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Analysis of thorium and uranium based nuclear fuel options in Fluoride salt-cooled High-temperature Reactor

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ABSTRACT

In order to utilize thorium in Fluoride salt-cooled High-temperature Reactor (FHR), neutronics analysis for thorium based fuels (^{233}U + Th, ^{235}U + Th and ^{239}Pu + Th) is carried out in a whole-core model of pebble bed FHR. Uranium (^{238}U) based fuels with the above three fissile nuclides are also analyzed for comparison. The atomic density of fissile material is kept constant at start-up for the six fuel types. Neutron characteristics including neutron spectrum, effective multiplicity factor (k_{eff}), temperature coefficient of reactivity (TCR), conversion ratio (CR) and burnup for the six fuel options are discussed. With the same fissile nuclide, the thorium based fuels have a higher initial k_{eff} than the uranium based fuels due to the smaller resonance absorption of ^{232}Th. As for fissile material, ^{233}U is the best candidate as a driver fuel in thermal and epithermal spectra due to its effective number of fission neutrons (η). Besides, the ^{232}Th/^{233}U fuel can be extended to radioactive waste management benefited from deeper burnup and lower level of radio-toxicity. The FHR core with thermal and epithermal spectra is more suitable for Th–U fuel cycle than U–Pu fuel cycle. These analyses can provide an approach for the further optimizations of thorium utilization in FHR.

1. Introduction

Most of present commercial reactors using enriched uranium (about 5%) with once-through fuel cycle will consume up the whole world's estimated uranium in a few decades along with the growing demand of energy (David, 2005). It is therefore important to develop advanced reactors with high efficiency of fuel utilization and corresponding fuel cycles (includes fuel types and fuel cycle modes) to solve the problem of nuclear fuel shortage. As an alternative nuclear fuel resource, thorium attracts more and more attentions to ensure sustainable energy generation. Thorium is a fertile fuel which is reported to be 3 ~ 4 times as abundant in the earth's crust as uranium (Wickleder et al., 2006). It will greatly expand the nuclear fuel resources through the conversion behavior from ^{232}Th to ^{233}U by a neutron capture. Th–U fuel cycle offers attractive features (Cycle, 1450), including better breeding capability in thermal reactors and lower radio-toxicity levels in nuclear waste.

Many countries and organizations have already started the research of strategy and engineering for thorium utilization since mid 1950s (Mathieu et al., 2006; García et al., 2013; Nuttin et al., 2005). The majority of options for the use of thorium previously proposed have relied on highly innovative reactor concepts (Lung, 1997), such as Molten Salt Reactor (MSR) (Merle-Lucotte et al., 2008), Liquid Metal Fast Breeder Reactor (LMFBR) (Ramanna and Lee, 1986), Super Critical Water Reactor (SCWR) (Chaudri et al., 2013) and Accelerator Driven Systems (ADS) (Salvatores et al., 1997). And the studies of thorium utilization with existing reactors, in most cases PWR specific, were also summarized (Puill, 1999).

To take the advantages of thorium, especially its great stability at high temperature and breeding capacity in thermal and epithermal spectra, thorium based fuels were tested in High-temperature gas-cooled Reactors (HTRs). Most of the researches and operating experiences of thorium utilization in HTR are focused on high enriched uranium (HEU) (Baumer and Kalinowski, 1991; Habush and Harris, 1968) or low enriched uranium (LEU) (Pohl, 2006; Ding and Kloosterman, 2014).

Fluoride salt-cooled High-temperature Reactor (FHR) (Ingersoll et al., 2004) synthesizes the advantages of MSR and HTR, which

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has similar neutronics with HTR, fueled with TRISO particle, differentiated only by its coolant with fluoride salt instead of helium gas. FHR can support conventional LEU fuel cycle and also advanced fuel options, such as thorium. The study on the neutronics performance of FHR has been concentrated on uranium (François-Paul and Fabien, 2006; Fratoni, 2008; U. M. Facilitators and M. Facilitators, 2013), while that of thorium is not enough. To achieve a high thorium utilization in FHR, University of California, Berkeley (UCB) is developing a pebble fueled FHR (PB-FHR) with a thorium blanket (Cisneros et al., 2012). In January 2011, the Chinese Academy of Science (CAS) launched the TMSR (Thorium-based Molten-Salt Reactor nuclear energy system) project with efforts for thorium utilization both in FHR (solid fuel) and MSR (liquid fuel) (Serp et al., 2014).

A whole-core model of PB-FHR was researched in UCB for uranium with varying graphite-to-heavy metal ratio (C/HM) to obtain deep burnup and sufficient negative temperature coefficient of reactivity (TCR) (François-Paul and Fabien, 2006). Since the TMSR project intends to achieve effective utilization of thorium (Jiang et al., 2012), it is necessary to study the potential utilization of thorium in FHR with a similar core geometry to UCB. Thorium and fissile materials are assumed to be homogenous mixed in each fuel kernel in a form of (X, Th) O_2 where X represents fissile materials (^{233}U, ^{235}U or ^{239}Pu). Three different uranium based fuels in a form of (X, ^{238}U) O_2 are also analyzed for comparison. It might not be somewhat suitable to analyze all the six type of fuels based on the UCB core and the related pebble geometries, which were just designed for the $^{235}\text{U} + {}^{238}\text{U}$ fuel. However, this kind of comparison under the same conditions should be able to provide an approach for the further optimization of fuel utilization in FHR. The optimization approaches of thorium fueled pebble are recommended from this analysis and the related work is being carried out.

Section 2 introduces the core description and simulation software. Section 3 presents the analysis at the beginning of life (BOL). Section 4 discusses the time-dependent characteristics. Section 5 gives the conclusions.

2. Analyses methodology

2.1. Fuel types

For convenience, the six fuel forms considered in this work are abbreviated as Th2/U3, Th2/U5, Th2/Pu9, U8/U3, U8/U5 and U8/Pu9. The atomic density of fissile material and the molar ratio of fissile to fertile fuels are approximately same in each fuel type. The C/HM of thorium fuels are around 370 while those of uranium fuels are about 375.

2.2. FHR core geometry

Fig. 1 shows the geometry model of FHR. The fuel pebbles are assumed to be regularly arranged in the columnar hexagonal lattices (Ilas et al., 2006) with a packing factor of 60% while the rest 40% is filled with FLiBe salt. Each pebble has a fuel mass of 11 g and contains 16,000 TRISO particles. In order to save computing time, it is assumed that the TRISO particles are uniformly distributed inside the pebble. Such fuels, embedded in graphite matrix that is stable at high temperature, allow irradiation for a long period and a deep burn to exploit fission energy. The fluoride salt density is 1.9 g/cm^3 (François-Paul and Fabien, 2006) at 1050 K (assumed operation temperature), in which the enrichment of ^{7}Li is 99.995%.

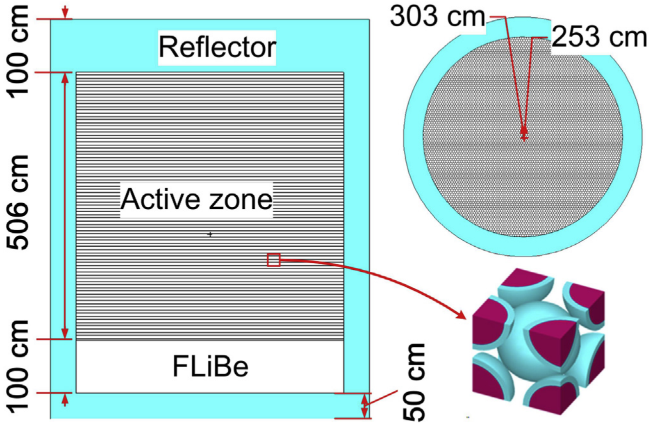

Fig. 1. Sketch of FHR.

2.3. Neutronics simulation software

Existing general-purpose codes are considered to be inadequate for FHR-specific phenomenon. The development programs for HTRs have already invested in advancing methods to account for the double heterogeneity (Schultz et al., 2010), such as the SCALE code (Goluoglu and Williams, 2005). SCALE (Scale, 2011) is a comprehensive modeling and simulating tool suited for nuclear criticality and safety analysis, in which a special DOUBLEHET is selected to deal with the double heterogeneous nature and the resonance self-shielding effect (Williams et al., 2005). The verification and validation of SCALE for modeling and analysis of HTRs (HTR-10, HTTR etc.) shows a relatively good agreement between the SCALE and MCNP calculations (Ilas et al.; Ilas, 2013; Kim, 2013). Both the Advanced High Temperature Reactor at the Oak Ridge National Laboratory (Ryan Kelly, 2013) and the Fluoride-salt-cooled, High-temperature Reactor (Allen et al., 2013) at UCB are analyzed by SCALE. Therefore, SCALE code is regarded as a suitable simulation tool at present for FHR.

In this work, SCALE version 6.1 is used for describing the thorium and uranium based FHR. A 238-group ENDF/B-VII library is selected for time-dependent cross-section processing which reveals fuel composition variation during irradiation. Additionally, the depletion is performed at a constant power (1000 MWth) and 388 nuclides are tracked in trace quantities. To improve the results accuracy, the calculation steps with a smaller time are needed especially at the beginning of the simulation to build in the equilibrium concentration of major fission products. Meanwhile, increasing the magnitude of time steps as the depletion progresses is also desired to save computing time (Allen and Knight, 2010). Under the above considerations, the FHR core is depleted for almost 3 years in 16 steps. Each depletion step is scheduled to skip 50 cycles and run a total of 200 cycles with nominally 2000 neutrons per cycle. The typical computing time of one depletion step is about 15 min.

3. Neutronics characteristics of FHR core with the six fuel types

3.1. Neutron spectrum and criticality

The neutron spectra of the six fuel types at BOL are shown in Fig. 2. With the similar C/HM, the spectra of different fuels reveal different inherent characteristics. There are resonance dips around 0.1 MeV energy range for each curve, corresponding to the inelastic