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Flexibility of ADS for minor actinides transmutation in different two-stage PWR-ADS fuel cycle scenarios

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ABSTRACT

A two-stage Pressurized Water Reactor (PWR)-Accelerator Driven System (ADS) fuel cycle is proposed as an option to transmute minor actinides (MAs) recovered from the spent PWR fuels in the ADS system. At the second stage, the spent fuels discharged from ADS are reprocessed by the pyro-chemical process and the recovered actinides are mixed with the top-up MAs recovered from the spent PWR fuels to fabricate the new fuels used in ADS. In order to lower the amount of nuclear wastes sent to the geological repository, an optimized scattered reloading scheme for ADS is proposed to maximize the discharge burnup and lower the burnup reactivity loss. Then the flexibility of ADS for MA transmutation is evaluated in this research. Three aspects are discussed, including: different cooling time of spent ADS fuels before reprocessing, different reprocessing loss of spent ADS fuels, and different top-up MAs recovered from different kinds of spent PWR fuels. The ADS system is flexible to be combined with various pyro-chemical reprocessing technologies with specific spent fuels cooling time and unique reprocessing loss. The reduction magnitudes of the long-term decay heat and radiotoxicity of MAs by transmutation depend on the reprocessing loss. The ADS system is flexible to transmute MAs recovered from different kinds of spent PWR fuels, regardless of UOX or MOX fuels. The reduction magnitudes of the long-term decay heat and radiotoxicity of different MAs by transmutation stay on the same order.

1. Introduction

The closed nuclear fuel cycle strategy and the utilization of the recycled plutonium in light water reactors (LWRs) have been determined by the Chinese government as the development roadmap of nuclear power industry in China. Until December 2015, there have been overall 28 pressurized water reactors (PWRs) in operation and 24 PWRs under construction in China (IAEA, 2016). The rapid development of nuclear power in China leads to the fast accumulation of high-level radioactive nuclear wastes (HLWs), especially minor actinides (MAs). The long-term radiotoxicity of the HLWs sent to the geological repository can be reduced by a factor of 100 if the MAs are fully recycled and incinerated (Salvatores and Palmiotti, 2011). For the incineration of MAs, the Accelerator Driven subcritical Systems (ADSs) show better safety characteristics due to the operation in subcritical state, and allow flexible fuel loading options in the core (Stanculescu, 2013; Taczanowski, 2000; Wallenius and Eriksson, 2005).

In order to lower the amount and radiotoxicity of nuclear wastes sent to the geological repository, a two-stage PWR-ADS fuel cycle is proposed as an option to transmute the minor actinides (MAs) recovered from the spent PWR fuels, as shown in Fig. 1. At the first stage, two basic fuel cycle scenarios are considered for PWR, i.e. the full utilization of uranium oxide (UOX) fuels, and the partial utilization of UOX and mixed oxide (MOX) fuels. The spent fuels discharged from the PWR core are reprocessed with the extended PUREX process to extract uranium (U), plutonium (Pu) and MAs, separately. For the UOX fuel utilization case, the recovered U and Pu are stored as the potential fuel material to be employed in the fast reactors, and the recovered MAs are incinerated in the ADS system. For the UOX/MOX fuel utilization case, the recovered U and Pu are fabricated as the MOX fuel assembly and loaded into the PWR core, and the recovered MAs are transmuted in the ADS system. At the second stage, the spent fuels discharged from ADS are reprocessed with the pyro-chemical process and the recovered actinides are mixed with the top-up MAs recovered from the spent PWR fuels to fabricate new fuels used in the ADS. In order to reduce the amount of HLWs lost to the geological repository, the discharge burnup of spent ADS fuels should be maximized and the fractional loss in the pyro-chemical process should be minimized (Yang and Khalil, 2001) (Fig. 2).

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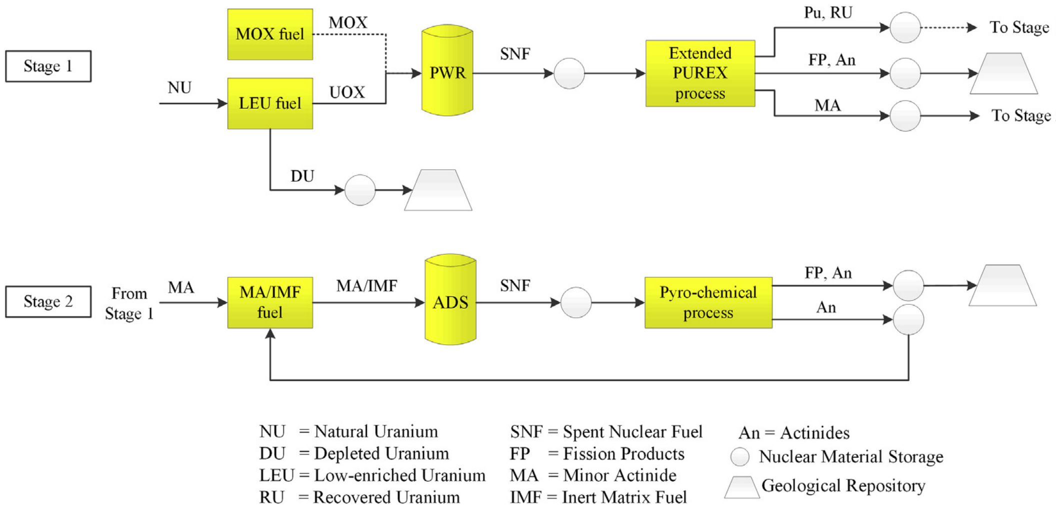

Fig. 1. Mass flow diagram of two-stage PWR-ADS fuel cycle.

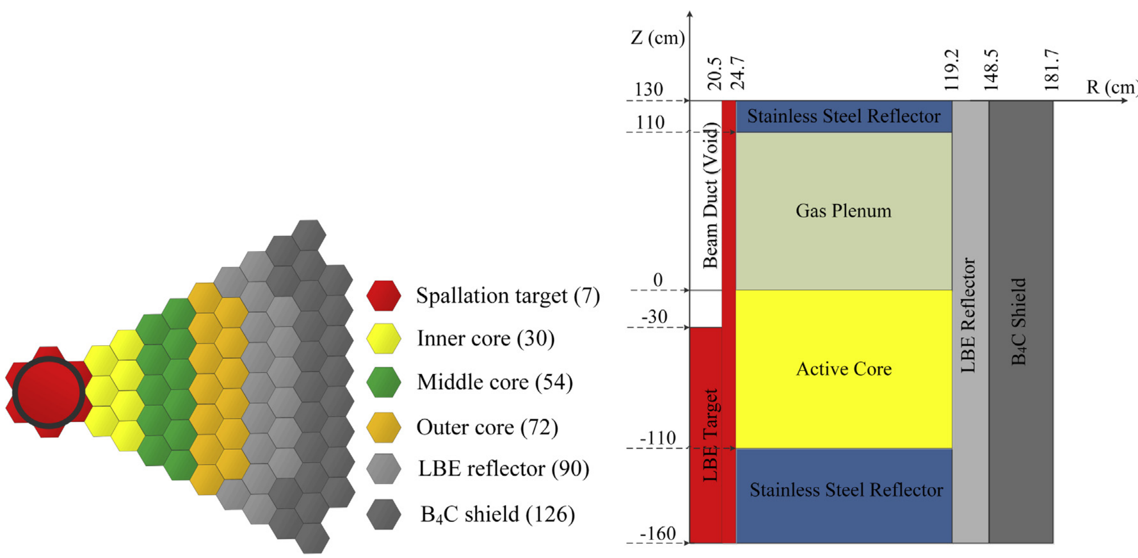

Fig. 2. Core layout of 800MWth accelerator driven minor actinide burner HEIT.

Lots of efforts have been devoted to the study of different fuel cycle scenarios using ADS to transmute transuranics (TRUs) or MAs. Cometto et al. assessed and compared the fuel cycle scenarios which employ ADS to burn TRUs recovered from the spent LWR fuels or MAs recovered from the spent LWR and fast reactor (FR) fuels (Cometto et al., 2004), and concluded that ADS is suited better as the MA burner due to the operational, technological and economic penalties. Ålander et al. simulated the fuel cycle scenarios burning TRUs recovered from spent LWR UOX or MOX fuels in ADS using the Nuclear Fuel Cycle Simulation (NFCSim) code (Ålander et al., 2006). Yang et al. evaluated the performance characteristics of a two-stage fuel cycle option involving continuous recycle of Pu in PWRs and burning of MAs in ADS (Yang et al., 2013). Most previous studies focused on the comparative study of different fuel cycle scenarios based on simplified R-Z geometry model or point depletion model, or the evaluation study of single fuel cycle scenario based on 3D neutronics calculation model. From the economic point of view, the amount of ADS in the nuclear park should be minimized and the same ADS system may be required to transmute MAs from different kinds of spent PWR fuels.

Extensive research is also carried out to develop the pyro-chemical processes to separate the actinides from the lanthanides. The pyro-chemical reprocessing process was applied for the first time as an integral part of the system in the Integral Fast Reactor (IFR) (Laidler et al., 1997). In the demonstration experiments using the nuclear fuels irradiated in the PHENIX reactor in France, 99.9% recovery of actinides was achieved with the pyro-chemical process (Malmbeck et al., 2011). However, the pyro-chemical reprocessing technology is far from maturation in the industrial scale. There are still large uncertainties on the cooling time of spent fuels before reprocessing and the reprocessing loss of actinides in the pyro-chemical process.

In this research, based on the 3D neutronics calculation model, a scattered reloading scheme for an industrial-scale accelerator driven MA burner HEIT proposed in the previous studies (Li et al., 2015) is optimized to maximize the discharge burnup and lower the burnup reactivity loss. Then the flexibility of the proposed ADS system for MA transmutation is analyzed. Three aspects are discussed, containing: different cooling time of spent ADS fuels before the pyro-chemical reprocessing, different reprocessing loss