Performance Improvement for Multi-recycling HTGR Incorporated with MA burning

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Abstract. Multi-recycling HTGR has been investigated by JAEA in order to reduce the environmental burden and non-proliferation of Pu. In the previous study, it is found that all actinoids except neptunium, which is not problematic from the viewpoint of toxicity and proliferation, can be recycled. However, the cycle length is slightly decreased compared with uranium fueled core due to the cumulated fertile TRU in the fuel composition. In the present study, Pu recycling HTGR is designed to incorporate with MA burning. As a result, the cycle length is increased by approximately 15% compared with TRU multi-recycling core, and if the MA burner can be achieved by IFR, the cost is decreased by 0.14 yen/kWh.

1. Introduction

TRansUranium (TRU) multi-recycling concept with thermal neutron High Temperature Gas-cooled Reactor (HTGR) has been investigated [1]. In the concept, the multi-recycling is formed by providing uranium-235 from outside of the cycle to reduce environmental burden and proliferation risk of fissile plutonium. This cycle can consume the TRU provided from outside of the cycle. The function is almost the same as Fast Breeder Reactors (FBRs).

On the other hand, FBR cycle incorporated with Minor Actinoid (MA) burning by Accelerator-Driven System (ADS) has been researched [2]. With the incorporation, the advantage may be obtained. Unfortunately, no advantage is found in this case with the multi-faced evaluation. The reason can easily be guessed that the role and characteristics of FBR and ADS are similar because of the Fast Reactor (FS) system for both reactors.

However, it is expected that the incorporation with the MA burner reactor such as ADS would bring certain advantages to the HTGR multi-recycling fuel cycle because of the thermal reactor.

Then, the specifications of the fuel cycle of multi-recycling HTGR incorporated with MA burning is evaluated in the present study. The outline of the fuel cycle and reactor concept is described in Section 2. The design method is described in Section 3. The specifications of the fuel cycle with MA burner are summarized and discussed in Section 4. The requirement for MA burner is described in Section 5.

2. Concept of multi-recycling HTGR

We proposed multi-recycling HTGR in the previous study [1]. The objectives are to reduce potential toxicity and fissile plutonium from the viewpoint of environmental burden and proliferation risk, respectively. The detailed concept is described as follows.
2.1. Concept of fuel cycle

Figure 1 shows the fuel cycle concept proposed in the previous study. The major characteristics is providing the fissile uranium-235 from outside of the fuel cycle. Actually, natural uranium is provided and it is enriched in the enrichment facility in the fuel cycle. Then, depleted uranium is defecated. In the enriched facility, the recovered uranium is also enriched and reused. The depleted uranium is particular because it includes a relatively larger amount of uranium-234 and uranium-236 due to the multi-recycling. However, it was confirmed that the toxicity is not problematic from the viewpoint of potential toxicity in the previous study. The nuclides disposed of as waste is Fission Products (FPs) and neptunium. Neptunium is not problematic from the viewpoint of potential toxicity and public dose by the groundwater model [3]. Moreover, the cycle length of the HTGR is significantly reduced with neptunium recycling. Therefore, the neptunium is aggressively disposed of in the representative scenario. The burden of MA recycling is found at this stage. In addition, this concept employs 4-group partitioning [4] to recover MA. Therefore, significant waste volume reduction can be achievable because of the high-loading glass canister and Sr-Cs calcined waste package.

In the present study, the fuel cycle with MA burner reactor is proposed as shown in Fig.2 to reduce the burn to the HTGR specification. The burning of neptunium is not essential even with the MA burner in the present study. The MA burner implicitly includes its fuel cycle because that may be different from that of power generation strata as same as the pyro-reprocessing of ADS [5].

2.2. HTGR reactor concept

The multi-recycled HTGR was designed based on GTHTR300 [6], which is a commercial-scale HTGR design with a 600 MW thermal power output. The detailed specifications and core configuration are described in Table 1 and Fig.3. Its annular core, which comprises two batches of fuel blocks, is loaded with 14 wt.% enriched uranium fuels. The cycle length is 730 days. The fuel columns are composed of eight fuel block layers aligned in the axial direction. Each fuel block is approximately 1 m high, yielding an approximate core height of 8 m. Because of the axial arrangement of the GTHTR300 core parts, an axial fuel reloading is assumed. As the loading pattern for GTHTR300 design, JAEA devised and implemented a method called sandwich refueling [6]. The fuel blocks are divided into irradiated and fresh fuel batches. The irradiated fuel blocks are sandwiched between the fresh fuel blocks.
Also, the uranium inventory is slightly reduced from its original 7.09 t [7], as the fuel structure was revised from the viewpoint of fuel fabrication [8]. The target cycle length and average discharged burn-up are 730 days and 120 GWd/t, respectively.

**Table 1.** Major specification of GTHTR300.

| Item                              | Value |
|-----------------------------------|-------|
| Thermal power (MWt)               | 600   |
| Electric generation (MWe)         |       |
| Gross:                            | 280   |
| Net:                              | 274   |
| Uranium inventory (ton)           | 7.01  |
| $^{235}$U enrichment (wt%)        | 14.0  |
| Cycle length (days)               | 730   |
| Number of batch (-)               | 2     |
| Discharge burn-up (GWd/t)         | 120   |

![Core configuration of GTHTR300.](image)

Table 2 shows the comparison of the specifications between the standard design of GTHTR300 and TRU multi-recycling HTGRs. The cycle length of the standard design is reduced by 100 days because of the revision of the design and improvement of the calculation code and nuclear data. The uranium enrichment is limited to be lower than 20 wt% in any part of the fuel cycle. In the enrichment facility, the uranium is enriched to 19.9 wt%. Later, it is mixed with the mixture of recovered plutonium and uranium. In Japan, the treatment of pure plutonium is prohibited and the recovered plutonium should be mixed with the same amount of the recovered uranium from the viewpoint of proliferation according to the Japan-U.S. reprocessing negotiation [9]. As a result, the uranium enrichment of fabricated fuel is reduced to approximately 18 wt%. It is increased by 4 wt% compared with the standard design. Even with the compensation of 4 wt% enrichment increase, the cycle length becomes lower than half due to the cumulated TRU for the whole TRU recycled case (TRU multi-recycling with Np). In the case of disposing of neptunium (TRU multi-recycling), the cycle length is slightly reduced compared with the standard design. Therefore, the case was selected as representative of the multi-recycling HTGR.

The other specifications of the multi-recycling HTGR are the almost same or improved. The excess reactivity becomes lower than half. The delayed neutron fraction is almost the same even with TRU.
recycling because the fission of uranium-235 is dominant due to the high enrichment fuel. The temperature coefficient becomes a more negative value. As described above, TRU multi-recycling is not problematic from the viewpoint of reactor safety.

| Table 2. Comparison of major specifications between HTGR designs. |
|---------------------------------------------------------------|
| Uranium Enrichment (wt%) | GTHTR300 | TRU multi-recycling | TRU multi-recycling with Np |
|---------------------------|----------|----------------------|-----------------------------|
| Cycle length (day)       | 630      | 610                  | 240                         |
| Discharged burn-up (GWd/t)| 107.8    | 104.4                | 41.1                        |
| Excess reactivity (BOC) (%Δk/kk') | 18.2 (0.06%) | 8.0 (0.13%) | 2.2 (0.57%) |
| Delayed neutron fraction (BOC) (%) | 0.606 (3.3%) | 0.540 (3.3%) | 0.529 (3.5%) |
| Delayed neutron fraction (MOC) (%) | 0.547 (2.9%) | 0.521 (3.9%) | 0.533 (3.1%) |
| Delayed neutron fraction (EOC) (%) | 0.517 (3.2%) | 0.514 (3.3%) | 0.512 (3.3%) |
| Temp. coeff. (BOC) (pcm/K) | -2.29 (6.5%) | -5.82 (2.6%) | -7.49 (2.5%) |
| Temp. coeff. (MOC) (pcm/K) | -3.84 (3.9%) | -5.71 (3.2%) | -6.54 (2.7%) |
| Temp. coeff. (EOC) (pcm/K) | -5.31 (3.2%) | -6.68 (2.8%) | -6.56 (2.8%) |

*The values in parentheses stand for statistics error corresponding to 1σ.*

3. Design method of multi-recycled HTGR
To design the multi-recycled HTGR, several processes are necessary to evaluate the whole fuel cycle not only for the core design.

3.1. Design method of whole fuel cycle
Figure 4 shows the mass flow of the proposed fuel cycle with the lead, lag time, and loss ratio. As described in Section II.B, the enrichment facility treats both of the natural uranium and recovered uranium. The enrichment is limited lower than 20 wt% at this stage. That is mixed with recovered plutonium with the same amount of uranium according to the Japan-U.S. reprocessing negotiation. Recovered MA is burned in the MA-Burner.

To reduce the potential toxicity, the loss ratio of TRU is limited to lower than 0.1% in the whole fuel cycle [10]. Here, the loss of the reprocessing is set at 0.1% instead of 0% in fuel fabrication.

To accelerate the iteration of the calculation and to obtain an accurate result, the decay calculation of the fuel cycle and the burn-up calculation of the reactor is performed by using a point burn-up calculation code ORIGEN [11]. The calculation time is so short less than 1 second that the number of iterations can be spent enough to obtain saturated solutions.

With the fuel composition evaluated in the fuel cycle calculation, Core burn-up calculation is performed as described in Section III.B. The calculation is also iterated until to obtain the saturated discharge fuel composition. At the same time, the cross-sections used by ORIGEN code in the fuel cycle calculation are revised at this stage because that should be prepared for the target reactor.
Figure 4. Fuel cycle mass flow of multi-recycle HTGR.

3.2. Design method of multi-recycled HTGR
The burn-up characteristics are evaluated by core burn-up calculation implemented in MVP [12] code, a Monte Carlo neutron transport code with evaluated nuclear data of JENDL-4.0 [13]. Moreover, the double heterogeneity of Coated Fuel Particles (CFPs) is directly analyzed using a statistical geometric model [14]. The MVP calculations were implemented in three-dimensional whole-core models. The core is composed of two batches as described in Section II.B. To evaluate equilibrium cycle core, the fuels were reloaded several times to obtain a saturated state according to the sandwich reloading scheme as described in Section II.B. To evaluate temperature coefficient, the reactivities are compared with a reference state and temperature increased state (100K increased for each region). Moreover, this study evaluates effective delayed neutron yields by using the prompt method [15].

3.3. Evaluation of enriched uranium composition
In the proposed cycle, recovery uranium is also enriched and recycled. Uranium isotopes except for uranium-235 and uranium-238 are important as well. Uranium-236 would be accumulated and affect criticality, and other components are released as depleted uranium to the environment and might have significant toxicity. To assess the feasibility of this cycle, the evaluation method for multi-component enrichment of uranium is necessary.

In general, to evaluate multi-component separation, matched abundance ratio cascade theory, which is extended the ideal cascade theory of two-component to match the abundance ratio in each feed point of cascade [16]. The abundance ratio is determined as a ratio of the mole number of targets to that of a key component. In general, uranium-238 is selected as the key component. In two components system, the target component is uranium-235 and the key component is uranium-238. By reducing the problem with each target component and common key component, the two components theory is extended to the multi-component theory. The target would be uranium-232, uranium-233, uranium-234, uranium-235, uranium-236 and, etc.

To evaluate the enriched composition by using the multi-component theory, the separation factor is necessary, and that is evaluated by assuming gas centrifuge [17] with the data of the peripheral velocity from 400-600 m/s and the temperature of 300K.

4. Specifications with MA burner
The specifications of plutonium multi-recycling HTGR with MA Burner is evaluated in the present study described as follows.

4.1. Specifications of Pu multi-recycling HTGR
Table 3 lists the calculation result of HTGR specification with a comparison with standard design and TRU multi-recycling HTGR. The cycle length and discharged burn-up shows a significant increase of approximately 10 %. The excess reactivity increases 5% $\Delta k/k'$ along with the improvement of criticality. However, that is lower than that of standard design by 5% $\Delta k/k''$. The delayed neutron fraction and reactivity coefficient of temperature is almost the same as that of the standard design.
Table 4 lists the fresh fuel composition of each design. In the plutonium multi-recycling HTGR fuel, the americium and curium are excluded, and the neptunium is originally excluded in the stage of TRU multi-recycling design due to the no effect to the environmental burden. With the reduction of 1.8 wt% of MA and 0.6 wt% of fertile plutonium, the significant specification improvement can be obtained.

Table 3. Comparison of major specifications between HTGR designs.

|                      | GTHTR300 | TRU multi-recycling | Pu multi-recycling |
|----------------------|----------|---------------------|--------------------|
| Uranium enrichment (wt%) | 14.0     | 18.4                | 18.8               |
| Cycle length (day)    | 630      | 610                 | 700                |
| Discharged burn-up (GWd/t) | 107.8   | 104.4               | 119.8              |
| Excess reactivity (BOC) (%Δk/kk') | 18.2 (0.06%) | 8.0 (0.13%) | 13.0 (0.13%) |
| Delayed neutron fraction (BOC) (%) | 0.606 (3.3%) | 0.540 (3.3%) | 0.560 (3.5%) |
| Delayed neutron fraction (MOC) (%) | 0.547 (2.9%) | 0.521 (3.9%) | 0.541 (3.5%) |
| Delayed neutron fraction (EOC) (%) | 0.517 (3.2%) | 0.514 (3.3%) | 0.527 (3.2%) |
| Temp. coeff. (BOC) (pcm/K) | -2.29 (6.5%) | -5.82 (2.6%) | -2.12 (8.0%) |
| Temp. coeff. (MOC) (pcm/K) | -3.84 (3.9%) | -5.71 (3.2%) | -2.66 (6.5%) |
| Temp. coeff. (EOC) (pcm/K) | -5.31 (3.2%) | -6.68 (2.8%) | -2.61 (6.4%) |

*The values in parentheses stand for statistics error corresponding to 1σ.

Table 4. Fuel composition of fresh fuel (wt%).

|             | GTHTR300 | TRU multi-recycling | Pu multi-recycling |
|-------------|----------|---------------------|--------------------|
| $^{234}\text{U}$ | -        | 0.3                 | 0.3                |
| $^{235}\text{U}$ | 14.0     | 18.4                | 18.8               |
| $^{236}\text{U}$ | -        | 9.9                 | 9.8                |
| $^{237}\text{Np}$ | -        | -                   | -                  |
| $^{238}\text{Pu}$ | -        | 1.3                 | 1.1                |
| $^{239}\text{Pu}$ | -        | 1.0                 | 0.9                |
| $^{240}\text{Pu}$ | -        | 0.7                 | 0.5                |
| $^{241}\text{Pu}$ | -        | 0.4                 | 0.4                |
| $^{242}\text{Pu}$ | -        | 1.1                 | 0.9                |
| Am          | -        | 0.7                 | -                  |
| Cm          | -        | 1.1                 | -                  |
4.2. Specifications for waste package generation and disposal

Table 5 lists the number of waste packages generated by electricity generation. The number is mainly determined by the reprocessing method and waste package specification [5]. The amount of MA is negligible compared with FPs, and the decay heat also negligible at this stage. With partitioning case, that is “GTHTR300 with partitioning”, “TRU multi-recycling”, and “Pu multi-recycling”, the number of waste packages is reduced by 60% compared with an ordinary reprocessing case of “GTHTR300”.

On the other hand, the repository footprint is listed in Table 6. That depends on partitioning, cooling time, and disposal method. In the case of “GTHTR300 with partitioning”, the longer cooling time of 150 years realize the horizontal emplacement. With the reduction of the number of waste packages, the repository footprint is reduced by 88.3% compared with the ordinary reprocessing case in the soft rock repository. With transmutation of americium-241 and long cooling time of 330 years, the decay heat can be minimized. With the small decay heat, the compact emplacement, in which bundled waste packages are piled up as shown in Fig. 5, can be realized. With the compact disposal, the footprint can be reduced by 99.7% for TRU multi-recycling HTGR and plutonium multi-recycling HTGR.

Table 5. Number of waste package generation (canister/TWeh).

|                | GTHTR300 | GTHTR300 with partitioning | TRU multi-recycling | Pu multi-recycling |
|----------------|----------|----------------------------|---------------------|--------------------|
| Vitrified waste| 2.31     | 0.502                      | 0.515               | 0.521              |
| Sr calcined waste| -       | 0.153                      | 0.152               | 0.153              |
| Cs calcined waste| -       | 0.178                      | 0.193               | 0.192              |
| Total           | 2.31     | 0.833                      | 0.860               | 0.866              |

Table 6. Specifications for waste disposal.

|                | GTHTR300 | GTHTR300 with partitioning | TRU multi-recycling | Pu multi-recycling |
|----------------|----------|----------------------------|---------------------|--------------------|
| Disposal method| Vertical | Horizontal                 | Compact             | Compact            |
| Cooling time from repro | 50 years  | 150 years                  | Vitrified: 60 years | Vitrified: 60 years |
| Repository footprint in soft rock (m²/TWeh) | 209 | 24.3 | 0.658 | 0.663 |
| Repository footprint in hard rock (m²/TWeh) | - | - | 0.823 | 0.829 |
4.3. **MA generation from Pu multi-recycling HTGR**

Tables 7 and 8 list the MA amount and its composition from PWR, GTHTR300, TRU and plutonium multi-recycling HTGR, with and without neptunium, respectively. The MA generation per electricity generation of GTHTR300 is smaller than that of PWR because of the higher thermal efficiency. The thermal efficiencies are 34.5 % and 45.6 %, respectively for PWR and HTGR. The MA generation from plutonium multi-recycling HTGR is five times larger than that from GTHTR300 because of the generation of neptunium from cumulated uranium-236, and that of americium and curium from cumulated plutonium. However, the MA generation can significantly be reduced by excluding neptunium the toxicity is not problematic due to its long lifetime.

For the MA composition of americium and curium, the amount of high order nuclides is a larger with the plutonium multi-recycling HTGR because of the cumulated plutonium-242, which exists almost the same amount of plutonium-239.

To confirm the reactivity worth of the MAs, that is evaluated by the equivalent fissile method [18], which is also employed to manage fuel composition in the prototype FBR Monju. The equivalent fissile method is as follows,

$$y^i = \nu \sigma_f^i - \sigma_a^i, \quad (1)$$

$$\eta^i = y^i / y_{key}, \quad (2)$$

$$W = \sum_i \alpha_i \eta^i, \quad (3)$$

where,

- $y^i$: equivalent fissile value for i-th nuclide (cm$^{-2}$),
- $y_{key}$: equivalent fissile value for key nuclide (cm$^{-2}$),
- $\nu \sigma_f^i$: microscopic production cross-section for i-th nuclide (cm$^{-2}$),
- $\sigma_a^i$: microscopic absorption cross-section for i-th nuclide (cm$^{-2}$),
- $\eta^i$: equivalent fissile coefficient for i-th nuclide (-),
- $\alpha_i$: atomic number fraction for i-th nuclide (-),
- $W$: reactivity worth of fuel material (-).

In general, plutonium-239 is selected as the key nuclide to manage plutonium composition, and this method is used to determine plutonium enrichment to keep certain reactivity worth of fuel material. In the present study, neptunium-237 is selected as the key nuclide to elucidate the reactivity worth of MAs. MA burner should be fast neutron systems such as FBR and ADS. Therefore, the condensed cross-section by FBR neutron spectrum prepared as ORIGEN code library named 1500MXIC in ORLIB-J40 [19]. That is represented for the MOX part of the inner core of large commercial FBR.

![Figure 5. Compact emplacement disposal.](image-url)
The reactivity worth is listed in Table 9. The worth shows the negative value for positive reactivity because of the negative equivalent fissile value of neptunium-237. The MA from plutonium multi-recycling HTGR contributes criticality, and it is significant for MAs excluding neptunium. For the ADS fuel design, the MA content should slightly be diluted by the matrix material to compensate for the increased criticality worth.

### Table 7. MA amount and its composition.

|          | PWR  | GTHTR300 | Pu multi-recycling |
|----------|------|----------|--------------------|
| MA amount (kg/TWeh) | 3.2  | 2.0      | 10.1               |
| Composition (wt%)   |      |          |                    |
| Np-237             | 53.00| 52.29    | 62.32              |
| Am-241             | 30.34| 26.05    | 8.31               |
| Am-242m            | 0.09 | 0.11     | 0.07               |
| Am-243             | 11.98| 16.26    | 19.39              |
| Cm-243             | 0.05 | 0.06     | 0.04               |
| Cm-244             | 4.17 | 4.89     | 8.95               |
| Cm-245             | 0.34 | 0.31     | 0.87               |
| Cm-246             | 0.03 | 0.02     | 0.06               |

### Table 8. MA amount and its composition without Np.

|          | PWR  | GTHTR300 | Pu multi-recycling |
|----------|------|----------|--------------------|
| MA amount (kg/TWeh) | 1.5  | 0.9      | 3.8                |
| Composition (wt%)   |      |          |                    |
| Am-241             | 64.55| 54.60    | 22.07              |
| Am-242m            | 0.19 | 0.24     | 0.17               |
| Am-243             | 25.49| 34.09    | 51.46              |
| Cm-243             | 0.10 | 0.12     | 0.09               |
| Cm-244             | 8.88 | 10.26    | 23.74              |
| Cm-245             | 0.73 | 0.66     | 2.30               |
| Cm-246             | 0.06 | 0.04     | 0.16               |

### Table 9. Reactivity worth of MAs in FR by equivalent fissile method (-)

|          | PWR  | GTHTR300 | Pu multi-recycling |
|----------|------|----------|--------------------|
| MA       | 0.59 | 0.49     | 0.27               |
| MA without Np | 0.12 | -0.07   | -0.96              |

5. Requirement for MA burner

To consume MA generated from plutonium multi-recycling HTGR, the introduction of MA burner is considered in the present study. Major topics are as follows.

5.1. Installation capacity of MA burner

To consider the installation capacity of MA burner, ADS is assumed because of the small fuel cycle due to the heavy loading of MAs. ADS is designed as small-sized Pb-Bi cooled FR, and the coolant also plays a role of spallation reaction target of proton beam as a neutron source to drive the subcritical reactor. The reactor power is 800MWt, and the transmutation rate of MA is 250 kg/y [20]. According to these specifications and MA generation amount, the installation unit number of ADS is evaluated,
and the result is listed in Table 10. The number stands for the installation unit number of ADS per electricity generation of each reactor in an equilibrium state. Comparing between PWR and GTHTR300, the installation number of ADS for GTHTR300 is very small because of the less MA generation. On the contrary, that of plutonium multi-recycling HTGR is very large due to the more MA generation. However, by excluding neptunium the insulation unit becomes close that of PWR for the whole MA, which is the representative scenario of ADS.

Table 10. Number of ADS per electricity capacity (unit/GWe)

|                | PWR   | GTHTR300 | Pu multi-recycling |
|----------------|-------|----------|-------------------|
| MA             | 0.090 | 0.062    | 0.318             |
| MA without Np  | 0.042 | 0.030    | 0.120             |

5.2. Cost impact to introduce MA burner

To consider the cost impact to introduce MA burner HTGR the difference in electricity cost between TRU multi-recycling HTGR and plutonium multi-recycling HTGR with MA burner. Neptunium is excluded as a transmutation target because of the unecessity. In the future, a detailed analysis should be performed. However, some cost-related terms are considered and the cost feasibility is confirmed. The conditions and cost-related terms are as follows.

- Based on GTHTR300 cost evaluation [21] revised to the latest condition [22].
- The cycle length change is considered via a change of capacity factor and fuel fabrication.
- The plutonium multi-recycling HTGR is regarded as a representative case in the comparison because the cycle length is almost the same as the design target of GTHTR300.
- MA burner cost is simply converted by the introduced capacity from the cost increase of 0.12 yen/kWh in LWR scenario [23].

Based on the latest electricity generation cost evaluation of LWR in Japan [24], where the cost is evaluated as 10.3 yen/kWh, the revised cost GTHTR300 is to be 9.0 yen/kWh. It is composed of a capital cost of 2.4 yen/kWh, the operation cost of 2.3 yen/kWh, the fuel cost of 1.8 yen/kWh, and social cost of 1.5 yen/kWh. The cost change is evaluated and the result is listed in Table 11. The capacity factor is slightly reduced by 1% in TRU multi-recycling HTGR. It increases the cost relating to capital cost and operational cost. Totally, the cost is increased by 0.07 yen/kWh. The fuel fabrication cost is 0.53 yen/kWh. Because of the reduced cycle length, the cost increased by 0.08 yen/kWh. Finally, the cost of TRU multi-recycling HTGR is increased by 0.15 yen/kWh. On the other hand, the cost of the plutonium multi-recycling core is increased by 0.16 yen/kWh. From the viewpoint of the cost, the cost is slightly increased by introducing MA burner. According to the cost evaluation of ADS [23], the cost may reduce to 0.01 yen/kWh by employing FR corresponding to ADS due to the cost reduction by removing accelerator and increasing of electricity generation. In that case, the installation of MA burner can improve the economy of multi-recycling HTGR by 0.14 yen/kWh.

Table 11. Cost change by MA recycling (yen/kWh).

|                | TRU multi-recycling | Pu multi-recycling |
|----------------|--------------------|--------------------|
| Capacity factor| +0.07              | -                  |
| Fuel fabrication| +0.08             | -                  |
| MA burner      | -                  | +0.16              |
| Total          | +0.15              | +0.16              |

5.3. Safety requirement of MA burner

In the ADS core, the neutron source did not affect to the transmutation characteristics. The neutron population in the subcritical reactor is expressed as follows,
\[ M = \frac{s_l}{1 - k_{\text{eff}}} \]  

where,  
- \( M \): neutron population in the reactor (\(\cdot\)),  
- \( s \): neutron source strength (s\(^{-1}\)),  
- \( l \): a lifetime of a neutron (s),  
- \( k_{\text{eff}} \): effective multiplication factor (\(\cdot\)).

The effective multiplication factor of ADS is designed around 0.95. Due to the eq.4, one neutron generated from the neutron source is multiplied by 20 times. In other words, 95% of a neutron is generated from the chain reaction. The transmutation characteristics are not different from that of critical FR.

The reason that ADS designed as a subcritical reactor is to ensure safety. However, the safety can be ensured not only by the neutronic characteristics but also by the thermal characteristics. In general, inherent safety feature of self-regulation of the reactor power in LWR is very famous. This safety feature can be realized by the characteristics of the thermal reactor and reduced moderation design [25]. On the contrary, in FR, positive reactivity is inserted when the coolant voided due to the threshold fission reaction. It is called positive sodium void reactivity. In general, commercial FBR occurs power burst and core melt, when a scrub is failed during the loss of forced coolant [10]. However, inherent safety can be realized even by FR with a large safety margin in thermal design. In the accident, the power is settled down safely by the Doppler effect if the coolant is not voided. This reactor concept is called the Integral Fast Reactor (IFR) [26]. IFR is designed as small-sized FR as same as ADS. MA burner based on IFR should be investigated to improve the economy of multi-recycling HTGR.

**Summary**

To find the advantage of incorporation of multi-recycling HTGR cycle with MA burner, the specification of plutonium multi-recycle HTGR and the requirement for MA burner have been investigated. Major conclusions are as follows.

- According to the previous study, there is no advantage to the incorporation of FBR multi-recycling with ADS.
- Plutonium multi-recycling HTGR can realize significant toxicity reduction and waste volume reduction as same as FBR and ADS, and the cycle length and discharged burn-up are increased by 15% comparing with TRU multi-recycling HTGR. On the other hand, the cycle needs to incorporate with MA burner.
- The installation capacity of MA burner is almost the same as the representative ADS scenario by excluding neptunium from the transmutation target even with the more MA generation characteristics.
- The cost increase by introducing MA burner is slightly larger than the cost reduction by the improvement of the specification of HTGR when ADS is assumed as the MA burner. If FR without accelerator can be introduced, the cost improvement of 0.14 yen/kWh can be expected.
- The neutron source of ADS does not affect its transmutation characteristics, and the subcritical design is to ensure safety. IFR may achieve enough safety as MA burner reactor, and the feasibility should be investigated in the future.

As summarized above, it is found that there is an advantage for the incorporation of multi-recycling HTGR with MA burner based on IFR.
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