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Analysis of the running-in phase of a Passively Safe Thorium Breeder Pebble Bed Reactor

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ABSTRACT

The present work investigates the running-in phase of a 100 MW_{th} Passively Safe Thorium Breeder Pebble Bed Reactor (PBR), a conceptual design introduced in previous equilibrium core design studies by the authors. Since U-233 is not available in nature, an alternative fuel, e.g. U-235/U-238, is required to start such a reactor. This work investigates how long it takes to converge to the equilibrium core composition and to achieve a net production of U-233, and how this can be accelerated.

For this purpose, a fast and flexible calculation scheme was developed to analyze these aspects of the running-in phase. Depletion equations with an axial fuel movement term are solved in MATLAB for the most relevant actinides (Th-232, Pa-233, U-233, U-234, U-235, U-236 and U-238) and the fission products are lumped into a fission product pair. A finite difference discretization is used for the axial coordinate in combination with an implicit Euler time discretization scheme.

Results show that a time dependent adjustment scheme for the enrichment (in case of U-235/U-238 start-up fuel) or U-233 weight fraction of the feed driver fuel helps to restrict excess reactivity, to improve the fuel economy and to achieve a net production of U-233 faster. After using U-235/U-238 startup fuel for 1300 days, the system starts to work as a breeder, i.e. the U-233 (and Pa-233) extraction rate exceeds the U-233 feed rate, within 7 years after start of reactor operation.

The final part of the work presents a basic safety analysis, which shows that the thorium PBR fulfills the same passive safety requirements as the equilibrium core during every stage of the running-in phase. The maximum fuel temperature during a Depressurized Loss of Forced Cooling (DLOFC) with scram remains below 1400 °C throughout the running-in phase, quite a bit below the TRISO failure temperature of 1600 °C. The uniform reactivity coefficients of cores with U-235/U-238 driver fuel are much stronger negative compared to U-233/Th driver fuel, which implies that the stronger reactivity insertion by water ingress and the reactivity addition by xenon decay during a DLOFC without scram can be compensated without fuel temperatures exceeding 1600 °C.

1. Introduction

The running-in phase of a 100 MW_{th} Passively Safe Thorium Breeder Pebble Bed Reactor (PBR) is investigated in the present work. The conceptual design of such a reactor was introduced in a previous work by the authors (Wols et al., 2015). The design combines inherent safety, a high outlet temperature, reduced lifetime of the radiotoxic waste and an enlarged resource availability. However, a high fuel pebble handling speed and fuel reprocessing rate is required. During previous design studies by the authors (Wols et al., 2015) the equilibrium core composition was determined.

However, U-233 is not available in nature, so the start-up of a thorium breeder PBR requires another fuel. Low enriched uranium will be considered as a start-up fuel in this work, but plutonium (and minor actinides) may also provide an alternative, its use has already been considered previously in combination with thorium inside PBRs (Rütten and Haas, 2000; Chang et al., 2006; Mulder et al., 2010). The build-up of certain relevant actinides, e.g. U-234, U-235 and U-236, may take quite some time. Therefore, it is important to determine from which moment the reactor starts breeding, i.e. a net production of U-233, and how much time it takes to converge to the equilibrium core composition.

In addition to answering these questions, the running-in phase strategy should also be chosen carefully in order to minimize the additional U-235 fuel consumption, achieve equilibrium quickly and to maintain a critical core configuration, while restricting the amount of excess reactivity, at any time. In order to achieve this, the fresh fueled core composition and the enrichment of the U-235/U-238 feed fuel during the initial start-up phase and the

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U-233 weight fraction of the driver fuel in the remainder of the running-in phase should be chosen carefully over time.

Finally, the thorium PBR should also be passively safe during the whole running-in phase. For this purpose, a basic safety analysis, i.e. calculation of the uniform reactivity coefficient, maximum power density, maximum fuel temperature during a Depressurized Loss of Forced Cooling (DLOFC) with scram and the maximum reactivity insertion due to water ingress, is performed at different moments of the chosen running-in phase strategy.

The most common code in literature for modeling the running-in phase of multi-pass PBRs is VSOP (Very Superior Old Programs) which was developed in Germany during the high temperature reactor program (Rütten et al., 2010). The VSOP code calculates the core depletion over the whole start-up phase until the equilibrium core, and was used for instance to model the running-phase of the HTR-10 (Xia et al., 2011). Furthermore, NRG's PANTHERMIX code is also capable of modeling the start-up phase of a PBR (Oppe et al., 2001; Marmier et al., 2013).

The calculation scheme previously applied by Wols et al. (2015) for the design of the reactor only provides the option to calculate the equilibrium core composition directly. This code scheme could be extended to a full time dependent version, but the calculations would become very time consuming. The scheme also does not offer enough flexibility to vary the relevant fuel management parameters over time. In this scheme, a burnup calculation is performed and afterwards the fuel concentrations are shifted to a new lower grid position.

For this work, a new calculation scheme was developed to perform the running-in phase calculations. This scheme solves the depletion equations in MATLAB for only the most relevant actinides (Th-232, Pa-233, U-233, U-234, U-235, U-236 and U-238), while the fission products are lumped into a single fission product pair. Furthermore, several simplifications were made in the cross section generation scheme to reduce the computation time. The depletion equations are solved including an axial fuel movement term, so fuel movement and depletion are accounted for simultaneously, increasing the flexibility of the model. A finite difference discretization is used for the height term and an implicit Euler scheme to solve the time dependent term. With this scheme, any of the relevant parameters can easily be varied over time.

A detailed description of the scheme and the simplifications used is given in Section 3, while Section 4 demonstrates that the influence of the simplifications in the depletion equations and the cross section generation scheme is fairly small ($\approx 0.3\%$) for the conversion ratio (CR) of the equilibrium core configuration. Though the ratio between the fissile atom production and consumption rate may deviate a bit more during the running-in phase itself, this will not influence the trends observed during the present work as the time-scales involved remain similar. Despite the simplifications used to reduce the computation time, the new running-in phase model provides a very useful and flexible tool to analyze and optimize the running-in phase strategy and to gain insight into the time-scales involved in the running-in phase.

The next section gives a more detailed introduction of the 100 MW_{th} Passively Safe Thorium Breeder Pebble Bed Reactor (PBR), followed by a description of the running-in phase model, calculation of the equilibrium core with the new model, results of the running-in phase calculations, a basic safety analysis of the thorium PBR during the running-in phase and conclusions and recommendations.

2. The thorium PBR equilibrium core design

The cylindrical core of the 100 MW_{th} Passively Safe Thorium Breeder Pebble Bed Reactor (PBR) consists of a central driver zone surrounded by a breeder zone. The driver zone has a 100 cm radius with a soft neutron spectrum for enhanced fission. The breeder zone of 200 cm thickness has a harder neutron spectrum to enhance conversion. The difference in spectra between the two zones is achieved by a difference in the metal loading per pebble. 30 g thorium, in the form of ThO_2, is loaded per breeder pebble and 3 g HM (10 w% U-233) per driver pebble. Breeder pebbles make two passes within 1000 days, while the driver pebbles are recycled four times in slightly more than 80 days to obtain a critical core configuration. It is assumed that the uranium content of the breeder and driver pebbles can, and will, be reprocessed after their final passage. The system's mass balance shows a higher extraction rate of U-233 (and Pa-233) than the insertion rate for the equilibrium core. A more detailed description of the equilibrium core calculation scheme is given by Wols et al. (2014a, 2015).

Furthermore, the system was also shown to combine breeding with passive safety, as fuel temperatures were shown to remain below 1600 °C during a DLOFC without scram and water ingress only causes a relatively small reactivity increase (+1497 pcm), which can be compensated by the temperature feedback only (Wols et al., 2015). An overview of the relevant fuel and core design parameters of the 100 MW_{th} passively safe thorium breeder PBR (Wols et al., 2015) is given in Table 1.

2.1. Geometry of the neutronics model

A schematic view of the reactor geometry used by the authors during past and current neutronic studies (Wols et al., 2014a, 2015) is shown in Fig. 1. The geometry is based upon the HTR-PM design (Zheng and Shi, 2008; Zheng et al., 2009). Porous side reflector regions model the presence of helium in the control rod and coolant channels. Pure helium regions, e.g. the top plenum, are homogenized with adjacent graphite regions to avoid neutronically thin media in the diffusion calculations. A density of 1.76 g/cm^3 is used for the graphite reflector material and 1.55 g/cm^3 for the carbon brick.

3. Running-in phase model

First, the calculational model for the running-in phase is discussed in Section 3.1, followed by a discussion of the cross section

Table 1
Core and fuel design parameters of the 100 MW_{th} thorium breeder PBR design.

Core design parameters	
Power	100 MW_{th}
Core radius	300 cm
Driver zone radius	100 cm
Core height	1100 cm
Pebble packing fraction	0.61
Driver/breed z. passes	4/2
Total res. time breeder	1000 d
Total res. time driver	80.38 d
$^{233}U_{in-out}$	+8.58 g/d
$^{233}Pa_{in-out}$	−8.91 g/d
Fuel design parameters	
Fuel mass breeder pebble	30 g HM
Fuel mass driver pebble	3 g HM
U-233 fraction of driver fuel	10 w%
Pebble radius	3.0 cm
Fuel kernel radius	0.25 mm
Fuel zone radius	2.5 cm
Material	**Thickness (mm)**
Porous Carbon buffer layer	0.09
Inner Pyrocarbon layer	0.04
Silicon Carbide layer	0.035
Outer Pyrocarbon layer	0.035