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MONTE-CARLO-BASED SIMULATION OF LWR CORES WITH INNOVATIVE FUEL CONCEPTS

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ABSTRACT

High resolution Monte-Carlo simulations show that the neutron spectrum, fuel burnup and fuel temperature feedback effect of a PWR core loaded with Thoria-based fuel (Th/Pu-O2) do not significantly differ from the MOX fuelled one due to the similar neutronic characteristics of both fertile materials (Th-232, U-238). The core physics of this fuel variant is characterized by an enhanced moderator/void temperature coefficient (by factor 2.4) and high incineration rate for Pu (approx. 60 %).

A PWR core loaded with the Molybdenum-based inert matrix fuel (IMF) -in contrast to MOX-, shows a harder spectrum, resulting in small temperature coefficients of reactivity and particularly in a higher fuel depletion rate as well as an enhanced TRU reduction performance. The incineration of Pu amounts to 46 % resulting, in turn, in generation of minor actinides of about 10 % of the total Pu consumption. The higher excess reactivity resulting from the initial Pu contents is controlled by the use of gadolinium oxide (dispersed) in the metallic matrix.

Key words: Monte-Carlo simulation, Thoria fuel, IMF, transmutation, fuel depletion, neutron spectrum

1. INTRODUCTION

During the last years, comprehensive research works have been conducted to study the neutronic performance, transmutation potential and safety characteristics of the so called Inert Matrix Fuels (IMF) including thoria-based fuel in the aim of reducing the current excess stockpiles of plutonium and other transuranium elements [1-3]. Among the others and as a new option metallic matrix consisting of depleted Molybdenum is proven to be one of the promising and feasible concept [4]. In comparison to the conventional fuel of UO_2 and MOX type, the new CERMET fuel as well as the thoria-based fuel matrix exhibit well-promising neutronic behaviour and safety characteristics with considerable transmutation potential for transuranium (TRU).

The purpose of the present work is to investigate at what extent and how the neutronic performance is influenced by the change of fuel type from MOX to Th/Pu-O2 fuel and IMF variant. Due to the complexity of reactor core configurations and respective neutronic processes, advanced models and methods are needed. For this aim parallelized MONTE-BURNS code based on the MCNP Monte-Carlo Code and ORIGEN is employed in combination with NJOY for the generation of nuclear data files [5-7].

2. SPECIFICATION OF FUEL VARIANTS

The design of the fuel assembly is based on a standard 17x17-25 PWR one of different fuel loadings. The MOX fuel assembly (14x14-16) contains a mixtures of PuO_2 and UO_2 with the enrichment of 3.90/0.71 wt% for Pufiss and U-235 respectively. Pu is originating from the 1st generation Pu discharged from current fleet of LWRs with a final burnup of 41 MWd/kgHM. Regarding the $(Th/Pu)O_2$ fuel the initial composition derives from the recovered Pu from a reference UO_2-core after a target burnup of 60 MWd/kgHM. With respect to the reactivity control boron is added to in the coolant in a certain concentration.

The IMF fuel pellets are composed of PuO_2 particles dispersed in a matrix consisting of depleted molybdenum. The PuO_2 content is 12 % (vol) with a Pu vector equivalent to the 1st generation Pu discharged from a standard UO_2 core after a burnup level of 41 MWd/kgHM. With respect to the control of the excess reactivity at BOC the fuel pins contain 6.0 wt% of Gd_2O_3 dispersed homogeneously in the matrix.

3. NUMERICAL METHOD FOR THE CORE PHYSICS SIMULATION

The complex structure of the reactor requires a precise geometrical description as realized in the MCNP Monte-Carlo code. It is applied to study the behaviour of FA and to produce core physics parameters, cross sections for using in the coupled isotope depletion code ORIGEN. With respect to the comparability of different loading configurations (MOX, $Th/Pu\text{-}O_2$ and IMF respectively), a homogenous core consisting of one fuel type is applied. Each cell in the lattice contains a detailed model of the fuel pin of the respective composition according to the fuel type, cladding (Zircalloy), gap and surrounding moderator with the additive of boron (1300 ppm at BOC). The effect of the surrounding FAs is taking into account by applying white (reflected) boundary conditions. In all cases a total power of 1000 MWe is assumed to represent a standard PWR. The variation of the isotopic concentrations in each fuel pin is calculated by performing depletion runs with ORIGEN. For the most isotopes the ENDF/B-VI and VII data libraries are employed.

4. NEUTRONIC BEHAVIOUR OF DIFFERENT CORES

Fig. 1 shows the variation of the multiplication factor for three different core loadings: MOX, $(Th/Pu)O_2$ and IMF respectively. Accordingly, the two first fuel types show very similar behavior due to the neutronic influence of Pu existing in these two fuels and small difference in the cross section of the respective fertile isotopes. The variation of keff in the IMF case shows a significant difference. This is due to the fact that in the case of $(Th/Pu)O_2$ and MOX fuelled cores, the depletion of fissile Pu is slowed by the generation of additional fissile material from the existing fertile uranium and thorium respectively (breeding). This result is explained by the comparison of the spectra depicted in Fig. 2. Accordingly the first two neutron spectra (MOX and Thoria-case) show negligible difference resulting from the similar effect of both fuel compositions. The spectrum in the IMF core displays a significant shift from thermal to epithermal region resulting from the lower absorption cross section of molybdenum. For the demonstration of this effect, the thermal part is additionally depicted in Fig. 2 in linear scale.

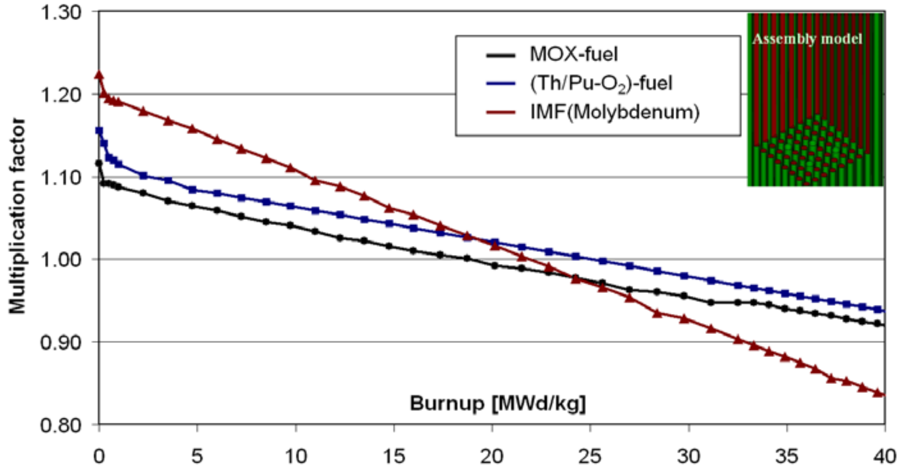

Fig. 1: Multiplication factor as a function of burn-up for different PWR core loadings

The study of safety characteristics of the selected fuels -expressed in temperature coefficients of reactivity- shows smaller values for the IMF core due to the neutronic effect of Molybdenum. The different isotopes of this nuclide have moderate resonance lines resulting in a less doppler broadening in epithermal energy range.

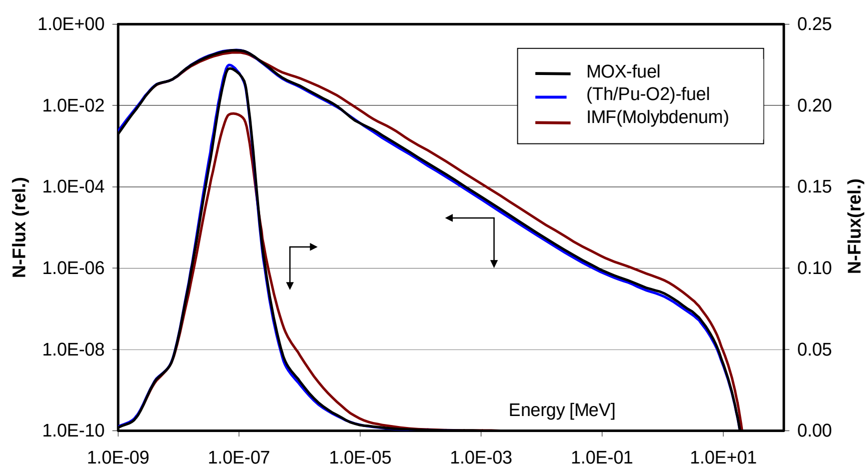

Fig. 2: Comparison of the neutron spectrum in the fuel pin for different fuel types

The moderator coefficient is also considerably lower due to the higher initial loading of Pu with an enhanced resonance line in upper thermal energy range. Due to the depletion of Pu with burnup, this coefficient changes significantly from BOC to EOC. The effect of the temperature on the boron worth is also considerably lower in the IMF concept than for the MOX and $(Th/Pu)O_2$ fuel respectively.

The simulation of the transmutation process indicates an enhanced performance of $(Th/Pu)O_2$ and IMF fuelled cores in both, reduction of Pu and TRU (per MW reactor power). A PWR core loaded with the new fuel variants shows an incineration rate for Pu which is about 60 % (Th/Pu-O_2) and 46 % (IMF) respectively. By comparison, the MOX core consumes 26.5 % only. This is due to the replacement of U-238 (MOX) by Thorium and Molybdenum respectively. As a consequence of Pu consumption MA are produced with a fraction of 14 % (MOX), 7 % ($(Th/Pu)O_2$) and 10 % (IMF) respectively, of total Pu depleted.

5. CONCLUSIONS

The burnup behavior of a standard PWR loaded with innovative thoria-based fuel is comparable with the MOX fuelled cores. Due to the similar Pu content and characteristics of both fertile materials these two fuels show minor different in the neutron spectrum and in the fuel temperature feedback effect (doppler coefficient). This thorium fuel option is also characterized by an enhanced moderator/void coefficient. The performance of such cores for the transmutation of TRU is higher than MOX fuelled cores due to the different burnup behaviour of both fertile nuclides.

The new IMF variant is distinguished by high fuel consumption rate and transmutation of TRU generated with the fission process. The core physics of such a core is characterised by a harder neutron spectrum and moderate safety parameters. Due to higher conductivity of the metallic matrix of this fuel a moderate temperature profile is expected in the fuel rods. For the control of the excess reactivity resulting from the high initial Pu loading burnable absorber (gadolinium oxide 6.0 wt%) is used that leads to the smoothing of the power density distribution and reactivity swing.

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