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Plutonium and Minor Actinides incineration options using innovative Na-cooled fast reactors: Impacting on phasing-out and on-going fuel cycles

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ABSTRACT

The flexibility of innovative Na-cooled fast reactors for burning Pu and/or Minor Actinides (MA) is investigated with respect to different fuel cycle strategies. Under phasing-out conditions, the burner systems are used for reducing to a minimum level the accumulated TRansUranic (TRU) inventory, whereas when continuous use of nuclear energy is envisaged (on-going case), burner systems may be dedicated to MA management only.

As an example of a phasing-out case, the accumulated German TRU inventory (at 2022) is assumed to be transmuted in a chosen time period of 150 years. For this purpose, two different burner fast reactors concepts, developed at KIT, are deployed in a Partitioning and Transmutation based fuel cycle. The effects are analyzed in order to confirm the behavior expected by the neutronics studies and to provide a basis for further optimization of the scenarios with respect to a number of reactors, deployment paces and fuel compositions.

Additionally the performance of the MA burner is assessed to provide an effective MA mass stabilization in case of a continuous use of nuclear energy. Preliminary results are compared with those of past studies based on the European Sodium-cooled Fast Reactor.

1. Introduction

Partitioning and Transmutation (P&T) technologies are developed for Spent Nuclear Fuel (SNF) management. Several objectives can be achieved by P&T, e.g. a stabilization of Minor Actinides (MA) inventories while keeping plutonium as a resource (resource optimization), or a significant reduction (within a reasonable timeframe) of accumulated TRansUranic (TRU) inventories to minimize the burden associated with their disposal (NEA–OECD, 2011; Fazio et al., 2013; Rineiski et al., 2013). Whatever is the considered objective, the development of innovative nuclear reactors able to efficiently burn MA or TRU is an important pre-requisite. Fast neutron spectrum reactors have unique neutronics features and, in particular, a very favorable neutron balance (the fission to capture ratios for MA and Pu isotopes are higher in a fast spectrum) that allow to envisage flexible options for P&T implementation. In fact, they can be designed to operate within a wide range of conversion ratio (CR) values and use fuels with practically any TRU composition (Gabrielli et al., 2013; Romanello et al., 2011; Salvatores et al., 1994).

For the present study, we consider two burner systems, both based on the French ASTRID design available in the open literature (Chenaud et al., 2013). The systems investigated at KIT are modeled for achieving a CR lower than one (where CR is defined as the ratio of the TRU production (from U) to the destruction rates (mainly due to TRU fission)).

The main modifications as compared to the initial ASTRID version are the reduction by 20% of the active core height and the same reduction of the total power. These modifications, followed by the elimination of the inner fertile blanket and a reduction of the lower axial blanket height, help to compensate the reactivity augmentation due to the increased Pu content and to avoid, at least partially, a deterioration of safety parameters expected as a consequence of the introduction of MA into driver fuel (Gabrielli et al., 2013).

In the paper, two scenarios with different objectives are considered. They are representative for different national

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strategies: a) a phasing-out scenario where the objective is to maximize the reduction of the accumulated TRU during the past operation of the nuclear reactor fleet; and b) a scenario where nuclear energy is continuously used and the utilization in future Fast Reactors (FR) of Pu is envisaged for resource optimization. We will call it "on-going scenario". In this case the burner systems are introduced for stabilizing the generated MA inventory.

As an example of a phasing-out scenario, it is assumed that the German accumulated TRU inventory (175 tons of TRU, produced by 19 German Light Water Reactors, LWR, scheduled to be gradually shut-down before the end of 2022) should be burned in about 150 years (Fazio et al., 2013; Rineiski et al., 2013; Renn, 2014).

As a first step of the analysis, the introduction in the fuel cycle of single unit has been considered. This choice has been made to confirm the behavior expected by neutronics studies and to find appropriate boundary conditions for future optimizations. In fact, the optimization of a nuclear fuel cycle scenario is a quite complex procedure, the results depend not only on the initial conditions regarding the inventory and composition of SNF, but also on the evolution of the isotopic compositions which is determined by reactor burning performance and by the scenario dynamics itself (e.g. by the time of system deployment). Therefore, several iterations between neutronics models and scenario simulations should be done.

To demonstrate the flexibility of critical burners, a simplified on-going scenario is considered as well in the following, while assuming a constant nuclear energy production. A transition from LWR to fast reactors, using the Pu available from spent fuel, is studied by introducing burner systems used mainly for stabilizing the MA inventory. The results are compared with previous studies based on the European Sodium-cooled Fast Reactor (ESFR) (Vezzoni et al., 2012c).

2. Methods and systems considered

The COSI6 code (Eschbach et al., 2013) is used for scenario analyses. This code is able to model many kinds of fuel cycle options using thermal or fast reactors once proper system specific libraries, generated by suitable neutronics codes, are provided to the embedded burn-up and depletion code (CESAR).

The use of the COSI6 code allows a better understanding of the characteristics of a fuel cycle (e.g. residual wastes, Pu and MA isotopic evolution etc.) and the impact of chosen fleet composition (sizes and types of systems). COSI6, indeed, takes into account parameters like fuel fabrication and reprocessing times, separation efficiency, natural decay evolution of materials on stocks (important for Pu241 mass assessment).

Based on a version of the ASTRID design (Chenaud et al., 2013), Pu and MA burner fast reactors have been modeled at KIT for achieving a CR lower than one. The two systems are characterized by the same geometry (see layout in Fig. 1) but different Pu to MA ratios (Table 1) in order to achieve the desired objective, i.e. burning of Pu or of MA. Compared to the ASTRID original design, the reduced by 20% total power and core active height values are adopted in order to compensate the reactivity augmentation (due to the increased Pu content) and partly to avoid as far as possible the expected deterioration of safety parameters (a lower Doppler reactivity coefficient and a more positive Na void reactivity coefficient) due to introduction of MA into fuel. The internal axial blanket of the original design has been removed and the lower axial blanket has been shortened for reducing the breeding of Pu. More details about the models have already been reported in Gabrielli et al. (2013).

New libraries for COSI6 simulations have been generated for both systems considered. For each burner, a 3D HEX-Z model has

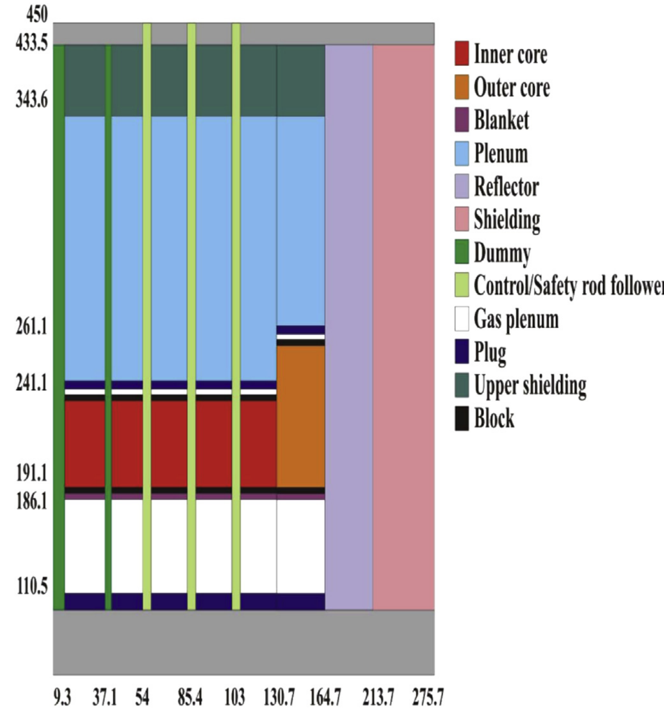

Fig. 1. RZ model of the ASTRID-like core (Gabrielli et al., 2013).

been prepared, and neutron transport calculations have been run by means of the ERANOS2.2 code (Rimpault et al., 2002) using JEFF3.1 nuclear data library (The JEFF-3.1 Nuclear Data Library, 2006). The same irradiation history for the two considered cases (phase-out and continuation), with 5 cycles of 365 effective full power days (efpd), has been considered (Gabrielli et al., 2013). The Pu and MA isotopic vectors (Gabrielli et al., 2013), refer to a typical LWR MOX SNF, reprocessed 30 years after discharge with a burn-up of about 45 MWd/kg (Artioli et al., 2008). The same approach has

Table 1
Pu and MA burners main parameters (Gabrielli et al., 2013).

	Pu burner	MA burner
Power (MWth)	1200	
Cycle length (efpd), no. cycles	365, 5	
MA/Pu ratio	1/20	1/2
Max. burn-up inner/outer core (MWd/kgiHM)	100/137	100/133
Initial HM (tons)	18.5	18.6
Conversion ratio (TRU)	0.68	0.55
Pu content (%)		
Inner core	25	23
Outer core	27	25
Pu239 eq.	16	13
MA content (%)		
Inner core (axial blanket)	1.31 (10.6)	11.8 (10.6)
Outer core (axial blanket)	1.42 (10.6)	12.8 (10.6)
Mass in core (kg)		
Initial Pu/initial MA	4800/297	4400/2170
Discharged Pu/discharged MA	4100/291	4170/1450
Burning capability (kg/TWhth)		
Pu burning	−13.2	−4.2
MA burning	−0.0	−14.5
Main safety parameters (BOL)		
K_D (pcm)	−571	−275
Void core ($\Delta\rho$, $)	3.1	5.9
Void core + plenum ($\Delta\rho$, $)	−3.4	−0.3