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Different techniques for reducing DLOFC fuel temperatures in a PBMR-DPP-400 core

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ABSTRACT

This article addresses 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 principle strategies used for reducing the maximum DLOFC temperatures were (a) flattening the peaks in the axial power density profile, 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 by (a) flattening of the peaks in the axial profiles of the equilibrium power density by adding thorium to the LEU fuel and (b) placing purposely-designed distributions of neutron poison in the central 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.

The result was a reduction 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.

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 (Kania et al., 2013). 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 (Reutler and Lohnert, 1983, 1984).

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 (Zhang et al., 2009). 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

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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 (Reitsma, 2004). 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 (Rütten et al., 2007) 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 h into the accident. The aim is to design the core such that this tipping point will be reached before the maximum industry guideline fuel

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