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Analysis of thorium and uranium fuel cycles in an iso-breeder lead fast reactor using extended-EQL3D procedure

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ABSTRACT

Use of thorium in fast reactors has typically been considered as a secondary option, mainly thanks to a possible self-sustaining thorium cycle already in thermal reactors and due to the limited breeding capabilities compared to U–Pu in the fast neutron energy range. In recent years nuclear waste management has become more important, and the thorium option has been reconsidered for the claimed potential to burn transuranic waste and the lower build-up of hazardous isotopes in a closed cycle. To ascertain these claims and their limitations, the fuel cycle isotopic inventory, and associated waste radio-toxicity and decay heat, should be quantified and compared to the case of the uranium cycle using realistic core configurations, with complete recycle of all the actinides. Since the transition from uranium to thorium fuel cycles will likely involve a transuranic burning phase, this transition and the challenges that the evolving fuel actinide composition presents, for instance on reactor feedback parameters, should also be analyzed. In the present paper, these issues are investigated based on core physics analysis of the Lead-cooled Fast Reactor ELSY, performed with the fast reactor ERANOS code and the EQL3D procedure allowing full-core characterization of the equilibrium cycle and the transition cycles. In order to compute radio-toxicity and decay heat, EQL3D has been extended by developing a new module, which has been assessed against ORIGEN-S and is presented here. The capability of the EQL3D procedure to treat full-core 3D geometries allowed to explicitly account for aspects related to core dimensions and safety parameters in the analysis, giving a better insight into the pros and cons of the thorium option.

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1. Introduction

Thorium fuel cycle has been widely studied in the past as a possible alternative to the use of uranium (Kazimi et al., 1999; Kuegler et al., 2007; MacDonald and Lee, 2004; Robertson, 1965), mainly for the development of a thermal breeder. Limited studies have been carried out concerning the use of thorium in Fast Reactors (FRs) (Tommasi in Gruppelaar and Schapira (2006) and Till et al. (1980)), historically conceived as breeder reactors, due to the superiority of the uranium/plutonium cycle from this standpoint.

Over the course of the years, waste management has emerged as one of the main problems for public acceptance of nuclear energy, while availability of fissile materials is still of limited concern, especially in western countries. The rationale for FR deployment has shifted from breeding to burning TRansUranic isotopes (TRUs) generated by the LWR fleet (NEA, 2006; Salvatores and Palmiotti, 2011). The use of thorium as fertile material instead of uranium typically increases the TRU burning rate (Sartori et al., 2011). In addition, the relatively low mass number of ^{232}Th leads to a characteristically low TRU inventory when a Th closed cycle is established (IAEA, 2002, 2005), with potentially beneficial impacts on the actinide radio-toxicity and decay heat. Some important safety feedbacks of the core (especially the coolant reactivity coefficient) are also improved in a thorium cycle (Pilarski and Lecarpentier, 2009; Till et al., 1980).

This study compares the performance of the UO_2-based and ThO_2-based fuel cycles in the iso-breeder (breeding gain equal to

Abbreviations: BEC, Beginning of Equilibrium Cycle; BOC, Beginning Of Cycle; BOL, Beginning Of Life; BR, Breeding Ratio; EEC, End of Equilibrium Cycle; EFPY, Equivalent Full Power Years; ELSY, European Lead SYstem; EOC, End Of Cycle; FA, Fuel Assembly; FP, Fission Products; FR, Fast Reactor; HN, Heavy Nuclides; LEADER, Lead-cooled European Advanced Demonstration Reactor; LFR, Lead Fast Reactor; pcm, per cent mille; TD, Theoretical Density; Th–Pu, core featured by ^{232}Th and ^{239}Pu as main fertile and fissile isotopes; Th–U, core featured by ^{232}Th and ^{233}U as main fertile and fissile isotopes; TRUs, TRansUranic isotopes; U–Pu, core featured by ^{238}U and ^{239}Pu as main fertile and fissile isotopes.

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zero, B.R. $-1.0 \sim 0.0$) ELSY (European Lead-cooled SYstem) core (Alemberti et al., 2011) focusing on the equilibrium core but also including start-up cores and transition cycles. An initial ^{238}U–Pu core has been selected for the UO_2 core while, for the ThO_2 core, both ^{232}Th–^{233}U and ^{232}Th–Pu start-up options have been considered. The Pu employed for the start-up cores is assumed to be reactor-grade Pu recovered from reprocessing of LWR (Light Water Reactor) used fuel. The core equilibrium state is the main case studied as it conveys the long-term potential of a given feed option. It represents the asymptotic state reached under the assumption of constant fuel management (reloading, cooling, reprocessing, feed) and it is independent of the initial core loading. While true equilibrium for all the actinide vector requires decades or centuries to be reached, the transition for the main isotopes determining safety and waste generation is completed in a relatively short time span, generally within a reactor's operating life. In addition, the more credible start-up cores and the transition cycles to equilibrium have also been investigated and will be discussed for each option.

Reactor physics analysis supporting this study has been performed with state-of-the-art equilibrium cycle methodologies, i.e. the ERANOS-based EQL3D procedure developed at the ''Paul Scherrer Institut'' (Krepel et al., 2009). This procedure enables realistic full-core 3-D simulations of the cycle-by-cycle behavior of a reactor. With respect to lumped approaches frequently adopted in literature (Salvatores et al., 2009; Coates and Parks, 2010), use of full core 3-D simulations allows direct evaluation of the core safety parameters, and a top-level assessment of the safety performance related to a fuel cycle selection. While computationally expensive, simulating the cycle-by-cycle operation of a reactor allows to continuously update microscopic and macroscopic cross-sections, accounting for self-shielding effects. Compared to equilibrium methodologies where the equilibrium is found from matrix inversion (Salvatores et al., 2009), the cycle-by-cycle iteration process maintains physical meaningfulness for the transitional steps toward equilibrium. Different transition scenarios with various rates of actinide build-up and ensuing impact on the core safety parameters can thus be conveniently investigated with EQL3D.

Since the present paper aims at characterizing thorium and uranium cycles also from a waste management viewpoint, the EQL3D procedure has been extended to provide radio-toxicity and decay heat from the main actinides. This extension is presented here together with the assessment studies performed using the ORIGEN-S code from Scale 5.1 package (SCALE, 2006). The features of the extended-EQL3D procedure have been employed in the present paper to calculate core configuration, isotopic composition, safety parameters, radio-toxicity and decay heat for the equilibrium and transition cores of ELSY with a thorium or uranium feed.

This paper is divided into six sections. Section 1 is the introduction. Section 2 presents the methodology, focusing on the extension of EQL3D to calculate core radio-toxicity and decay heat. Sections 3 and 4 present the uranium and thorium cores selected for the analyses. Section 5 compares the results obtained for the thorium and uranium fuel cycles. Finally, in Sections 6 and 7, the conclusions of the study are drawn and possible future developments are discussed.

2. Methodology

The present paper compares uranium and thorium cycles in the ELSY on the basis of the respective equilibrium cores, and of the transition toward them. The results presented in this paper have been obtained by means of the neutronic code ERANOS 2.2N (Rimpault et al., 2002). In particular, the EQL3D procedure (Krepel et al., 2009) developed at the Paul Scherrer Institut (Switzerland) has been employed. Starting from an initial fuel composition, EQL3D simulates the cycle-by-cycle behavior of a reactor. The main assumptions are constant imposed reactor power, constant mass of actinides in the fabricated fuel and constant fuel management. Under these assumptions, the simulated reactor always reaches its final equilibrium state. The resulting reactivity indicates the capability of the reactor to support a closed fuel cycle: breeder or iso-breeder reactors are expected to show a positive reactivity at equilibrium. The core is represented in its full dimensionality, thus allowing a meaningful characterization in terms of core performance as well as safety-related parameters, both at equilibrium and during the transition toward it.

The assumption of fixed mass of actinides implies that the density of the remanufactured fuel, from BOL (Beginning Of Life) to equilibrium, remains constant. In principle, the fuel theoretical densities will vary through the recycles due to the changing fuel actinide composition. As far as oxide fuels are concerned, pure ThO_2 and PuO_2 have theoretical densities equal to 10.0 g/cm^3 and 11.46 g/cm^3, respectively (Orlov et al., 2001; Rodriguez and Sundaram, 1981). In addition, the determination of the smeared density (i.e., the fuel mass divided by the volume inside the active part of the pins) depends on the fuel form and manufacturing technique, which is still speculative at this stage. Also the smeared density will likely change through the cycles of manufacturing as a result of challenging conditions from increasingly radioactive fuel and He release from alpha decay of higher actinides. Smeared densities are typically 80–90% of the Theoretical Density (TD). For simplicity, a smeared density of 87% TD (Alemberti et al., 2011), and the UO_2 theoretical density of 10.96 g/cm^3 (Orlov et al., 2001) were assumed for all cases considered. Uranium is the main component in a U–Pu core and the second in a Th–U core. The value adopted is between ThO_2 and PuO_2 densities, thus representing a reasonable value for the Th–Pu core. While the adopted value likely underestimates the U–Pu fuel density and overestimates that of Th–U, the impact on the core actinide content is expected to be marginal. In fact, in Fiorina et al. (2011), the actinide content necessary for a thorium iso-breeder was found to be fairly independent of the actinide density of the adopted fuel. The assumed fuel density will impact core dimensions, leading to a slightly larger difference between the iso-breeder U–Pu and Th–U core height than that calculated in this paper.

Full recycle of actinides has been assumed for this study, i.e. during reprocessing fission products are removed, all actinides are recycled and either natural thorium or uranium is added as feed until the actinide mass of the initial fresh fuel is restored. Due to the scoping nature of the calculations performed, a single-batch irradiation scheme has been assumed for convenience. Under this assumption, the entire core is irradiated for the full fuel irradiation time, unloaded (and ideally replaced with another one), cooled for an equally long period, reprocessed, and reloaded once again. For simplicity, the irradiation time will then be referred to as cycle. The approximations related to the use of a single-batch irradiation scheme are discussed in some details e.g. by Artioli et al. (2009) and Krepel et al. (2010).

Full core flux and burn-up calculations have been performed with ERANOS in the 33 energy-group structure optimized for FR calculation. The multigroup nodal transport theory code VARIANT has been used for flux calculations (Ruggeri, 1999), employing a P3 approximation with simplified spherical harmonics. The 33-group cross-sections have been obtained from assembly-wise lattice calculations using the collision-probability code ECCO in 1968 energy groups based on the JEFF3.1 library available in ERANOS (Sublet et al., 2006). The ECCO lattice calculations have been performed with the consistent solution method (Rimpault, 1997).

Each Fuel Assembly (FA) has been discretized in 8 axial nodes for fuel depletion calculations. Evolution of masses is computed for each of the 8 nodes of each FA according to the specific power derived through the full core flux calculations. During each cycle,

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