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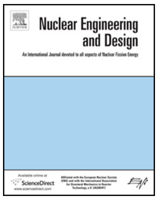

Reactivity control system of a passively safe thorium breeder pebble bed reactor

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HIGHLIGHTS

- A worth of over 15,000 pcm ensures achieving long-term cold shutdown in thorium PBR.
- Control rod worth in side reflector is insufficient due to low-power breeder zone.
- 20 control rods, just outside the driver zone, can achieve long-term cold shutdown.
- BF_3 gas can be inserted for reactor shutdown, but only in case of emergency.
- Perturbation theory accurately predicts absorber gas worth for many concentrations.

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ABSTRACT

This work investigates the neutronic design of the reactivity control system for a 100 MW_{th} passively safe thorium breeder pebble bed reactor (PBR), a conceptual design introduced previously by the authors. The thorium PBR consists of a central driver zone of 100 cm radius, surrounded by a breeder zone with 300 cm outer radius. The fissile content of the breeder zone is low, leading to low fluxes in the radial reflector region. Therefore, a significant decrease of the control rod worth at this position is anticipated.

The reactivity worth of control rods in the side reflector and at alternative in-core positions is calculated using different techniques, being 2D neutron diffusion, perturbation theory and more accurate 3D Monte Carlo models. Sensitivity coefficients from perturbation theory provide a first indication of effective control rod positions, while the 2D diffusion models provide an upper limit on the reactivity worth achievable at a certain radial position due to the homogeneous spreading of the absorber material over the azimuthal domain. Three dimensional forward calculations, e.g. in KENO, are needed for an accurate calculation of the total control rod worth.

The two dimensional homogeneous calculations indicate that the reactivity worth in the radial reflector is by far insufficient to achieve cold reactor shutdown, which requires a control rod worth of over 15 000 pcm. Three dimensional heterogeneous KENO calculations show that placing 20 control rods just outside the driver channel, between 100 cm and 110 cm radius, can provide sufficient reactivity worth, also if one or two control rods fail to insert.

Finally, the insertion of a neutron absorber gas is investigated as an additional emergency shutdown system. For this type of problem, perturbation theory is found to give a good estimate of the reactivity effect, because a relatively small perturbation $\Delta\Sigma_a$ is now applied over the whole volume of the core. BF_3 can be considered the most suitable absorber gas candidate, among four gases investigated, due to its wide availability and the relatively low amount required to achieve a sufficient reactivity worth.

1. Introduction

The neutronic design of the reactivity control system for a 100 MW_{th} passively safe thorium breeder pebble bed reactor (PBR), a conceptual design introduced in previous work of the authors (Wols et al., 2015), is investigated in the present work. This thorium breeder PBR design combines inherent safety, high outlet temperature, reduced lifetime of the radiotoxic waste and enlarged resource availability, at the price of a strong requirement on the fuel pebble handling speed and a high reprocessing rate. This conceptual design differs significantly from other recent investigations of thorium utilization in PBRs, which mainly focus on reducing the uranium

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consumption or the burning (or reduced production) of plutonium and minor actinides (Rütten and Haas, 2000; Chang et al., 2006; Mulder et al., 2010; Xia and Li, 2013). Although a concept for a thorium net-breeder (Teuchert, 1986) was already introduced many years ago, it would have required active cooling due to its large radius, almost 6 m, and power (3000 MW_{th}).

The cylindrical core of the passively safe thorium PBR consists of a central driver zone, 100 cm radius with a soft neutron spectrum to enhance fission, which is achieved by using a 3 g heavy metal (HM) loading per driver pebble. The breeder zone of 200 cm thickness has a 30 g HM loading per pebble to achieve a harder neutron spectrum, which enhances conversion. The system operates at a thermal power of 100 MW, and combines net-breeding with passive safety features, i.e. fuel temperatures remain below 1600 °C during a depressurized loss of forced cooling (DLOFC) without scram and water ingress only leads to a relatively small reactivity increase (+1497 pcm) (Wols et al., 2015).

In modular PBR designs, the radial reflector is the preferred option for the placement of control rods with metallic parts (Reutler and Lohnert, 1984), because the control rods can move freely and the rods can be cooled sufficiently. Furthermore, the thermal neutron flux close to the reflector is quite high due to the thermalized neutrons reflected back into the core, which ensures a sufficient control rod worth can be achieved. Therefore, this approach is also taken in the HTR-PM (Sun et al., 2013), which also has a secondary shutdown system by dropping graphite balls containing neutron absorber material into holes inside the radial reflector.

Inside the passively safe thorium breeder PBR design (Wols et al., 2015), the power production is very low close to the radial reflector, so the effectiveness of control rods is expected to be very small. Therefore, the insertion of control rods into the active core region might be unavoidable for a sufficient reactivity worth.

This might be achieved by using guide channels in which the control rods can be inserted or extracted from the core, like in the German AVR (Yamashita et al., 1994). Driving control rods directly into the pebble bed is less desirable to avoid pebble crushing, although this method was used effectively for reactor shutdown in the Thorium High Temperature Reactor (THTR-300) (Bäumer and Kalinowski, 1991). An alternative option would be a reactor design with control rods inside a central reflector. This could also offer the opportunity for radial cooling of the pebble bed (Muto and Kato, 2003; Muto et al., 2005), which might increase the thermal and pumping efficiency of the design as all of the coolant would flow through both the hot driver and the cold breeder channel in the two-zone thorium breeder PBR (Wols et al., 2015).

The first part of this work investigates where control rods might be positioned in the design to obtain a sufficient reactivity worth. These studies are performed using different calculation techniques, being forward 2D(R, Z) diffusion calculations with the inhouse developed neutron diffusion solver DALTON (Boer et al., 2010), perturbation theory and 3D KENO (ORNL, 2009) models. As control rods give a strong local perturbation, a 3D method like KENO is expected to yield the most accurate results. But the simplified 2D DALTON models can be used to provide an upper limit of the reactivity worth at a certain radial control rod position, because the self-shielding effect of the neutron absorber material is underestimated due to its homogeneous distribution.

In the second part of the work, the insertion of an absorber gas is studied as an emergency shutdown system. The achievable reactivity worth as a function of the amount of absorber gas inserted is calculated for different gases, using 2D(R, Z) forward neutron diffusion calculations and perturbation theory. For this application, first order perturbation theory might still provide a good estimate of the reactivity worth as the perturbation introduced is rather homogeneous.

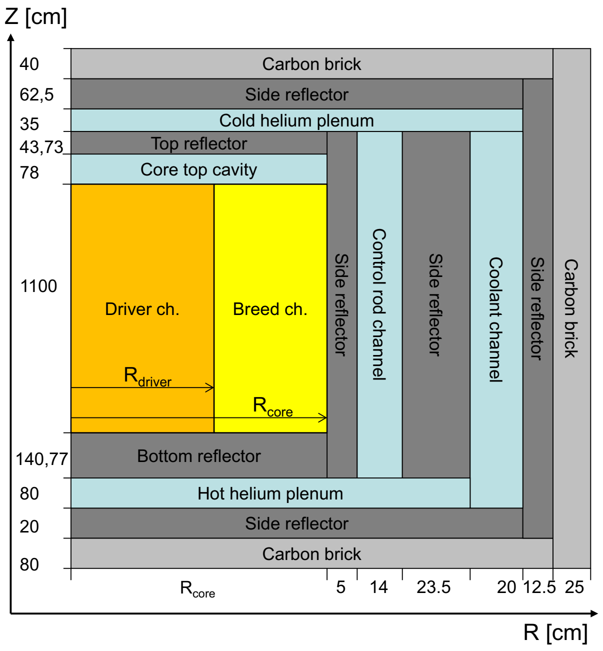

Fig. 1. Schematic view of the thorium PBR geometry used in the neutronics calculations. The geometry is strongly based upon the HTR-PM (Zheng and Shi, 2008). The control rod channel shown is located at the original position of the HTR-PM (not to scale).

Section 2 introduces the core model of the 100 MW_{th} thorium PBR design, followed by a calculation of the reactivity worth required to achieve cold shutdown in Section 3. In Section 4, the methodology for the control rod positioning calculations and the results are discussed, followed by the absorber gas studies for emergency shutdown and conclusions.

2. Core model of the 100 MW_{th} passively safe thorium breeder PBR

The thorium PBR (Wols et al., 2015) consists of a two-zone cylindrical core with a central driver zone of 100 cm radius surrounded by a breeder zone of 200 cm thickness. Breeder pebbles with a 30 g heavy metal (HM) loading, yielding a relatively hard spectrum for enhanced conversion, make two passes through the breeder channel within 1000 days. The driver pebbles (3.0 g HM, 10 w% U-233) make 4 passes, to ensure a sufficient reduction of the axial power peaking factor without causing an unnecessarily high demand on the fuel pebble handling speed. After their final passage the breeder and driver pebbles are extracted for reprocessing. The driver pebble residence time is adjusted to obtain a critical core configuration, and the system's mass balance shows the extraction rate of U-233 (and Pa-233) is higher than the insertion rate during equilibrium operation. The present conceptual design choice and a detailed description of the coupled DALTON/THERMIX code scheme, used for analyzing the DLOFC transients are given by Wols et al. (2015), while a more detailed description of the equilibrium core calculation scheme is given by Wols et al. (2014a).

A schematic view of the reactor geometry used during past (Wols et al., 2014a,2015) and present neutronic studies is shown in Fig. 1. This geometry is strongly based upon the HTR-PM (Zheng and Shi, 2008; Zheng et al., 2009). There are porous regions inside the side reflector to model the presence of helium regions like control rod channels, in their original configuration of the HTR-PM (Sun et al., 2013), and coolant channels. Pure helium regions, like the top plenum, are homogenized with adjacent graphite regions to avoid the use of neutronically thin media in the diffusion calculation. For