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

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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 breading of substantial amounts of ^{233}U. 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

Depressurised 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 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 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 produces 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

II.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 I. 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 I: 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.

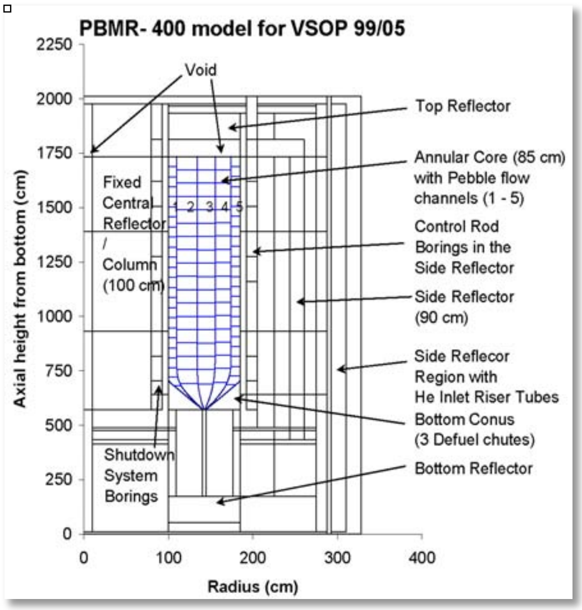

Figure 1: Reactor geometry used for VSOP simulations.

Table II: 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, 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

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

Error! Reference source not found. 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.

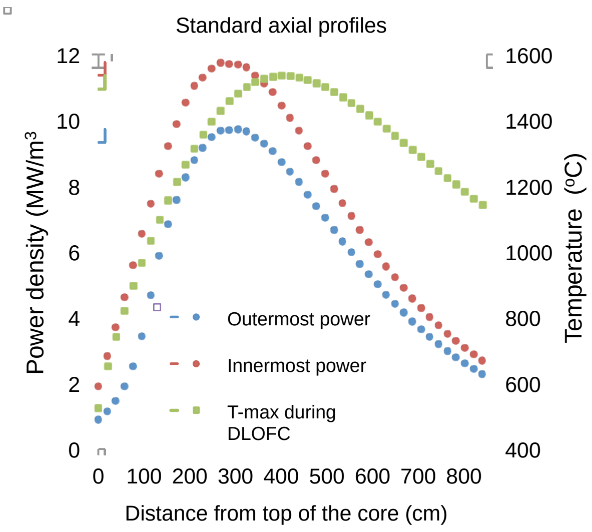

Figure 2: Axial equilibrium power density profiles for the standard six-pass cycle core and the maximum DLOFC temperature profile, shown on a separate scale.

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 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 of 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.

II.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 per 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

III.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 III: Fuel performance for different heavy metal loadings

HM content (g)	C	T_{Eq} (^{o}C)	T-DLOFC (^{o}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

HM content (g)	C	T_{Eq} (^{o}C)	T-DLOFC (^{o}C)
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 g 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 decreases 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 loadings, the conversion ratio increased and the DLOFC temperature decreased, 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 13 g/sphere is reached. Thereafter the equilibrium fuel temperature increases continuously to reach a value above the safety limit at 21 g/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 cossisions with fuel particles becomes smaller and therefore the core becomes more under-moderated, i.e. the more neutrons will be captured in the epithermal resonaces 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 quezed 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 temperture ocured 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 looses 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.

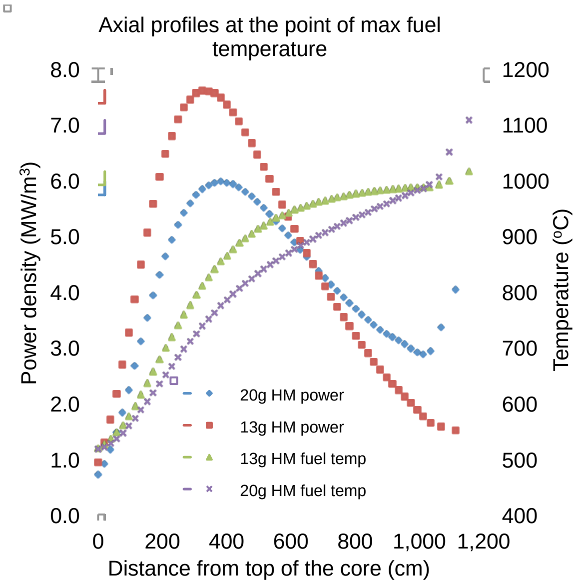

Figure 3: Axial equilibrium power density and equilibrium fuel temperature profiles comparison for 13 g/sphere and 20 g/sphere Th-LEU mixture for the central fuel flow channel.

III.B. Effects of the Heavy Metal Loading on Axial Profiles

The results presented in Table 3 of the previous section impose 20 g/sphere as our maximum permissible heavy metal loading because 21 g/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
9 g/sphere LEU and those of a 20 g/sphere Th-LEU is made. Figure 4 shows the axial equilibrium fission power density profiles in the innermost fuel flow channel for the LEU 9 g/fuel sphere (i.e. the pure LEU fuel cycle) and for the Th-LEU 20 g/fuel sphere mixture.

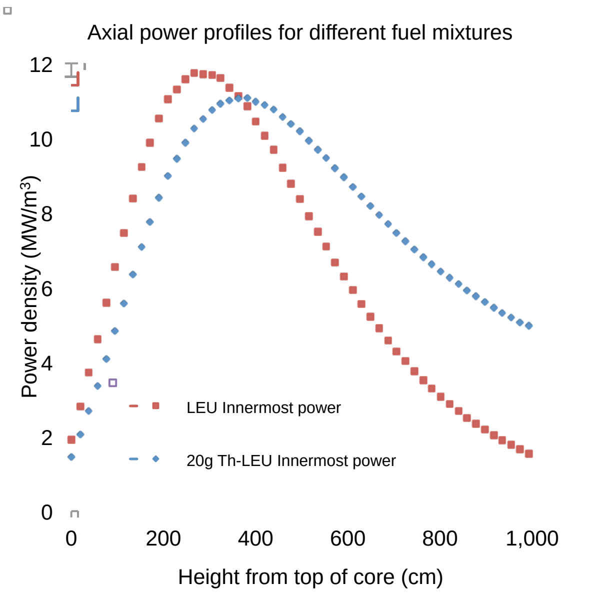

Figure 4: Axial equilibrium power density profiles comparison for LEU and Th-LEU mixture in the innermost channel

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 11.13 MW/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 °C for the LEU to 1492 °C for the Th-LEU.

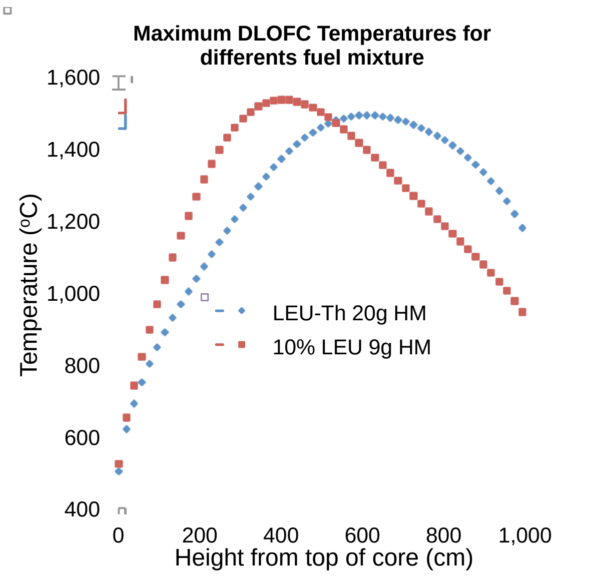

Figure 5: Axial DLOFC temperature profile comparison for the two fuel cycles.

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.

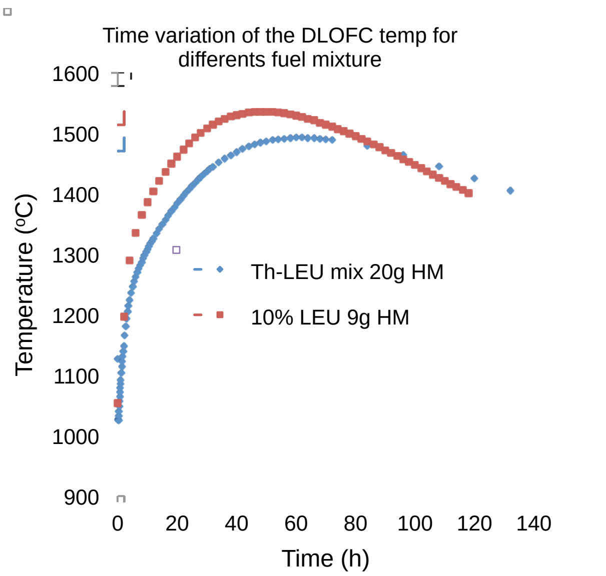

Figure 6: DLOFC temperature as a function of time into the accident for the two fuel types

IV. DISCUSSION

The maximum DLOFC temperature of 1492 °C for the Th-LEU mixture was 44 °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. CONCLUSIONS

- 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 °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.

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REFERENCES

1. Z.ZHANG et al, *Nuclear Engineering and Design*, **239**, 1212 (2009).
2. F.REITSMA, "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*, Chicago, Illinois, American Nuclear Society (CD-ROM).
3. D.E.SERFONTEIN et al, *Nuclear Engineering and Design*, **271,** 99 (2014).
4. D.E.SERFONTEIN, *Nuclear Engineering and Design*, **271,** 492 (2014)
5. B.BOER et al, *Annals of Nuclear Energy*, **36**, 1049 (2009).
6. B.BOER et al, *Nuclear Engineering and Design*, **240**, 2384 (2010).
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. D.E.SERFONTEIN, E.J.MULDER, *Nuclear Engineering and Design*, **271**, 106 (2014).
9. U.HANSEN, R.SCHULTEN & E.TEUCHERT, *Nuclear Science and Engineering*, **47**, 132, (1972).
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. F.J.WOLS et al, "Fuel Pebble Design Studies of a High Temperature Reactor using Thorium", *Proceedings of the HTR 2012,* Tokyo-Japan (2012).
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. F.J.WOLS et al, *Nuclear technology*, **186**, 11 (2014).