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Feasibility Study for Minor Actinides Transmutation in Conventional Power Reactors

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Feasibility Study for Minor Actinides Transmutation in Conventional Power Reactors

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Abstract. The handling and storage of the spent fuel from the current nuclear power reactors is one of the major ecological challenges in front of the nuclear energy industry, due to its long period of high radiotoxicity. It is mainly caused by the long-lived minor actinides generated in the nuclear fuel. Therefore profound study of the possibilities for shortening the terms of storage of spent nuclear fuels and some of high radioactive waste through the currently available technologies is necessary. The possibility for transmutation of Neptunium, Americium and Curium isotopes, as most abundant in the spent nuclear fuel of the wide-spread Light Water Reactors is evaluated in the paper using one of the most recent tools, available for the purpose. The most technologically accessible option, the current nuclear power reactors is analysed. The fuel in the cores of the LWR (PWR) and the PHWR (CANDU) type of reactors are modelled and the variation of the quantity of Neptunium, Americium and Curium isotopes after typical fuel campaigns for these reactors is estimated. The obtained results show that under the investigated conditions both types of reactors show potential for decrease of the minor actinides quantity in spent fuel before its final disposal, therefore provide a vital option toward sustainable and environmentally friendly nuclear spent fuel management.

1. Introduction

The sustainable management of the spent nuclear fuel (SNF) from the current nuclear power reactors is troubled by the high radioactivity of some of the long-lived radioisotopes, contained in it. Therefore, the profound study of the possibilities for shortening the terms of storage of radioactive waste through the currently available technologies is of great importance. The most reliable, effective and currently the only technological solution for a significant reduction of radiotoxicity by reducing plutonium isotopes and minor actinides is the transmutation process [1]. Artificial transmutation technology has the potential to significantly reduce the negative effects of radioactive waste on humans and the environment by reducing the concentration of long-lived isotopes in the spent fuel from the nuclear power reactors. Therefore the transmutation of radioactive waste is considered to solve part of the main problems of nuclear energy. One of the main problems of the spent fuel storage and handling is the minor actinides abundance in it. The minor actinides include Neptunium, Americium, Curium, Berkelium, Californium, Einsteinium, and Fermium. From the point of view of the storage and processing of spent nuclear fuel, the most important isotopes contained in it are Neptunium, Americium and the isotopes of Curium and Californium. Of these, the largest share are the isotopes of the elements Neptunium (app. 50%), Americium (app. 47%) and Curium (app. 3%), all of which are extremely radiotoxic [2, 3]. One of the most accessible approaches for their transmutation is to transform them into shorter-lived isotopes using the reactors' cores of the current nuclear power reactors fleet. The current paper focuses on assessing the possibility to use the PWR (Pressurized Water Reactor) [4] and the CANDU (CANada Deuterium Uranium) pressurized heavy-water reactor (PHWR) [5] for transmutation of minor actinides emerged from PWR spent fuel, by means of the burnup process numerical modelling.

2. Calculations

The recently released Version 2.2 of the SERPENT 2 [6] code is used in the calculations. It is a burnup and transport code that models the nuclear particles behavior using the Monte Carlo Method and therefore has a potential to be applied in different aspects of the nuclear reactor research. Its worth mentioning that Monte Carlo methods are very different from diffusion transport methods, since Monte Carlo obtains answers by simulating individual particles and scores different responses (tallies) of their average behavior, rather than solving explicitly some equation. The SERPENT code is also capable to be used for modelling detectors response in experiments' set-ups, cross-sections behavior, and nucleus production from different reactions, etc. There are numerous major advantages from user point of view, when using of the SERPENT code. These include the possibility to obtain identity of the source and the geometry of the model for calculations with the investigated object, integrated model's geometry visualization, up-to-date crosssections libraries with continuous representation of the sections by energy and many others are available for the SERPENT 2 software.

Using the mentioned tools and abilities of the code, an adequate 3D model of the PWR (figure 1) and CANDU (figure 2) reactors' assemblies are created. The model represents pin-by-pin representation of the reactors assemblies. The CANDU model represents the fuel batch, the fuel pressure tube and the calandria tube. The PWR model represents 15x15 grid fresh fuel assembly with 4.3% Uranium-235 enrichment. The initial minor actinides generation is performed for 1280-day long fuel campaign (app. 4 years with 320 days each), power density of 41.6 kW/kgU, burn-up of 53.2 MWd//kgU and neutron flux of 5.38×10^{13} n/cm^2.s. The amounts in grams of the minor actinides' isotopes in 1 cubic centimeter (cc) of SNF are shown in table 1. These are then loaded for subsequent transmutation in the same type of PWR assembly, and in a typical CANDU reactor fuel batch. The transmutation in PWR reactor core is performed in the same conditions as those applied during the initial generation of the minor actinides. The modelling for the CANDU reactor has been performed for a continuous fuel campaign of 302 days (without outages), a thermal output of 35 kW/kgU, a burnup 10.6 MWd//kgU, and a neutron flux of 8.53×10^{13} n/cm^2.s. ENDF/B-VII.1 [7] based cross sections are used for the calculations.

Table 1. Initial amounts of the minor actinides in the SNF.

Isotope	Mass in 1cc *SNF, g*	Isotope	Mass in 1cc *SNF, g*	Isotope	Mass in 1cc *SNF, g*
Am-241	3.15E-04	Cm-244	8.71E-04	Np-238	1.84E-05
Am-243	1.97E-03	Cm-245	4.56E-05	Np-239	8.09E-04
Cm-242	1.95E-04	Cm-246	7.47E-06		
Cm-243	6.19E-06	Np-237	5.33E-03		

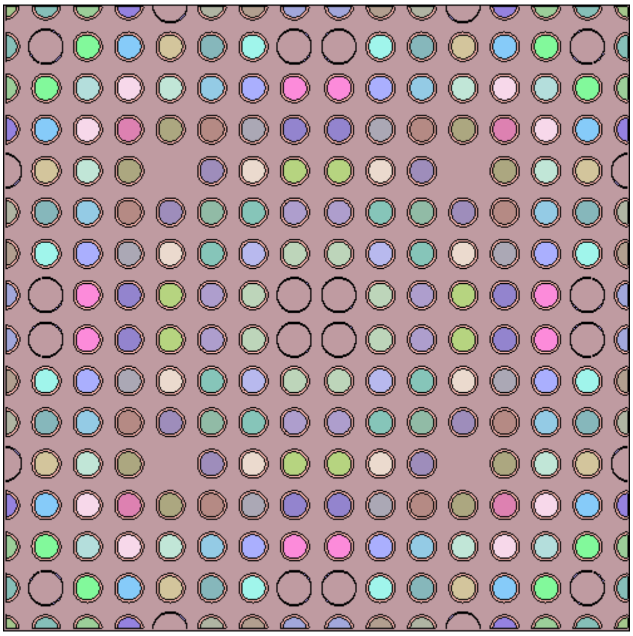

Figure 1. 3D SERPENT model of PWR assembly for burnup calculation

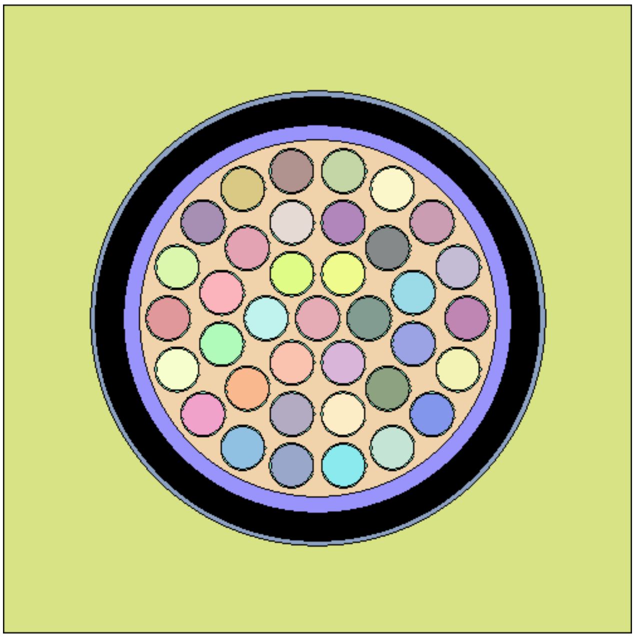

Figure 2. 3D SERPENT model of CANDU assembly for burnup calculation

3. Results

Results from calculations with the SERPENT 2 Monte Carlo code were obtained for evaluating the possibility for transmutation in PWR and CANDU power reactors of selected minor actinides' isotopes were obtained. Am-241, Am-243, Cm-242, Cm-243, Cm-244, Cm-245, Cm-246, Np-237, Np-238, Np-239 were modelled. The results of the final distribution in the spent nuclear fuel and the difference with the initially loaded quantity (final/initial-1, %) are presented in table 2 for transmutation in the PWR reactor core and in table 3 for CANDU reactor core.

Table 2. Transmutation in PWR reactor core.

Isotope	Final mass in 1cc SNF, *g*	Difference, %
Am-241	3.27E-04	3.80
Am-243	2.30E-03	16.51
Cm-242	2.06E-04	5.78
Cm-243	7.71E-06	24.75
Cm-244	2.39E-03	174.85
Cm-245	1.79E-04	292.13
Cm-246	1.06E-04	1314.61
Np-237	6.88E-03	29.11
Np-238	2.35E-05	27.72
Np-239	8.04E-04	-0.55

It is clearly seen from the table that the reloading of minor actinides in the PWR reactor core for the purpose of their transmutation leads to significant reduction of their final quantity in the PWR spent fuel. The most abundant elements – Americium and Neptunium increase in up to 30% after the transmutation cycle and only the Curium shows significant increase.

Table 3. Transmutation in CANDU reactor core.

Isotope	Final mass in 1cc SNF, *g*	Difference, %
Am-241	8.62E-05	-72.65
Am-243	9.93E-04	-49.71
Cm-242	1.58E-04	-18.83
Cm-243	9.46E-06	52.85
Cm-244	1.77E-03	103.50
Cm-245	1.53E-04	234.51
Cm-246	4.53E-05	506.70
Np-237	3.29E-03	-38.35
Np-238	2.00E-05	8.62
Np-239	1.22E-03	51.28

Based on the results presented in table 3 it may be concluded that burning the minor actinides from PWR spent fuel in the CANDU reactor core is even better option, since the quantity of more of the investigated Americium and Neptunium isotopes decreases during the campaign. Neither of the rest Americium and Neptunium isotopes increases with more than 80% thus assuring effective decrease of their quantity before final disposal. Again the Curium isotopes show significant increase, but it is up to factor of 2 less than those in the PWR case for the highest increasing isotope.

4. Conclusion

Feasibility study for minor actinides transmutation in two conventional power reactors, using the newly released version 2.2 of the SERPENT 2 Monte Carlo code has been performed. The transmutation of the most abundant in the LWR spent fuel actinides Am-241, Am-243, Cm-242, Cm-243, Cm-244, Cm-245, Cm-246, Np-237, Np-238, Np-239 is modelled. Two types of reactors' cores were investigated – the LWR PWR and the PHWR CANDU. The initially generated quantities of the investigated isotopes were determined in the PWR spent nuclear fuel. The variation of their quantity after typical fuel campaigns for both nuclear reactors is estimated. The results show that under the investigated conditions the CANDU reactor core provides better transmutation, but in both cases is observed effective decrease of the minor actinides quantity in spent fuel before its final disposal. It may be concluded that the transmutation of minor actinides in the cores of the current nuclear power reactors fleet provides a vital option toward sustainable and environmentally friendly spent nuclear fuel management and should be investigated in details using the most modern available scientific tools.

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