Preliminary Analysis of High-Flux RSG-GAS to Transmute Am-241 of PWR’s Spent Fuel in Asian Region

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Abstract. A preliminary study of minor actinides (MA) transmutation in the high flux profile RSG-GAS research reactor was performed, aiming at an optimal transmutation loading for present nuclear energy development. The MA selected in the analysis includes Am-241 discharged from pressurized water reactors (PWRs) in Asian region. Until recently, studies have been undertaken in various methods to reduce radiotoxicity from actinides in high-level waste. From the cell calculation using computer code SRAC2006, it is obtained that the target Am-241 which has a cross section of the thermal energy absorption in the region (group 8) is relatively large; it will be easily burned in the RSG-GAS reactor. Minor actinides of Am-241 which can be inserted in the fuel (B/T fuel) is 2.5 kg which is equivalent to Am-241 resulted from the partition of spent fuel from 2 units power reactors PWR with power 1000MW(th) operated for one year.

1. Introduction

Generation of electricity by nuclear power plant (NPP) involves the production of radioactive waste. It is reported that the total discharged spent fuel derived from nuclear power plants in the world, with a capacity of approximately 400GWe, will accumulate more than 450,000 tonnes in 2020 [1], which should be managed in a geological disposal.

Spent fuel contains about 3,000 tonnes of Pu, about 140 tonnes of Np-237 (which will be increased to approximately 500 tonnes due to the decay of Pu-241 and Am-241) and about 120 tonnes of the amount of americium. Long life fission products (LLFP) will also accumulate in spent fuel, such as the I-29 (about 60 tonnes), and Tc-99 (about 250 tonnes) [2]. On the other hand, activities of decommissioning nuclear power plants also produce significant quantities of waste for disposal in geological disposal.

To support the geological disposal in the back-end technology, the transmutation of actinides and LLFP contained in high level waste (HLW) have been studied extensively. To minimize the long term of risk radiotoxicity, theoretical and experimental studies, especially in Europe and Japan have been underway to transmute LLRN (long-lived radioactive nuclides): actinides, particularly Pu, minor actinides (MA) such as Np, Am and Cm; and fission products (FP) to short-lived fission products (SLFP) or stable species.

Minor actinides in HLW is a difficult problem since they have a very long half-life. The development of nuclear technology and the geological disposal of HLW including MA is currently
regarded as the most realistic method. However, there is a problem of uncertainty after about 1,000 years, since the immobilization technology can only presume the scenario for about $10^3$ years [3,4].

Potential risks of HLW can largely be calculated until $10^3$ years after the time out, as defined for engineering barrier, due to the technology of glass or ceramics to accommodate HLW known only capable for around those mentioned years. The most potential risk in the HLW is the isotope with a half-length, i.e Tc-99, I-129, and MA isotopes, namely Np-237, Am-241, Am-243, except FP isotopes (Sr-90, Cs-137 ) and MA from Cm-244 which has a half-life until about $10^3$ years.

To solve this problem, the concept of geological disposal of HLW supported by partitioning and transmutation technologies is proposed [4]. It is primarily focused on the transmutation of long-lived radionuclides into shorter-lived species by utilizing neutron fission. This method is very attractive to eliminate MA (Am-241, Am-243 and Np-237) and LLFP (Tc-99, I-129) while producing energy[5,6]. Among MA isotopes which regarded as a long-term radiological risk is Am-241

RSG-GAS is a research reactor with a maximum power of 30MWt. The fuel is a plate type fuel. RSG-GAS core configuration is arranged to yield high neutron flux of $1 \times 10^{14}$ n/cm$^2$/s. This high flux profile is very effective to burn/transmute MA nuclide obtained from PWR’s spent fuel.

A preliminary study of Am-241 transmutation in the high flux profile RSG-GAS research reactor was performed, aiming at an optimal transmutation loading for present nuclear energy development. The analysis assumed the Am-241 nuclide is obtained from partitioning process discharged from pressurized water reactors (PWR) in Asian region.

2. Theory

In this study, the concept of transmutation was evaluated to develop the transmutation system of a high-flux RSG-GAS research reactor for significantly transmute MA nuclides to reduce the potential risk of geologic disposal. Figure 1 shows the conceptual design of recycle transmutation loop, which is connecting transmutation reactor with reprocessing and partitioning process.

![Figure 1. Conceptual design utilization of RSG-GAS as the high-flux reactor to transmute minor actinides derived from the processing, separation and fabrication of PWR spent fuel in Asia.](image-url)
As shown in Figure 1, the spent fuel from PWR power reactors in Asia were reprocessed to gain the uranium and plutonium to be reprocessed and used in the MOX fuel reactors. The next step after reprocessing was to separate and take out the stable and short-life FP which will be stored in geologic disposal facility. Based on their half-life Cm nuclides was assumed to be stored in an interim storage, and eventually stored in a geologic disposal facility. Plutonium nuclides as a result storing Cm nuclides in an interim storage was return back to the reprocessing and partitioning process.

The MA nuclides (in this study is Am-241 selected due to its longest half-life time), which was reprocessed and partitioned from the facility, was manufactured as B/T (burning and transmutation) fuel for RSG-GAS reactor. This study is aimed to preliminary calculate the amount of Am-241 can be transmuted in the RSG-GAS.

3. Calculation

Flowchart of computation used in this study is shown in Figure 2. Code SRAC2006 executes calculations cells with the collision probability method ($P_{ij}$ module) to cover the entire range of neutron energy calculation. This Code solves linear equations which describe the behaviour of neutrons in a steady state condition is described by following the following equations, where the system under consideration is divided into N regions and neutron energy range is divided into group G. Some other physical quantities are defined as follows[7]:

Volume region $i$:

$$V_i = \int dV$$

Flux for the whole region $i$ of energy group $g$:

$$\phi_{ig} = \int dV \int dE \phi(r, E)$$

Collision probability within the region $i$ to region $j$ for the group $g$:

$$P_{ijg}$$

Scattering cross section which is used to evaluate the neutron equilibrium

$$\sum_{a,mg} = \sum_{g \in G} \Sigma_{amg \rightarrow g} + \sum_{g \in G} \Sigma_{mg} \cdot \phi \Sigma_{smg}$$

where:

- $\Sigma_{mg}$ = total cross section of nuclide $m$ of group $g$
- $\Sigma_{fmg}$ = fission cross section of nuclide $m$ of group $g$
- $\Sigma_{amg}$ = absorption cross section of nuclide $m$ of group $g$
- $\Sigma_{smg}$ = scattering cross section of energy group $g$ to $g'$

The mass balance of burning and transmutation (B/T) fuel was calculated from the cell depletion calculation. The time required to achieve the equilibrium state of the core can be estimated by performing a series of cell depletion calculations starting with a typical cell composition.

In each successive calculation, the same isotopic composition with that used in the original cell calculation, were added to the remains of the B/T fuel at the end of cycle (EOC). The amount of new fissile materials and the fuel density were adjusted accordingly to keep the fuel cycle length and burn up in the same conditions. The atomic density of isotope-$i$ in each region, $N_i$, can be expressed by
\[ N_i = \frac{F_i \rho_F N_A}{M_F} \]  

(5)

where

- \( F_i \): weight fraction of nuclide-\( i \) in fuel
- \( \rho_F \): material density g/cm\(^3\)
- \( N_A \): Avogadro’s number, \(6.022045 \times 10^{23}\) mol\(^{-1}\)
- \( M_F \): average molecular weight of fuel, g/g-mol

\[ \text{Figure 2. Flowchart of calculation using computer code SRAC2006} \]

4. Results and Discussion

The literature retrieval was undertaken to obtain the data of high level waste (HLW) generated from spent fuel of PWR nuclear power plants in the region. The overall spent fuel assumed to be processed and separated in the processing and separation facilities in the Asian region as well. Similarly, the fabrication of fuel for burning and transmutation (B/T-fuel) is performed at a fuel fabrication facilities in Asia.
Data on nuclear power plants in Asia can be seen in Table 1, included in the table also is data regarding the processing facilities, separation and fabrication.

### Table 1. Data of nuclear power plants (NPP) operating in the region and fuel recycling capabilities possessed by some Asian countries [8].

| Country       | NPP in operation | NPP under construction | NPP planned | Research Reactor | Fuel Cycle Capability |
|---------------|------------------|-------------------------|-------------|------------------|-----------------------|
| Australia     | 0                | 0                       | 0           | 1                | UM                   |
| Bangladesh    | 0                | 0                       | 2           | 1                |                       |
| China         | 30               | 24                      | 40          | 16               | UM, C, E, FF          |
| India         | 21               | 6                       | 22          | 4                | UM, FF, R, WM         |
| Indonesia     | 0                | 0                       | 1           | 3                | FF                   |
| Japan         | 43               | 3                       | 9           | 14               | C, E, FF, R, WM       |
| S. Korea      | 25               | 3                       | 8           | 2                | C, FF                |
| Malaysia      | 0                | 0                       | 0           | 1                |                       |
| Pakistan      | 3                | 2                       | 2           | 1                | UM, E, FF             |
| Philippines   | 0                | 0                       | 0           | 1                |                       |
| Taiwan        | 6                | 2                       | 0           | 1                |                       |
| Thailand      | 0                | 0                       | 0           | 2                |                       |
| Vietnam       | 0                | 0                       | 4           | 1                |                       |
| Total Asia    | 128              | 40                      | 88          | 48               |                       |

Note:
UM : Uranium Mining  
C : Conversion  
E : Enrichment  
FF : Fuel fabrication  
R : Reprocessing  
WM : Waste management on Geologic Disposal

HLW handling scenarios (Figure 1) of PWR spent fuel in the Asian region prepared by RSG-GAS research reactor as a burning and transmutation reactor; using radionuclide transmutation into short-lived fission products or unstable nuclides.

The study aimed to evaluate the available technologies of RSG-GAS research reactor to operate with fuel transmutation (B/T-fuel). The evaluation includes the analyzing of the effectiveness of the transmutation of MA into fission products by utilizing the high flux of RSG-GAS reactor.

Nuclide selected for transmutation is Am-241 separated / partitioned in the spent fuel PWR in Asian countries, in this case selected third countries that intensively use the nuclear power plants in the region, which are Japan, China and South Korea.

### Table 2. Data of PWR operating in Asia (Japan, China and South Korea)[9]

| Country | Power (MW) | Burn-up (MWd/THM) | U enrichment (%) |
|---------|------------|-------------------|-----------------|
| Japan   |            |                   |                 |
| Genkai  | 3478       | 60000             | 4               |
| Ikata   | 2022       | 48000             | 4-5             |
| Mihama  | 1666       | 37000             | 4               |
| Ohi     | 4710       | 70000             | 4               |
Based on these data and the composition of the spent fuel generated at end of cycle (EOC) of PWR, and then calculated the composition of transuranic (especially the minor actinides) which can be separated from the fuel. A typical composition of actinides from LWR spent fuel 1 unit 1 GWe enrichment 3.3% U-235, 150 days after the EOC and the burn-up = 33000 MWD / Mg (HM) in Table 3.

**Table 3.** Actinide of 1 GWe LWR spent fuel with 3.3% U-235, 150 days after the EOC, burn-up = 33 GWD / Ton (HM) [10].

| Radionuclide | Half-life (y or d) | Mass (kg/y) |
|--------------|-------------------|-------------|
| 238U         | 2.47 x 10^5 y     | 3.14        |
| 235U         | 7.1 x 10^5 y      | 2.15 x 10^2 |
| 236U         | 2.39 x 10^7 y     | 1.14 x 10^2 |
| 237U         | 6.75 d            | 9.15 x 10^-7|
| 238U         | 4.51 x 10^9 y     | 2.57 x 10^4 |
| Total U      |                   | 2.60 x 10^4 |
| 237Np        | 2.14 x 10^6 y     | 2.04 x 10^1 |
| 239Np        | 2.35 d            | 2.05 x 10^-6|
| Total Np     |                   | 2.04 x 10^1 |
| 236Pu        | 2.85 y            | 2.51 x 10^-4|
| 238Pu        | 86 y              | 5.99        |
| 239Pu        | 24,400 y          | 1.44 x 10^2 |
| 240Pu        | 6,580 y           | 5.91 x 10^1 |
| 241Pu        | 13.2 y            | 2.77 x 10^1 |
| 242Pu        | 3.79x 10^3 y      | 9.65        |
| Total Pu     |                   | 2.46 x 10^2 |
| 241Am        | 458 y             | 1.32        |
| 243Am        | 7,950 y           | 2.48        |
| Total Am     |                   | 3.81        |
It is assumed target of Am-241 of 2.5 kg is inserted in the reactor core RSG-GAS. Calculation of homogenized fuel cells are consists of Am-241 with AlMg2 cladding and water moderator. Calculations were used 8 neutron energy group. The results of calculation of the macroscopic cross section of Am-241 can be seen in Figure 3.

From the graph of the fission and absorption cross-section (Figure 3) it can be concluded that the Am-241 which has a cross section of the thermal energy absorption in the region (Group 8) is relatively large, it will be easily burned (transmuted) in the RSG-GAS reactor.

![Figure 3. Macroscopic cross section of Am-241](image)

5. Conclusions
Minor actinide Am-241 which has a cross section of the thermal energy absorption in the area (group 8) is relatively large; it will be effectively transmuted in the RSG-GAS reactor. Am-241 which can be inserted in the fuel transmutation (B/T fuel) of 2.5 kg which is equivalent to Am-241 resulting from the partition of spent fuel from 2 units of 1000MWt PWR power reactors operated for one year. For the spent fuel from power reactors PWR in Asia (Japan, China and South Korea), which amounted to 17 units, then the minor actinides from spent fuel will be burnt in the RSG-GAS for around ~ 9 years.

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