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Uncertainty Estimation of Neutronics Parameters in Minor Actinides Transmutation Fast Reactors

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Abstract – *The uncertainties of neutronics parameters such as effective multiplication factors, sodium void reactivity and minor actinides transmutation rates in minor actinides transmutation fast reactors are estimated using sensitivity analyses. The method to estimate the minor actinides transmutation rates has been introduced. The uncertainties are estimated for a 750 MWe class fast reactor with minor actinide content of 6.5%. From numerical calculations it is seen that the uncertainties for the multiplication factor and sodium void reactivity are slightly increased with the addition of minor actinides, but the main difference is the components of the uncertainties. The U-238 inelastic scattering cross-section has a large contribution for the uncertainty of the multiplication factor, and the Na-23 inelastic cross section has a large contribution for the uncertainty of the sodium void reactivity in the reactor with minor actinides. The uncertainties of the total minor actinides transmutation rates are estimated to be about 3%. It is seen that the uncertainties of the transmutation rates of Am-243 and Cm-244 are rather large.*

I. INTRODUCTION

Minor actinides (MAs) included in high level radio-active wastes 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 through nuclear transmutations by using fast reactors or accelerator driven systems [1].

Salvatores discussed in 2005 on nuclear fuel cycle strategies including partitioning and transmutation [2], and pointed out that the best approach to manage radioactive waste transmutation is the use of fast reactors. In 2011 Salvatores and Palmiotti reviewed the status of research activities of radioactive waste partitioning and transmutation (P&T) [3]. 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). Independent on the coolant choice the MA transmutation effectiveness is noted to be almost 7.5~7.7% per year.

Recently, Takeda developed a method to calculate MA transmutation amounts for individual MA nuclides [4]. The method was applied to calculate MA transmutation amounts for homogeneous and heterogeneous MA loading cases. For the homogeneous MA loading case in which the MA content was set to 6.5%, the MA transmutation behaviors were compared at the burnup period of 1 year and 6 years. It was found that for the 1 year burnup Am-241 changed to Am-242m, Cm-242 from Am-241, and the overall fission contribution to the transmutation amount was rather small. However for the 6 years burnup the overall fission contribution becomes large. This is due to a lot of transmutation from original MA nuclides to Pu isotopes. It is noted that the total MA transmutation amount increases with burnup time, but its gradient with respect to burnup time decreases after 9 years, and the transmutation amount by overall fission increases almost linearly with burnup time. Thus the transmutation processes are rather complicated.

Also MA transmutation fast reactors have hard neutron spectra due to the relatively large neutron absorption by MA nuclides in lower energy ranges. In higher energy ranges, MA cross sections have relatively large uncertainties. So uncertainties of neutronics parameters calculated for MA transmutation fast reactors are generally larger than those calculated for conventional fast reactors without MAs. To quantitatively estimate the increases of uncertainties it is desirable to perform uncertainty analyses of neutronics parameters in MA transmutation fast reactors. As neutronics parameters we consider effective multiplication factors and MA transmutation amounts. In evaluating the uncertainties of MA transmutation amounts the uncertainties for individual MA nuclides are considered.

Uncertainties for static performance parameters are estimated by using the SAGEP code [5] which calculates sensitivity coefficients based on the generalized perturbation theory, and those for burnup performance parameters are estimated by the SAGEP-BURN code [6] which calculates sensitivity coefficients of burn-up performance parameters. In the next chapter the method to calculate sensitivities and uncertainties of MA transmutation is described.

II. UNCERTAINTY CALCULATION METHOD FOR MA TRANSMUTAITON

1. Calculation Method

Let us first derive a method to calculate sensitivities and uncertainties of MA transmutation amounts of nuclide i in region j, which is defined by the difference of number densities of nuclide i before (t=0) and after (t=T) a burnup period:

$$\Delta N_{i,j} = N_{i,j}(0) - N_{i,j}(T) \qquad (1)$$

The sensitivity of $\Delta N_{i,j}$ is calculated by

$$S_{\Delta Ni,j} = \frac{d\Delta N_{i,j}(T)/\Delta N_{i,j}(T)}{d\sigma/\sigma} = \frac{N_{i,j}(0)}{\Delta N_{i,j}} S_{Ni,j}(0) - \frac{N_{i,j}(T)}{\Delta N_{i,j}} S_{Ni,j}(T) \quad (2)$$

where $S_{N\,i,j}(0)$ and $S_{N\,i,j}(T)$ are the sensitivities of the number densities Ni,j(0) and Ni,j(T), respectively, and σ is a cross section. The sensitivity of the total MA transmutation amount in the whole core is calculated by

$$S_\Delta = \sum_j \frac{\Delta_j}{\Delta} \sum_i \frac{\Delta N_{i,j}}{\Delta N_{t,j}} S_{\Delta N_{i,j}} \quad (3)$$

where Δj is the volume of the j-th region , and Δ is the total core volume. Furthermore、$\Delta N_{t,j}$ is defined by

$$\Delta N_{t,j} = \sum_i \Delta N_{i,j} \quad (4)$$

The uncertainty of MA transmutation amounts is calculated by the following sandwich rule:

$$V = S_\Delta W S_\Delta{}^t \quad (5)$$

where W is the cross -section covariance data. The cross section covariance data of JENDL-4.0 [7] was used for W.

2. Calculation Model

We have applied the above equation to the MA transmutation fast reactor with electric power of 750 MW (thermal power of 1765 MW). The cross sectional view of the reactor is shown in Fig. 1. The core has a sodium plenum region above the inner core and the outer core to reduce the sodium void reactivity when sodium is boiled. Furthermore, there is an internal blanket between the upper and lower inner cores. The internal blanket also reduces the sodium void reactivity, and has a role to control the rapid propagation of core melting in severe accidents. The MA content defined by MA amount to total heavy metal is 6.4 and 6.7% in the inner and outer cores [4]. The MA composition of TRU(trans-uranium) fuel is shown in Table 1. The burnup period was set to 3394.5 days, which corresponds to 6 batch refueling with 1 cycle of 18.6 months [4].

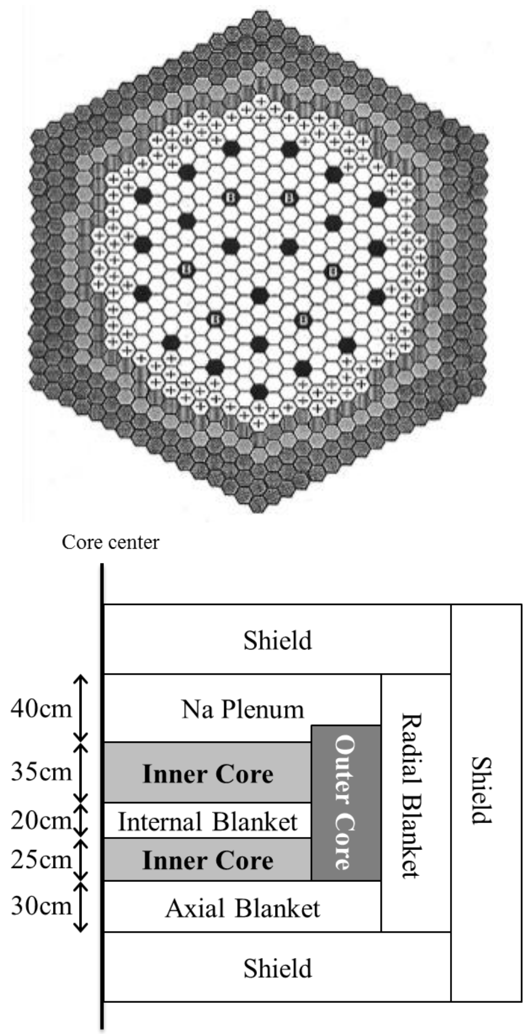


Fig. 1. Cross sectional view of MA transmutation fast reactor

Table 1 TRU fuel composition used in calculations

Isotope	Comp. [wt%]
Np-237	6.8
Pu-238	3.2
Pu-239	42.7
Pu-240	23.2
Pu-241	3.1
Pu-242	8.3
Am-241	10.3
Am-242m	0.009
Am-243	2.0
Cm-242	0.000
Cm-243	0.005
Cm-244	0.34
Cm-245	0.08
Cm-246	0.011

III. NUMERICAL RESULTS

Here we show the results of uncertainties for k-eff and MA transmutation amounts.

The k-eff uncertainty for the MA transmutation reactor is 0.71%dk/k, which is close to that for the MONJU core with uncertainty of 0.66%dk/k. However, the contributions of individual cross sections to this uncertainties are very much different. Figure 2 shows the contributions. For MONJU the U-238 capture cross section and the fission spectrum have large contributions, but for the MA transmutation fast reactor the U-238 inelastic cross section is the main contributor because of the hard neutron spectrum of the MA transmutation reactor. In the core the MA content is about 6.5%, and the Am-241 capture cross section has a large contribution. However the contribution is 11.0% as shown in Fig. 2, and it is less than the contributions of the fission spectrum and Pu-239 fission cross section. Thus in the MA transmutation fast reactor the contribution to the k-eff uncertainty is mainly caused by the neutron hard spectrum, not the direct effect of MA cross section uncertainties.

Table 2 shows the uncertainty of sodium void reactivity for the MA transmutation reactor. The total uncertainty is 8.7%, and the main contributor of this uncertainty is the Na-23 inelastic scattering. The contribution of the Am-241 capture cross section is rather small. Thus as in the k-eff uncertainty the uncertainty of the sodium void reactivity is caused by the hard neutron spectrum due to the content of MAs.

Table 3 shows the calculated uncertainties of transmutation of individual MA nuclides and total MA transmutation. The total MA transmutation amount is mainly due to Np-237 and Am-241 because the most of initial MA is composed of the two nuclides. The uncertainties of the transmutation amounts of these nuclides are about 3 %, and the uncertainty of total MA transmutation is also about 3 %. However the transmutation uncertainties of Np-239, Am-243, Cm-243 , Cm-244 and Cm-245 are rather large. These nuclides do not decrease with burnup but increase with burnup except for Am-243. The number density of Am-243 is nearly constant with burnup. The largest increase of the number density with burnup is for Cm-244. The Cm-244 has a large contribution to neutron emission and decay heat. So the large uncertainty of 9.6% for the Cm-244 build-up have to be taken into account in considering fuel handling and management.

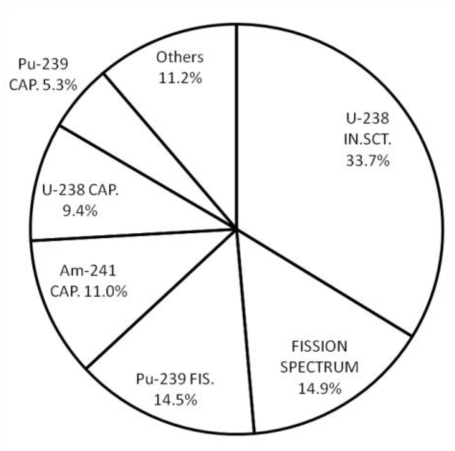
Table 2 Uncertainty of sodium void reactivity in the MA transmutation fast reactor

Cross sections	Uncertainty (%)
Na-23 inelastic scattering	7.2
Na-23 elastic scattering	1.7
U-238 capture	1.5
U-238 inelastic scattering	2.5
Pu-239 fission	1.4
Am-241 capture	2.4
Total	8.7

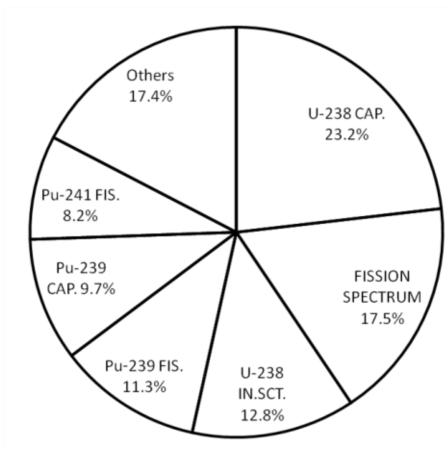
Table 3 Uncertainties of Transmutation of Individual MA Nuclides and Total MA

MA nuclides	Transmutation uncertainties (%)
Np-237	2.53
Np-239	29.42
Am-241	3.40
Am-243	133.06
Cm-242	1.91
Cm-243	24.73
Cm-244	9.64
Cm-245	28.69
Total MA	2.88

Figures 3 and 4 show the contributions of various cross sections to the transmutation uncertainties of Np-237, Np-239 , Am-241, Am-243 and Cm-244. The main contributors to the uncertainties of Np-237 and Am-241 are the capture cross sections of Np-237 and Am-241, respectively. However, for Cm-244, for example, the contributions of Am-243 capture cross section, Cm-244 capture cross section and Pu-242 capture cross sections are rather large as shown in Fig. 4.

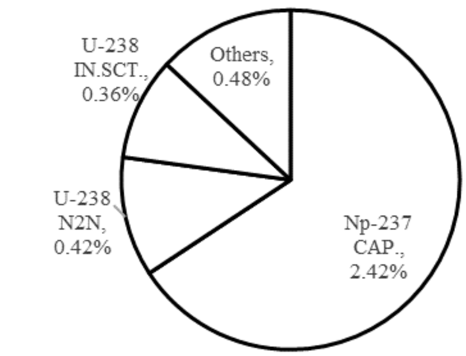


MA transmutation reactor core

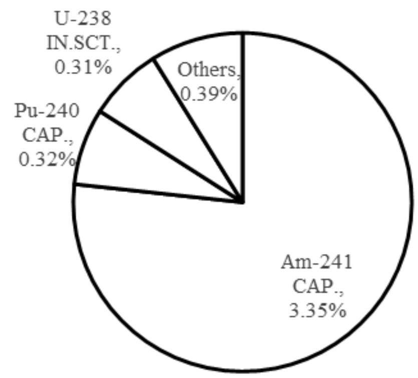


MONJU core

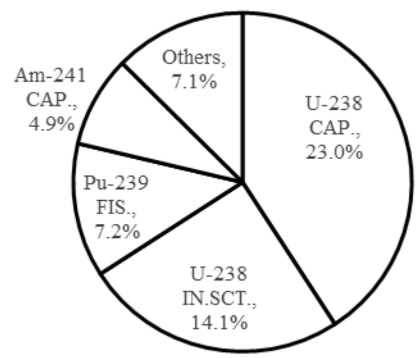
Fig. 2 Contribution of individual cross sections to k-eff uncertainties



Np-237



Am-241



Np-239

Fig.3 Contributions to the uncertainties of transmutation amounts of Np-237, Np-239 and Am-241

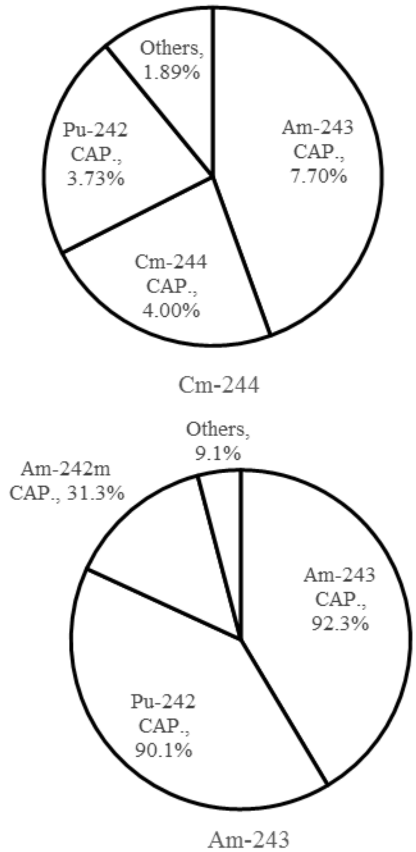


Fig.4 Contributions to the uncertainties of transmutation amounts of Am-243 and Cm-244

IV. CONCLUSIONS

From numerical results it was seen that for k-eff uncertainty for the MA transmutation fast reactor the uncertainty of U-238 inelastic cross section has a large contribution because of the hard spectrum of the core. For uncertainties of MA transmutation amounts, the uncertainties of transmutation of Np-237 and Am-241 were about 3%, and so the uncertainty of the total MA transmutation was also about 3%. However the uncertainties of Np-239, Am-243, Cm-243, Cm-244 and Cm-245 were found to be rather large. The Cm-244 which has a large contribution to neutron emission and decay heat has a large uncertainty for transmutation amount of about 9.6% in 1σlevel.

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