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Transmutation of minor actinides in the pressurized water reactors

Bin Liu [a,*], Kai Wang [b], Jing Tu [c], Fang Liu [a,c], Liming Huang [a], Wenchao Hu [a]

[a] School of Nuclear Science & Engineering, North China Electric Power University, Beijing 102206, China
[b] Shanghai Institute of Applied Physics, Jiading, Shanghai 201800, China
[c] Northwest Institute of Nuclear Technology, Xian, Shanxi 710024, China

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ABSTRACT

We study the effects of adding MA nuclides to the PWR core and the MA nuclide transmutation rate in the PWRs. Our calculation results show that even 1% homogeneous addition of MA nuclides to the nuclear fuel can reduce k_{eff} of the PWRs drastically. The uniform distribution of MA nuclides in the uranium dioxide fuel can also affect the lifetime of a fuel loading. Calculation results also indicate that the uniform distribution of MA nuclides in the uranium dioxide fuel results in a reactivity mismatch and control difficulties in the PWRs. The spatial self-shielding effects of the heterogeneous distributions of MA nuclides in the PWR core can avoid the initial reactivity to drop significantly, and the reactivity mismatch and control difficulties in the PWRs can be also overcome.

During 300-day-exposure of MA nuclides in the PWRs 14.8% Pu-238 and 7.7% Pu-239 of the initial MA nuclides are created, this explains at least 22.5% MA nuclides transmute to plutonium isotopes during 300-day-exposure in PWRs by various nuclear processes. We may incinerate plutonium-239 and plutonium-238 isotopes in the subsequent MOX fuel loading of the PWRs. Alternatively, we may also use Pu-238 created in the transmutation of MA nuclides in the PWRs to fabricate the nuclear batteries. Pu-238 mainly transmuted from neptunium-237 in PWRs, neptunium-237 constitutes 56.2% of the total minor actinides in the depleted nuclear fuel of PWRs. The majority of commercial reactors in operation in the world are PWRs, if we get the neptunium-237 transmuted in the PWRs during their power generating, the inventory of high level long-lived radioactive minor actinides in the world will be greatly reduced.

Our study show MA nuclides actually can act as the burnable poisons in the PWRs. MA nuclide transmutation materials may be used to partially substitute for the burnable poisons in the PWRs, or reduce the concentration of the boric acid in the coolant of the PWRs and increase the negative temperature coefficient of the PWRs. This is a distinct advantage to transmute MA nuclides in the PWRs. The transmutation characteristics of MA nuclides in PWRs and high flux thermal reactors are also compared in this research.

1. Introduction

Pressurized water reactors (PWRs) constitute the large majority of world nuclear power plants and are one of the three types of light water reactor (LWR), the other types being boiling water reactors (BWRs) and supercritical water reactors (SCWRs). In a PWR, the primary coolant is pumped under high pressure to the reactor core where it is heated by the energy generated by the fission of nuclear fuel atoms. The heated water then flows to a steam generator where it transfers its thermal energy to a secondary system where steam is generated and flows to turbines which, in turn, spin an electric generator. PWRs were originally designed to serve as nuclear propulsion for nuclear submarines.

Boron and control rods are used to maintain primary system temperature at the desired point. In order to decrease power, the operator throttles shut turbine inlet valves. The operator can control the steady state operating temperature by addition of boric acid and/or movement of control rods. Reactivity adjustment to maintain 100% power as the fuel is burned up in most commercial PWRs is normally achieved by varying the concentration of boric acid dissolved in the primary reactor coolant. Boron readily absorbs neutrons and increasing or decreasing its concentration in the reactor coolant will therefore affect the neutron activity correspondingly.

Transmutation of high level long-lived radioactive minor actinides (MAs) and long lived fission products (LLFPs) eliminates a very long-term radioactive hazard and replaces it with a much shorter-term one (Iwasaki, 2002; Konings and Conrad, 1999; Konings et al., 1998; Takeda and Yokoyama, 1997). The nuclear transmutation reactions may be fission reactions or neutron capture reactions.

* Corresponding author. Tel.: +86 10 61773174; fax: +86 10 61773156.
E-mail address: Liu_Bin@ncepu.edu.cn (B. Liu).

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Studies show that pressurized water reactors or thermal reactors (Artisyuk et al., 2005; Fioni et al., 2002; Liu et al., 2013; Takeda et al., 2002), fast reactors (Iwasaki and Hirakawa, 1994; Wakabayashi, 2002), subcritical reactors (Beller et al., 2001; Herrera-Martnez et al., 2007) and other neutron sources (Kotschenreuther et al., 2009) all can be used to transmute the MAs nuclides and LLFPs, only the technology of thermal reactors and fast reactors is mature, the majority of commercial reactors in operation in the world are pressurized water reactor, so to study the minor actinide transmutation characteristics in the pressurized water reactors are very important.

Np-237, Am-241 and Am-243 have very large thermal neutron capture cross sections in the thermal energy region, these MA nuclides can capture neutrons readily and become Pu-239, Am-242, Am-244, Cm-243 and Cm-245 which have very large fission cross sections (Iwasaki, 2002; Iwasaki and Hirakawa, 1994), therefore people may transmute these MA nuclides in the pressurized water reactors effectively and generate power simultaneously. Np-237, Am-241 and Am-243 have very large thermal neutron capture cross sections, when these MA nuclides are introduced in the pressurized water reactor within the fresh fuel, the initial reactivity of the reactor decreases. As the pressurized water reactors continue in operation, the consumption of MA nuclides and fuel may lead to the increase of the reactivity, this means that MA nuclides act as the burnable poisons in the pressurized water reactors in some ways (Stacey, 2001). This is one of distinct advantages to transmute MA nuclides in the pressurized water reactors, in this way we may reduce the concentration of the boric acid in the coolant of the pressurized water reactors and increase the negative temperature coefficient of the reactors, all these measures can drastically reduce the possibility of the critical accident in a fuel cycle.

In this paper, we combine the well developed thermal neutron reactor core design technology with MA transmutation technology to study the MA transmutation characteristics in the pressurized water reactors. We concentrate on the characteristics of the MA transmutation in the pressurized water reactors, which include the transmutation core design, the effects to reactor k_{eff} after adding MA nuclides to the pressurized water reactor, transmutation rate and the burnup chain calculation of MA nuclides in the pressurized water reactors. We also compare the MA transmutation characteristics in the pressurized water reactors with the MA transmutation characteristics in the high flux thermal reactor which we finished previously (Liu et al., 2013).

2. The PWR transmutation core design

We establish a PWR transmutation core by using MCNP code (Briesmeister, 2000). MCNP code has criticality calculation feature for critical systems (Liu et al., 2010). We use MCNP code to study the transmutation characteristics of MA nuclides in the pressurized water reactors. We calculate the variations of k_{eff} and neutron flux after adding the different MA nuclides to pressurized water reactor, we also calculate the transmutation rate of MA nuclides and the remaining transuranic nuclides after MA nuclide 300-day-exposure in this pressurized water reactor.

2.1. The PWR core configuration

The core of the PWR consists of the fuel assemblies, control rods and water which act as both the coolant and moderator with boric acid dissolved in it. We simulate a core of a standard pressurized water reactor (Glasstone and Sesonske, 1994) by MCNP code. Fig. 1 depicts the structure and composition of the simulated PWR core which includes the pattern of fuel rods, control rods, burnable poison rods, transmutation rods, etc. The symbolic denotation of the letters in Fig. 1 is listed in Table 1.

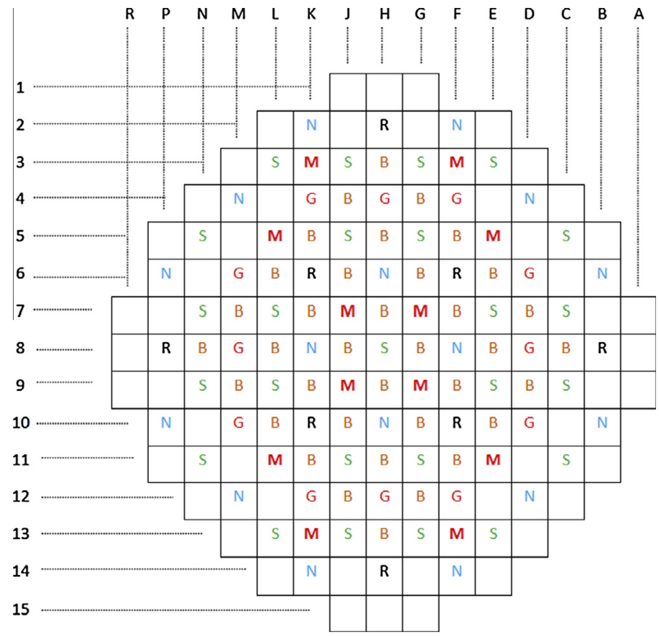

Fig. 1. Representative control element pattern in a PWR transmutation core.

2.2. The key parameters of the PWR

The key parameters of a pressurized water reactor are listed in Table 2. In the simulation calculations, the fuel used in this pressurized water reactor is UO_2 fuel, the enrichment of the nuclear fuel is 3.65%.

2.3. The effects after adding MA nuclides to the PWR core

To study the effects of adding MA nuclides to the pressurized water reactor core, in our simulation calculation we introduce MA nuclides to the pressurized water reactor core in two different ways. One is to mix MA nuclides to the uranium dioxide nuclear fuel homogeneously, this means all the fuel rods have MA nuclide transmutation materials; another way is that MA nuclide transmutation materials distribute in PWR core heterogeneously, that is the MA nuclide transmutation materials form the transmutation rods, which are exactly the same as the fuel rods in geometry, and the transmutation rods insert to the fuel assemblies to replace some fuel rods in some pattern. In this way, the MA nuclide transmutation materials are completely isolated from the uranium dioxide nuclear fuel.

Because the small delayed neutron fraction of the miner actinides, we would like to emphasis here that loading a large amount of MA nuclides into the core of PWRs may alter the physics characteristics in several ways and threaten the safety of the reactor. In the transmutation of MA nuclides, the PWR reactor must remain in critical condition. This indicates that the transmutation of minor

Table 1
Type and number of fuel assembly in PWR core.

Fuel Assembly (FA)	Denotation	FA type	FA number
Regulating FA (power)	G	Grey rod FA	12
	N	Black rod FA	16
Regulating FA (temperature)	R	Black rod FA	8
Scram FA	S	Black rod FA	29
Burnable Poison FA	B	B_4C	34
Transmutation FA	M	Minor Actinides	12