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Minor actinides transmutation on pressurized water reactor burnable poison rods

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ABSTRACT

Minor actinides are the primary contributors to long term radiotoxicity in spent fuel. The majority of commercial reactors in operation in the world are PWRs, so to study the minor actinide transmutation characteristics in the PWRs and ultimately realize the successful minor actinide transmutation in PWRs are crucial problem in the area of the nuclear waste disposal. The key issues associated with the minor actinide transmutation are the appropriate loading patterns when introducing minor actinides to the PWR core.

We study two different minor actinide transmutation materials loading patterns on the PWR burnable poison rods, one is coating a thin layer of minor actinide in the water gap between the zircaloy cladding and the stainless steel which is filled with water, another one is that minor actinides substitute for burnable poison directly within burnable poison rods.

Through considering the loading patterns, loading amount and self-shielding effect and so on, when the outer diameter of MA is 0.520 cm, the transmutation rate of MA is 38.5%, it is the optimal configuration, firstly transmutation rate and loading amount of MA with the pattern of MA in the water gap of burnable poison rods are larger than ones with the pattern of MA substitute for part burnable poison. Secondly the highest transmutation rate means the least loading amount of MA and the lowest transmutation rate means the most loading amount of MA. In order to keep reasonable transmutation rate and loading amount, when the outer diameter of MA is 0.520 cm, it would not reduce dramatically the amount of MA and the MA loading of this loading pattern is equivalent to the discharge amount of five pressurized water reactor, at the same time, the transmutation rate can keep reasonable level.

1. Introduction

Production of electric energy by nuclear reactors entails production of plutonium and radioactive nuclear waste. A typical 1000 MW(e) pressurized water reactor (PWR) generates about 20–30 tons of spent fuel per year. Most of the spent fuel (generally more than 98.5%) is composed of uranium and short lived fission products, which do not pose a long term radiological hazard. Approximately 0.4 wt% of spent fuel mass is in the form of long lived fission products cesium, strontium, technetium, and iodine; About 1 wt% of spent fuel composed of plutonium and minor actinide isotopes (Madic et al., 2007).

Transuranic elements such as plutonium, neptunium, americium, and curium, are the primary contributors to long term radiotoxicity in spent fuel. Nuclear transmutation is the conversion of one chemical element or isotope into another. This occurs either through nuclear reactions, or through radioactive decay. The nuclear transmutation is the only way to reduce the radioactive hazard of the high level long-lived radioactive minor actinides (MA) to our environment. Transmutation of neptunium, americium, and curium has the potential to help solve the problems posed by the management of radioactive waste by reducing the proportion of long-lived isotopes it contains. In transmutation of the minor actinides in the depleted reactor fuel the intention is to convert the minor actinides into fission products or some useful transuranic materials. By doing so, people may make use of the energy released from the nuclear transmutation to generate power (Liu et al., 2014).

Although thermal neutron reactors (Shwageraus et al., 2004; Liu et al., 2014; S. Şahin et al., 2006), fast neutron reactors (Meiliza et al., 2008; Nishihara et al., 2010), subcritical reactor (Ismailov et al., 2013; Yapici et al., 2008) all can be used to transmute the

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minor actinides, only the technology of thermal reactors is mature, the majority of commercial reactors in operation in the world are pressurized water reactors, So up to now, the thermal neutron reactors, especially the pressurized water reactor, still dominates the power reactor in the world, see Fig. 1 for details (IAEA, 2016). So to study the minor actinide transmutation characteristics in the pressurized water reactors are crucial problem in the area of the nuclear waste disposal. Actually, tremendous research works about the transmutation of minor actinides in different types of reactors have been done in the past a couple of decades, these research works mainly focus on comparing the transmutation characteristics of MA in different types of reactors. (Artisyuk et al., 2005; Beller et al., 2001; Herrera-Martnez et al., 2007; Iwasaki and Hirakawa, 1994; Takeda et al., 2002; Acir and Coskun, 2012; Wakabayashi, 2002).

The study shows that the cross sections of the MA nuclides in the thermal energy regions are much greater than in the fast neutron energy regions (Iwasaki, 2002; Iwasaki and Hirakawa, 1994; Sohail et al., 2014). As a matter of fact, 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 and become Pu-238, Am-242m, Cm-243 and Cm-245 which have very large fission cross sections and some useful nuclides. Minor actinides may be transmuted in the thermal rectors very effectively, so people should consider transmuting MA nuclides in the pressurized water reactors seriously.

Up to present, very few research works about the transmutation of MA come right down to the specific loading pattern of MA in the different types of reactors. However, finding an optimal MA loading pattern in a reactor is a successful starting point of whole research works of MA transmutation in a specific reactor. Yang et al. proposed to transmute the minor actinides and LLFP in the film coating on fuel rods or annular transmutation target to reduce the self-shielding effects and improve the minor actinides and LLFP transmutation rate (Yang et al., 2004). Liu et al. studied the minor actinide transmutation characteristics in the high flux thermal reactor (Liu et al., 2013) and the pressurized water reactors (Liu et al., 2014). No matter which ways to introduce the MA to PWR reactor cores, MA uniform distribution with fuel, heterogeneous distributions in the reactor core or film coating MA on fuel rods, all these approaches need either to change the composition of the fuel, configuration of the reactor core or the structure of the fuel rods. All these modifications to the reactor core will change the physical characteristics of the reactor, and all these changes need to make modifications on the well proven thermal reactor core design technology. So the cost to rebuild a thermal reactor core to transmute the MA or LLFP may be tremendously and impractically.

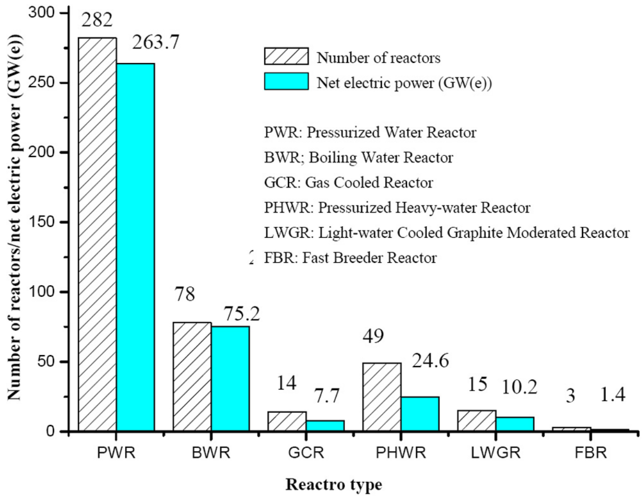

Fig. 1. Type and number of reactors in operation.

To avoid the above problems in transmutation of the MA in the thermal reactors, Hu et al. study two different minor actinide transmutation materials loading patterns on the PWR burnable poison rods (Hu et al., 2015). one is to coat a thin layer of minor actinide in the water gap between the zircaloy cladding and the stainless steel which is filled with water, another one is that minor actinides substitute for burnable poison directly within burnable poison rods. Simulation calculation indicates that the two loading patterns can load approximately equivalent to 5–6 PWR annual minor actinide yields without disturbing the PWR k_{eff} markedly.

Based on the two minor actinide loading patterns, in this paper, our research works will concentrate on studying the burnup characteristic by loading the MA transmutation materials in the PWR burnable poison rods. We combine the conventionally well developed thermal reactor design technology with MA transmutation technology to simulate the change of minor actinide nucleus density with operation time by DRAGON code. At last, we try to find an option minor actinide transmutation material loading pattern with PWRs.

2. The configuration of PWR transmutation core

We simulate reactor core of China Guangdong Daya Bay 900 MW pressurized water reactor (Su and Yang, 2005) to study the MA transmutation characteristics. Fig. 2 depicts the configuration of China Guangdong Daya Bay 900 MW PWR core which includes the distribution pattern of the fuel assemblies. Table 1 lists the key parameters of the fuel assemblies of this 900 MW PWR. All the fuel assemblies are the typical 17 × 17 PWR fuel assemblies, every fuel assembly has 264 fuel rods, 24 control rod guide tubes and 1 neutron detector guide tube. For easy calculation, all the fuel assemblies have the same U-235 enrichment 2.1%.

The reactor with the first fuel loading has very large excess reactivity, to ensure the moderator temperature coefficient is negative during PWR operation, the boron concentration is not

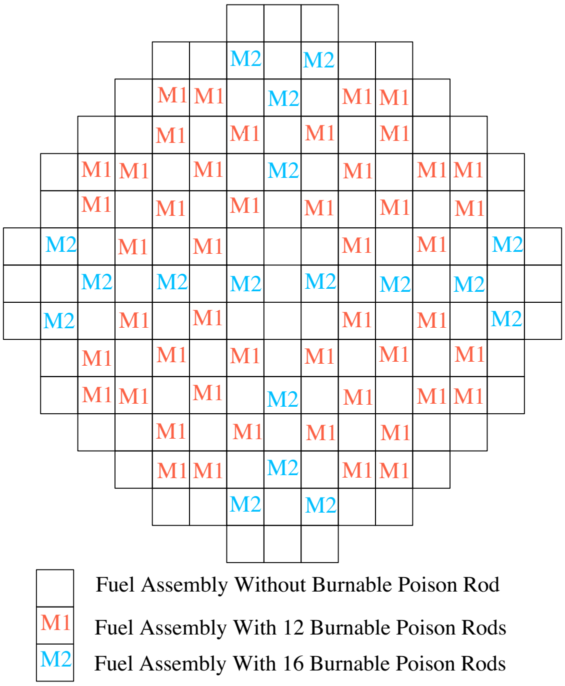

Fig. 2. Burnable poison rod assembly distribution in PWR.