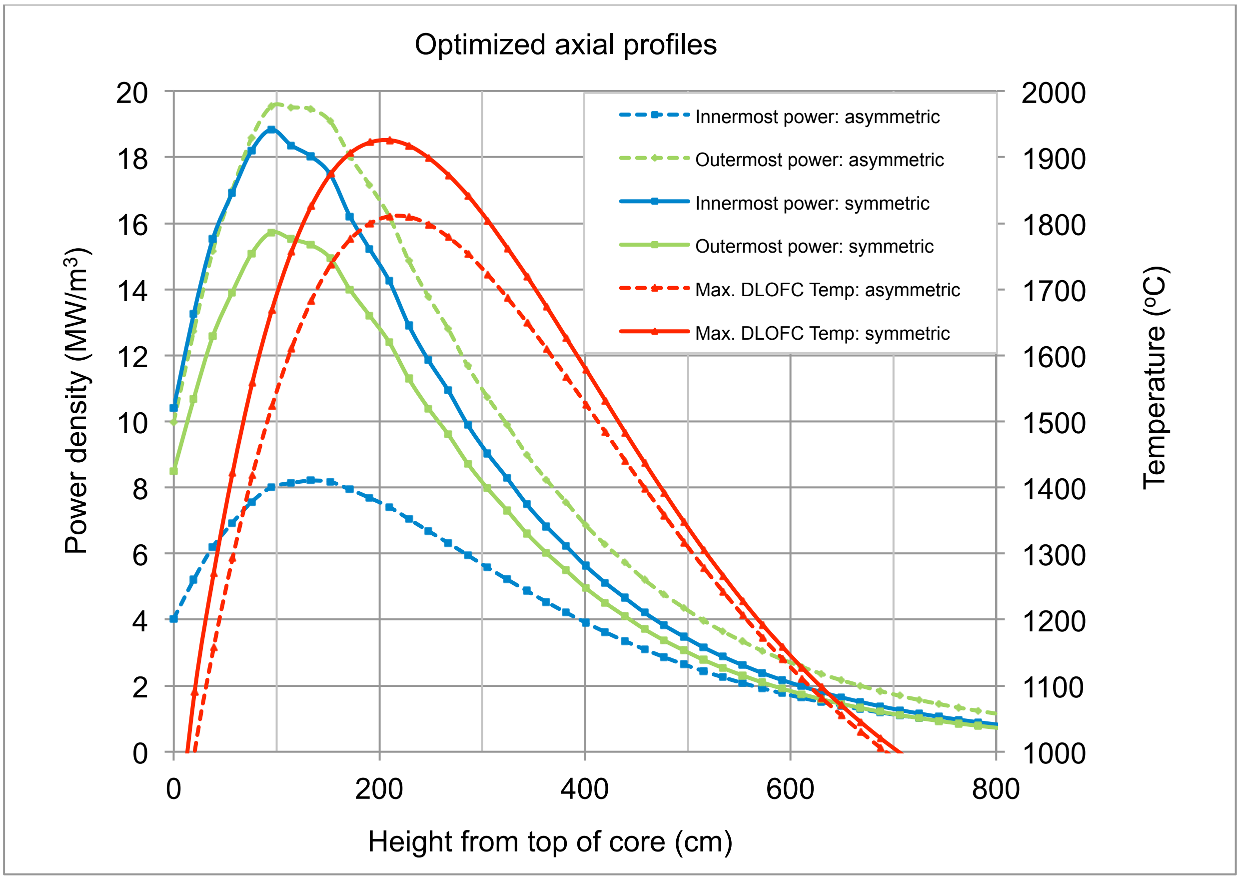

Figure 6: Axial power and maximum DLOFC fuel temperature profiles for producing a lower maximum DLOFC temperature, shown on a separate scale, for both the radially symmetric and asymmetric LEU-Th fuel cycles.

It is clear from this figure that the asymmetry strongly influenced the equilibrium power density profiles as the peak in the innermost profile for the symmetric core was substantially higher than for the outermost one, while the peak in the innermost profile of the asymmetric core was much lower than for its outermost profile. Because this would substantially reduce the distance over which most of the decay would have to be evacuated towards the external reflector during the DLOFC accident for the asymmetric case, it is surprising that the reduction in maximum DLOFC temperature was so small, i.e. from 1910°C to 1810°C. It suggests that the maximum DLOFC temperature is much less sensitive to manipulation of the radial profiles of the power density than to the manipulation of its axial profiles.

In order to attempt to reduce the maximum DLOFC temperature further from the 1810 °C down to below 1600 °C, the same concentrations of ^{10}B neutron poison were again inserted into the central reflector, as was done for the radially symmetric core. Figure 4 below shows that the axial power DLOFC temperature profile is quite similar in shape to that of the symmetric core in Figure above, with the main difference being that the maximum DLOFC temperature for the asymmetric case of 1448 °C is substantially lower than the 1509 °C for the symmetric case. This can be ascribed to the fact the asymmetry of the core already suppressed the power in the innermost part of the core, and the addition of the suppression zone by the inclusion of neutron poisons in the central reflector further suppresses the first power peak at the top of the core, making the second power peak's height closer to that of the first. As observed with the symmetric core, the closer in height the second innermost power peak gets to the first, the less its likelihood to flatten the DLOFC temperature profile, suggesting that a change in the neutron poison concentration in order to increase the difference in heights between the two innermost power peaks would produce even better results. Once more these results were obtained at the cost of a loss in burn-up, which had to be compensated for by increasing the fuel enrichment from 2.575 a/o% to 3.483 a/o% in the inner part of the core and from 9.864 a/o% to 9.968 a/o% in the outer part of the core, in order to restore the original burn-up.

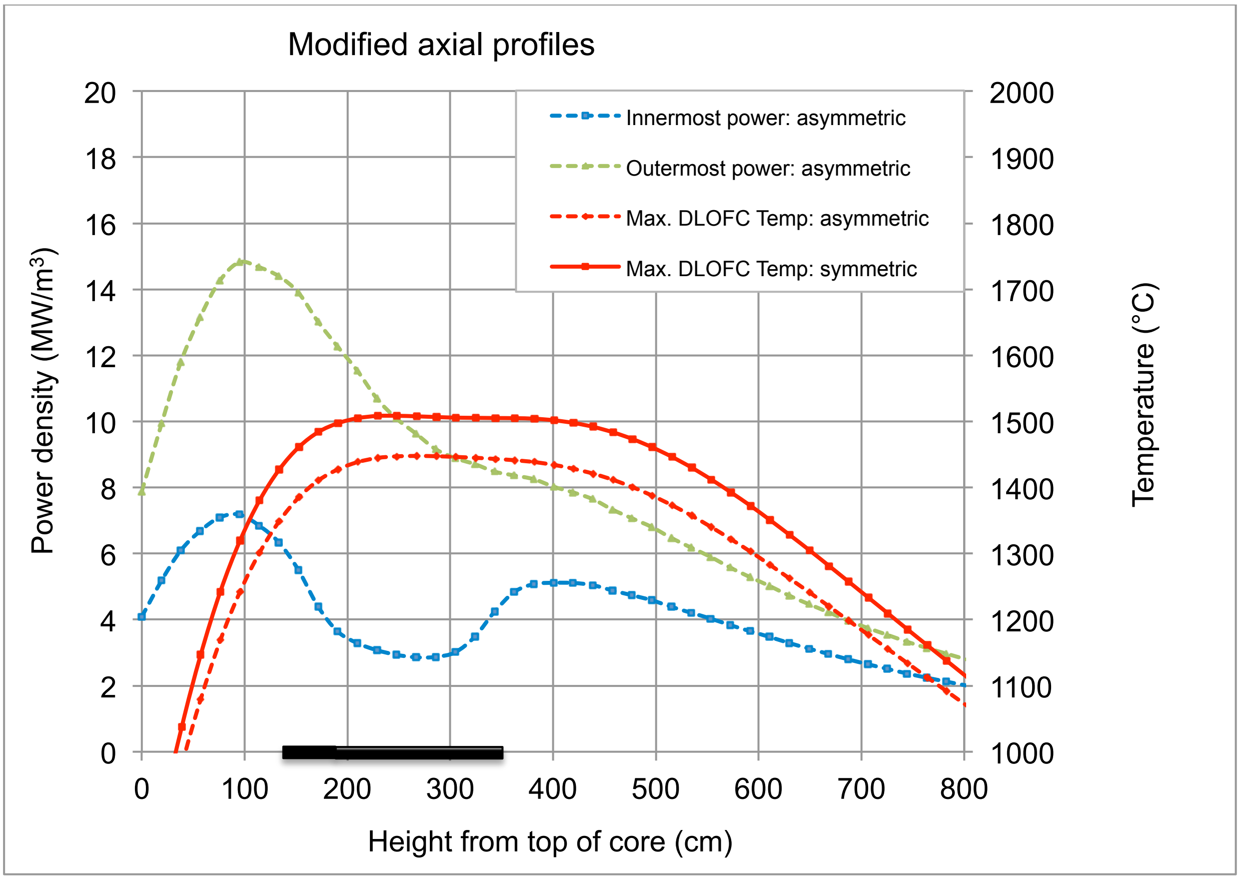

Figure 7: The asymmetric core with modified power and temperature profiles with a ^{10}B concentration of 6.75×10^{-6} atoms/(barn.cm) in the suppression region of the central reflector and a ^{10}B concentration of 0.544×10^{-6} atoms/(barn.cm) in a 57cm region above the suppression, to further reduce the maximum DLOFC temperature of the asymmetric core.

Figure 8 presents the time dependence of the DLOFC temperature for both the symmetric and the asymmetric cores, with the same ^{10}B concentration of 6.75×10^{-6} atoms/(barn.cm) in the suppression region of the central reflector and a ^{10}B concentration of 0.544×10-6 atoms/(barn.cm) in a 57 cm region above the suppression zone. The two graphs have the same shape, reaching their respective maximum values of 1509°C after 62 hours 1448°C after 64 hours into the accident for the symmetric and the asymmetric core respectively.

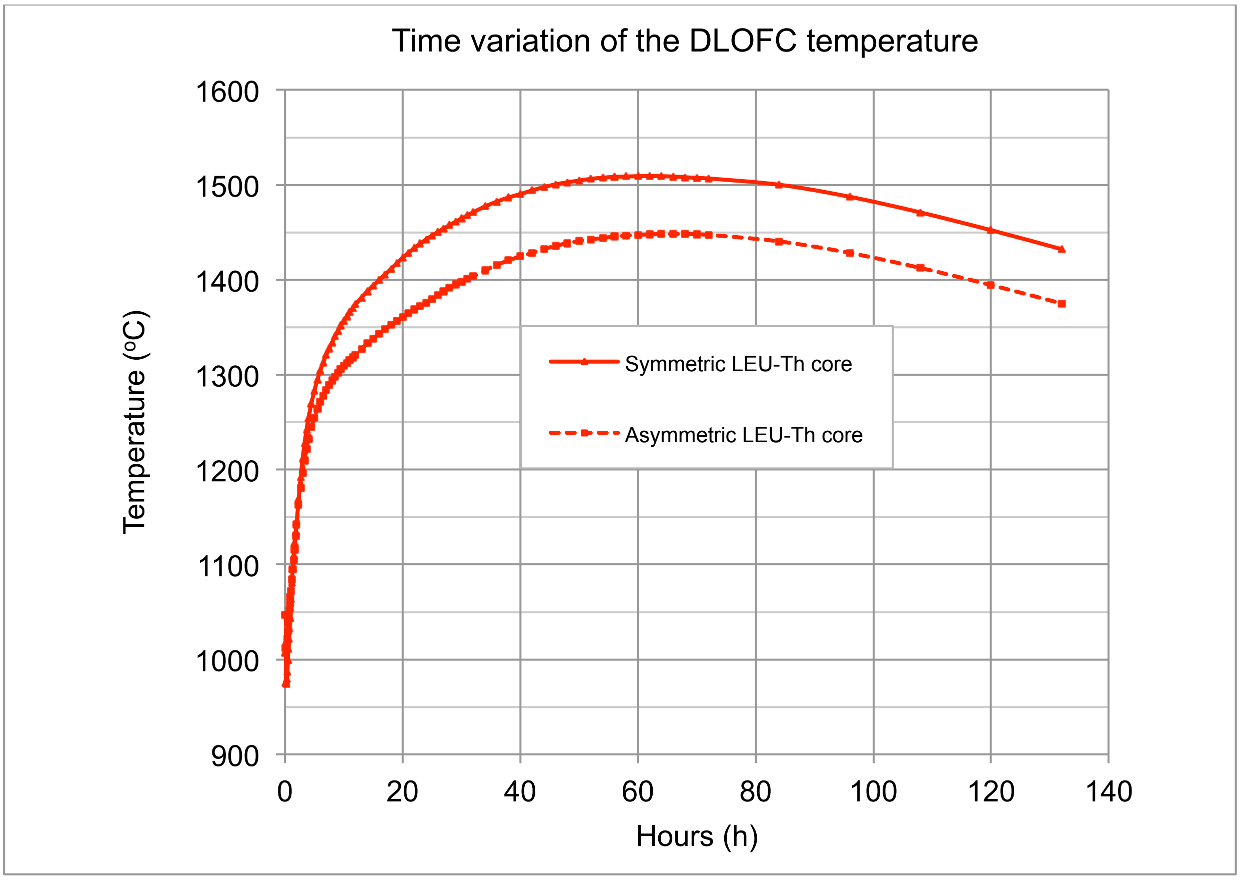

Figure 8: Time profiles for maximum DLOFC temperatures with a ^{10}B-concentration of 6.75×10^{-6} atoms/(barn.cm) in the suppression region of the central reflector and a ^{10}B concentration of 0.544×10^{-6} atoms/(barn.cm) in a 57cm region above the suppression zone.

5. Discussion and conclusion

During the course of this optimization study aimed at reducing the maximum DLOFC temperature of a PBMR-400 fueled with a mixture of thorium and LEU in OTTO loading scheme, the following were found:

- The ^{10}B neutron poison concentration in the central reflector sharply reduced the maximum DLOFC temperatures, but also reduced in the burn-up. In order to restore the burn-up, the enrichment of the fresh fuel had to be increased.
- Although the neutron poison was introduced in the central reflector, and this had the most significant effect in the innermost power density profiles, its effect was still substantial in the outermost power profiles, showing substantial neutronic coupling between the inner and the outer parts of the core. However this coupling was substantially less for the asymmetric core in that the shape of the outermost power

density profile appears substantially dissimilar to that of the manipulated innermost profile. This was probably caused by the fact that asymmetry "pushed" the neutron flux out towards the external reflector, which reduced the neutron flux at the position of the poison in the central reflector and thus reduced the importance of this poison concentration.

- The flattening of the DLOFC temperature profile was not achieved by flattening the axial power profiles, but rather by splitting the large peak in the innermost power profile into a somewhat smaller peak at the top of the core, followed by a depression zone and an even smaller peak in the bottom half of the core. This has to do with the fact that the long time lag of about 60 hours from the start to the DLOFC accident to the maximum DLOFC temperature causes the decay heat from these two power peaks to diffuse through the core and thus to merge into one flattened DLOFC temperature profile.
- There is a strong relation between the ratio of the heights of the peaks in the innermost power profile and the flattening of the DLOFC temperature profile in that the first innermost power peak should be substantially higher than the second one, in order to produce a flat temperature profile. This has to do with the fact that the equilibrium core is substantially cooler near the top and can thus safely absorb more decay heat near the top.

The placement of a ^{10}B concentration in the central reflector produced a maximum DLOFC temperature of 1509°C and 1448°C respectively for the symmetric core and the asymmetric core. The lower temperature for the asymmetric core comes at the cost of greater complexity and thus additional licensing risk.

Neutron poison was successfully used in combination with a mixture of LEU and thorium to reduce the maximum DLOFC temperature of a medium-sized annular core pebble-bed reactor (PBMR-400). Thorium in the fuel helped to reduce the peaking factor, while the neutron poison distribution shaped the axial power profile.

The study was conducted with ^{10}B for the sake of simplicity. However, in practice ^{10}B, which is a burnable poison, will have to be replaced with a non-burnable poison, such as natural hafnium, in order to maintain the poison concentration over the life of the plant. This problem does not arise in the case of this study as VSOP 99/05 doesn't follow the depletion of ^{10}B in the central reflector but rather considers its concentration to remain the same, which is not the case in practice.

The following follow-up studies are proposed:

- A comparative study of different neutron poison distribution in the central reflector, the external reflector, or even both reflectors, in order to optimize the power profiles even further in terms of burn-up, equilibrium and accident fuel temperatures.
- The increase in fuel enrichment could increase fuel cost. Therefore a tradeoff between reducing DLOFC temperatures even further by increasing the neutron poison densities further and limiting fuel cost would be an interesting study.
- A detailed study on the optimum asymmetry level of the core together with a clear relationship between the heights of the first and second peaks of the innermost power profile.
- Repeating the optimization process with substantially higher fuel enrichments. Higher enrichment fuels would reduce fuel manufacturing cost, due to the much higher burn-ups and thus much higher cumulative energy produced per fuel sphere that would be achieved. However, it would also sharply increase the peakedness of the axial power profiles, which will increase the maximum DLOFC temperatures. Therefore, higher poison concentrations and different poison distributions will have to be used in order to restore the lower maximum DLOFC temperatures.
- Repeating the optimization process for cylindrical cores that do not have central reflectors. All poisons will thus have to be placed in the external reflectors. This will complicate matters by shifting the radial power inwards, which would partly offset the reductions in maximum DLOFC temperatures that would be obtained by flattening the peaks in the axial maximum DLOFC temperature profiles.

References

[1] Kania MJ, Nabielek H, Verfondern K, et al Testing of HTR UO2 TRISO fuels in AVR and in material test reactors. J Nucl Mat. 2013;441:545-562.

[2] Reutler H, Lohnert GH. The Modular High-Temperature Reactor. Nucl Technol. 1983; 62:22-30.

[3] Reutler H, Lohnert GH. Advantages of going modular in HTRs. Nucl Eng Des. 1984; 78(2):129-136.

[4] Zhang Z, Wu Z, Wang D et al. Current status and technical description of Chinese 2 x 250MWth HTR-PM demonstration plant. Nucl Eng Des. 2009; 239:1212-1219.

[5] Reitsma F. The Pebble Bed Modular Reactor Layout and Neutronics Design of the Equilibrium Cycle. Proceedings of PHYSOR 2004 -The Physics of Fuel Cycles and Advanced Nuclear Systems: Global Developments; 2004 April 25-29; Chicago (IL) [CD-ROM].

[6] Hansen U, Schulten R, Teuchert E. Physical Properties of the "Once Through Then Out" Pebble-Bed Reactor. Nucl Sci and Eng. 1972; 47:132-139.

[7] Serfontein DE. Sharp reduction in maximum fuel temperatures during loss of coolant accidents in a PBMR-400 core, by means of optimised placement of neutron poisons. Nucl Eng Des. 2014; 271:492-498.

[8] Tchonang Pokaha M, Serfontein DE. Using thorium to reduce the maximum fuel temperatures during depressurized loss of coolant accidents in a once-through-then-out (OTTO) PBMR DPP-400 core. J Nucl Sci Technol. 2017;54(5):589-599.

[9] Rütten HJ, Haas KA, Brockmann H et al V.S.O.P. (99/05) (release 2): Computer code system for reactor physics and fuel cycle simulation. 2007,Jülich: Institut für Sicherheitsforschung und Reaktortechnik [Software]

[10] Lamarsh JR, Barata AJ. Nuclear reactor fuels. Introduction to Nuclear Engineering. 3rd ed.; 2001. p. 327.

[11] van Dam H. Long-term control of excess reactivity by burnable particles. Ann Nucl Energy. 2000 5;27(8):733-743.

[12] Kloosterman JL. Application of boron and gadolinium burnable poison particles in UO_2 and PUO_2 fuels in HTRs. Ann Nucl Energy. 2003;30:1807-1819.

[13] Tran HN, Kato Y. An optimal loading principle of burnable poisons for an OTTO refueling scheme in pebble bed HTGR cores. Nucl Eng Des. 2009;239:2357-2364.

[14] Serfontein DE. Deep Burn Strategy for the Optimized Incineration of Reactor Waste Plutonium in Pebble Bed High Temperature Gas-Cooled Reactors. North-West University, South Africa; 2011.

6 DIFFERENT TECHNIQUES FOR REDUCING DLOFC FUEL TEMPERATURES IN A PBMR-DPP-400 CORE

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6.1 Motivation and Relative contributions of authors

6.1.1 Motivation

This is the capstone article of an article-based PhD on the topic of modifying the fuel cycles of Pebble Bed Reactors in order to reduce their maximum fuel temperatures during Depressurised Loss of Forced Coolant (DLOFC) accidents, in order to prevent unacceptable levels of release of radioactive fission products from the fuel into the environment. The article presents a review of the literature on the subject, with emphasis on, and reference to the three previous papers in this series. The lessons learnt in the preceding papers are discussed, gaps in our understanding of the topic are identified, and an attempt is made to fill these gaps with new investigations.

6.1.2 Relative contribution of authors

Prof. D.E. Serfontein was the study leader during this stage of the research with the task to provide guidance and support to M. Tchonang Pokaha whilst also evaluating the academic soundness and strength of the research. All research was conducted and documented by M. Tchonang Pokaha.

6.2 Article 4: DIFFERENT TECHNIQUES FOR REDUCING DLOFC FUEL TEMPERATURES IN A PBMR-DPP-400 CORE

Abstract: The principle strategies used for reducing the maximum DLOFC temperatures were (a) flattening the peaks in the axial profiles of the maximum DLOFC temperature, in order to increase the surface areas over which effective evacuation of decay heat takes place. This reduces the resulting maximum heat fluxes and temperatures in the hotspots; and (b) "pushing" the radial profiles of the equilibrium power density outward towards the external reflector, thereby decreasing the distance, and thus the thermal resistance, over which the decay heat has to be evacuated towards the external reflector. Easier radial evacuation of decay heat reduces the maximum DLOFC temperatures, which always occur in the inner layers of the fuel core.

These strategies were applied for both 6-pass recirculation fuelling schemes and Once Through Then Out (OTTO) fuelling schemes. The techniques used for flattening the peaks in the axial profiles of the maximum DLOFC temperature were (a) flattening of the peaks in the axial profiles of the equilibrium power density by adding thorium to the LEU fuel in order to improve the breeding and conversion ratios, which slowed the depletion of the enrichment of the fuel with increasing burn-up and thereby increasing the power density in the bottom parts of the fuel core; and (b) placing purposely-designed distributions of neutron poison in the central reflector in order to supress the normal peaks in the axial profiles of the equilibrium power density. The poison in the central reflector simultaneously served the purpose of pushing the power densities outward from the central towards the external reflector.

This strategy was further implemented by creating asymmetric cores in which the enrichment of the fuel in the outer fuel flow channels was higher than in the inner ones, which automatically shifts the fission power out to these higher enriched outer fuel zones.

The result was large reductions in the maximum DLOFC temperatures from 1536°C to 1298 °C for the multi-pass and from 2273°C to 1448°C for the OTTO. The use of neutron poison in the central reflector to flatten the peaks in the axial profiles of the maximum DLOFC temperatures reduced the maximum DLOFC temperature much more effectively than any of the other techniques.

Keywords: fuel cycle; DLOFC; pebble bed reactor; power density profile; neutron poison; thorium

1. Introduction and the working of VSOP

1.1 Introduction

High Temperature Gas-cooled Reactors (HTGRs) are regarded as one of the more mature options available in the Gen-IV designs. Their main advantage is based on their strong passive safety features, which render excessive release of radioactive material in the environment highly improbable. This is due to the use of TRISO coated fuel particles in HTR fuel, allowing high burn-up and almost complete retention of all fission products up to a fuel temperature of about 1600°C [1]. In order to make these reactors inherently safe by design, Reutler and Lohnert in the early 1980s presented the idea of modular HTRs to restrict the power output and the dimensions of the reactor in order to limit the maximum fuel temperature in all operating and severe accident conditions to below 1600°C [2,3].

The HTR-PM currently under construction in China embraces this philosophy. It combines two 250 MW_{th} reactors to drive a single 210 MW_e turbine, each reactor having a cylindrical core of 3 m diameter and 11 m height [4]. On the other hand, the 400 MW_{th} Pebble-Bed Modular Reactor Demonstration Power Plant (PBMR-DPP-400) developed in South Africa since the mid-1990s diverted slightly from Reutler's idea. Apart from its higher nominal power output, the main design innovation of the PBMR-DPP-400 is the use of a central graphite reflector, in addition to the external reflector. This central reflector pushes the fuel spheres outwards toward the external reflector. For a fixed fuel core volume, this increases the outer diameters of the fuel core, external reflectors, core barrel conditioning system and core barrel and thus the surface areas through which decay heat can be evacuated from these structures to the reactor containment building. Pushing the fuel outwards also reduces the distance over which the decay heat has to be evacuated through the fuel and thus reduces the thermal resistance and thereby increases the rate at which decay heat can be evacuated to the external reflector. All these factors decrease the maximum Depressurised Loss of forced Coolant (DLOFC) fuel temperatures. This allows for a higher safe equilibrium power output [5]. However, uncertainty about some technical issues regarding the safety case of this reactor led to the South African National Nuclear Regulator (NNR) postponing the final decision to grant this reactor a construction licence. This delay was a substantial contributing factor to the eventual demise of the project. It will be shown in this article that the methods presented here could have reduced the maximum DLOFC temperatures of the

PBMR-400 to such an extent that these safety concerns could have been removed, the license could have been obtained and the project could have been saved.

The carbon nuclei in the two-meter thick graphite central reflector and in the external reflector moderate the neutrons that enter them very effectively and thus reflect a large flux of thermal neutrons back into the fuel. This causes fission power peaks in the fuel directly adjacent to both reflectors. Unfortunately, the peak against the central reflector is substantially higher than the one against the external reflector. This concentrates the decay heat in the inner layers of the fuel core, which increases maximum fuel temperatures during a DLOFC.

The slow rate at which fuel spheres flow from the top to the bottom of the core results in burn-up levels at the bottom of the core which are substantially higher than at the top. The top-to-bottom gas flow direction also produces much higher fuel temperatures at the bottom than at the top. Together, these factors result in fuel reactivity and thus in power densities that are substantially lower at the bottom than at the top of the core, giving rise to a sharp peak in the axial power profiles, typically in the top third of the fuel core.

One strategy that is often used to reduce the peaking factor of PBRs is the multi-pass fuel recirculation scheme in which the fuel passes in the core many times before reaching its target burn-up. This strategy is investigated in the first part of this article, while the second section focuses on the Once-Through-Then-Out (OTTO) fuelling cycle, and finally conclusions are drawn from the lessons learned. Given that most of the results presented in the present article are based on the PBMR-DPP 400, its adopted safety limits, simulation parameters and reactor geometry used in the input model for the VSOP 99/05 [6] diffusion code used for this work are presented in the Table 1 below.

1.2 The working of the VSOP neutronics code

The VSOP 99/05 suite of codes was used for the neutronic and thermos-hydraulic calculation in this article. It is a diffusion code. It requires as input the geometry of the reactor fuel core, as well as the atomic number densities for each isotope that the core consists of, together with other physical attributes such as the temperatures of different regions, the helium coolant gas flow rates and inlet temperature and pressure. It then iteratively solve the diffusion equation which produces the neutron flux in four discrete energy groups together with all the required nuclear reaction cross-sections for each energy group. From this it calculates all the important reaction rates, such as the fission rate of ^{235}U, the rate of radiative capture in ^{238}U, which simultaneously yields the depletion rate of ^{238}U and the production rate of ^{239}Pu. From this the depletion, breeding and transmutation evolution of all important isotopes, as a function of burn time, are calculated for the present fuel loading in the core. After a stipulated burn cycle the core is refuelled: All fuel layers move one position down, at pre-specified fuel flow speeds, five in designated fuel flow channels. The layer at the bottom of each channel falls out of the core. For a Once-Through-Then-Out refuelling scheme, this whole fuel layer is sent to the spent fuel tank. For the six-pass recirculation refuelling scheme of the PBMR-400, only the oldest fuel batch (Pass (6) is sent to the spent fuel tank. Pass (1) then becomes Pass (2) and is sent back to the top of the core and reintroduced into the first fuel layer at the top, which became vacant when the fuel moved down. Similarly the old Pass (2) becomes the new Pass (3), etc. The space for Pass (1) fuel in each top layer is then filled with fresh fuel from the fresh fuel tank. This process repeats itself throughout the while life of the core.

From the reaction rates the neutron multiplication factor (k_{eff}) and all other important parameters regarding the neutron economy of the core is calculated. Once the neutronic calculations have converged, the fission heat production rates are calculated from the fission rates and are sent to the THERMIX thermo-hydraulics code, which use them to iteratively recalculate the heat flow and from that temperature distribution throughout the core, including the temperature of the coolant gas. THERMIX then send the updated temperature distribution back to VSOP.

Since most neutronic reaction rates are temperature sensitive, VSOP uses the new temperatures to iteratively recalculate the neutron fluxes, cross-sections, reaction rates and the evolution of the atomic number densities of the isotopes. This is repeated after each burn and refuelling session. It then uses this new data to recalculate the heat production rates, where after it again send it to THERMIX, so that the whole process repeats iteratively until the whole burn history of the core has been calculated for the life of the plant and all relevant results are then summarised in an output file.

In order to calculate the temperatures during a DLOFC accident, THERMIX is informed that all helium coolant flow and pressure has been lost and that the fission reaction has stopped instantaneously, as described above. The heat production rate then decreases to only about 7% of full power decay heat production, which also decreases exponentially over time.

However, since all active cooling has been lost, this small heat production must now be evacuated by means of only conduction and radiation. The result is that heat production exceeds heat evacuation and thus the core starts to heat up. As time progresses the decay heat production falls to below 1% and the heat evacuation rate increases as the core heats up. At some point heat evacuation then starts to exceed heat production, where after the core slowly starts to cool down. This tipping point is normally reached between 24 and 48 hours into the accident. The aim is to design the core such that this tipping point will be reached before the maximum industry guideline fuel temperature 1600°C is reached. Experimental measurements suggests that if this temperature is not breached, no large leakages of radioactive decay products will occur through the coating layers around the fuel particles.

For our DLOFC calculations, the following assumptions were made: during a DLOFC accident, the reactor loses the helium coolant flow through a large pipe break and rapid depressurization. For the thermal hydraulic calculations, the reactor is considered at its nominal steady-state conditions, where after the loss of coolant happens instantaneously and the fission power is taken from 400 to 0 MW instantaneously. The decay heat in the absence of helium cooling will then heat up the core. This decay heat is evacuated by conduction and thermal radiation between pebbles, then from the pebbles to the external reflectors and then all the way out to the atmosphere. The geometry of the core is shown in Fig. 1 and summarised in Table 2.

Table 1: Adopted safety limits for Pebble Bed Reactor fuel.

Parameter	Limit
Maximum equilibrium power density	4.5 kW/fuel sphere. For the 15,000 coated particles in the standard PBMR fuel sphere. This translates into 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 conditions

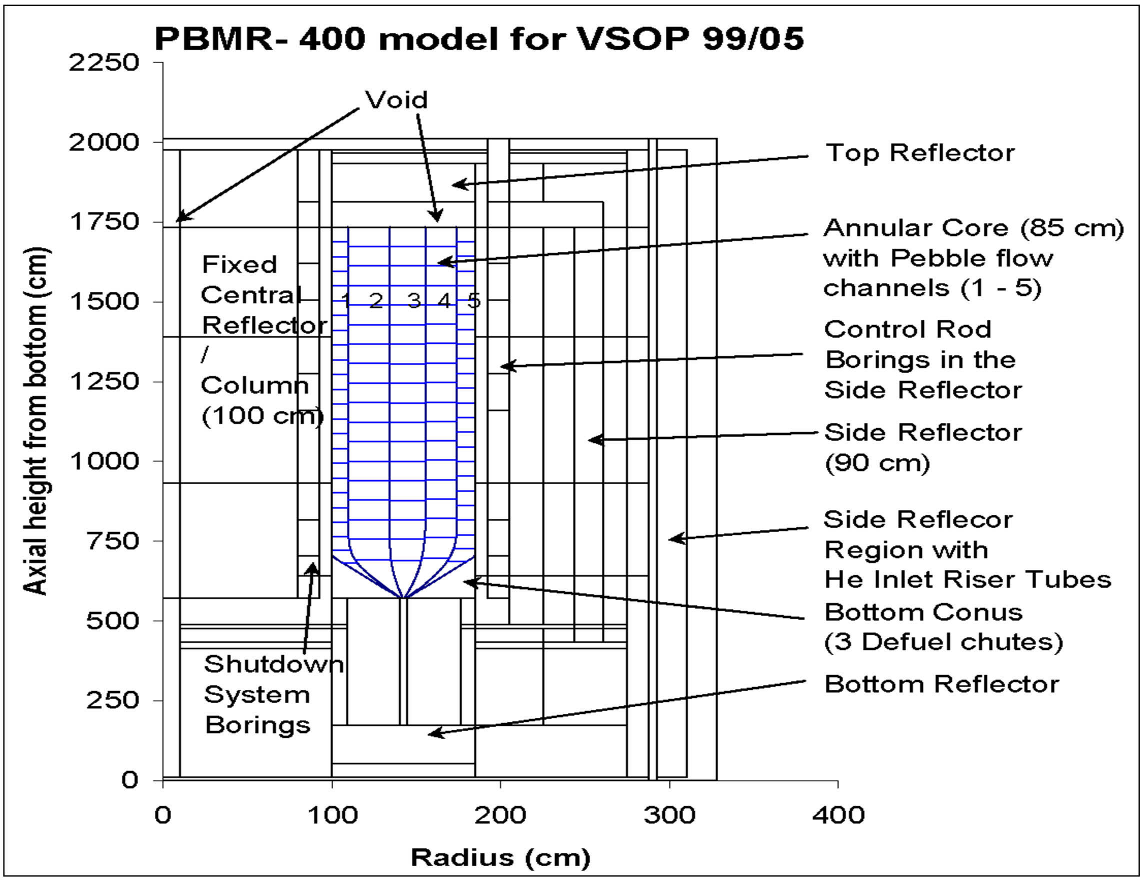

Figure 1: Annular reactor geometry model for the PBMR-400, used for VSOP simulations.

Table 2: Simulation parameters for the annular PBMR DPP-400 reactor core

Parameter	Unit	Value
Volume of fuel core	m^3	83.73
Packing fraction of fuel spheres		0.61
Height of core	m	11.625
Radii of fuel core annulus: inner/outer	m	1.00 / 1.85
Fuel recirculation	Nr. of passes	1 or 6
Number of fuel flow channels		5
Flow pattern	Steps / channel	24 / 18 / 18 / 18 / 24
Pressure of helium	Bar	90
Heating of helium	°C	500 → 944
Helium mass flow, after reduction for cold bypass	kg/s	173.4
Cold bypass	%	10.0
Fuel sphere geometry		
Outer radius of zones: inner fuel matrix/outer graphite shell	cm	2.5/3.0
Heavy metal per fuel sphere	g	9 for LEU, 9-20 for Th+LEU
Coated particles		
Diameter of fuel kernels	cm	0.05
Fuel composition		ThO_2/UO_2
Fuel density	g/cm^3	10.4

2. Multi-pass fuel recirculation scheme

In the case of the PBMR-400 DPP, the combined axial and radial power peak is situated about a third from the top of the core and directly adjacent to the central reflector [7]. This becomes a concern in the case of a DLOFC accident, because this peak in the equilibrium power profile creates a DLOFC temperature hotspot. The decay heat power during a Depressurised Loss of Forced Coolant (DLOFC) accident is directly proportional to the equilibrium thermal fission power density that preceded the accident. Therefore, the peak in the equilibrium power density also produces a similar peak in the DLOFC decay heat power density, which leads to DLOFC temperature hotspot some distance below the power hot-spot. This hotspot causes a safety concern in the sense that it causes the maximum DLOFC fuel temperatures in this hotspot to increase towards the industry guideline limit of 1600 °C for normal equilibrium power output. If, however, the equilibrium power output is reduced in order to reduce the maximum DLOFC temperature, this reduces the revenues from power sales and thus the profitability of the plant.

Studies have been conducted on the neutronic and thermal-hydraulic simulation of the standard 6-pass recirculation scheme for the standard 9.6 wt % enriched, 9 g heavy metal (HM) per fuel sphere low-enriched uranium (LEU) fuel in the PBMR DPP-400 reactor. Maximum temperatures during a simulated DLOFC accident were all below the industry guideline limit of 1600 °C, which ensures that the leakage of radioactive fission products through the TRISO coatings around the fuel kernels will remain below the acceptable limits [5,7]. However, in the temperature range of concern, i.e. above about 1200°C, this leakage increases exponentially with fuel temperature. Therefore, even just relatively small reductions in fuel temperature will result in relatively large reduced leakage rates. Also, deviations of the actual reactor geometry and isotopic composition, fuel geometry and isotopic composition or coolant flow rates and flow patterns from the simulated ones could result in actual maximum fuel temperatures that are substantially higher than the simulated ones. Therefore it would be prudent to allow a safety margin between the simulated maximum fuel temperatures and the allowable fuel temperature limits. Substantial reductions of the maximum DLOFC fuel temperatures can be obtained by manipulating the axial and radial power profiles. A standard approach is to flatten the axial power profile by increasing the number of fuel recirculation passes, as has been achieved for the 10 passes [8] of the indirect Rankine steam cycle of HTR-PM. However, the designers of the PBMR-400 rejected more passes since they were concerned that this would grind too much graphite dust particles off the fuel spheres, which could damage the helium turbine blades of the direct Brayton cycle [9] Furthermore, the resulting shorter out-of-core time available for measuring the burn-up of the fuel spheres could jeopardise these measurements.

An improvement of the power profiles with the use of a tailor-made neutron poison distribution in the central reflector sharply reduced the maximum DLOFC temperature from 1581 °C to 1298 °C [10]. Unfortunately this temperature reduction came at the cost of a 22% reduction in the burn-up of the fuel. However, the use of neutron poisons in the central reflector limits this technique to annular cores with a central reflector.

Another optimisation study combined a multi-pass scheme with multi-zone refuelling in the PBMR-400 core [8]: the fresher fuel was placed in the outer fuel zones and the more depleted fuel in the inner fuel region, together with a radial outer-to-inner gas flow and smaller pebbles reported maximum DLOFC temperature was reduced from 1640 °C to 1369 °C [11]. However, changing the coolant flow pattern is a major and complicated modification to the original design and therefore this concept was not explored in the present study.

A comparative study of three different fuel-loading patterns was conducted in a pebble bed reactor [12]. The first pattern used a single fuel zone with multi-pass refuelling, the second used a two fuel zone in which the outer annular zone is filled with multi-pass fuel with low burn-up and fresh fuel, and the inner cylindrical zone is filled with higher burn-up fuel. The third pattern used a two-fuel zone in which the inner zone is filled with pure graphite spheres and the outer zone with fuel in a multi-pass scheme. The results showed that, for a given reactor with a fixed power output, the lowest value of the maximum DLOFC temperature was obtained with the third loading pattern with the graphite spheres in the inner region, followed by the second loading pattern with higher burn-up fuel in the inner zone, while the single zone core producing the highest temperature.

3. Statistical and systematic errors in the temperature results

3.1 Statistical errors

Stochastic codes utilise ray-tracing methods of individual neutrons on the core, using for instance the MCNP. The code produces results that are by definition random and thus contain a statistical uncertainty, in other words, each time you recalculate with MCNP, using identical input values, you get a slightly different set of results. These statistical uncertainties decrease as one increases the number of random events that are traced in a burn cycle. Unfortunately such ray tracing requires a large number of calculations per neutron event and immense numbers of neutron events must be calculated in order to obtain results with reasonable statistical accuracy. Stochastic codes may thus take months or years to calculate simple full-core problems and therefore they are normally not used for this purpose.

The diffusion approximation allows diffusion codes to calculate results much faster than more accurate codes, such as transport codes or stochastic codes. The VSOP 99/05 suite of codes is such a diffusion code. The result is that it can calculate 40 year of full-core full-detail plant life in about 30 minutes on a standard laptop computer. It is furthermore a deterministic code, i.e. it does not suffer from statistical uncertainties. Put differently, if one were to run the VSOP code several times, with the same input, you will each time get exactly the same result.

Unfortunately that does not mean that that result is correct. The fuel sphere mixing inside most Pebble Bed Reactors is fundamentally statistically uncertain, especially where multi-pass fuel recirculation is used, as in the design of the original PBMR-400. Fresher and older fuels spheres are randomly dropped onto the top of the fuel pile in the core, where after they bounce around and then come to rest in random positions. Unfortunately VSOP assumes perfect mixing of the fuel spheres at the time of refuelling and thus this stochastic effect is completely ignored. This obviously introduces errors into the VSOP results.

The random placement of fuel spheres means that there is a substantial probability that a number of fresh fuel spheres will randomly land in the same spot, where they will then form a power and thus a temperature hot spot, during normal equilibrium operation. By the same logic, randomly distributed cold spots will also form with each refuelling. However, the probability that hot spots from successive refuelling sessions will form in the same place is very small. Rather, a hot spot in one refuelling might be followed by a colder spot during the next refuelling, which will partly even out the effect of the first hot spot.

More importantly, the heating of the core during a DLOFC accident is a very slow process, taking typically 24 to 48 hours to reach the maximum fuel temperature. This means that there is plenty of time for the decay heat to redistribute: excess decay heat produced in hot spots will thus flow to colder spots. DLOFC temperature hotspots are thus smoothed out to a much larger extent than the power or temperature hot spots during normal operation.

Since overheating of fuel during a DLOFC is our main concern in this article, the effect of fuel hot spots is thus less of a problem than it might initially seem.

It should furthermore be borne in mind that the main risk we want to mitigate is the leakage of a large total amount of radioactive fission products out of the TRISO coating layers around the fuel kernels. Obviously any DLOFC temperature hot spot will increase such leakage in that spot. However the leakage will also be less in the colder spots. These two effects will thus partly cancel each other out, with the results that the total amount of radioactivity leaked in a core with a mixture of hot and cold spots will be similar to that of a core in which perfect fuel mixing was achieved. This makes VSOP's inability to simulate these hot and cold spots less of a problem.

Since our study focused largely on the OTTO refuelling cycle, the random placement of fuel spheres will be even less problematic, as all the fuel spheres that are dropped in at the top are fresh and thus have the same fuel properties. The only remaining statistical effect is thus that the top of the fuel pile will not be smooth and flat, as is assumed in VSOP. However, this unevenness will only occur at the very top of the core. However, the peaks of the axial power profiles, as well as the peak of the axial DLOFC temperature profiles occurs at a substantial distance below the top of the core. Therefore the effect of any unevenness at the top of the core is unlikely to reach down to the depths at which the power density and DLOFC temperature peak.

3.2 Systematic errors

The VSOP code contains a number of assumptions that result in substantial systematic errors in its results.

- The diffusion approximation introduces substantial errors in areas where there are sharp discontinuities between the material properties of adjacent regions, for instance where the fuel spheres and reflectors meet, or where the control rods and the reflectors meet.
- The VSOP models used in this study assumed that all the helium coolant gas flows through the fuel core, i.e. there are no bypass flows through the reflectors. However it is well known that the reflector blocks contain gaps between them that will result in substantial bypass flows though the reflectors. This will result in less coolant flow through the fuel, which means that the equilibrium fuel temperatures will be substantially higher than reported

by the VSOP models. The reflectors, on the other hand, will be substantially cooler than reported. Since the fuel thus enters a DLOFC accident at a higher temperature than reported, it can also be expected that the maximum DLOFC temperature will be higher than reported. On the other hand, the reflectors serve as heat sinks that will quickly absorb substantial amounts of heat from the fuel, especially at the start of the DLOFC when the reflectors are much cooler than the fuel. The fact that the reflectors will, at the start of the DLOFC, in reality be cooler than reported, will cause them to be more effective heat sinks and thus they will initially cool the fuel faster than reported. This should partly offset the effect of the elevated equilibrium fuel temperatures.

- The fresh reflector graphite contains small concentrations of impurities that will act as neutron poisons and will thus slightly suppress the reactivity of the core at the start of operations of a new core. However these poisons will over time burn away to insignificant levels. The VSOP models do not follow thus burning away of the neutron poisons, but rather assumes average values for them, which are kept constant over the whole life of the core. VSOP will thus overestimate the reactivity of the fresh core, while it will underestimate it towards the end of life of the core.
- The thermal heat conduction coefficient of the graphite in the reflector blocks is high for fresh unirradiated blocks, but diminishes substantially over time with increasing irradiation. Lower heat conduction ability means that heat is evacuated more slowly during a DLOFC accident and that the maximum fuel temperature will thus increase over the years, as the actual heat conduction coefficient slowly decreases. As a conservative measure, VSOP thus assumes the lower heat conduction coefficient of older reflector blocks throughout the whole life of the core. This means that VSOP will overestimate the maximum DLOFC temperatures during the early stages of the plant's life, when the fresher reflector blocks still have better heat conductivity coefficients.
- A two dimensional geometry was used for the present simulations. Thus was done by assuming cylindrical symmetry for the core, i.e. collapsing the core in the azimuthal direction onto a flat surface. This is a reasonable approximation as most of the core and its surrounding structures actually are cylindrically symmetric. However, important exceptions are the control rods and the three exit shoots for the fuel at the bottom of the core. The assumption of cylindrical symmetry will thus introduce substantial errors in these non-symmetrical regions.
- Manufacturing errors might result in substantial deviations between the real and the modelled geometry and chemical compositions of both the fuel spheres and the structures in

and around the core. Such manufacturing errors will introduce systematic errors into the results.

- ^{10}B was used as neutron poison in the central reflector in the present study. However ^{10}B is a burnable poison and thus its ability to manipulate the axial and radial power density profiles in the fuel will diminish during the life of the plant. However, this burning away of the poison was not taken into account in the calculations. As these poison concentrations played a key part in reducing the maximum DLOFC temperature, the neutron poison's ability to limit the maximum fuel temperatures during a DLOFC will diminish as the core ages. A probable solution of this problem would be to switch to non-burnable poisons. One option might be to replace the ^{10}B containing reflector blocks with silicon carbide (SiC) blocks. The Si nuclei absorb many more neutrons than the carbon nuclei and therefore they should be an effective neutron poison, but one, which is non-burnable and will thus outlast the reactor.

The VSOP six-pass fuel recirculation model separated the fuel core into five discreet axial fuel flow channels, each occupying the annulus between two radii. The fuel in Channel (1) against the central reflector and in Channel (5) against the external reflector flow slower, due to friction against the reflectors, while the fuel in the three central channels all flow faster and at the same speed. In reality, the fuel flow speed varies continuously through the core, with the lowest speeds against the reflector and the highest speed in the middle. Furthermore, each channel is divided into a number of discreet layers.

While these may be reasonable approximations, they are not fully accurate. In reality, refuelling occurs continuously in time and thus the fuel flows down continuously from top to bottom, without any discreet axial fuel layers. The radial fuel placement also happens continuously, i.e. there are no discreet radial fuel flow channels. By the same logic the axial fuel flow speed varies continuously, as a function of radius, with the lowest speeds against the central and external reflectors and the highest speed in the middle.

3.3 Implications of these error sources on the results of this study are as follows

1. All the actual physical parameters of this study carry substantial statistical uncertainties, which VSOP by definition ignores. The results are also subject to substantial systematic errors, as discussed above. Furthermore, no attempt was made in the present study to estimate the magnitudes of these errors. The reason is that VSOP was not designed to estimate these errors. Therefore a separate study with separate modelling tools, such as

MCNP, will have to be conducted in order to estimate these errors. However, such complex simulations would fall outside the scope of the present study.

2. While the absolute values of the maximum DLOFC temperatures are important safety parameters, it should be noted that the focus of this study was to calculate the reductions in these temperatures that could be achieved by means of the methods that were deployed. Therefore the focus was more on the relative changes than on the absolute values of the temperatures:

4. Reporting of own results

The following summarises the series of studies by Tchonang Pokaha and Serfontein, which culminated in the present article. Firstly a single-zone fuel core was studied, using a mixture of thorium and LEU [13]. The heavy metal loading was then increased by adding a substantial amount of thorium to the fuel. This resulted in a reduction in the peaking factors of the axial power profiles, which in turn yielded a drop in the maximum value of the DLOFC temperature; the lowest value of the maximum DLOFC temperature of 1492 °C was obtained for a heavy metal loading of 20 g/sphere of a mixture of thorium and 20 Atom-percent (a/o%) LEU with an effective enrichment of 7.207 a/o%. This is 44 °C lower than the 1536 °C of the standard six-pass 9 g/sphere 10 a/o% LEU.

Inspired by the multi-zone fuel loading study by Li and Jing [12], more simulations were done on a two-zone core for the PBMR-400 for both 10 a/o% LEU fuel and a mixture of thorium and 20 a/o% LEU. In this configuration, the fuel circulates in the external zone of the core (flow channels 3-5) for the first four passes, where after it circulates in the inner zone of the core (flow channels 1 and 2) for the remaining two passes. Figure 2 below presents the radial power profiles for symmetric and asymmetric core using Th-LEU fuel.

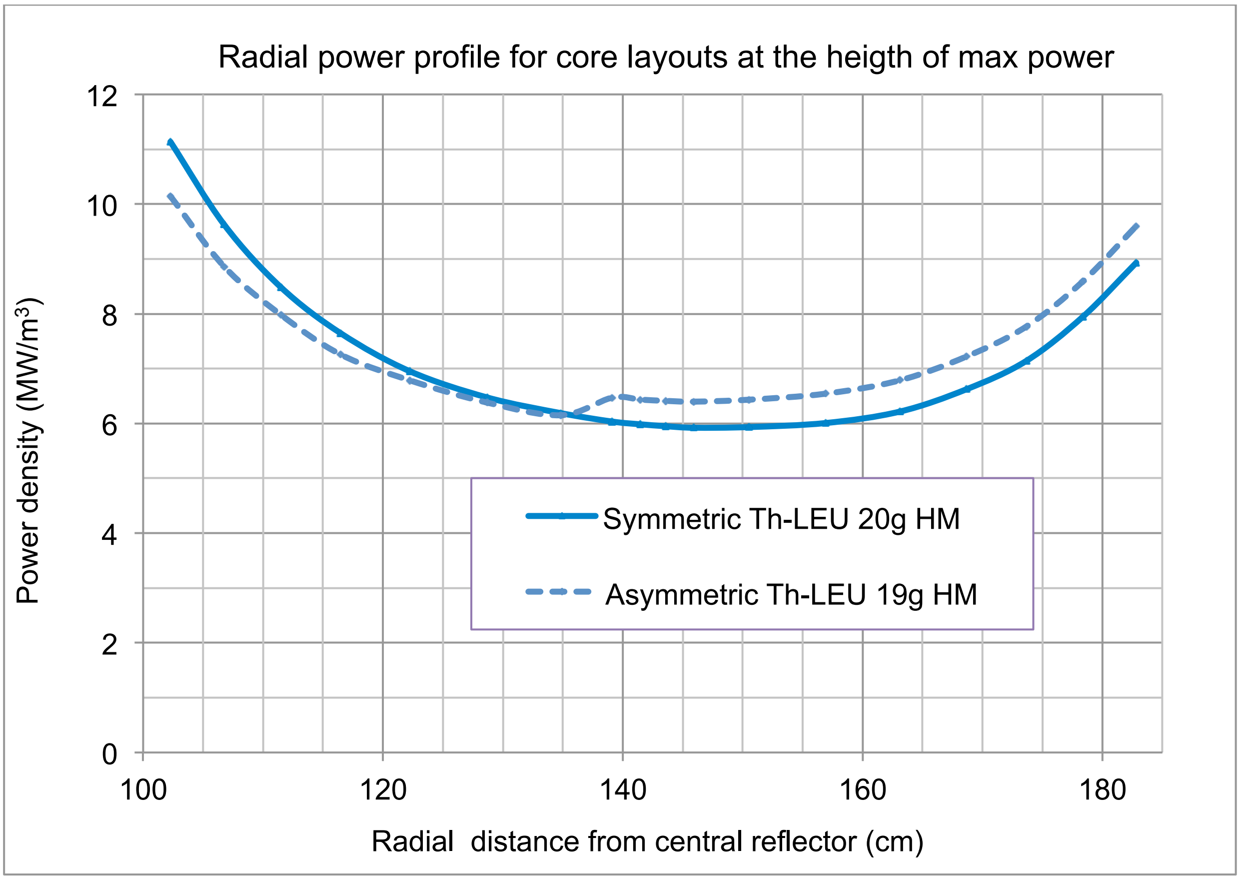

Figure 2: Radial equilibrium power density profiles comparison Symmetric and Asymmetric Th-LEU mixture at the axial height of maximum power.

The elevated power density in the outer zone, which started about 39 cm from the central reflector, is due to the higher enrichment of the lower burn-up fuel in the outer zone, versus the lower enrichment of the higher burn-up fuel in the inner zone. When this experiment was designed, it was believed that the much higher burn-up in the inner fuel zone would result in a much-reduced power there, as was the case for LEU fuel, shown in Fig. 3 below. It was also hoped that the resulting concentration of power in the outer fuel zone would sharply reduce the distance over which the decay heat has to be evacuated to the external reflector and that this would greatly reduce the maximum DLOFC temperature. However, as was shown in Fig. 2 above, the power in the inner zone of the asymmetric core was only slightly lower than in the outer zone. More surprisingly the power density directly adjacent to the central reflector was slightly higher than against the external reflector. This surprising result was found to be due to the fact that the conversion ratio of 0.6 for the Th-LEU mixture is substantially higher than the 0.4 for the pure LEU. This means that the fuel depletion with increasing burn-up is substantially lower for the Th-LEU fuel. Therefore, the average enrichment and therefore the average power density of the highest burn-up passes 5 and 6 were only slightly less than for the low burn-up pass 1 to 4. These surprisingly high power densities in the inner fuel zone was further elevated directly adjacent to central reflector by the higher influx of thermal neutrons from the central reflector, compared to the external reflector. Even so, the innermost power density for the Asymmetric case is only 5.6% more than for the outermost one, which is a much smaller excess than the 24.6% for the Symmetric case. This resulted in a further reduction of the maximum DLOFC temperature from 1492 °C to 1487 °C obtained 62 hours into the accident. This reduction is, however, too small to be of practical value. It must be pointed out that for the asymmetric core, the heavy metal loading was reduced to 19 g/sphere in order to maintain the equilibrium fuel temperature below 1130 °C [5].

Fig. 3 presents the radial power profiles for the symmetric and asymmetric cores using the LEU fuel.

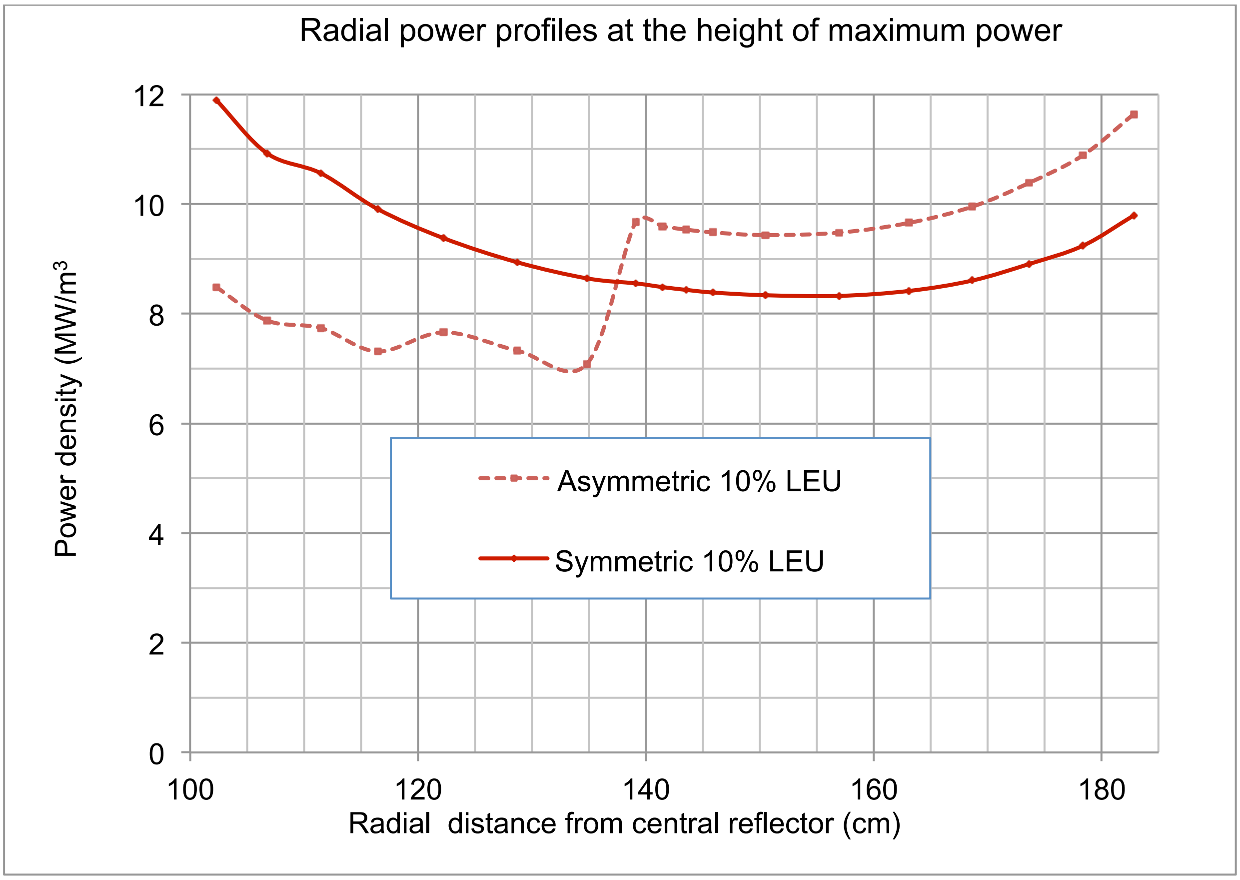

Figure 3: Radial equilibrium power density profile comparison for LEU for the Symmetric versus the Asymmetric cores at the height of maximum power.

It shows a substantial increase in power density of about 37% where the fuel change from the high burn-up fuel in the inner zone to the lower burn-up fuel in the outer zone. Also the power peaks close to the external reflector as was desired. This decreased maximum DLOFC temperature from 1536 °C of 1488 °C.

It is noteworthy that the maximum DLOFC temperature with the Th-LEU fuel mixture is only reached after 62 hours into the accident, as compared to 50 hours into the accident for the LEU, as is shown in Fig. 4, which shows the different DLOFC temperatures as a function of time. This spreading out of the maximum DLOFC temperature peak over a longer period is one of the mechanisms that contributed to a lower maximum DLOFC temperature, since it allows for the evacuation of a large total amount of decay heat, with lower heat fluxes at any given time. This is also an advantage because it allows more time for possible remedial actions to be taken in order to prevent fuel damage and eventual radioactivity release into the environment.

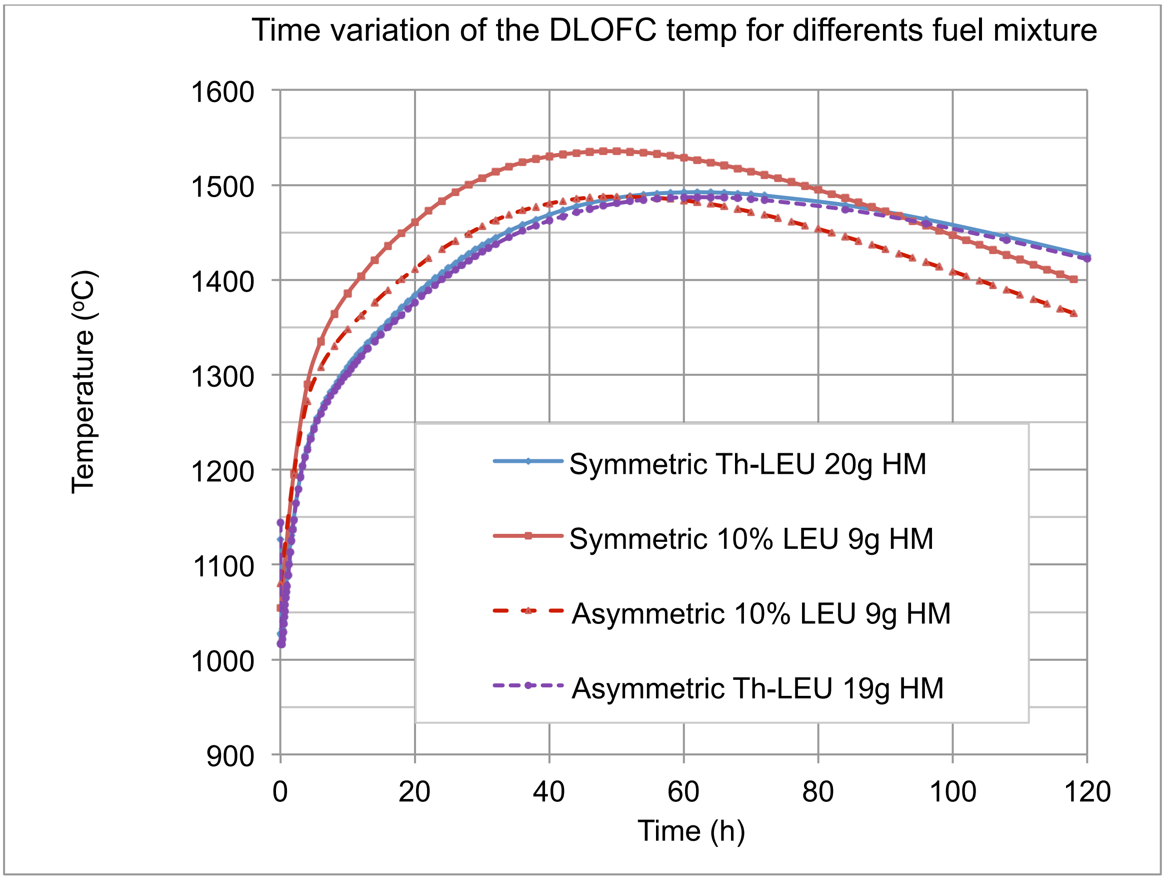

Figure 4: DLOFC temperature as a function of time into the accident for the two fuel types, and for the symmetric and asymmetric cores.

The use of an asymmetric core brings an extra level of complexity in the sense that it is difficult to maintain the physical boundary between the two fuel types without bringing an additional separation structure at the top of the core. If such a structure were to break, it could threaten the safety of the reactor and therefore its inclusion could bring extra licensing risks.

In reducing the maximum value of the DLOFC temperature of a pebble bed reactor using a multi-pass refuelling scheme, the use of neutron poisons in the central reflector is easier and simpler to implement and produced the largest reduction in the maximum DLOFC temperature. This strategy could be adapted in a cylindrical core by placing the neutron poisons in the external reflector or by having a two-zone core in which the inner zone are fed with fuel spheres doped with neutron poisons, similar to Mulder [12].

5. Once through then out fuelling scheme.

On the other end of the spectrum the number of recirculation passes can be reduced to one in the Once-Through-Then-Out (OTTO) refuelling scheme. This is done to simplify the design of the reactor and thus to reduce its construction cost. However, the fact that all the fuel spheres at the top of the core are then fresh and all those at the bottom fully depleted sharply increases the power density at the top and sharply reduces it at the bottom. The peak in the axial power profile thus becomes much sharper, which sharply increases the maximum DLOFC temperature, which then necessitates a sharp reduction in the total power output in order to reduce the maximum DLOFC temperature. Such a reduction in power output obviously reduces the revenue from power sales. OTTO cycles also produce a substantially lower maximum burn-up of the fuel spheres, which increases fuel cost.

Mulder [12] has shown that a remarkable flattening of the axial power profile of an OTTO cycle can be achieved by adding substantial amounts of ^{10}B to the fresh fuel. Similar results were obtained using various other burnable poisons in different shapes and sizes in the fresh fuel [13,14]. The use of neutron poison in the fresh fuel reduces the reactivity of especially the fresh fuel and will thus unfortunately reduce the average total fuel burn-up, which will increase fuel cost. This effect can however be countered by increasing the enrichment of the fresh fuel.

An alternative to neutron poison in the fresh fuel of the OTTO cycle, namely a mixture of thorium and LEU, was studied by Tchonang Pokaha and Serfontein [15]. An improvement of the axial and radial power profiles of PBMR DPP-400 in a Once-Through-Then-Out (OTTO) refuelling scheme was found. The maximum DLOFC temperature was reduced by adding thorium to the fuel and making the fuel layout radially asymmetric by placing lower enriched fuel in the inner parts, and higher enriched fuel in the outer parts of the core. These measures resulted in a reduction of the peaking factor of the axial power profiles, and thus helped to suppress the hotspots in the axial DLOFC temperature profiles and 'pushing' the power radially outwards as already explained. These two mechanisms resulted in a reduction in the maximum DLOFC temperature for the OTTO cycle from 2273 °C to 1927 °C for the symmetric and to 1812 °C for the asymmetric core. However, these temperatures were still above the 1600 °C limit. Maximum DLOFC temperatures below 1600 °C were thus obtained by reducing the power output from 400 to 320 MW_{th} [15].

In another strategy aimed at reducing the maximum DLOFC temperature by Tchonang Pokaha and Serfontein, an optimised distribution of neutron poisons was placed in the central reflector for the OTTO cycle. This strategy reduced the maximum DLOFC temperatures from 1925 °C to 1509 °C for the symmetric core and from 1811 °C to 1448°C for the asymmetric core. However, the lower temperature for the asymmetric core came at the cost of having to separate the fuel in the core into two zones, which will likely result in extra licensing risks, as has been argued above. Even lower values of the maximum DLOFC temperature could be achieved by increasing the ^{10}B concentrations in different regions of the reflector, but the fuel enrichment would then also have to be increased in order to compensate for the resulting loss in burn-up [16].

6. DISCUSSION

For the multi-pass recirculation scheme in the PBMR-DPP 400, maximum DLOFC temperatures of 1492 °C and 1487 °C were obtained for the symmetric and asymmetric Th-LEU mixture core respectively as shown above. These were 44 °C and 49 °C lower than the 1536 °C for the symmetric LEU fuel core. Thus suggest that the reduction of less than 50 °C in maximum DLOFC temperature was too small to act as a justification for switching from a single-zone LEU to Th-LEU and even more so, to an asymmetric LEU-Th core, especially in view of the additional licensing risk this will probably produce.

Switching from a symmetric to an asymmetric LEU core resulted in a reduction of less than 50 °C, from 1536 °C to 1488 °C. Even so this is probably not worth the additional licensing risk.

However, these improvements are relatively small compared to the 1297.6 °C maximum value obtained by Serfontein by placing a ^{10}B distribution in the central reflector. This suggests that placing an optimised neutron poison distribution in the central reflector is the simplest and most effective way to reduce the maximum DLOFC temperature for a multi-pass refuelling cycle in the PBMR-400 DPP.

In the case of an OTTO scheme, the addition of a substantial amount of thorium to the LEU fuel increased the conversion ratio, and thereby also reduced the peaking factor of the axial power profile considerably, thus lowering the maximum DLOFC temperature from the original 2273 °C to 1927 °C for the symmetric core. This represents a large 346 °C drop. The radial power profile was also improved with the asymmetric core, which further reduced the maximum DLOFC temperature by more than 100 °C to 1812 °C. Lastly, a targeted ^{10}B distribution was again inserted into the central reflector had in order to try and achieve the 1600 °C safety limit.

The reason for the upper limit in the equilibrium fuel temperature of 1130 °C that was selected for this project is that a direct Brayton helium power conversion cycle was used for the PBMR-400 DPP. Thus the fear is that highly radioactive ^{110m}Ag being released through the coating layers around the hottest fuel kernels would plate out on the cold surface of the turbine blades, thus creating radiation safety challenges during maintenance [5]. However, the industry-accepted equilibrium temperature for pebble bed reactors using an indirect Rankine steam cycle is 1200°C [14]. With this higher temperature limit, the heavy metal content could have been increased even further, which would have raised the equilibrium fuel temperature, but would have reduced the maximum DLOFC temperature even further.

Also, it should be noted that the 1600 °C maximum DLOFC temperature safety limit comes from the early days of coated particle development. A change of philosophy, based on the effective total release of radioactive material in the environment should be promoted, given that in most the cases, only a small portion of the fuel sees the high temperature for a small time interval during a severe accident. This small portion of the fuel is often at the top of the core where, for an OTTO cycle, the burn-up level is still low and thus the integrity of the coating layers are still substantially higher than for the higher burn-up fuel lower down. Therefore the release of radioactive ^{110m}Ag will probably be lower than expected.

The study reported that one manipulation method would reduce the maximum DLOFC temperature from 1492°C to 1487°C, i.e. a reduction of only 5°C. If we were to assume a statistical uncertainty in the VSOP results of 20°C, that would mean that these two temperatures do not differ statistically significantly and that therefore no conclusion about a temperature reduction can be made. However, as has been explained above, VSOP is a deterministic code and therefore there are no statistical variations in its results. Rather it is the actual temperatures in the reactor that displays statistical variations, due to the random placement of fuel spheres. Therefore statistical variations cannot be used to bring the validity of the VSOP result of a 5°C temperature reduction into question. That having been said, the reduction in fission product release that will be caused by a 5°C temperature reduction is so small that it will probably result in only an insignificant improvement in the safety case. Therefore it has no practical value.

As has been explained, the VSOP results do, however, carry substantial systematic errors. We could for instance assume that VSOP's ignoring of the helium coolant bypass flows would imply that actual temperatures would be 20°C higher than reported by VSOP. However, bypass flows would raise temperatures throughout the core and in our case, regardless of whether a specific neutron poison distribution was inserted into the reflector, or not. We could thus assume that bypass flows would raise both these temperatures by approximately the same amount, i.e. 20°C. This would mean that the manipulation method under discussion would then reduce the maximum DLOFC temperature from the actual elevated 1512°C to 1507°C, i.e. the systematic error would not affect the validity of the result that the manipulation reduced the actual temperature also by about 5°C.

By the same logic, a random hot spot in the fuel, created by the random placement of fuel spheres at the top, would also not destroy the validity of the result: such a fuel hot spot could well increase the maximum DLOFC fuel temperature. However, placing the neutron poison distribution in the central reflector would also reduce this elevated DLOFC temperature, presumably by a similar margin. So even the presence of statistical hot spot fluctuations in the real reactor would not necessarily invalidate the finding that the said placement of neutron poisons in the central reflector would also reduce the elevated temperature in the real reactor by about 5°C. So, as long as we are only interested in the temperature change of our intervention, as opposed to the absolute value of the temperatures, our VSOP result is not threatened by either the statistical or the systematic errors/uncertainties in either VSOP or in the actual physical core.

7. CONCLUSION

The results for several techniques aimed at reducing the maximum DLOFC fuel temperature for the PBMR-400 DPP reactor have been reported in this article. These include (a) flattening the peaks in the axial profiles of the maximum DLOFC temperature, in order to increase the surface areas over which effective evacuation of decay heat takes place and (b) "pushing" the radial profiles of the equilibrium power density outward towards the external reflector, thereby decreasing the distance, and thus the thermal resistance, over which the decay heat has to be evacuated towards the external reflector. These strategies were applied for both 6-pass recirculation fuelling schemes and Once-Through-Then-Out (OTTO) fuelling schemes. The techniques used for flattening the peaks in the axial profiles of the maximum DLOFC temperature were (a) adding thorium to the LEU fuel in order to improve the breeding and conversion ratios, which slowed the depletion of the enrichment of the fuel with increasing burn-up and thereby increasing the power density in the bottom parts of the fuel core; and (b) placing purposely-designed distributions of neutron poison in the central reflector in order to supress the normal peaks in the axial profiles of the equilibrium power density. The poison in the central reflector simultaneously served the purpose of pushing the power densities outward from the central towards the external reflector. The strategy of pushing the power outwards was further implemented by creating asymmetric cores in which the enrichment of the fuel in the outer fuel flow channels was higher than in the inner ones, which automatically shifts the fission power out to these higher enriched outer fuel zones.

All these strategies produced significant reductions in the maximum DLOFC temperatures. However these reductions were relatively small for the addition of thorium and disappointingly small for introducing asymmetric cores. On the other hand large reductions were obtained by placing targeted distributions of neutron poisons in the central reflector of the core. The advantages and disadvantages of the different techniques can be summarised as follows:

- Multi-pass recirculation refuelling produced much lower maximum DLOFC temperatures and substantially higher burn-ups than OTTO cycles.

- Adding thorium to the fuel substantially reduced this temperature even further. Whether this is worth the cost and effort involved in changing the licensing conditions of the fuel plant will have to be determined by means of fuel cost studies.
- However, making the core asymmetric produced such a small reduction in temperature that it is most likely not worth the extra cost and licensing risk produced by the required changes to the core structures. Therefore this technique is not recommended.
- Adding a targeted neutron poison distribution to the central reflector was highly effective in reducing the maximum DLOFC temperature, both for the multi-pass and OTTO cycles. Due to its simplicity and lack of substantial licensing risk, this technique is recommended as the best option.
- Switching from a multi-pass to an OTTO cycle substantially reduced the complexity of the plant and should thus also successfully reduce its capital cost. Unfortunately this also produced a large increase in maximum DLOFC temperature. This loss was successfully reversed by adding thorium to the fuel and neutron poison to the central reflector. However, the addition of poison resulted in a loss of burn-up. This was again successfully reversed by increasing the enrichment of the fresh fuel. Unfortunately this will also increase fuel cost. Therefore the profitability of switching to an OTTO cycle will have to be investigated by detailed costs studies.
- A very important lesson learnt from this study is that, although the mixture of thorium and LEU at an appropriate ratio increases the conversion ratio and the overall fuel performance, it is only effective in reducing the maximum DLOFC temperature for an OTTO fuelling scheme. The most effective means of reducing the maximum DLOFC temperature in all fuelling schemes is the use of neutron poison.
- It was also discovered that the peak in the DLOFC temperature profile is not flattened by flattening the peak in the axial power profile, but rather by keeping the said peak, creating a depression zone followed by a second smaller one after the depression zone. The ratio between the two peak heights plays a crucial role in flattening the axial DLOFC temperature profile, and thus in reducing its maximum value.
- The above mentioned studies pave the way for the following future works:
  - An in-depth investigation in the cost related to both the asymmetry layout of the core and the loss in reactivity caused by the OTTO cycle and the neutron poison distribution.

- While the present study was conducted for the PBMR-400 DPP, a similar work could be done on other HTRs: The results of the Th-LEU mixture can be expected to also apply directly to PBRs that do not use a central reflector, such as the Chinese HTR-PM.
- All the improvements that were achieved can be expected to yield even better results in Prismatic Block type HTRs. In PBRs, manipulating the fuel distribution is difficult, since this can only be done once, i.e. when inserting the fuel at the top of the core the composition or placement in different radial zones can be manipulated. Thereafter, the fuel flows down without any opportunity for further manipulation in the axial fuel distribution. However, in Prismatic Block reactors, manipulations of both the fuel and poison distributions can be performed in both the radial and axial directions. Using burnable poisons distributions to maintain the reactivity of the core with increasing burn-up is already a standard feature of prismatic block HTR cores. However, the improved neutron economy and thus more breeding that comes with introducing large quantities of Th into the core will slow the rate of decrease of the reactivity of the core with increasing burn-up. Therefore, less burnable poisons will be required to maintain the reactivity. This will result in less parasitic absorption of neutrons and thus even more neutrons will become available for breeding. Therefore, the opportunity for fine-tuning the core for reduction of both equilibrium and DLOFC temperatures should produce even better results in Block Reactors.

References

[1] Kania MJ, Nabielek H, Verfondern K, et al Testing of HTR UO2 TRISO fuels in AVR and in material test reactors. J Nucl Mat. 2013;441:545-562.

[2] Reutler H, Lohnert GH. The Modular High-Temperature Reactor. Nucl Technol. 1983; 62:22-30.

[3] Reutler H, Lohnert GH. Advantages of going modular in HTRs. Nucl Eng Des. 1984; 78(2):129-136.

[4] Zhang Z, Wu Z, Wang D et al. Current status and technical description of Chinese 2 x 250MWth HTR-PM demonstration plant. Nucl Eng Des. 2009; 239:1212-1219.

[5] Reitsma F. The Pebble Bed Modular Reactor Layout and Neutronics Design of the Equilibrium Cycle. Proceedings of PHYSOR 2004 -The Physics of Fuel Cycles and Advanced Nuclear Systems: Global Developments; 2004 April 25-29; Chicago (IL) [CD-ROM]

[6] Rütten HJ, Haas KA, Brockmann H et al V.S.O.P. (99/05) (release 2): Computer code system for reactor physics and fuel cycle simulation. 2007, Jülich: Institut für Sicherheitsforschung und Reaktortechnik [Software]

[7] Serfontein DE, Mulder EJ, Reitsma F. Optimisation of Deep Burn Incineration of Reactor Waste Plutonium in a PBMR DPP-400 core. Nuclear Engineering and Design 2014;271:99-105.

[8] Boer B, Kloosterman JL, Lathouwers D, et al. In-core fuel management optimization of pebble-bed reactors. Ann Nucl Energy. 2009;36:1049–1058.

[9] Private communication with E.J. Mulder, 2008.

[10] Serfontein DE. Sharp reduction in maximum fuel temperatures during loss of coolant accidents in a PBMR-400 core, by means of optimised placement of neutron poisons. Nucl Eng Des. 2014;271:492-498.

[11] Boer B, Kloosterman JL, Lathouwers D, et al. Optimization of a radially cooled pebble bed reactor. Nucl Eng Des. 2010;240:2384-2391.

[12] Li F, Jing X. Comparison of fuel loading pattern in HTR-PM. 2nd International Topical Meeting on High Temperature Reactor Technology; 2004 Sept 22–24; Beijing, China.

[13] Tchonang Pokaha M, Serfontein DE. Reducing DLOFC fuel temperatures by mixing thorium with LEU in a single-zone six-pass fuel cycle in a PBMR-DPP-400 core. 8th International Topical Meeting on High Temperature Reactor Technology; 2016 November 6-10, 2016; Las Vegas, USA

[14] Mulder EJ. Pebble bed reactor with equalised core power distribution - inherently safe and simple. Aachen: Faculty of Mechanical Engineering, University of North-Rhine Westfalia; 1998.

[15] Kloosterman JL, van Dam H, Van Der Hagen THJJ. Applying burnable poison particles to reduce the reactivity swing in high temperature reactors with batch-wise fuel loading. Nucl Eng Des. 2003;222:105-115.

[16] Tran HN, Kato Y, Muto Y. Optimization of burnable poison loading for HTGR cores with OTTO refueling. Nucl Sci Eng. 2008;158:264–271.

[17] Tchonang Pokaha M, Serfontein DE. Using thorium to reduce the maximum fuel temperatures during depressurized loss of coolant accidents in a once-through-then-out (OTTO) PBMR DPP-400 core. J Nucl Sci Technol. 2017;54(5):589-599

[18] Tchonang Pokaha M, Serfontein DE. Neutron poison distribution in the central reflector to reduce the DLOFC temperature of a Th-LEU fueled OTTO PBMR DPP-400 core. J Nucl Sci Technol. 2018.

7 Discussion of study and Conclusion

7.1 Claims of having achieved the outcomes for a PhD

The author claims to have achieved at least the North-West University's norm for the minimum number of articles as stated in the academic rules 5.4.2.7, 5.4.2.8 and 5.4.2.9 together with the minutes of the post graduate faculty management committee meeting held on 13 June 2012. All these rules are summarised in the preface of this thesis and here follows the proof in terms of the article.

1) Article 1 could be seen as carrying less weight than a Journal article, as it is only a conference paper, but at least it is the flagship conference in the field of High Temperature Gas-cooled Reactors and the paper was peer-reviewed and is already published.
2) Article 2 is a Journal article in one of the journals in our field with the highest impact factors and it is published.
3) Article 3, which is also a Journal article is not yet published but has been reviewed and accepted by the same journal as Article 2
4) Article 4, another Journal article is not yet published, but has been submitted for review to another high impact factor journal in the field.

7.2 Assessment of the originality of results

The author further claims to have attained the North-West University's stated outcomes for obtaining a Ph.D. degree in that the following original contributions have been made:

8. An original research problem was formulated, namely: **to design a fuelling scheme for the PBMR-DPP-400 that will substantially reduce the maximum DLOFC fuel temperature, while maintaining the power output and without substantially reducing the fuel economy**.

9. A critical literature survey was presented. From this literature survey the originality of the research aims and objectives was shown, as has already been motivated in Paragraph 1.2 above.

10. The evidence that these original aims have been achieved are now summarised:

i. The suitability of a Th/LEU mixture fuel for use in the PBMR-DPP-400 in its original layout was demonstrated

ii. An improved thorium fuel composition, together with the neutronics core distribution in both an homogeneous and an asymmetric core was determined.

iii. The comparison of the results obtained with this new fuel cycle layout and the reference layout in terms of reducing the maximum DLOFC fuel temperature of the PBMR-DPP-400 gave the following conclusion:

- In the case of a six-pass recirculation, the combined effect of thorium, heavy metal loading and asymmetry of the core produced a reduction in the maximum DLOFC temperature in the same range as an asymmetric core using the reference fuel of the PBMR-DPP-400.
- In the case of a OTTO core, the mixture of thorium and LEU with an increase of the HM loading produced an impressive drop in the maximum DLOFC fuel temperature.
- The asymmetry of the core further reduced substantially the maximum DLOFC temperature, although the obtained temperatures were still above the limit of 1600°C
- Temperatures below 1600°C were obtained by reducing the nominal power of the reactor, thus reducing the financial income of such reactor.

iv. A neutron poison distribution in the central reflector as an alternative to the power reduction was determined. This process showed that the peak in the axial DLOFC temperature profile was not suppressed by suppressing the peak in the axial power profile, but rather by creating a second smaller peak in the axial power profile close to the bottom of the core.

v. An evaluation of the fissile enrichment of the spent fuel demonstrated the proliferation resistance of this fuel cycle.

7.3 Implication of the results

The main implication of this optimisation of the axial and radial power profiles aimed at substantially reducing the maximum DLOFC temperature by means of mixing thorium with LEU in an homogeneous or asymmetric core will be as follows:

- As the leakage of radioactive fission products through the coating layers around the fuel particle increase exponentially with increasing temperature, even a small decrease in fuel temperature will produce a relatively large reduction in the leakage rate of fission products.
- The use of thorium in combination with LEU thus presents thorium as a supplement to improve the safety characteristics of LEU fuel in the PBMR-400 core, rather than as a competitor to the well-established LEU fuel. If these results could lead to the introduction of thorium into HTR fuels, thus would be a breakthrough as thorium is currently not scheduled to be used in any of the main HTR projects that are being developed.

Another contribution of this study is the impact of the U-238 from the LEU in denaturing the fissile ^{233}U in the spent fuel of thorium-based fuel cycles and thus improving their proliferation resistance. This is worth a further discussion on proliferation resistance versus effectivity of the application of Th/U-233.

7.4 Suggestion for future studies

- A comparative study of different neutron poison distribution in the central reflector, the external reflector, or even both reflectors, in order to optimize the power profiles even further in terms of burn-up, equilibrium and accident fuel temperatures.
- A detailed study on the optimum asymmetry level of the core together with a clear relationship between the heights of the first and second peaks of the innermost power profile.
- The increasing neutron poison concentrations will reduce burn-up and will therefore increase fuel cost. Therefore a trade-off between reducing DLOFC temperatures even further by increasing the neutron poison densities further and consequently increasing fuel cost by reducing burn-up is proposed.
- Repeating the optimization process with substantially higher fuel enrichments. Higher enrichment fuels could reduce fuel manufacturing cost, due to the much higher burn-ups and thus much higher cumulative energy produced per fuel sphere that would be achieved. However, it would also sharply increase the peakedness of the axial power profiles, which will increase the maximum DLOFC temperatures. Therefore, higher (and probably differently shaped) poison concentrations will thus have to be used in order to reduce the maximum DLOFC temperature. However, this

will decrease burn-up and will thus increase fuel cost. An optimum enrichment will thus have to be determined.

- Repeating the optimization process for cylindrical cores that do not have central reflectors. All poisons will thus have to be placed in the external reflectors. This will complicate matters by shifting the radial power inwards, which would partly offset the reductions in maximum DLOFC temperatures that would be obtained by flattening the peaks in the axial maximum DLOFC temperature profiles. However, since cylindrical cores are the dominant feature in Pebble Bed reactors that are currently being developed, optimising poison distributions for them could make an important contribution to their performance.
- The higher HM contain makes the core more under-moderated. When considering the potential of water (steam) ingress into the core the reactivity control and shut down system would be required be able to cover the reactivity increase due to added moderation. Similarly, the change in neutron spectrum due to the addition of neutron poisons in the central reflector region needs further investigation. All these need to be done in order to move the results of this thesis from academic to possible practical implementation.
- The ^{10}B was simulated as a homogeneous addition to the outer layer of the reflector. In practice one would typically prefer boron rods. The point that the VSOP code is not geared to accurately model the effect of such boron rods was extensively treated in (Serfontein, 2011): the two-dimensional code cannot accurately represent the three-dimensional rods. Furthermore the diffusion code cannot accurately calculate the absorptive effect of high concentrations of neutron poison. Therefore the point of the present study was to study the effect that a selected level of simulated neutron absorption in specific regions would have on the maximum DLOFC temperatures. However, we are well aware that the levels of neutron poison concentration that we used to produce these levels of neutron absorption would in practice produce levels of neutron absorption that would be substantially different from the simulated values. Fully compensating for these deviations between simulated and actual effects is a complex problem, which fell outside the scope of the present study.

7.5 Final conclusion

The thorium fuel cycles and core configurations investigated in the PBMR-DPP-400 reactor showed great potential in reducing the maximum DLOFC fuel temperature, without reducing the nominal power output of the reactor. The reduction in DLOFC temperatures were the greatest for the OTTO core. All fuel and core configuration met the stated safety limits and all fuel cycles were very proliferation resistant. A techno-economic study of these fuel cycles would give answers in term of the cost competitiveness of such thorium-based fuel cycles.

Bibliography

Abram, T. & Elshahat, A., E. 2012. Advanced nuclear reactors and passive safety. (In G. & et al., eds. In: Nuclear power plants. Nova Science Publishers, Inc. p. 41-68).

Artisyuk, V.V., Saito, M. & Ezoubtchenko, A. 2008. Development of methodology to assess proliferation resistance of nuclear heavy metals. *Progress in nuclear energy,* 50:647-653.

Baumer, R. & Kalinowski, I. 1991. THTR commissioning and operating experience. *Energy,* 16(1-2):59-70.

Baumer, R., Kalinowski, I., Röhler, I., Schöning, J. & Wachholz, W. 1990. Construction and operating experience with the 300-MW THTR nuclear power plant. *Nuclear engineering and design,* 121(2):155-166.

Boer, B., Kloosterman, J.L., Lathouwers, D. & Van Der Hagen, T.H.J.J. 2009. In-core fuel management optimization of pebble-bed reactors. *Annals of nuclear energy,* 36:1049-1058.

Boer, B., Lathouwers, D., Kloosterman, J.L. & Van Der Hagen, T.H.J.J. 2010. Optimization of a radially cooled pebble bed reactor. *Nuclear engineering and design,* 240:2384-2391.

Crossland, I. 2012. Nuclear power: Origins and outlook. (In Crossland, I., ed. Nuclear fuel cycle science and engineering. Woodhead Publishing Limited. p. 3).

Ding, M., Boer, B., Kloosterman, J.L. & Lathouwers, D. 2009. Evaluation of experiments in the AVR with the DALTON-THERMIX coupled code system. *Nuclear engineering and design,* 239:3105-3115.

Duderstadt, J.J. & Hamilton, L.J. 1976. Nuclear reactor analysis. John Wiley and Sons Inc.,.

ENDF/B-VII.-1. 2013. JANIS database 4.0, build 5.4.647, 1 nov 2013, OECD nuclear energy agency. http://www.oecd-nea.org/janis/ Date of access: September 3, 2015.

European, C. 2003. External costs: Research results on socio-environmental damages due to electricity and transport. http://www.extern.info/externpr.pdf Date accessed: 04 Feb. 2016: Directorate-General for Research. ExternE project. (nr. EUR 20198).

Ezoubtchenko, A., Saito, M., Artisyuk, V.V. & Sagara, H. 2005. Proliferation resistance properties of U and pu isotopes. *Progress in nuclear energy,* 47(1-4):701-707.

Hansen, U., Schulten, R. & Teuchert, E. 1972. Physical properties of the "once through then out" pebble-bed reactor. *Nuclear science and engineering,* 47:132-139.

IAEA-TECDOC-1450. 2005. Thorium fuel cycle - potential benefits and challenges. Vienna: International Atomic Energy Agency.

Kang, J. 2005. Analysis of nuclear proliferation resistance. *Progress in nuclear energy,* 47(1-4):672-684.

Kang, J. & von Hippel, F.N. 2001. U-232 and the proliferation-resistance of U-233 in spent fuel. *Science & global security,* 91-32.

Kania, M.J., Nabielek, H., Verfondern, K. & Allelein, H. 2013. Testing of HTR UO2 TRISO fuels in AVR and in material test reactors. *Journal of nuclear materials,* 441:545-562.

Kloosterman, J.L. 2003. Application of boron and gadolinium burnable poison particles in UO_2 and PUO_2 fuels in HTRs. *Annals of nuclear energy,* 30:1807-1819.

Kloosterman, J.L., van Dam, H. & Van Der Hagen, T.H.J.J. 2003. Applying burnable poison particles to reduce the reactivity swing in high temperature reactors with batch-wise fuel loading. *Nuclear engineering and design,* 222:105-115.

Krüger, K.J. & Ivens, G.P. 1985. Safety-related experiences with the AYR reactor. PROCEEDINGS OF A SPECIALISTS' MEETING ON SAFETY AND ACCIDENT ANALYSIS FOR GAS-COOLED REACTORS, OAK RIDGE NATIONAL LABORATORY, OAK RIDGE, 13-15 May, 1985.

Lamarsh, J.R. & Barata, A.J. 2001. Nuclear reactor fuels. (In Anon. Introduction to nuclear engineering. 3rd ed. p. 119).

Lamarsh, J.R. & Barata, A.J. 2001. Nuclear reactor fuels. (In Anon. Introduction to nuclear engineering. 3rd ed. p. 327).

Leverenz, R. 2006. The EPR- A safe and competitive solution for future energy needs. Nuclear energy for new europe, Portoroz, Slovenia, September 18-21, 2006.

Li, F. & Jing, X. 2004. Comparison of fuel loading pattern in HTR-PM. 2nd international topical meeting on HIGH TEMPERATURE REACTOR TECHNOLOGY, Beijing, China, September 22-24, 2004.

Mulder, E.J. 1998. Pebble bed reactor with equalised core power distribution - inherently safe and simple. Faculty of Mechanical Engineering, University of North-Rhine Westfalia, Aachen. (Ph. D.).

Private communication with E.J. Mulder, 2008.

Reitsma, F. 2004. The pebble bed modular reactor layout and neutronics design of the equilibrium cycle. PHYSOR 2004 -the physics of fuel cycles and advanced nuclear systems: Global developments, on CD-ROM, american nuclear society, lagrange park, IL. Chicago, Illinois, April 25-29, 2004.

Reutler, H. & Lohnert, G.H. 1984. Advantages of going modular in HTRs, *Nuclear engineering and design,* 78(2):129-136.

Reutler, H. & Lohnert, G.H. 1983. The modular high-temperature reactor. *Nuclear technology,* 62:22-30.

Rütten,H.J., Haas,K.A., Brockmann,H., Scherer,W. &Sen,S. . 2007. V. S. O. P. (99/05) (release 2): Computer code system for reactor physics and fuel cycle simulation. . Jülich: Institut für Sicherheitsforschung und Reaktortechnik[Software].

Serfontein, D.E. 2014. Sharp reduction in maximum fuel temperatures during loss of coolant accidents in a PBMR-400 core, by means of optimised placement of neutron poisons. *Nuclear engineering and design,* 271:492-498.

Serfontein, D.E. 2011. Deep burn strategy for the optimized incineration of reactor waste plutonium in pebble bed high temperature gas-cooled reactors. North-West University, South Africa. (PhD).

Serfontein, D.E. & Mulder, E.J. 2014. Thorium-based fuel cycles: Reassessment of fuel economics and proliferation risk. *Nuclear engineering and design,* 271:106-113.

Serfontein, D.E., Mulder, E.J. & Reitsma, F. 2014. Optimisation of deep burn incineration of reactor waste plutonium in a PBMR DPP-400 core. *Nuclear engineering and design,* 271:99-105.

Tchonang Pokaha, M. & Serfontein, D.E. 2017. Using thorium to reduce the maximum fuel temperatures during depressurized loss of coolant accidents in a once-through-then-out (OTTO) PBMR DPP-400 core. *Journal of NUCLEAR SCIENCE and TECHNOLOGY,* 54(5):589-599.

Tchonang Pokaha, M. & Serfontein, D.E. 2016. REDUCING DLOFC FUEL TEMPERATURES BY MIXING THORIUM WITH LEU IN A SINGLE-ZONE SIX-PASS FUEL CYCLE IN A PBMR-DPP-400 CORE. HTR 2016, Las Vegas, NV, November 6-10, 2016.

Tchonang Pokaha, M. & Serfontein, D.E. 2018. Neutron poison distribution in the central reflector to reduce the DLOFC temperature 0f a th-LEU fueled OTTO PBMR DPP-400 core. *Journal of NUCLEAR SCIENCE and TECHNOLOGY*.

Tchonang Pokaha, M. & Serfontein, D.E. Different techniques for reducing DLOFC fuel temperatures in a PBMR-DPP-400 core. *Nuclear engineering and design,* 2018:210-218

Tran, H.N. & Kato, Y. 2009. An optimal loading principle of burnable poisons for an OTTO refueling scheme in pebble bed HTGR cores. *Nuclear engineering and design,* 239:2357-2364.

Tran, H.N., Kato, Y. & Muto, Y. 2008. Optimization of burnable poison loading for HTGR cores with OTTO refueling. *Nuclear science and engineering,* 158264-271.

van Dam, H. 2000. Long-term control of excess reactivity by burnable particles. *Annals of nuclear energy,* 27(8):733-743.

Wols, F.J., Kloosterman, J.L. & Lathouwers, D. October 2012. Fuel pebble design studies of a high temperature reactor using thorium, *Proceedings of the HTR 2012 (tokyo, japan)*.

Wols, F.J., Kloosterman, J.L., Lathouwers, D. & Van Der Hagen, T.H.J.J. 2014. Core design and fuel management studies of a thorium-breeder pebble bed high-temperature reactor. *Nuclear technology,* 186:11-16.

Wu, Z., Lin, D. & Zhong, D. 2002. The design features of the HTR-10. *Nuclear engineering and design,* 218:25-32.

X-energy. October 2014. Xe-100 reactor. https://www.x-energy.com/copy-of-technology Date of access: 01/11/2018.

Yonghee, K., Cho, C. & Venneri, F. 2007. Long-cycle and high-burnup fuel assembly for the VHTR. *Journal of NUCLEAR SCIENCE and TECHNOLOGY,* 44(3):294-302.

Zhang, Z., Wu, Z., Wang, D., Xu, Y., Sun, Y., Li, F. & Dong, Y. 2009. Current status and technical description of chinese 2 x 250MWth HTR-PM demonstration plant, *Nuclear engineering and design,* 239:1212-1219.

Zoran, V.s. 2007. The nuclear renaissance and AREVA's reactor designs for the 21th Century: EPR and SWR-1000. Nuclear energy for new europe 2007, Portoroz, Slovenia, September 10-13, 2007. Date of access: 04 Feb 2016.