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# Minor actinides transmutation performance in a fast reactor

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ABSTRACT

Results obtained in the project named "Study on Minor Actinides Transmutation using Monju Data", which has been sponsored by the Ministry of Education, Culture, Sports, Science and Technology in Japan (MEXT) are described. In order to physically understand transmutation of individual MA nuclides in fast reactors, a new method was developed in which the MAs transmutation is interpreted by two formulas. One corresponds to the difference of individual MA nuclides amounts before and after a burnup period, and the other is the sum of amount of fission of a relevant MA nuclide and the net plutonium production from the MA nuclide during a burnup period. The method has been applied to two fast reactors with MA fuels loaded in cores homogeneously and in a blanket region heterogeneously. Numerical results of MA transmutation for the two reactors are shown.



## 1. Introduction

After the accident of the TEPCO's Fukushima Daiichi nuclear power plant (NPP), the nuclear back-end issues concerned with spent nuclear fuels and radioactive waste have been focused in Japan. The Ministry of Education, Culture, Sports, Science and Technology in Japan (MEXT) has launched a national project entitled "technology development for the environmental burden reduction". Radioactive wastes have a large environmental burden. Minor actinides (MAs) are contained in high level radio-active wastes and they have long-lived radio-activity and high decay heat. The disposal of high level radio-active wastes in deep ground seems the most practical way. However for the safe and reliable maintenance of the disposal, it is desirable to reduce MAs included in high level wastes through nuclear transmutations by using fast reactors or accelerator driven systems (Tommasi et al., 2001).

This paper describes the results of "Study on Minor Actinides Transmutation Using Monju Data", which is one of the studies adopted in 2013 as the national project. Many studies have been conducted to transmute minor actinides (MAs) by using fast reactors.

Salvatores discussed in 2005 on nuclear fuel cycle strategies including partitioning and transmutation (Salvatores, 2005), and pointed out that the best approach to manage radioactive waste transmutation is the use of fast reactors. In 2011 Salvatores and Palmiotti reviewed all-inclusively the status of research activities of radioactive waste partitioning and transmutation (P&T) Salvotores and Palmiotti, 2011. As for partitioning they concluded that the radiotoxicity inventory can be reduced up to a factor of 10 if all of Pu is recycled and fissioned. Reduction factor higher than 100 can be obtained if, in addition, the MAs are burned.

A prerequisite for these reduction figures is a complete fissioning of the actinides for which multi-recycling is a requirement. Losses during reprocessing and fabrication must be below 1% and probably in the region of 0.1%. In addition the transmutation performance was investigated for different types of reactors: thermal neutron reactors, critical fast reactors, and subcritical source-driven reactors. In thermal reactors minor actinides act as poison, and a higher percentage of U-235 is needed to maintain criticality when Np and Am are recycled. When all MAs are recycled, MA inventory is dominated by the buildup of Cm. So this fuel would be very difficult to handle. For the transmutation using fast reactors they compared the transmutation performance for homogeneous and heterogeneous recycling modes, and for reactors using different fuels (oxide fuel, nitride fuel, metal fuel) and different coolants (Na, lead, He). For homogeneous recycling mode they concluded that the effect of coolant choice in fast reactor design will be negligible from the viewpoint of the MA transmutation. Independent on the coolant choice the MA transmutation effectiveness is almost 7.5–7.7% per year. The transuranics (TRU) consumption rate was investigated for continuous recycle of TRU-based fuel, and they concluded that the TRU consumption rate depends on the conversion ratio; the maximum theoretical consumption rate of 1 g/MWt-day is obtained for the zero conversion ratio because the fuel does not contain U. They pointed out the advantage of the heterogeneous recycling mode that less radioactive TRUs (Pu and Np) of light water reactor (LWR) spent fuel can be used for

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driver fuels and remaining MAs (Am and Cm) can be used for target assemblies, and the potential difficulties such as recycling, handling and fabricating of target assemblies.

Ohki et al. presented the design of a homogeneously MA loaded core of JSFR (Japanese sodium cooled fast reactor) and a heterogeneously MA loaded core with Am bearing fuel (Ohki et al., 2007). They proposed an effective loading method of Am targets; the ring-shaped target loading pattern between the inner and the outer core regions is favorable for achieving satisfactory core characteristics and MA transmutation.

Fujimura et al. proposed the sodium cooled fast reactor (SFR) core concept in which MA was transmuted using target assemblies with moderator (Fujimura et al., 2011). The zirconium-hydride was chosen as the moderator. They found that the use of the moderator rods in target assemblies by 25% the MA transmutation amount becomes maximum and sodium void reactivity is 20% smaller than that of a reference homogeneous core with no MAs.

Lena Andriolo et al. proposed SFR concepts (CFV core) with the sodium plenum and confirmed that the sodium plenum had a potential to reduce the sodium void reactivity without spoiling core performance (Andriolo et al., 2012).

The purpose of our study is to achieve harmonization of a large amount of MA transmutation and reduction of sodium void reactivity by designing homogeneous and/or heterogeneous MA loaded cores with the sodium-plenum. To increase MA transmutation amount it is necessary to increase MA contents in fuel. In the ASTRID core the MA content is set to 2% for Am in the homogeneous MA loading case, and 10% in the heterogeneous loading case (Andriolo et al., 2012). In this study we are planning to increase the MA content up to about 20%. To understand core characteristics of such MA transmutation cores we have to calculate MA transmutation processes in detail. To calculate detailed transmutation processes we developed a new method to understand MA transmutation processes for individual MA nuclides (Takeda et al., 2014). In this method we introduced two definitions of the MA transmutation, and decomposed them into four terms. The method is briefly described in Section 2 to show the physical meanings of the terms introduced in reference Takeda et al. (2014). Numerical results obtained by the methods are shown in Section 3 for 750 MW(e) MA transmutation fast rector cores. Section 4 draws some conclusions.

## 2. Calculation method of MA transmutation

Usually the MA transmutation is defined by the difference of MA amounts before and after a burnup period. However, this definition of MA transmutation does not clearly explain the MA transmutation processes of individual MA nuclides such as Np, Am, Cm. The transmutation of individual MA nuclides are dependent on neutron flux, burnup period and neutron spectrum. Therefore, we developed a new method to calculate the MA transmutation of individual MA nuclides (Takeda et al., 2014). Let us briefly describe the new definition of transmutation of each MA nuclide.

In this new method we first perform the conventional burnup calculations, and store the burnup-dependent fluxes in individual regions which are used in the second step calculation. In the second step, we consider only the relevant MA in each region, and perform burnup calculations using the flux obtained in the first step.

In this second step calculation a nuclide $k$ will be produced from the original nuclide $l$. So we can calculate the production rate of the nuclide $k$ at time $T$ from the initial nuclide $l$ as

$$P_{lk} = \tilde{N}_k(T)/\tilde{N}_l(0) \tag{1}$$

where $\tilde{N}_l(0)$ is number density of nuclide $l$ at time 0 and $\tilde{N}_k(T)$ is number density of nuclide $k$ at time $T$. These number densities are calculated by assuming that only the nuclide $l$ is present at $t = 0$. Using the production rate, the overall fission due to the initial nuclide $l$ is calculated by

$$\mathrm{OF}^l = \sum_k \int_0^T \sigma_f^k(t)\tilde{N}_k(t)\phi(t)dt \tag{2}$$

where $\sigma_f^k(t)$ is the fission cross section of nuclide $k$ at time $t$, $\phi(t)$ is the neutron flux at time $t$ and $\Sigma$ means summation over all nuclides $k$ produced from the initial nuclide $l$. This includes all the fissions caused by the initial nuclide $l$. Furthermore, the production of other MA nuclides except the initial nuclide $l$ can be calculated by

$$\mathrm{OMA}^l = \tilde{N}_l(0) \sum_{k\in MA, k\neq l} P_{lk} \tag{3}$$

The Pu and U production from the nuclide $l$ is given by

$$\mathrm{PU}^l = \tilde{N}_l(0) \sum_{k\in U.Pu} P_{lk} \tag{4}$$

The production of the nuclide $l$ from Pu and U is given by

$$\mathrm{PUM}^l = \sum_{k\in U.Pu} \tilde{N}_k(0)P_{kl} \tag{5}$$

The production of the nuclide $l$ from other MAs is given by

$$\mathrm{MAM}^l = \sum_{k\in MA, k\neq l} \tilde{N}_k(0)P_{kl} \tag{6}$$

Therefore, the net transmutation of nuclide $l$ is calculated by

$$\mathrm{TR1}^l = \mathrm{OF}^l + \mathrm{OMA}^l + \mathrm{PU}^l - \mathrm{PUM}^l - \mathrm{MAM}^l \tag{7}$$

When we consider the total MA transmutation for all MA nuclides, the second and the fifth terms cancel each other. Therefore the total transmutation is given by

$$\mathrm{TR} = \sum_l \mathrm{TR1}^l = \sum_l (\mathrm{OF}^l + \mathrm{PU}^l - \mathrm{PUM}^l) \tag{8}$$

Thus we can also define the MA transmutation of the nuclide $l$ by

$$\mathrm{TR2}^l = \mathrm{OF}^l + \mathrm{PU}^l - \mathrm{PUM}^l \tag{9}$$

The above transmutation rate is composed of two terms; first is the amount of incineration rate by fission and the second is the net transmutation rate to fuel (U and Pu). The first term is denoted as overall fission, and is composed of the direct fission of the relevant nuclide plus the fission of other nuclides transmuted by decays or neutron reactions. The net production rates of U and Pu are calculated from the difference between the production rates of U and Pu from the relevant MA nuclide and the MA production from the initial U and Pu.

Let us discuss the difference between TR1 and TR2. TR1 is defined by the difference of amounts of nuclide $l$ before and after burnup and contains the MA amount of other MA nuclides transmuted from the relevant MA nuclide. TR2 does not contain the amount and is composed of the overall fission and the net Pu production as explained above. Using the two formulas we will explain the MA transmutation for individual MA nuclides in the next section.

## 3. Numerical results of MA transmutation

The above two formulas have been applied to two type of MA loading patterns in a sodium-cooled fast reactor. One is the homogeneous MA loading pattern in cores as shown in Section 3.1, and the other is the heterogeneous MA loading pattern in the blanket region as shown in Section 3.2.