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Impact of impurity in transmutation cycle on neutronics design of revised accelerator-driven system

Takanori Sugawara *, Ryota Katano, Kazufumi Tsujimoto

Japan Atomic Energy Agency, 2-4 Shirakata, Tokai-mura, Naka-gun, Ibaraki 319-1195, Japan

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ABSTRACT

Partitioning and transmutation technology will be a promising technology to reduce the burden of the geological disposal of the high-level radioactive waste. The Japan Atomic Energy Agency has investigated a lead-bismuth eutectic cooled accelerator-driven system (ADS) to transmute minor actinides (MAs) in the transmutation cycle. This study aims to revise the ADS design and to investigate the impact of impurities in the transmutation cycle on the ADS neutronics design.

The impact of impurities in the transmutation cycle is investigated for the revised design. For the uranium from the partitioning, the accompaniment of 20 wt% U against the Pu weight is acceptable although the MA transmutation amount will be decreased slightly. For the rare earth (RE) from the partitioning, the accompaniment of 5 wt% RE against the MA weight is allowable. In the reprocessing, the decontamination factor, DF = 10 for RE is enough from the viewpoint of the neutronics design. The impact of the fuel composition accuracy is also investigated. The uncertainty of the ZrN ratio against the MA fuel should be less than 0.2% to minimize a surplus proton beam current due to the uncertainty.

Through these investigations, the required conditions for the impurities in the partitioning, the MA fuel fabrication and the reprocessing processes were clarified from the viewpoint of the ADS neutronics design.

1. Introduction

Partitioning and transmutation (P&T) technology of long lived radioactive nuclides such as minor actinides (MAs) will be a promising technology to reduce the burden of the geological disposal of the high-level radioactive waste (HLW). The Japan Atomic Energy Agency (JAEA) has been continuously performing research and development (R&D) on the P&T technology. The R&D on the P&T technology in JAEA is based on two concepts: one is the homogeneous MA recycling concept in fast breeder reactors (FBRs) and the latter is the dedicated MA transmutation cycle concept, double-strata strategy, using an accelerator-driven system (ADS) (Oigawa et al., 2011). This paper treats the transmutation cycle with ADS. The transmutation cycle consists of partitioning of MA from HLW, MA fuel fabrication, transmutation by ADS and reprocessing of spent fuel discharged from ADS as shown in Fig. 1.

JAEA has investigated a lead-bismuth eutectic (LBE) cooled subcritical reactor with high intensity proton accelerator, continuously (Tsujimoto et al., 2004, 2007; Nishihara et al., 2008). Based on this reference ADS, various R&D activities for the partitioning, the MA fuel fabrication, the transmutation by the ADS and the reprocessing have been carried out and various research results and knowledge have been derived. It is required to reflect these results to the ADS design and optimize it.

For the previous reference design, the ideal condition without impurities was supposed in the neutronics design. It is considered the impurities will affect the transmutation performance of the ADS negatively since the neutron economy will deteriorate by the capture reaction of the impurities. For the realization of the transmutation cycle, the effect of the following impurities should be considered in the neutronics design.

- Partitioning: Aqueous separation process is supposed as the partitioning process. Uranium will come to be mixed in the MA fuel as an accompaniment of plutonium. Rare earth (RE) will accompany MAs because the chemical behavior of RE in aqueous solution is similar to MAs (Am and Cm).
- MA fuel fabrication: JAEA supposes uranium-free MA and plutonium (MA + Pu) nitride fuel as the ADS fuel. The carbothermal reduction (Greenhalgh, 1973) of the oxide is considered to fabricate the MA nitride fuel. In this method, carbon is added to MA

* Corresponding author.
E-mail address: sugawara.takanori@jaea.go.jp (T. Sugawara).

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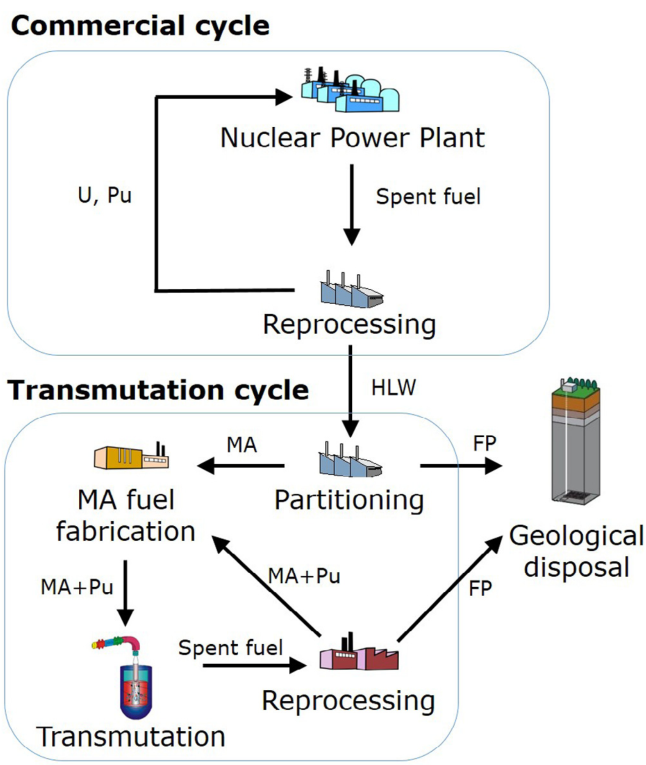

Fig. 1. Concept of double-strata strategy.

oxidized materials and nitride is derived by heating. A tiny amount of carbon and oxide will be mixed into the MA fuel in this method.

- Reprocessing in the transmutation cycle: Pyrochemical reprocessing is supposed to reprocess the spent fuel discharged from ADS. RE will be mixed into the MA fuel.

The impact of these impurities is very important for not only the ADS neutronics design but also the investigations for the partitioning, the MA fuel fabrication and the reprocessing, because target setting of decontamination factor for each impurity has a large impact for the plant design of each process.

On the basis of these backgrounds, this study aims to revise the ADS design and to investigate the impact of impurities in the transmutation cycle. Section 2 presents the revision of the ADS design prior to the investigation of impurities. Three items, the subcriticality of the ADS core, the size of the fuel assembly and the cooling time after the burnup are discussed and a new reference design will be presented. Section 3 investigates the impact of impurities in the transmutation cycle on the ADS neutronics design. Uranium, RE, carbon and oxide are considered as the impurities. Section 4 concludes this study.

2. Revision of ADS design

2.1. Core design

The current ADS plant design is based on the feasibility research for LBE cooled ADS (Tsujimoto et al., 2004). The design parameters for the core fuel are based on the neutronics design for power flattening (Nishihara et al., 2008). The ADS consists of a 1.5 GeV-20 mA proton LINAC and a subcritical core with 800 MW thermal power. The MA transmutation amount is about 250 kg per 300 effective full power days (EFPDs). This transmuted amount corresponds to the MA amount discharged from 10 units of the light water reactor with 1 GW electric power and 45 GWd/tHM burnup. Table 1 shows the main parameters for the previous reference design.

Three items are revised in this study. The first one is an upper limitation of the effective multiplication factor, k_{eff}. Detail of this item is described in the next section. The second one is the size of a fuel assembly (FA). The width of FA in the previous design was 232.9 mm and one FA bundled 391 MA fuel pins. It is supposed that the small size of FA is desirable from the viewpoint of fuel fabrication and transportation because the decay heat of MA is large. In the previous design, the estimated decay heat was about 20 kW per FA as the fresh fuel. To reduce the decay heat generation of FA, the width of FA was reduced to 133.5 mm and the number of fuel pins per FA became 121. Table 1 compares the parameters of FA for the previous design with those for new design. The number of FA became 276 which was about three times larger than the previous one. On the other hand, it was expected the decay heat generation of FA became one third.

The third one is the cooling time after the burnup. In the previous design, the cooling time was 2.5 years which consisted of 3 months unloading, 18 months cooling, 6 months refabrication and 3 months reloading. However, as described above, the size of FA was changed and the number of FA increased three times. The composition of the cooling time was revised as below; 9 months unloading, 12 months cooling, 18 months refabrication and 9 months reloading. Total cooling time was revised from 2.5 years to 4 years.

2.2. Subcriticality

2.2.1. Outline for the revision of subcriticality

Subcriticality which is a parameter to describe the difference from the critical state is very important factor for the ADS neutronics design. Table 2 summarizes the relationship between the subcriticality and typical characteristics for the ADS neutronics design. If the subcriticality is small, a margin for the critical accident is small. On the other hand, required proton beam current to make the core power constant will be small because neutron multiplication in the core is large. Power distribution will be gentle due to a gentle flux distribution if the subcriticality is small. Small proton beam current is preferable for the design of an accelerator and a beam window which is the boundary of the accelerator and the core. From the viewpoint of temperature limitation for the core component, especially a cladding tube, the gentle power distribution is desirable.

The upper limitation of the k_{eff} value was 0.97 in the previous design. The maximum proton beam current during the burnup cycle was 20 mA and the design of the beam window was performed based on this value (Sugawara et al., 2010). Although feasible beam window concept which satisfied all terms in a design code was presented in Sugawara et al. (2010), it was necessary to mitigate the design condition such as the maximum proton beam current to suggest more feasible beam window concept which had more safety margin. For the cladding tube temperature, Nishihara et al. (2008) proposed the four different-inert-ratio zones concept, which had four fuel zones whose fuel compositions were different, to flatten the power distribution. However, it was pointed out that the four different-inert-ratio zones concept was complicate in the MA fuel fabrication. To mitigate the design condition of the beam window and the cladding tube temperature, possibility of increasing the upper limitation of the k_{eff} value was investigated.

In the previous design, the method proposed by Kim et al. (2002) was adopted to determine the upper limitation of the k_{eff}