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Comparative analysis of thorium and uranium fuel for transuranic recycle in a sodium cooled Fast Reactor

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ABSTRACT

The present paper compares the reactor physics and transmutation performance of sodium-cooled Fast Reactors (FRs) for TRansUranic (TRU) burning with thorium (Th) or uranium (U) as fertile materials. The 1000 MWt Toshiba-Westinghouse Advanced Recycling Reactor (ARR) conceptual core has been used as benchmark for the comparison. Both burner and breakeven configurations sustained or started with a TRU supply, and assuming full actinide homogeneous recycle strategy, have been developed. State-of-the-art core physics tools have been employed to establish fuel inventory and reactor physics performances for equilibrium and transition cycles. Results show that Th fosters large improvements in the reactivity coefficients associated with coolant expansion and voiding, which enhances safety margins and, for a burner design, can be traded for maximizing the TRU burning rate. A trade-off of Th compared to U is the significantly larger fuel inventory required to achieve a breakeven design, which entails additional blankets at the detriment of core compactness as well as fuel manufacturing and separation requirements. The gamma field generated by the progeny of U-232 in the U bred from Th challenges fuel handling and manufacturing, but in case of full recycle, the high contents of Am and Cm in the transmutation fuel impose remote fuel operations regardless of the presence of U-232.

1. Introduction

Several past and recent studies have investigated the potential of Th-based Fast Reactors (FRs) for burning excess TRansUranics (TRUs) and extending use of resources (Till et al., 1980; Gruppelaar and Schapira, 2006; Touran et al., 2010; Franceschini et al., 2012; Fiorina et al., 2013a,b). Use of Th in a burner design is appealing because of the potential for achieving high TRU burning rates. In a breeder design, Th is characterized by low inventories of Pu (especially Pu-239 and higher Pu isotopes), Am and Cm, which reduce actinide decay heat and radiotoxicity for up to ~10,000 years of post-irradiation decay relatively to a counterpart U cycle. While these features may not necessarily translate into tangible waste management benefits, they can play favorably in terms of public acceptance. The main disadvantages of thorium are related to the absence of industrial infrastructure, complicated by severe challenges and less experience in reprocessing and fuel manufacturing.

The focus of the present paper is to compare the reactor inherent safety and fuel cycle aspects of Th vs. U in TRU-burner sodium-cooled FRs and breakeven core configurations, sustained or started with a TRU supply. The sodium-cooled Toshiba-Westinghouse Advanced Recycling Reactor (ARR) with TRU-burner and breakeven core configurations has been employed for the analysis. The performance of Th and U burners relying on same core design and fuel management scheme is compared. In this way the differences in burning rates and ensuing impact on inherent safety for a reference design are shown. The U fuel design is also adjusted to decrease the Conversion Ratio (CR) and match the burning rate of the Th design. This provides an additional comparison of the safety performance for two designs with same burning rate. Finally, the safety performance of Th and U breakeven designs is discussed.

Thorium presents in these cases specific advantages and drawbacks. It is advantageous when the primary concern is to improve, or mitigate, the detrimental impact on safety of coolant voiding. The improved safety margins may allow high TRU inventory and burning rates, thus reducing the number of transmutation reactors needed in a double-strata like scenario (Salvatores, 2005; Taiwo and Hill, 2005). On the other hand Th is disadvantaged by a lower

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breeding potential which for breakeven design implies use of additional blankets compared to the U design, at the detriment of core compactness, as well as fuel manufacturing and separation requirements.

The paper is organized as follows: the core physics tools and methodologies are introduced in Section 2; the core design, fuels and feeds investigated are discussed in Section 3; the main results, with a focus on inherent safety and fuel cycle aspects, are presented in Sections 4 and 5 respectively. The conclusions are provided in Section 6.

2. Methodology

The present paper compares the U and Th cycles in FRs on the basis of the respective equilibrium cores, including the transition cycles. Results have been obtained with the reactor physics code system ERANOS 2.2N (Rimpault et al., 2002), supported with the EQL3D procedure developed at the Paul Scherrer Institut (Krepel et al., 2009, 2012) and subsequently extended for Th-based FRs, as well as for computation of waste radiotoxicity and decay heat (Fiorina et al., 2013a). Three-dimensional core cycle-by-cycle simulations have been performed to allow explicit characterization of the core behavior and safety-related parameters at the equilibrium cycle and during the transition cycles.

Full recycle of actinides from discharged fuel reprocessing has been assumed in all cases, i.e. after a fixed cooling time fission products are removed from the discharged fuel, actinides are recovered and recycled into the next fuel batch admixed with either natural U or Th to restore the fertile inventory, and supplemented by LWR (Light Water Reactor) TRUs for the reactor burner options.

Due to the scoping nature of the calculations performed, a one-batch irradiation scheme has been assumed for convenience. Under the assumed scheme, the core is irradiated for a period of time corresponding to the batch irradiation time, i.e., 3 years in this case, unloaded (and ideally replaced with another one), cooled for an equally long period, reprocessed, and reloaded once again. The Beginning of Cycle (BOC) and End of Cycle (EOC) reactivities of a corresponding multi-batch cycle scheme can be approximated by properly averaging the reactivity from the one-batch core. For instance, the EOC reactivity of a 3-batch core design, where each third of the assemblies is burned respectively for 1/3, 2/3 and the entire fuel irradiation time, can be obtained averaging reactivities at 1/3, 2/3 and at the end of the cycle of the one-batch core. The underlying assumption is that core reactivity is a linear function of the isotope concentrations. One-batch simulations using the above averaging technique to represent a typical multi-batch core have been employed throughout this study, including the evaluation of the core safety coefficients. This is a reasonable approximation as discussed e.g. in Artioli et al. (2009) and Krepel et al. (2010). It is also worth mentioning that the degree of approximation associated to the averaging technique here employed reduces when the reactivity variation during a cycle is almost linear, which is the case of all the calculations performed in this paper. A control rod program has not been defined for this scoping study, and all depletion calculations are performed with control rods completely extracted from the core.

Full core flux and burn-up calculations have been performed with ERANOS in a 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 nodal cross-sections have been obtained from assembly-wise lattice calculations using the collision-probability code ECCO in 1968 energy groups with the JEFF3.1 based library available in ERANOS (Sublet et al., 2006). The ECCO cell calculations have been performed with the consistent solution method (Rimpault, 1997).

The active fuel height of each fuel assembly (FA) has been discretized in 6 axial nodes, plus 2–6 nodes for the axial blankets when present. Masses are tracked on a nodal basis and depleted according to the specific power derived through the full core flux calculations. During each 3-year cycle, fluxes are recalculated every 6 months. Macroscopic cross-sections are computed 3 times between two flux recalculations to take into account the evolving concentrations, and the specific power of each node is accordingly renormalized to maintain a constant core power. The microscopic cross-sections are recalculated once per cycle during the first few cycles, but less frequently when approaching the equilibrium. Microscopic cross-sections are calculated for each fuel zone, e.g. inner and outer zone – see Section 3.

3. Core designs, start-up core and feed selections

The FR design employed is the 1000 MWt or 420 MWe sodium-cooled Toshiba-Westinghouse ARR (Dobson, 2008). Some modifications have been made to the original core design to lower the CR in the burner configurations, as well as to increase it in the breakeven configurations. The core designs for the various options are reviewed in this Section.

3.1. Reactor designs

The core designs employed are summarized in Table 1 for the various options. The base core design features a total of 324 driver assemblies split in two regions of respectively 132 (outer core) and 192 (inner core) fuel assemblies. Each hexagonal assembly consists of 271 pins arranged in a triangular array with a 0.65 cm outer diameter cladding. The axial length of the driver fuel is 60 cm. The fuel management consists of 3-batch reloads with annual refueling intervals. Although one-batch irradiation schemes are used in this paper, the averaging techniques described in Section 2 will be used to predict the core parameters at BOC and EOC.

The main differences between burner and breakeven designs are the presence of radial and axial blankets in the breakeven cores (see Fig. 1a and b) and the fuel type chosen. Specifically, the U and Th TRU-burner options intended for the first-wave deployment rely on oxide fuel. The breakeven configurations, with longer time frame deployment, feature metallic fuel due to its superior breeding performance. Zr alloying has been assumed for U metal fuel but not for Th metal fuel. The choice of using metallic Th fuel without Zr alloying is justified by the lower swelling of Th metal when compared with U metal (Rodriguez and Sundaram, 1981). Zirconium can be added as a diluent material to increase the eutectic temperature, if needed. This will not change the core neutronic performances but will require an additional row of breeding radial blanket to compensate for the lower fertile content and associated internal breeding. Sodium bonding is adopted for the metallic fuel, He bonding for the oxide fuel.

The radial blankets employed in the breakeven designs consist of a peripheral blanket and one blanket region at the core center. Bottom and top axial blankets are also employed. In order to compensate for the deficit in breeding performance, the Th fuelled design features 60-cm thicker axial blankets relative to the U fuelled design. Although not optimized, the breakeven core designs are suitable for a top-level comparison of the core physics performance of U and Th fuels.

3.2. Fuel type, feed selection and initial core loading

As noted, oxide fuel has been selected in this work for the TRU-burner ARR cores. Metallic fuel with and without Zr alloying is