Advanced fuel cycles options for LWRs and IMF benchmark definition

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Abstract

In the paper, different advanced nuclear fuel cycles including thorium-based fuel and inert-matrix fuel are examined under light water reactor conditions, especially VVER-440, and compared. Two investigated thorium based fuels include one solely plutonium-thorium based fuel and the second one plutonium-thorium based fuel with initial uranium content. Both of them are used to carry and burn or transmute plutonium created in the classical UOX cycle. The inert-matrix fuel consist of plutonium and minor actinides separated from spent UOX fuel fixxed in yttria-stabilised zirconia matrix.

The article shows analysed fuel cycles and their short description. The conclusion is concentrated on the rate of Pu transmutation and Pu with minor actinides cumulating in the spent advanced thorium fuel and its comparison to UOX open fuel cycle.

Definition of IMF benchmark based on presented scenario is given.

Keywords: VVER-440, thorium, plutonium, inert matrix fuel, fuel cycle, reprocessing, transmutation

1. INTRODUCTION

Introduction of advanced nuclear fuel cycles into operating conditions needs consistent studies of fuel material behaviour under neutron irradiation. This work is focused on the study of plutonium and minor actinides changes using an advanced nuclear fuel – thorium based fuel and inert matrix based fuel – in VVER-440 light water reactor.

The analysed cycles are based on reprocessing of spent UOX fuel burnt in VVER-440 reactor type under normal operating conditions, separation of plutonium, fabrication of an advanced fuel type and its reuse in the same reactor type, VVER-440. The calculated and compared values are the plutonium transmutation rates. All fuel cycles were calculated by HELIOS 1.9 spectral code.

2. ANALYSED CYCLES AND MODEL

Calculated and compared fuel types contain plutonium-thorium mixed oxide (PuThOX), similar plutonium-thorium fuel with uranium content (UPuThOX) and advanced inert matrix fuel (IMF). Designed and analysed fuel cycles with mentioned fuel types are compared with classical open UOX fuel cycle.

The basic scheme of the thorium nuclear fuel cycle under light water reactor conditions is in Figure 1. PuThOX equilibrium fuel cycle is as follows: The cycle starts with fabrication of the classical nuclear fuel, UO_2, which is used nowadays in reactors worldwide. After burning the fuel in a VVER-440 reactor and its storage for 5 years the fuel is reprocessed, plutonium is separated. These separated plutonium isotopes are then mixed with thorium and fixed in oxide pelletsand then used in the light water reactor. It’s irradiation causes changes of radioactive nuclei to non-active nuclei or nuclei with a short half time of decay in transmutation reactions. To fulfil assembly multiplication properties similar to those used in UOX VVER-440 core the amount of added plutonium has to be adjusted. Plutonium separated from one UOX core is not sufficient to fulfil similar multiplication properties of fresh PuThOX fuel for one core, so in the case of equilibrium cycle more UOX reactors are needed.

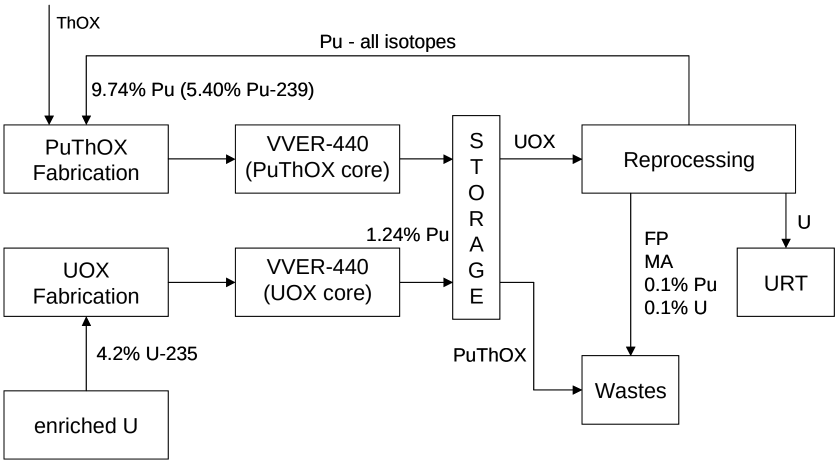

Fig. 1. PuThOX fuel cycle

In the case of thorium fuel with uranium content another reprocessing step – separation of uranium isotopes – is added. Uranium oxides are mixed together with separated plutonium oxides and thorium oxide. The difference is shown in Figure 2. Problems to fulfil assembly multiplication properties are similar as in the case of PuThOX fuel, the only difference is in the total numbers of UOX cores needed to operate one UPuThOX core. In the case of UPuThOX fuel it is less than a half as in the case of PuThOX fuel.

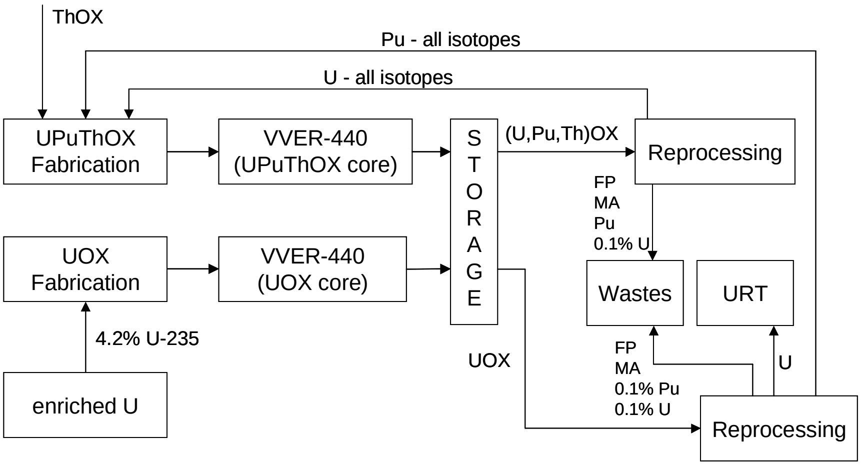

Fig. 2. UPuThOX fuel cycle

Inert matrix fuel (IMF) is a fuel prepared by mixing separated plutonium and minor actinides into an yttria stabilized zirconium matrix. The advance of the inert matrix fuel is in the non-proliferation resistance against outside impacts. The cycle is similar to MOX fuel cycle: Natural uranium is enriched and burnt in a light water reactor in the same way as before to target burn-up 50000 MWd/tHM and after a cooling time of 5 years the spent fuel is reprocessed. Separated plutonium and minor actinides are then mixed with the zirconium inert matrix and loaded into a fresh assembly. To ensure symmetrical distribution of power loading, a new type of fuel assembly was modelled. Detailed information about computation models is given in the following text.

The analysed fuel cycle with inert matrix fuel is operated in the self-cleaning manner. Separated plutonium and minor actinides from one burnt UOX assembly are loaded into one advanced assembly to selected pins. The cycle calculates only with 0.1% of Pu and MA losses during the separation process. There is no multirecycling of the inert matrix fuel. A scheme of the advanced cycle is in Figure 3.

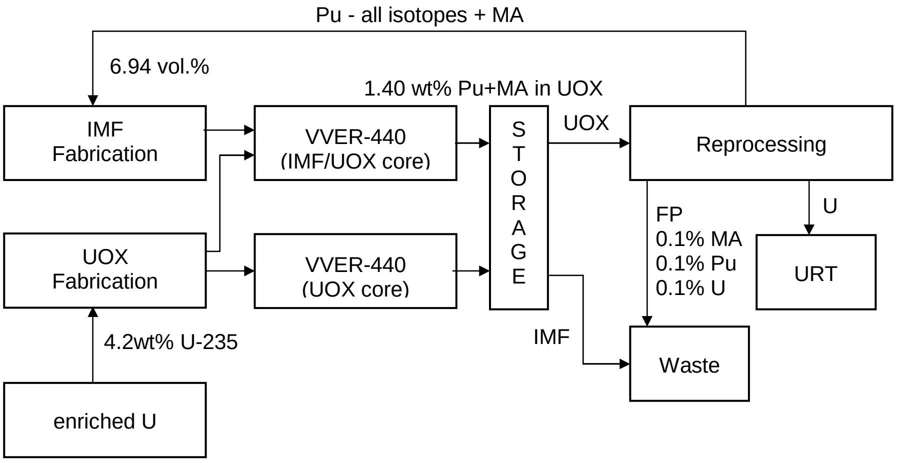

Fig. 3. IMF fuel cycle

Optimization of fissile material content assures the ability of the use of this advanced fuel in normal VVER-440 operating conditions. Figure 4 shows the multiplication factor reached with selected fission material content in the fuel. Table 1 summarizes the fissile isotope content in different fuel types. More about the cycles can be found in ref. [6, 7].

Table 1. Fissile isotope content in the fuel

	UOX	PuThOX	UPuThOX	IMF
UOX cores needed	0	7.90	3.40	0
U-235 input rate	4.2	0.00	2.20 (U-233)	0.00
Pu input rate	0.0	9.74	4.14	1.249
Pu-239 input rate	0.0	5.40	2.29	0.652
MA input rate	0.0	0.00	0.00	0.084

Calculation properties and variables were set to reach the target burn-up of 50 GWd/tHM in 5 years cycle (4 outages, 320 fpd cycle).

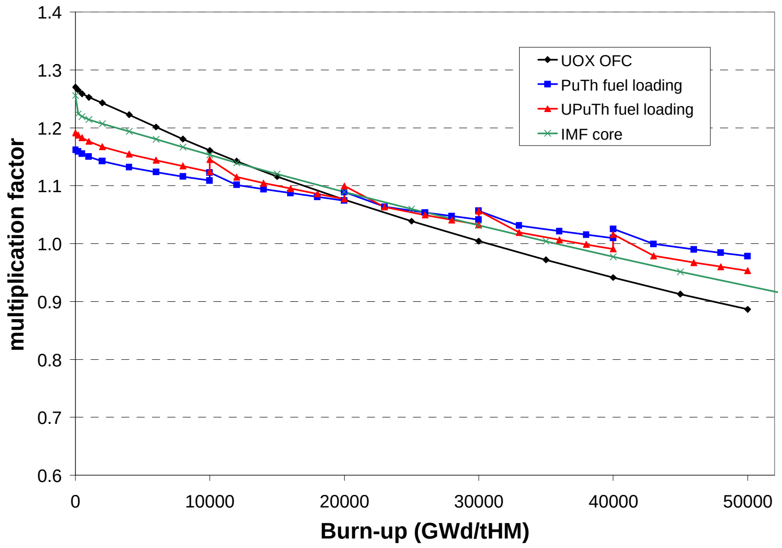

Fig. 4. Multiplication factor as a function of burnup

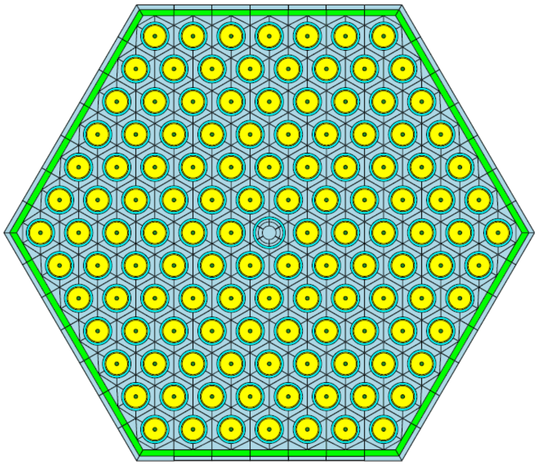

Fig. 5a: Model of VVER-440 assembly

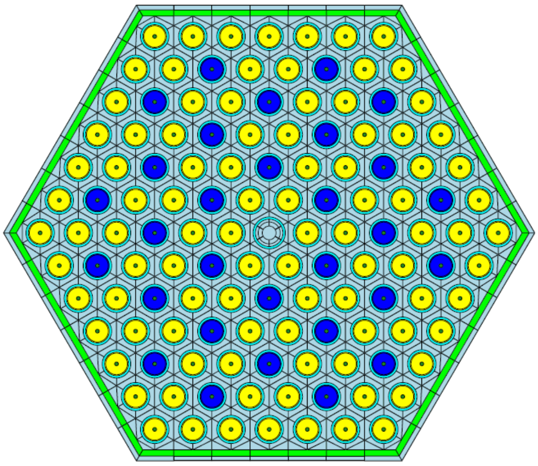

Figure 5b: Model of advanced VVER-440 assembly

Two models of VVER-440 assemblies were prepared. The first one, Figure 5a, is the VVER-440 assembly with one type of fuel pins. This assembly was used for calculations of open and thorium based fuel cycle. To perform calculations with inert matrix fuel an advanced VVER-440 assembly was prepared, Figure 5b, with two different fuel types. The advanced fuel is placed into dark pins, the rest are fresh UOX pins. The assemblies are computed in an infinite lattice – neutrons which escape from the one surface of the assembly enter the assembly at the other one.

3. RESULTS

Table 2 shows in different equilibrium fuel cycles comparison of plutonium content, Pu transmutation rates and total Pu with MA generation. Pu content in spent fuel is in the case of PuThOX app. 4 times higher than in the case of UOX, which is caused by high initial Pu content. Pu content in the case of UPuThOX fuel is in comparable range to UOX fuel, even if fresh fuel contains Pu isotopes. UPuThOX fuel shows higher Pu transmutation potential as PuThOX fuel. IMF fuel offers high Pu transmutation rate with the lowest Pu and MA generation rate in comparison with all mentioned fuel cycles.

Table 3 summarizes MA content in the fuels. In both types of thorium fuel MA content is higher as in UOX spent fuel, but UPuThOX fuel shows smaller MA production, due to initial content of U-233 and lower content of Pu as in the case of PuThOX fuel. IMF shows the lowest content of MA in spent fuel.

Table 2. Potencial of Pu transmutation

	UOX	**PuThOX**	**UPuThOX**	**IMF**
Pu initial (kg/tHM)	0	97.38	41.42	14.05
Pu in spent fuel after 5y cooling (kg/tHM)	12.37	51.39	15.25	3.21
MA in spent fuel after 5y cooling (kg/tHM)	1.48	6.15	3.39	1.22
Pu transmutation rate (%)	0	47.22	63.18	77.08
Pu transmutation rate (kg/TWhe)	0	13.22	17.64	7.32
Rate of Pu and MA in the fuel entering reactors (%)	0	9.74	7.88	-
Rate of Pu and MA in the spent fuel, after 5-years cooling (%)	1.38	5.75	1.81	-
Pu generation rate (kg/TWhe)	32.2	15.5	10.5	6.2
MA genetration rate (kg/TWhe)	3.8	3.3	2.9	2.7

Table 3. MA content in the fuel (g/tHM)

MA	**UOX**	**PuThOX**	**UPuThOX**	**IMF**
Am	7.01E+02	5.34E+03	2.35E+03	6.88E+02
Cm	8.77E+01	8.07E+02	5.63E+02	5.31E+02
Cf	1.91E-05	2.63E-04	3.56E-04	4.34E-03
∑MA	1.47E+03	6.15E+03	3.39E+03	1.22E+03

4. IMF BENCHMARK DEFINITION

Simple IMF benchmark based on the mentioned IMF fuel cycle is designed. The basic geometry data are based on the specifications of a VVER-440 fuel assembly. Figure 5b above shows schematically the mapping of the fuel assembly, which contains 126 pins of the fuel. 96 of them (yellow) are the classical UOX pins of 4.2% U-235 enrichment, 30 of them (blue) are pins loaded with IM fuel. The main geometry and operational parameters are given in Table 4.

Table 4. Main geometry and parameters of VVER-440 assembly

Core data		
Thermal power	MW	1375
Number of fuel assemblies	---	349
Active height	cm	250
Boron-10 composition	w/o	19.8
Boron-11 composition	w/o	80.2
Boron concentration	ppm	456
Assembly data		
Assembly configuration	---	hexagonal
Assembly pitch	cm	14.7
Shroud outer dimension	cm	14.5
Shroud thickness	cm	0.15
Number of fuel rods	---	126
Instrumentation tube position	---	central
Fuel rod		
Clad material		Zirconium
Fuel diameter	cm	0.757
Fuel inner hole diameter	cm	0.14
Clad diameter	cm	0.91
Clad thickness	cm	0.07
Pin pitch	cm	1.22

Instrumentation tube		
Material		Zirconium
Outer diameter	cm	1.03
Inner diameter	cm	0.88
Temperatures		
Fuel	K	982
Clad	K	558
Moderator	K	558
Densities		
Cladding density nominal	g/cm^3	6.555
Moderator density	g/cm^3	0.76
Theoretical UO$_2$	g/cm^3	10.07
Theoretical IMF	g/cm^3	6.5

The fuel assembly is composed of two different fuel types. UOX pins are made of pure 4.2% U-235 oxide, no impurities are taken into acount. Inert matrix fuel is composed of Pu and MAs from the spent UOX fuel dispersed in zirconium matrix. The Pu and MAs vector used in IM fuel is equivalent to 1st generation Pu and MAs discharged from the first IM loading to VVER-440 with a discharged burnup of 50 MWd/tHM of UOX fuel. (see Table 5). To simplify benchmark natural zirconium dioxide is used as matrix instead of yttrium stabilised matrix. Calculated burnup is 50 MWd/tHM of UOX fuel.

Table 5. Fuel composition of fuel types

UOX fuel		**IMF fuel**					
	*1/(barn*cm)*		*1/(barn*cm)*		*1/(barn*cm)*		*1/(barn*cm)*
O-16	4.47410E-02	O-16	8.0249549E-02	Am-241	3.6143060E-05	Bk-249	2.2704335E-14
U-235	1.90018E-03	natural Zr	3.8812254E-02	Am-243	1.6808271E-05	Cf-249	1.4283559E-12
U-238	5.57558E-08	Np-237	5.0737229E-05	Am-242m	1.2047355E-07	Cf-250	4.6322753E-13
		Np-238	3.1967676E-20	Cm-242	1.1710720E-09	Cf-251	2.7949109E-13
		Np-239	3.1967767E-20	Cm-243	4.9758432E-08	Cf-252	5.0872569E-14
		Pu-238	2.6827605E-05	Cm-244	6.1059686E-06		
		Pu-239	4.6552515E-04	Cm-245	4.9055160E-07		
		Pu-240	2.2381144E-04	Cm-246	6.1342599E-08		
		Pu-241	1.0929358E-04	Cm-247	8.8052646E-10		
		Pu-242	6.4039171E-05	Cm-248	9.5044786E-11		

Requested output dara are:

1. multiplication factor as a function of burnup
2. fuel composition after 5 years of cooling (IM fuel namely)

Results should be formated in a tabular way, free of format. This benchmark is defined as mathematical test.

5. CONCLUSION

Equilibrium advanced fuel cycles calculations were performed. Result shows the ability of thorium fuel to perform partial plutonium transmutation, but not prevention of plutonium creation. Thorium fuel under light water reactor conditions will produce less than half of plutonium only as is produced nowadays using UOX fuel. The same should be said about IMF fuel under LWR conditions. IMF fuel cycle offer high transmutation potentional of Pu and the lowest Pu and MA generation rate of all mentioned fuel types and cycles. The difference between Pu generation rate of UOX and IMF fuel cycle is 32.2 kg/TWhe to 6.2 kg/TWhe, which represent more than 80% smaller plutonium production per same produced energy.

Advanced fuel cycles with thorium and inert matrix fuel need more detailed study of safety assessment. Possibilities like use of thorium-based and inert matrix fuel in different reactor types, different core loadings, etc. have to be studied as well.

The simple IMF benchmark is defined. All suggestions are welcome.

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