Characteristic behaviour of Pebble Bed High Temperature Gas-cooled Reactors during water ingress events

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Abstract – The presence of water on the tube-side of the steam generators in high temperature gas-cooled reactors (HTGRs) with indirect cycle layouts presents a possibility for a penetration of neutron moderating steam into the core, which may cause a power excursion.

This article presents results on the effect of water ingress into the core of the two South African Pebble Bed Modular Reactor design concepts, i.e. the PBMR-200 MWth and the PBMR-400 MWth developed by PBMR SOC Ltd. The VSOP 99/05 suite of codes was used for the simulation of this event. Partial steam vapour pressures were added in stages into the primary circuit in order to investigate the effect of water ingress on reactivity, power profiles and thermal neutron flux profiles.

The effects of water ingress into the core are explained by increased neutron moderation, due to the addition of $^1\text{H}$, which leads to a decrease in resonance capture by $^{238}\text{U}$ and therefore an increase in the multiplication factor. The more effective moderation of neutrons by definition reduces the fast neutron flux and increases the thermal flux in the core, i.e. leads to a softer spectrum. The more effective moderation also increases the average increase in lethargy between collisions of a neutron with successive fuel kernels, which reduces the probability for neutron capture in the radiative capture resonances of $^{238}\text{U}$. The resulting higher resonance escape probability also increases the thermal flux in the core.

The softening of the neutron spectrum leads to an increased effective microscopic fission cross section in the fissile isotopes and thus to increased neutron absorption for fission, which reduces the remaining number of neutrons that can diffuse into the reflectors. Therefore water ingress into the core leads to a reduced thermal neutron flux in the reflectors. The power density spatial distribution behaved similarly to the thermal neutron flux in the core.

Analysis of possible mechanisms was conducted. The results show that in order to curb the increase in the multiplication factor, the level of under-moderation in the fuel can be decreased by reducing the heavy metal loading of the fuel spheres and/or the porosity of the graphite reflector block must be increased in order to increase water ingress into the reflectors. For the PBMR-400 the diameter of the central reflector can also be reduced. Results from past studies of water ingress into Pebble Bed Reactors were used to validate and verify the present simulation approach and results.
I. INTRODUCTION

I.A. Problem Statement

High Temperature Gas-cooled Reactors (HTGRs) are attracting worldwide interest because of their high gas outlet temperatures, allowing high temperature process heat applications beyond electricity generation, such as hydrogen production. However, since the development of the AVR gas-cooled pebble bed reactor, water ingress has been viewed as one of the more severe accidents that can take place in high temperature reactors, unless the quantity of water and steam entering the primary helium system can be limited. Designers have introduced many design measures to prevent and limit water ingress, also from the lessons learned from the AVR (where the steam generator was positioned directly above the core).

Water is a very effective neutron moderator and therefore water ingress causes the neutron energy spectrum to soften, which normally gives rise to an increase in the reactivity and thus of the power output of the fuel core, which clearly needs to be analysed and taken into account in the safety design and analysis to prevent any potential danger.

The problem is that the interplay between the different mechanisms involved in this reactivity excursion is complex. In order to fully evaluate water ingress events a detailed model of the complete reactor system is needed. This includes the steam generator, the secondary system isolation and flow paths from the break position to the reactor, the moisture detector positions, its response time to SCRAM the reactor and many others. Another approach may be to consider a much simplified approach during the conceptual design phase to minimise the potential dangers from water ingress through an optimal core neutronic reactor design. This optimisation must, however, be seen within the overall picture where the design must also be technically and economically viable.

I.B. Reactor designs and the relevance of water ingress

The phenomenon of water ingress was studied by Lohner [1] for the 200 MW in German HTR-Module. The HTR-Module is a 200 MW high temperature, helium-cooled pebble bed reactor [2]. This reactor had a standard Rankine power conversion cycle in which the hot helium gas from the primary circuit through the core is circulated through a steam generator to deliver steam to the secondary circuit, which drives the turbine. The presence of water on the tube-side of the steam generators presents a possibility for penetration of neutron moderating steam into the core which may cause a power excursion for most core layouts. The steam is also likely to cause graphite corrosion, resulting in the release of a mixture of hydrogen and carbon monoxide (CO) gas, which may pose an explosion risk if water ingress is not limited by the design. Due to the fact that the steam in the secondary circuit is at a higher pressure than the helium coolant in the primary circuit, water or steam may flow from the secondary into the primary circuit if a tube rupture or leak were to occur in the steam generator.

The evolution of conceptual designs of the PBMR in South Africa [3] started in the 1990s, with the design derived from the 200 MW in German HTR-Module. The first design concept to be investigated was the PBMR 268 MW in with an electrical power output into the grid of 110 MW with a core geometry consisting of a dynamic central reflector of graphite spheres moving as part of the core with a nominal diameter of 1.75 m. One significant departure from the HTR-Module is that in this reactor design the hot high pressure helium from the primary circuit drives a helium turbine in a Brayton cycle. The absence of high pressure water/steam dramatically reduces the probability and quantities of possible water ingress into the core, with the only possible source of water being the pre- and intercooler.

After the PBMR 268, an investigation of a reactor power increase to 400 MW was launched. This provided an opportunity to consider a core with a fixed central reflector of 2 m, a core outer diameter of 3.7 m and an effective nominal height of 11 m [4].

In partnership with Westinghouse and in support of the contributions to the NGNP project in the USA, a 500 MW annular and a 200-250 MW cylindrical core design were developed at PBMR SOC Ltd [5]. The 200 MW design was based on the HTR-Module. In this work it thus also referred to as the PBMR-200. Both these designs could potentially be coupled to an indirect cycle or to a process heat application via an intermediate heat exchanger.

I.C. Reactivity theory of water ingress

When steam ingress into the fuel core occurs, the influx of ¹H in the water, as an additional and very effective moderator, increases the reactivity of the reactor, since the neutron spectrum softens, which in turn increases the effective microscopic fission cross section. Due to improved neutron moderation the overall neutron diffusion coefficient also decreases, which in turn decreases the overall neutron diffusion into and thus the thermal neutron flux in the reflectors. This then reduces radiative capture of neutrons in the graphite in the reflectors and in the external metal components and thus the neutron leakage from the core [1]. A decrease in the thermal neutron flux in the external reflector, however,
increases the rod worth of the absorbers in the external reflector, so that in a shutdown or partially shut down core the overall effect of water ingress is the sum of reactivity increase and rod worth decrease. These effects can be explained as follows in more detail:

The effects of water ingress into the core are explained by more effective neutron moderation, due to the addition of \(^1\text{H}\), which leads to decreased resonance capture by \(^{238}\text{U}\) and increased fission in the fissile fuel isotopes and therefore an increase in the multiplication factor. The more effective moderation of neutrons occurs because the mass of the \(^1\text{H}\) nucleus, i.e. a proton, is almost equal to that of the incoming neutron. Therefore the neutron loses, on average, 50\% of its energy per collision with the \(^1\text{H}\), as opposed to only about 14\% per collision with the much heavier \(^{12}\text{C}\). Therefore ingress of a relatively small amount of steam can cause a relatively large increase in moderation. This more effective moderation by definition reduces the fast neutron flux and increases the thermal flux in the core, i.e. leads to a softer neutron spectrum.

The more effective moderation also increases the average lethargy increase between collisions of a neutron with successive fuel kernels. This reduces the probability for the neutron energy to fall within the capture resonances during collisions with the fuel kernels, which reduces the probability for neutron capture in the radiative capture resonances of \(^{238}\text{U}\). The resulting higher resonance escape probability also increases the thermal neutron flux in the core. Both these effects increase the neutron multiplication factor of the reactor (\(k_{\text{eff}}\)) and thus its reactivity.

The softening of the neutron spectrum leads to an increased effective microscopic fission cross-section for the fissile fuel isotopes and thus to increased neutron absorption for fission, which reduces the remaining number of neutrons that can potentially diffuse into the reflectors. This is because more neutrons now reach thermal energies, where the microscopic fission cross-section is much larger than in the epithermal and fast energy regions. Even inside the thermal energy region, the neutron flux is now larger at lower energies, where the microscopic fission cross-section is again larger than at the higher thermal energies. Water ingress into the core on the one hand makes the core more transparent for the epithermal neutrons by reducing resonance capture in \(^{238}\text{U}\), which would suggest that more neutrons may escape into the reflectors. On the other hand it makes the core more opaque due to the increased absorption of thermal neutrons in the fissile fuel isotopes. This last mechanism dominates and therefore water ingress into the core makes the core more opaque, which reduces the diffusion of neutrons into and thus the neutron flux in the reflectors, which reduces neutron capture in the graphite reflectors, which reduces the core leakage and thus increases the reactivity. The main neutron leakage mechanism is escape of fast neutrons into the reflector, moderation in the reflector and subsequent capture in the graphite. With the more effective moderation in the fuel core (due to water ingress) the fast neutron flux decreases as does the average mean free path of neutrons. The overall core leakage therefore decreases. The reduced core leakage (of fast and thermal neutrons) thus increases the reactivity.

Finally, the effective microscopic cross section for radiative capture (\(\sigma_t\)) in the \(^1\text{H}\) in the steam is much higher than for natural graphite (\(^{238}\text{C}\)). Therefore steam ingress causes an increase in neutron captures in the \(^1\text{H}\), which partially offsets the increase in reactivity described above and thus limits this reactivity increase.

Steam ingress into the riser tubes in the external reflectors produces the opposite effect to ingress into the fuel core: in the reflectors resonance capture is negligible and there is no fissile fuel present. That means that the softer spectrum, due to increased moderation, simply increases the effective microscopic cross section and thus the probability for radiative capture in both the \(^{238}\text{C}\) in the reflector blocks and the \(^1\text{H}\) in the steam, which leads to a consistent decrease in reactivity with increasing steam ingress into the reflectors. The mechanisms behind this phenomenon will be explained in more detail in the section on the results for water ingress into the reflectors only.

I.D. Research Questions

Based on the problem statement above, the research questions were studied in the Masters Degree thesis of Khoza [7], which are summarised in this paper:

1. How will the reactivity of each of the reactors be influenced by water ingress into the fuel core and reflectors?
2. What are the mechanisms that drive these reactivity changes?
3. How can the designs of these reactors be modified to eliminate undue risk from water ingress?

II. RESEARCH AIMS

The aims of this study [7] are to:

- Study the characteristic behaviour of the two reactors in the event of water ingress and the impact thereof on \(k_{\text{eff}}\) and the steady-state flux distribution and power profiles.
• Study the difference in the mechanisms and reactivity effects of water ingress
  o into the fuel core only,
  o into the riser tubes in the external reflector only and
  o into both the fuel core and the riser tubes in the external reflector.
• Use the knowledge gained regarding these mechanisms and effects to propose design changes that will mitigate the reactivity increases for realistic water ingress scenarios.
• Use past results from simulations of water ingress into Pebble Bed Reactors to validate and verify the present simulation approach and results.

III. METHODS AND COMPUTER MODELS

Reactor parameters used to create 2-D \((r,z)\) models for V{SOP 99/05 neutron diffusion simulation code [8] are outlined in Table 1 below with the equilibrium core parameters for PBMR-400 [9]and PBMR-200 [2]. These methods and the characteristics of the standard Low Enriched Uranium (LEU) fuel cycle for the PBMR-400 reactor are described in more detail in [10] and [11].

Table 1: Summary of equilibrium core parameters for PBMR-400 and PBMR-200.

<table>
<thead>
<tr>
<th>Description</th>
<th>Unit</th>
<th>PBMR-400</th>
<th>PBMR-200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core thermal power</td>
<td>MW</td>
<td>400</td>
<td>200</td>
</tr>
<tr>
<td>Core diameter (inner/outer)</td>
<td>m</td>
<td>2.0/3.7</td>
<td>3</td>
</tr>
<tr>
<td>Core height (average)</td>
<td>m</td>
<td>11.0</td>
<td>9.4</td>
</tr>
<tr>
<td>Core geometry</td>
<td></td>
<td>Annular</td>
<td>Cylindrical</td>
</tr>
<tr>
<td>Volume of the core</td>
<td>m(^3)</td>
<td>83.73</td>
<td>66.16</td>
</tr>
<tr>
<td>Fuel sphere diameter</td>
<td>cm</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Inner radius of the fuel free zone in fuel sphere</td>
<td>cm</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Helium coolant temperatures (inlet/outlet)</td>
<td>°C</td>
<td>500/900</td>
<td>250/700</td>
</tr>
<tr>
<td>Primary system pressure</td>
<td>bar</td>
<td>90</td>
<td>70</td>
</tr>
<tr>
<td>Fuel sphere heavy metal loading</td>
<td>g</td>
<td>9</td>
<td>7</td>
</tr>
<tr>
<td>(^{235})U enrichment</td>
<td>wt%</td>
<td>9.6</td>
<td>7.8</td>
</tr>
<tr>
<td>Average residence time in core</td>
<td>Days</td>
<td>~930</td>
<td>~923</td>
</tr>
<tr>
<td>Average discharge burn-up</td>
<td>MW/dt</td>
<td>91 450</td>
<td>80 000</td>
</tr>
<tr>
<td>Total number of fuel spheres</td>
<td></td>
<td>~452 000</td>
<td>~360 000</td>
</tr>
<tr>
<td>Number of fresh fuel spheres loaded per day</td>
<td></td>
<td>~486</td>
<td>~320</td>
</tr>
<tr>
<td>Number of fuel spheres re-circulated per day</td>
<td></td>
<td>~2 936</td>
<td>~2000</td>
</tr>
</tbody>
</table>

The models shown in the table above and in Figure 1 and Figure 2 below were established based on the approximations and simplifications described below:
• Both models are created in 2-D configuration and as a result some 3-D effects are modelled in an approximate way.
• The control rod channel is neutronically important and was modelled as a grey absorber curtain conserving the overall reactivity effect.
• In the PBMR-200 model the bottom cone was approximated to be flat while the upper pebble bed fuel heaps were also flattened in both models.

![Figure 1: PBMR-400 VSOP core model.](image1)

![Figure 2: PBMR-200 VSOP core model.](image2)
The fuel core was divided into batches that were all filled with the fuel material, while the outer lying regions of the reactor comprise of the reflector material, vessel material, void regions, etc. According to this discrete mesh pattern, the simulation will provide batch-wise data for the fuel shuffling, cost evaluation and the decay heat production parameters during steady state and quasi-steady state transients.

In the water ingress simulation, all the fuel regions, the gas-flow pipes (riser tubes) and the void areas above the fuel core were identified and earmarked for possible steam vapour ingress. The areas in the THERMIX input model (for the thermo-hydraulics simulations) were then mapped (one-to-one correspondence) to the VSOP-Batches numbers for the neutronics simulations. These batch numbers were then used to specify the region into which water ingress takes place. The reactor fuel reloading was stopped and the appropriate critical time step point (middle of the last steady state burn-up cycle) taken in order to prepare for water ingress and to determine the changes in $k_{\text{eff}}$ from this reference point. The water ingress was then initiated.

To simulate this event, steam was added into the core and the chosen reflector batches. The amount of water ingress was determined by specifying successive increases in the partial vapour pressure of steam in the respective regions. The resulting partial steam vapour pressures were 30, 60, 100, 200, 300 and 400 bar.

It should be emphasised that the high partial pressures are, of course, not physically possible. Primary pressure relief valves are designed to open at given set point values to prevent overpressure of the system. In the event that they might fail, additional safety valves (that open at a higher pressure) are included in the design. These will relieve the pressure before any vessel or pipe failure occurs. During a release through the pressure relief system, the amount of steam in the reactor will be reduced. The valves will close again when the over-pressure condition has been resolved. Only pressures a few bar above 90 bar for the PBMR-400 and 70 bar for the PBMR-200 would thus be considered as practically possible.

In performing the steady state $k_{\text{eff}}$ neutronic analysis, these non-physical higher water concentrations were included not only in order to analyse the reactor physics in more detail, but also to determine the location of the turn-around point at which the system becomes over-modерated and the $k_{\text{eff}}$ starts to decrease with increasing water concentrations.

Using the void fraction of 0.61 and the corresponding porosity 0.39 for the pebble bed core, the steam masses in the fuel cores only were calculated from these partial steam vapour pressures, as shown in Table 2 below.

**Table 2: Mass equivalent of partial steam vapour pressures used in the simulations.**

<table>
<thead>
<tr>
<th>Partial steam vapour pressure (bar)</th>
<th>Amount of water added (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>275</td>
</tr>
<tr>
<td>60</td>
<td>549</td>
</tr>
<tr>
<td>100</td>
<td>915</td>
</tr>
<tr>
<td>200</td>
<td>1831</td>
</tr>
<tr>
<td>300</td>
<td>2746</td>
</tr>
<tr>
<td>400</td>
<td>3661</td>
</tr>
</tbody>
</table>

Note that in many other studies on water ingress the mass of water in the primary system (including the steam generator) is often used as the basis to show results and this will explain the large differences in the water ingress masses used in different studies.

**IV. RESULTS AND DISCUSSION**

In order to be able to analyse the mechanisms behind these phenomena, the changes in reactivity with increasing water ingress are shown for ingress into the riser tubes and control rod holes in the external reflectors and riser tubes in the bottom reflectors only, water ingress into the fuel core only and water ingress into the combination of these riser tubes and the fuel core are compared for PBMR-200 and PBMR-400 in Figure 3 to Figure 5 respectively [7].

**IV.A. Reactivity changes for water ingress into the reflectors only**

Figure 3 compares $k_{\text{eff}}$ as a function of partial steam vapour pressure during water ingress into only the reflectors for the PBMR-400 up to 400 bar and the PBMR-200 up to 300 bar.

![Figure 3: Comparison of the value of $k_{\text{eff}}$ for the PBMR-200 and the PBMR-400, for the case of water ingress into the reflectors only.](image)

Ingress was limited to the riser tubes for the helium coolant and was therefore limited to the
bottom and external reflectors, as there are no primary helium coolant flow channels in the top reflectors (since the coolant enters from the side reflector into the cavity above the pebble bed in the PBMR proposed designs) or the central reflectors.

It can be observed from this figure that increasing water ingress into the reflectors only leads to a substantial and consistent straight line reduction in $k_{\text{eff}}$, with the magnitude of this reduction much larger for the PBMR-400 than for the PBMR-200.

As has been explained above, the $^1\text{H}$ nuclei in the ingressing steam are much more effective moderators than the $^{12}\text{C}$ nuclei in the natural graphite ($^{10}\text{B}$) reflector blocks. Therefore ingress of relatively small amounts of water will cause relatively large increases in the moderation rate, i.e. the neutron energy spectrum will soften substantially. This can explain the observed decrease in reactivity: the external graphite reflectors are thick and therefore there is ample opportunity for fast and epithermal neutrons that diffuse from the fuel into the reflectors to be fully thermalised before they diffuse back into the fuel. Most neutrons that diffuse back into the fuel are thus already fully thermalised and therefore the spectrum of the neutron flux that flows back into the fuel from the external reflectors is not substantially softened by adding additional water moderator to these reflectors. Therefore no associated increase in the fission rate is to be expected.

At high and epithermal energies the microscopic cross-section for radiative capture ($\sigma_t$) is very low for both the $^1\text{H}$ in the water and the $^{12}\text{C}$ in the reflector blocks. However it increases sharply with decreasing energy in the thermal region. Therefore the neutrons are unlikely to be captured by either the $^{10}\text{B}$ of $^1\text{H}$ before they have been thermalised. However, once they have been thermalised, they become very vulnerable to being captured by both, unless they can quickly escape back to the fuel and be absorbed by the fissile fuel isotopes for fission. Therefore, in order to be thermalised in the reflector and stand a good chance to return to the fuel to cause fission, a fast neutron migrating deep into the reflector should migrate back to as close as possible to the fuel core, before being thermalised, so that the homestretch back to the fuel will be short enough. However water ingress into the riser tubes creates the scenario where fast or epithermal neutrons get slowed down significantly faster by the $^1\text{H}$ when crossing the riser tube on its journey from the fuel into the reflector. This increases the probability that it will be fully thermalised before being able to escape back to close to the core, in which case it is highly likely that it will be captured in either the $^{10}\text{B}$ or $^1\text{H}$ in the reflector. This explains why increasing water ingress into the external reflectors consistently causes more neutron captures in these reflectors, i.e. increased leakage of neutrons from the core and thus a reduction in $k_{\text{eff}}$.

The much larger observed reduction in $k_{\text{eff}}$ in the PBMR-400 can be explained as follows:

The 85 cm fuel annulus of the PBMR-400 is much thinner than the 150 cm radius of the cylindrical fuel core of the PBMR-200. The water ingress into the external reflectors will mainly result in a reduction in the number of thermal neutrons that diffuse back from the external reflector to the fuel. However, the inner fuel layers of the PBMR-200 will be situated much further away from this incoming flux of thermal neutrons from the external reflector and will thus be less affected by a reduction in its magnitude. Therefore a fixed percentage reduction in the incoming flux from the external reflector will result in a larger reduction in $k_{\text{eff}}$ for the PBMR-400 than the PBMR-200. Put differently, the fraction of the total number of thermal neutrons in the normal equilibrium core that have been thermalised in the external reflector will be substantially smaller for the PBMR-200 and therefore it will be less affected by a reduction in the number of these neutrons, compared to the PBMR-400. This explanation is further supported by the fact that the radial power profile of the PBMR-400 has local peaks against both the internal and external reflectors, while the power profile of the PBMR-200 peaks in the centre of the core and is substantially lower against the external reflector, which also suggests diminished importance of thermal neutron influx from the external reflector for the PBMR-200.

IV.B. Reactivity changes for water ingress into the fuel core only

Figure 4 compares $k_{\text{eff}}$ for the PBMR-400 and the PBMR-200 as a function of partial steam vapour pressure during water ingress into the fuel core only.

![Figure 4: Comparison of the $k_{\text{eff}}$ for the case of water ingress into the core only.](image)

$k_{\text{eff}}$ initially increases sharply with increasing water ingress for both reactors, but then peaks at 200 bar for the PBMR-200 and at 300 bar for the PBMR-
400, where after it declines slightly. $k_{\text{eff}}$ reached a maximum of 1.0518 in the PBMR-400, compared to a slightly lower 1.0484 in the PBMR-200. The initial increase in $k_{\text{eff}}$ is substantially slower for the PBMR-400 than for the PBMR-200. However, as $k_{\text{eff}}$ peaks earlier for the PBMR-200, the graphs cross over at about 200 bar. These results can be explained as follows:

Most Pebble Bed Reactor fuels are undermoderated in that the fuel free path lengths that the average neutron traverses through graphite between encounters with fuel kernels, is too short to achieve high levels of moderation between subsequent collisions with fuel kernels. Therefore many neutrons will not have been moderated down to energies below the region of the epithermal resonances of $^{238}\text{U}$ when they experience consecutive collisions with fuel kernels and thus a substantial fraction of them will be captured in the resonances of $^{238}\text{U}$. Therefore the resonance escape probability will be substantially below 100% and thus $k_{\text{eff}}$ will be significantly reduced by these resonance captures. However, with increasing water ingress into the voids between the fuel spheres, $k_{\text{eff}}$ initially increases with increasing moderation. This is because quicker or more effective moderation increases the probability for the neutrons to be slowed down to below the epithermal capture resonances of $^{238}\text{U}$ before they hit consecutive fuel kernels, thereby enabling them to escape resonance capture. Alternatively a quicker or more effective moderation rate increases the magnitude of the energy jumps between hitting subsequent fuel kernels. This increases the neutron’s probability to jump over individual capture resonance energies, without being captured. Increasing moderation thus increases the resonance escape probability and thus increases $k_{\text{eff}}$.

As the moderation increases, it reaches a point where resonance capture becomes negligible and thus the resonance escape probability approaches 100%. Further increases in the moderation rate will thus not produce significant increases in the resonance escape probability and thus also not in $k_{\text{eff}}$. However, further water ingress increases the moderation rate and will slow more neutrons down to thermal energies, which will cause increased radiative capture in the $^1\text{H}$ and to a much smaller extent in the $^{12}\text{C}$ in the core. More steam in the voids between the fuel spheres will also increase the number density of $^1\text{H}$ and consequently its macroscopic capture cross section. Combined with the fact that, for low thermal energies, the microscopic capture cross-section of $^1\text{H}$ is much higher than for $^{12}\text{C}$, the capture rate in $^1\text{H}$ can then increase substantially with further water ingress, which will mean that $k_{\text{eff}}$ will decrease with further water ingress. This state is called over moderation.

One would have expected that the substantially higher loading of $^{238}\text{U}$ per fuel sphere in the PBMR-400 would have resulted in a more under-moderated core than the PBMR-200 and that therefore the PBMR-400 should experience a substantially higher increase in reactivity with increased moderation due to water ingress into the core. One possible explanation for the absence of such a large observed increase in $k_{\text{eff}}$ and for the initially slower increase in $k_{\text{eff}}$ for the PBMR-400 is the following:

The fuel of the PBMR-400 has a higher heavy metal (HM) loading of 9 g LEU/fuel sphere and lower moderation ratio of 425, compared to the lower 7 g/fuel sphere for the PBMR-200 and a higher moderation ratio of 550. The average fuel-free distance between subsequent collisions with the fuel kernels is thus shorter for the PBMR-400, which would suggest that the PBMR-400 fuel would be more under-moderated and that $k_{\text{eff}}$ should thus increase faster with increasing moderation due to water ingress than for the PBMR-200. However, due to the thin 85 cm thick fuel annulus of the PBMR, compared to the much thicker 150 cm radius fuel cylinder of the PBMR-200, and the additional central graphite reflector of the PBMR-400, the core of the PBMR-400 will be flooded with thermal neutrons from the reflectors on both sides to a much greater extent than from only the external reflector in the PBMR-200. The spectrum in the PBMR-400 can therefore be expected to be softer, i.e. effectively better moderation than in the PBMR-200. This assumption can be tested by comparing the capture rates in the resonances of $^{238}\text{U}$: logically the more under-moderated a core is, the higher the fraction of neutrons that will be captured in these resonances. From the neutron losses in Figure 9 and Figure 10 these capture rates can be compared. Before water ingress only 18% of neutrons in the equilibrium core of the PBMR-400 were captured in $^{238}\text{U}$, compared to 19.5% in the PBMR-200, which indeed suggests that the PBMR-200 is more under moderated than the PBMR-400. In Figure 4 above $k_{\text{eff}}$ at 200 bar steam ingress was equal for the two reactors, despite our initial expectation that it would be higher for the PBMR-400. Therefore 200 Bar will be chosen as a point of comparison of the mechanisms of the reactivity effect of steam ingress in Figure 9 and Figure 10. At 200 bar the % neutron capture in the resonances of $^{238}\text{U}$ has decreased to 14% for both the reactors, which means that the reduction in the capture was 4% for the PBMR-400, compared to a substantially larger 5.5% for the PBMR-200, which explains the initial faster increase in $k_{\text{eff}}$ with steam ingress for the PBMR-200. This result confirms our assumption that the influx of thermal neutrons from its two proximal reflectors gives the PBMR-400 a softer spectrum and thus a less under-moderated core than the PBMR-200, despite the higher heavy metal loading of the PBMR-400 fuel.
The larger influx of thermal neutrons from the reflectors furthermore means that more thermal neutrons are available for capture by the ingressed \(^1\text{H}\) in the PBMR-400 core. Therefore the increase in \(k_{\text{eff}}\), due to the increase in the resonance escape probability produced by better moderation, will be partly countered by additional captures in \(^1\text{H}\) and to a lesser extent in \(^{135}\text{C}\) of the large number of well thermalised neutrons in the PBMR-400 core, which can further explain the unexpectedly slow increase in \(k_{\text{eff}}\) observed in the PBMR-400.

**IV.C. Reactivity changes for water ingress into both the fuel core and reflectors**

The effects on the reactivity of simultaneous water ingress into both the core and reflectors are compared for the PBMR-400 and PBMR-200 in Figure 5 below. For the PBMR-200 \(k_{\text{eff}}\) initially climbs faster and has a higher peak of 1.044 compared to that of the PBMR-400 which has a peak of only 1.041. The PBMR-200 reaches its peak at 200 bar and then drops to a \(k_{\text{eff}}\) value of 1.036 at 300 bar. For the PBMR-400, a maximum value of \(k_{\text{eff}}\) is reached only at about 250 bar and then drops to 1.034 at 400 bar.

![Figure 5: Reactivity increase with water ingress into both the core and reflectors for the PBMR-200 and PBMR-400.](image)

It is interesting to note that the PBMR-200 has now overtaken the PBMR-400 in that its peak \(k_{\text{eff}}\) is higher for water ingress into both the core and external reflector, while it was lower for ingress into the core only. This can be explained by the fact that in Figure 3 the reduction in \(k_{\text{eff}}\) for water ingress into the external reflector only was about twice as large for the PBMR-400 than for the PBMR-200. The slightly larger reactivity increase of the PBMR-400 for water ingress into the core only was thus more than offset by its much larger reduction in reactivity for water ingress into the reflector only. Preliminary explanations of these unexpected results were already given above and more will be offered below.

**IV.D. Flux distribution results**

Figure 6 below compares the effect of water ingress into both the core and external reflectors on the calculated steady-state thermal flux profiles for the PBMR-400 and the PBMR-200 cores. The fluxes for the PBMR-400 shown were taken at 300 bar partial steam vapour pressure and 612 cm from the top of the core and at 200 bar and 374.40 cm from the top of the core for the PBMR-200.

![Figure 6: Comparison of the effect of water ingress into both the core and external reflectors on thermal flux profiles, for both reactors.](image)

It can be seen that for both reactors water ingress into the core causes a substantial increase in the thermal flux in the central regions of the fuel core, which then changes into substantial reductions in the reflectors regions and smaller reductions in the fuel directly adjacent to it. This can be explained as follows. As was discussed in Par. I.C. above on the Reactivity Theory of Water Ingress, more effective moderation in the core by \(^1\text{H}\) in the steam leads to a softer spectrum with a higher flux of neutrons that were moderated directly in the core. The lower fast flux (less leakage) and the increased absorption of thermal neutrons by the fissile fuel isotopes also make the core more opaque to neutrons, so that fewer neutrons manage to escape into the reflectors. Therefore fewer neutrons are moderated in the reflectors and therefore the thermal neutron flux that streams back to the core from the reflectors is also smaller. This explains the higher thermal flux in the centre of the core and lower flux in the fuel directly adjacent to the reflectors.

**IV.E. Power density distribution results**

Figure 7 below shows a comparison of radial power profiles for the PBMR-400 and the PBMR-200 due to water ingress into both the core and reflector. The power density can be seen to exhibit similar behaviour to that of the thermal neutron flux in the core. This is logical since fissions are mostly produced by the thermal neutrons. The power
density increased in the central core regions of both cores (centre of the core and centre of the annulus respectively) after water ingress and once again is lower towards the side reflector.

**IV.F. Detailed analysis of mechanisms driving reactivity changes due to water ingress**

The mechanisms that drive the observed changes in reactivity were studied in order to obtain a better understanding of the process, which may lead to design changes that can mitigate these changes. The individual component fractions that contribute to the following parameters, which contribute to the value of $k_{\text{eff}}$, were studied:

1. Fuel utilisation, i.e. fraction of neutrons absorbed in fissile fuels.
2. Neutrons absorbed in non-fissile nuclides in the core.
3. Leakage from the core, i.e. neutrons that end up leaking out of the pressure vessel or captured in the reflectors, pressure vessel, control rods etc.
4. The fractions of fission neutrons produced by the different fissile fuels and the number of fission source neutrons emitted per neutron absorbed in the fissile fuel ($\eta$).

**IV.G. Neutron production by fissile isotopes**

Figure 8 below shows the distortion of the neutron production by fissile isotopes for the PBMR-400 and the PBMR-200 as a function of partial steam vapour pressure during water ingress into both the core and reflector. From this figure, it can be observed that water ingress into the core led to a substantial swing in the fractional neutrons produced away from $^{239}$Pu towards $^{235}$U. The $^{235}$U neutron production increased by $2.89\%$ for the PBMR-200 and by $4.22\%$ for the PBMR-400. These increases were sharp from 0 to 200 bar steam, after which they flattened out, which corresponds to $k_{\text{eff}}$ that increased sharply to about 200 bar and then peaked.

The $^{239}$Pu fractional neutron production decreased by $3.83\%$ and $2.72\%$ for the PBMR-400 and PBMR-200 respectively. In both cases the neutron production from fission in $^{241}$Pu was small and did not change significantly with water ingress. The reasons for this swing are not obvious:

The microscopic fission cross section for $^{239}$Pu at thermal energies is about twice that of $^{235}$U, so one would expect that a softening of the spectrum, due to more effective moderation, should increase the fission rate in $^{239}$Pu more than in $^{235}$U.

The swing away from neutron production due to fissioning of $^{239}$Pu to that of $^{235}$U could possibly be explained by the influence of the thermal fission resonance of $^{239}$Pu at $0.3$ eV, as was discussed by Serfontein [10]. Since this resonance lies very far above the peak of the Maxwellian energy spectrum of the thermalised neutron flux at normal operating temperatures, very few thermalised neutrons, from the very small high energy tail of the Maxwellian spectrum, will produce fission in this resonance. However, neutrons that are already in the thermal energy window, but are still in the process of being slowed down to thermal energies, may well produce fissions in this resonance. Therefore quicker or more effective moderation, due to water ingress into the fuel core, may cause more neutrons to escape this fission resonance by being thermalised before being able to produce fission in this resonance. This mechanism will reduce fissions in the $0.3$ eV $^{239}$Pu fission resonance and will correspondingly increase fissions of all the fissile fuels at well thermalised, i.e. lower, energies. However, since the number density of $^{235}$U is much larger than that of $^{239}$Pu, such a shift to lower energies favour fission in $^{235}$U.
Another possibility is a swing away from fast and epithermal fissioning of $^{239}$Pu: it is known that the fast and epithermal microscopic fission cross section for $^{235}$U is much larger than for $^{239}$U. Therefore, the under-moderated neutron spectra that exist before water ingress should produce larger amounts of fast and epithermal $^{239}$Pu fissions, compared to $^{235}$U, relative to their number densities. However, the more effective moderation induced by water ingress into the core will substantially reduce the fast and epithermal neutron fluxes, which will reduce the relative advantage of fast and epithermal $^{239}$Pu fissions. Fissions will thus shift towards the lower end of the thermal energy region. Since the number densities of $^{235}$U are much higher than for $^{239}$Pu, $^{235}$U can be expected to produce most of these thermal fissions, which may explain the observed swing. However, more detailed studies will be required in order to find out exactly which mechanisms produced the observed results. For one thing the capture-to-fission ratio is relatively high for $^{239}$Pu in the epithermal region as well as in the 0.3 eV thermal fission resonance. Therefore, while improved moderation may reduce $^{239}$Pu fissions in these two regions, which will reduce $k_{\text{eff}}$, it may also reduce captures, which will increase $k_{\text{eff}}$. So it is difficult to predict exactly what the nett reactivity effect of this mechanism will be.

IV.H. Neutron losses in heavy metals and fission products

Figure 9 below shows the distortion of the neutron losses in the PBMR-400 as a function of partial steam vapour pressure during water ingress into both the core and external reflector.

Figure 9: Neutron losses in the PBMR-400 after water ingress into both the core and reflectors.

From this figure, it can be observed that neutron losses by radiative capture in $^{238}$U decreased by 6.1% and there was also a significant decrease in losses in $^{240}$Pu, which together led to a substantial increase in the resonance escape probability and thus increased $k_{\text{eff}}$, as was already discussed above. It can also be seen that many of these neutrons that now escaped capture, ended up as thermal neutrons that were absorbed by $^{235}$U and mostly caused fissions. This increased the neutron losses in $^{235}$U substantially by 2.8%, which also increased $k_{\text{eff}}$, as was already discussed above. Once again the neutron losses in $^{237}$U initially increased sharply, but then peaked at about 200 bar, similar to $k_{\text{eff}}$. The core leakage decreased significantly by 1.09%, which means a substantially larger fraction of neutrons remained in the core and could thus produce more fissions. These factors combined to produce the observed strong increase in $k_{\text{eff}}$ and the peaking after 200 bar.

Figure 10 below shows the distortion of the neutron losses in the PBMR-200 as a function of partial steam vapour pressure during water ingress into both the core and reflector.

IV.J. Fission source neutrons emitted per neutron absorbed

Figure 11 below compares distortion of the fission source neutrons emitted per neutron absorbed in fissile nuclides ($\eta$) for the PBMR-400 and the PBMR-200, as a function of partial steam vapour pressure ingress into both the core and reflector.
Figure 11: Distortion of $\eta$ due to water ingress into both the core and reflector of the PBMR-400 and PBMR-200.

It can be observed from this figure that $\eta$ moved in the opposite direction than $k_{\text{eff}}$, i.e. where $k_{\text{eff}}$ increased from 0 to 200 bar steam, $\eta$ decreased and then reversed the trend above about 200 bar. Since, according to the four-factor formula [6], $k_{\text{eff}}$ should be directly proportional to $\eta$, their opposing movements imply that the negative impact on $k_{\text{eff}}$ of the initial decreases in $\eta$ has been more than countered by the positive impacts of the increasing resonance escape probability, increasing fuel utilisation and decreasing leakage. The observed distortion of $\eta$ may partly be explained by the variations in weighting of the $\eta$ values of $^{239}$Pu (2.15) and $^{235}$U (2.07) as the contribution from fission of $^{235}$U first increased and then decreased (as seen in Figure 8). However, as has been explained the matter is more complex than this, as $\eta$ for $^{239}$Pu depends strongly on the energy of the neutron that caused the fission, e.g. for fast neutrons $\eta$ for $^{239}$Pu is higher than for any of the other fuel isotopes, but in the epithermal and in the thermal fission resonances it is substantially lower than for the rest and then picks up again below 0.3 eV. One thus needs to know exactly where the bulk of the neutron spectrum was located at each stage of steam ingress, in order to be able to accurately explain the observed phenomena.

V. DISCUSSION OF RESULTS

Simulation of the effects of water ingress into both the core and reflector on the reactivity of the PBMR-400 MW and PBMR-200 MW reactors was performed and the results were compared to a study conducted by Teuchert et al.[12] They studied the reactivity insertion due to water ingress of 600 kg for a moderation ratio ($N_{\text{H}}/N_{\text{C}}$) of a full core load of 7 g heavy metal pebbles in the HTR-Module. These results were then used as a benchmark and compared to the PBMR-200 results as shown in Figure 12 below.

The value that corresponds to a mass of 600 kg of water can be estimated to a partial steam vapour pressure of less than 100 bar for the PBMR-200.

It can be observed from the figure above that the values of $k_{\text{eff}}$ for the PBMR-200 values were observed to be substantially above those of the HTR-Module. When the partial steam vapour pressure was increased above 100 bar, the deviation became more pronounced. The maximum $k_{\text{eff}}$ value reached for the HTR-Module at 150 bar was approximately 1.033. For the PBMR-200, the maximum $k_{\text{eff}}$ value of 1.044 was reached at 200 bar partial steam vapour pressure.

The PBMR-200 has the same heavy metal loading (of 7 g) as the HTR-Module but for the benchmark reactivity insertion simulation, the $^{235}$U enrichment was increased from 7.8% to 8.17%. This compensates for the loss in burnup (relative to the PBMR-400 model) obtained per fuel sphere and increased fuel loading needs due to the lower heavy metal loading.

Another detail that can account for the difference in the $k_{\text{eff}}$ values between the two reactors after water ingress could be the difference in the fuel sphere power loading which is 1.3 kW/sphere for the PBMR-200 but was increased from 1.4 to 2.1 kW/sphere in the HTR-Module.

It should be noted that these result were obtained using very high partial steam vapour pressures of up to 300 bar for the PBMR-200 and up to 400 bar for the PBMR-400. The partial steam vapour pressures were increased until after the peak value of $k_{\text{eff}}$ had been reached. Realistically, the primary relief systems are designed to protect the pressure vessels against overpressure. Therefore these much higher steam pressures will not be reached. During the simulations, it was found that the PBMR-400 reached its peak at a higher partial steam pressure than the PBMR-200. The expected steam pressure in the PBMR-200 should then be below 70 bar and 90 bar for the PBMR-400. The maximum realistic reactivity increase would therefore be around 3% for the PBMR-200 and 2.8% for the PBMR-400. It is
important to note that these increases in reactivity can easily be compensated by the control rods (or reserve shutdown systems).

VI. PROPOSALS FOR FUTURE DESIGN CHANGE STUDIES

Based on the findings of this study, the following changes to the designs appear beneficial and should thus be investigated:

- Decreased $^{239}\text{U}$ loading, compensated by increased enrichment.
- Vertical holes in most of the reflector blocks in order to increase steam ingress into the reflectors, also in the central reflector of the PBMR-400.
- Decreased diameter of the central reflector of PBMR-400, in order to decrease leakage in the central reflector. This will decrease the reduction in leakage during steam ingress, which will limit the increase in reactivity.

VII. CONCLUSIONS

- The details of the mechanisms and effects of water ingress on the reactivity of the PBMR-400 MW and PBMR-200 MW reactors were investigated. The impact of water ingress on $k_{\text{eff}}$ the flux distribution and power profiles were studied.
- The present simulation approach and results were successfully validated and verified against simulations results from the literature of water ingress into Pebble Bed Reactors.
- Preliminary explanations of many unexpected results were offered, but more detailed studies will be required in order to obtain more accurate explanations.

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IX. REFERENCES


