# MASS BALANCE OF THE PU AND MINOR ACTINIDES RECYCLING METAL FUEL SYSTEM

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## Abstract

The mass flow of Plutonium and minor actinides is calculated for a future LWR-FBR fuel cycle model, in which a certain scale of power generation by LWRs is continued for a long period before the replacement by FBRs begins. The burnup of the LWR spent fuel is considered to be higher than the current standard. It is assumed that all the Plutonium and minor actinides recovered from LWRs are kept and used to start-up and feed metal fuel commercial FBRs. The results show that the accumulated Plutonium and minor actinides from the LWRs can be consistently consumed without further accumulation, by gradually establishing the same scale of the FBR power generation and its fuel cycle. The optimum content of the minor actinides in the standard FBR fuel is about 2 weight percents. If the FBR era is to come in the future, the extended LWR era causes no significant problem in terms of the consumption of the accumulated transuranic.

## Introduction

Recovering minor actinides from the LWR spent fuel and utilising them in FBRs is expected to reduce the long-term radiotoxicity in the nuclear waste. It is proposed to recycle the minor actinides from the LWRs into metal fuel FBRs and their fuel cycle together with the recovered Plutonium [1]. Metal fuel FBRs show suitable performances for the consumption of minor actinides, and their pyro-reprocessing is quite compatible with the recycle of the minor actinides. In this case, the minor actinides content in the FBR feed is limited to as low as a few weight percents to keep the core safety parameters acceptable. A low content is also preferred to make a simple casting fuel fabrication method feasible [2]. But it is shown that the consumption of all the transuranic elements, i.e. Plutonium and minor actinides, from the LWRs is possible by introducing them widely into the commercial FBR fuel cycle.

However, the introduction of FBRs is being delayed recently. It causes the accumulation of the transuranic from LWRs. The relative amount of the minor actinides becomes larger during the extended decay period. Pursuing higher burnup of the LWR fuel can be another source for increasing the pressure of minor actinides accumulation.

In this study, considering these circumstances, the feasibility of the concept of the transuranic consumption by the commercial FBR fuel cycle is examined by evaluating the mass flow of the Plutonium and minor actinides for an LWR-FBR fuel cycle model. In this model, a certain scale of power generation by LWRs is continued for a long period before the replacement by FBRs and the consumption of the accumulated transuranic begin.

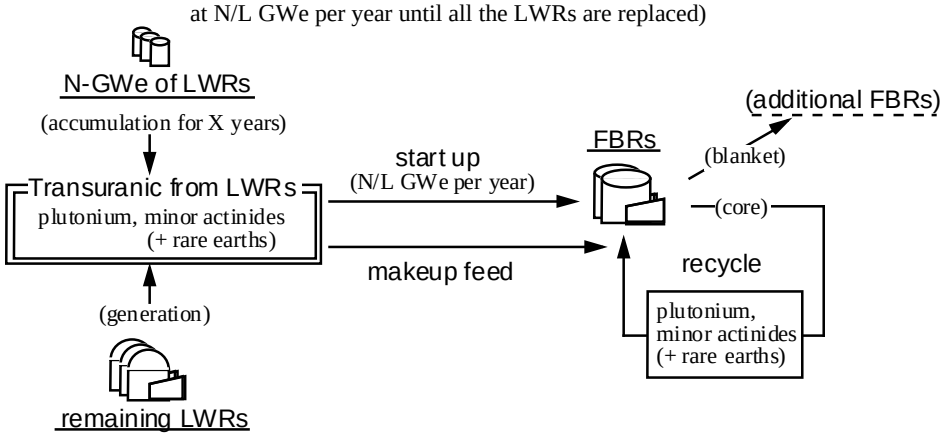
## Analytical Mdel

### *LWR-FBR fuel cycle*

Figure 1 illustrates the LWR-FBR fuel cycle model considered in this study. It is supposed that a fixed scale of power generation by LWRs is continued for a certain period until the introduction of FBRs begins. The transuranic elements recovered from the spent fuel are accumulated during this period. After this period, FBRs are started up to replace those LWRs that reaches the reactor lifetime, so that the scale of the power generation is maintained. More than 1/L of the LWRs should be replaced per year if the lifetime is L years. The accumulated transuranic from the LWRs are used to both startup and feed the FBRs. The transuranic generated by the remaining LWRs after the beginning of the FBR introduction are also fed to FBRs. If any transuranic from the LWRs remains after L years, when all the LWRs are replaced by the FBRs, it is used to renew earlier FBRs that reach the lifetime.

All the Plutonium and minor actinides discharged from the FBR cores are reprocessed and recycled to the FBR cores. The minor actinides content in the recycled FBR fuel is set to be larger than their fraction in the FBR spent fuel, so that some minor actinides from the LWRs can be accepted. The Plutonium enrichment is determined to satisfy the refuelling interval length and other design specifications for the FBRs. As long as the Plutonium from the LWRs remains, it is used to make up the enrichment of the recycled fuel. The Plutonium bred in the blanket goes out of this fuel cycle model. It is used to build additional new FBRs.

Figure 1. **An LWR-FBR fuel cycle model**
(N-GWe of LWRs are operated for X years before the replacement by FBRs begins.
The reactor lifetime is L years and the replacement is continued
at N/L GWe per year until all the LWRs are replaced)




***Composition of the transuranic from LWRs***

A large PWR is chosen to represent the LWRs and the averaged discharge burnup is set to be 48 GWd/t or 60GWd/t reflecting the ongoing effort toward higher burnup goals. The refuelling batch number is three for both cases, with the interval of 15 or 18 months respectively. The burnup and following decay calculations are conducted with ORIGEN2 code. The discharged material is reprocessed after 5 years cooling time and all the transuranic are partitioned and recovered. The overall recovery ratio of 99.5% is assumed for all the transuranic elements according to the target value of the pyro-partitioning technology development [3].The decontamination factor of the rare earth fission products is about 10, which means that the partitioned minor actinides are accompanied by about the same amount(weight) of rare-earth fission products. The composition of the transuranic and the rare-earth elements do not change with the pyro-partitioning. Table 1 summarises the obtained transuranic compositions for the period of 5, 30, 60 and 90 years after discharge. The length of the storage period plays a significant role in increasing the fraction of the minor actinides, mainly due to the decay of $^{241}$Pu to $^{241}$Am.

Table 1. **The composition of the transuranic from the LWRs** (based on the burnup of one ton-U fuel)

1) Burnup = 48GWd/t

| decay period (year) | 5 | 30 | 60 | 90 |
|---|---|---|---|---|
| Pu amount (kg) | 10.9 | 9.9 | 9.6 | 9.5 |
| Pu composition[a] (w/o) | 3/53/24/12/7 | 2/58/27/4/8 | 2/61/28/1/8 | 2/61/28/0/9 |
| MA amount (kg) | 1.4 | 2.3 | 2.6 | 2.7 |
| MA composition[b] (w/o) | 51/30/14/5/0 | 33/57/8/1/0 | 32/60/8/0/0 | 34/58/7/0/0 |

2) Burnup = 60GWd/t

| decay period (year) | 5 | 30 | 60 | 90 |
|---|---|---|---|---|
| Pu amount (kg) | 11.5 | 10.4 | 10.1 | 9.9 |
| Pu composition[a] (w/o) | 4/51/25/12/8 | 3/56/28/4/9 | 3/58/29/1/9 | 2/59/30/0/9 |
| MA amount (kg) | 1.8 | 2.7 | 3.0 | 3.1 |
| MA composition[b] (w/o) | 55/25/14/5/0 | 38/52/9/1/0 | 36/55/8/0/0 | 38/53/8/0/0 |

[a]Pu(Plutonium) composition = $^{238}$Pu/$^{239}$Pu/$^{240}$Pu/$^{241}$Pu/$^{242}$Pu.
[b]MA(minor actinides) composition = $^{237}$Np/$^{241}$Am/$^{243}$Am/$^{244}$Cm/$^{245}$Cm.

***The metal fuel FBRs and their fuel cycle***

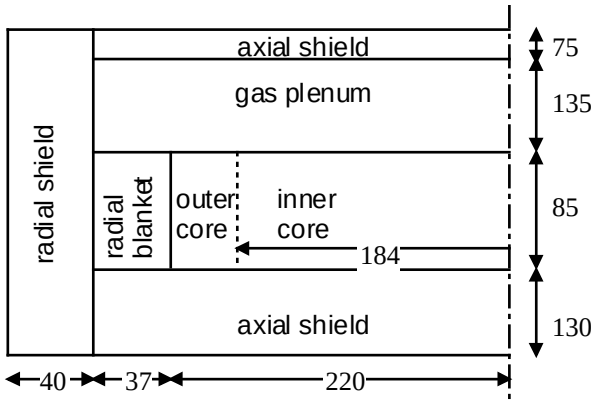
As the model for the commercial FBR, a 1,500MWe metal fuel FBR design is used [4]. The refuelling interval of the core is 18 months and the averaged discharge burnup of 150 GWd/t is achieved. Other major specifications are summarised in Table 2.

Table 2. **The design specifications for the metal fuel FBR**

| Item | Specification |
|---|---|
| Core output | 1,500MWe (3,900MWt) |
| Cycle length | 18 months, FPD (4 batches) |
| Core configuration | homogeneous |
| Fuel and cladding material | U-Pu-Zr, ferritic stainless |
| Coolant Temperature (inlet/outlet) | 355/510°C |
| Maximum cladding Temperature | 650°C |
| Maximum linear power | 500W/cm |
| Averaged discharge burnup | 150GWd/t |

The core has a homogeneous configuration with two Plutonium enrichment regions and radial blankets, as is shown in Figure 2. The Axial blanket is not necessary as long as high breeding performance is not required, since the radial blanket can provide 4-5% fissile gain which is enough to makeup the burnup loss. The neutronic calculations are conducted with a diffusion code that can handle the transuranic burnup and decay chains. Group constants are prepared using JFS3-J32, which is a 70-group constant set for fast reactors [5]. Although the absorption by the rare-earth elements accompanying the minor actinides in the fresh fuel is taken into account, their burning is not considered. A sub-channel code is used for the thermal hydraulic design and the resulting region-wise averaged temperatures are used to calculate the reactivity coefficients.

Figure 2. **Configuration of the 1,500MWe FBR Core. Dimensions are in cm.**




The spent fuel discharged from the core is reprocessed after 3 years cooling time with pyro-reprocessing. The recovered Plutonium and minor actinides are returned to the core. The overall recovery ratio of all the transuranic is 99.5% and the rare-earth fission product decontamination factor is 10. The burnup loss of the Plutonium is made up by the stock Plutonium from the LWRs. Table 3 summarises the core performance characteristics at the equilibrium cycle. Here, the composition after 60 years storage is used for the makeup feed from LWRs. Usually the minor actinides fraction in the FBR discharge is less than 1%. In the case of 'no-MA-makeup' where no minor actinides from the

LWRs are accepted, the content of the recycled minor actinides and rare earth fission products in the fresh fuel come to 0.6% and 0.4% at the equilibrium. In the cases of 2% and 5% minor actinides content, the minor actinides from the LWRs are used to fill up the specified minor actinides content in the fresh fuel. As shown in Table 3, the Plutonium enrichment becomes slightly smaller when the content of the minor actinides is greater. But the safety parameters can be degraded because of the harder spectrum and the fast fission of the minor actinides. Also shown Table 3 are the performance parameters for the case of 'once-through', in which the transuranic from the FBRs are not recycled and the fresh fuel is made only from the material from LWRs. The material requirement for the initial startup is derived from these cases. It should be noted that these cores can achieve a high breeding ratio of >1.35, if upper and lower axial blanket of ~30cm thickness are added. With that high breeding performance, it may be possible to realize a system doubling time of shorter than 30 years.

Table 3. **The FBR feed compositions and core performance parameters at the equilibrium cycle**

| | no-MA-makeup [a] | MA-enriched [a] | | once-through [a] |
|---|---|---|---|---|
| MA & RE content [b] (w/o) | 0.6/0.4 | 2.0/1.5 | 5.0/3.5 | 2.0/2.0 |
| MA composition [c] (w/o) | 14/34/2/30/17/3 | 23/46/5/13/11/2 | 28/52/6/6/6/2 | 32/60/8/0/0/0 |
| Pu enrichment [d] (w/o, inner/outer) | 14.8/20.3 | 14.7/19.7 | 14.1/19.3 | 15.0/20.1 |
| Pu composition [e] (w/o) | 2/58/30/4/6 | 3/57/30/4/6 | 8/54/28/3/7 | 2/61/28/1/8 |
| Burnup reactivity (%_k/k) | 2.0 | 1.8 | 1.5 | 1.9 |
| Internal conversion ratio | 0.90 | 0.90 | 0.91 | 0.88 |
| Breeding ratio | 1.07 | 1.07 | 1.09 | 1.05 |
| Doppler const. (%Tdk/dT, $x10^{-3}$) | -2.09 | -2.20 | -2.26 | -2.27 |
| Coolant coeff. (¢/°C) | 0.254 | 0.273 | 0.310 | 0.279 |

[a] no-MA-makeup = no minor actinides from the LWRs are accepted.
MA-enriched = minor actinides from the LWRs are accepted according to the fixed content specification.
once-through = no transuranic from the FBRs are recycled.
[b] MA & RE content = weight percent of minor actinides and rare earth fission products in (heavy metal + RE).
[c] MA composition = $^{237}$Np/$^{241}$Am/$^{242m}$Am/$^{243}$Am/$^{244}$Cm/$^{245}$Cm.
[d] Pu enrichment = weight percent of Plutonium in (heavy metal + RE).
[e] Pu composition = $^{238}$Pu/$^{239}$Pu/$^{240}$Pu/$^{241}$Pu/$^{242}$Pu.

**Mass Flow of the LWR-FBR Cycle**

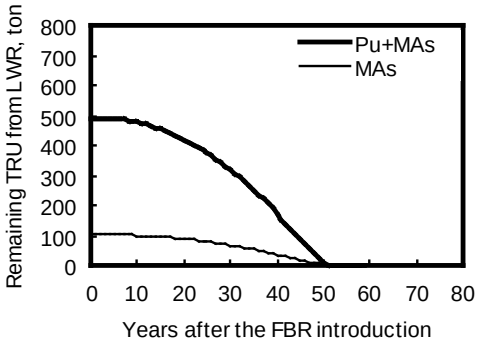
In this section, the calculated results for the mass flow of the LWR-FBR fuel cycle model are described. The scale of power generation can be arbitrary. For this study, 50GWe is chosen for better understanding of the results, which corresponds to the requirement of about 800 ton-Uranium per year when PWRs with the averaged discharge burnup of 48GWd/t are assumed. For simplicity, the transuranic discharged from decommissioned LWRs are not considered. Those recovered from decommissioned FBRs are also not taken into account because they are supposed to go out of this fuel cycle model and be used to build additional new FBRs, together with the Plutonium bred in the blanket.

Figure 3 shows how the Plutonium and minor actinides from LWRs are consumed once the introduction of the FBRs is started after the 50GWe of LWRs are operated for 50 years. The

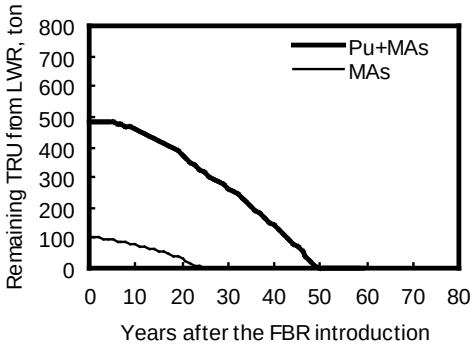
accumulated amount of Plutonium and minor actinides at the year zero are about 400 ton and 100 ton respectively, of which compositions are assumed to be those of the material after 60 years storage. The reactor lifetime is set to be 40 years and, accordingly, 1/40 of the LWRs is replaced by FBRs of which minor actinides content is 2%. The remaining amount of the transuranic from LWRs starts to decrease as the replacement continues, and both Plutonium and minor actinides are finished in 50 years. It means that the transuranic accumulated during the extended LWR era can be consumed within the FBR fuel cycle of the same scale, though it takes as long a period as the period before the introduction of FBRs.

Figure 3. **The remaining transuranic from the LWRs after the beginning of the FBR introduction**

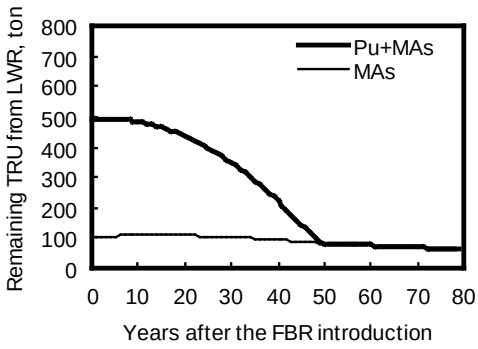
•50GWe LWRs are operated for 50 years before the FBR introduction.
•The LWR discharge burnup is 48GWd/t.
•The reactor lifetime is 40-years, and 1/40 of the LWRs are replaced per year.




(a) The minor actinides content of the FBR fuel is 2%.




(b) The minor actinides content of the FBRs is 5%.

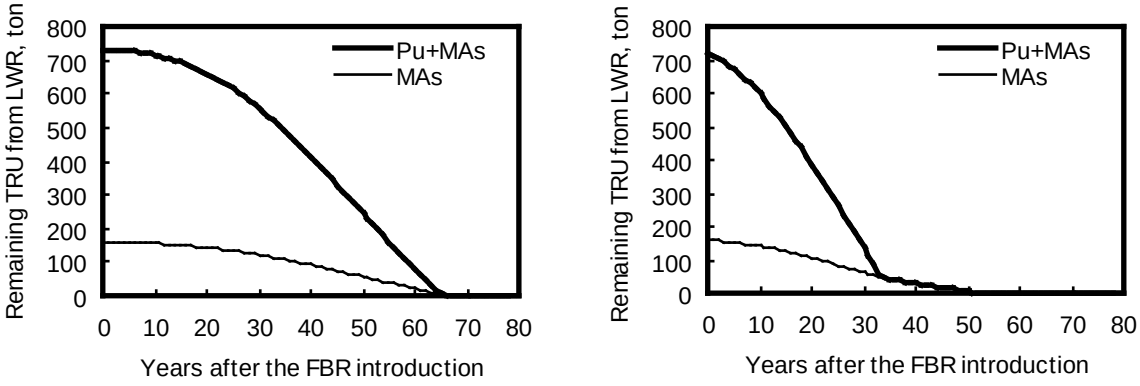



(c) The minor actinides content of the FBRs is 1%.

The changes of the remaining transuranic amount calculated for the cases in which minor actinides contents are 5% and 1% are compared in Figure 3(b) and 3(c). The minor actinides are consumed much faster in the former case, as is shown in Figure 3(b). But it appears not necessary to go up to 5% content considering that it still takes about 50 years to consume all the Plutonium. In the latter case, Figure 3(c), minor actinides can not be consumed as fast as Plutonium and it takes very long to finish all the minor actinides after the Plutonium is finished. It would be needed to utilise the additional FBRs that are started up with the extra Plutonium bred in the blanket.

Figure 4**. The remaining transuranic from the LWRs: the impact of a longer accumulation period**

•50GWe LWRs are operated for 75 years before the FBR introduction.
•The LWR discharge burnup is 48GWd/t.
•The minor actinides content of the FBR fuel is 2 weight percent.




(a) 1/40 of the LWRs are replaced per year. (b) 1/20 of the LWRs are replaced per year.

Figure 4(a) shows the result calculated for the case in which the period of the LWRs operation before the FBR introduction is extended to 75 years. The composition of the accumulated transuranic is assumed to be that of the material after 90 years storage. The content of the minor actinides in the FBR fuel is 2%. The consumption takes longer than that of the cases shown in Figure 3, because of the larger initial amount. It takes about 65 years to finish both the Plutonium and minor actinides. When the rate of the replacement is doubled, the Plutonium consumption is more accelerated than the minor actinides consumption and some amount of the minor actinides is left after the Plutonium is finished, as is shown in Figure 4(b). But this can be easily consumed in the operating FBRs and finished before 50 years.

Figure 5 shows the results for the cases where the burnup of the LWRs is raised to 60GWd/t and the period before the FBR introduction is either (a) 50 years or (b) 75 years. The content of the minor actinides is 2%. The scale of the heavy metal mass flow is reduced to 640 ton-U/y, reflecting the higher burnup. The minor actinides tend to remain slightly longer than the Plutonium, due to the larger fraction in the LWR spent fuel. But the overall consumption of the accumulated transuranic is quicker than the cases of Figure 3 and 4 owing to the smaller initial amount.

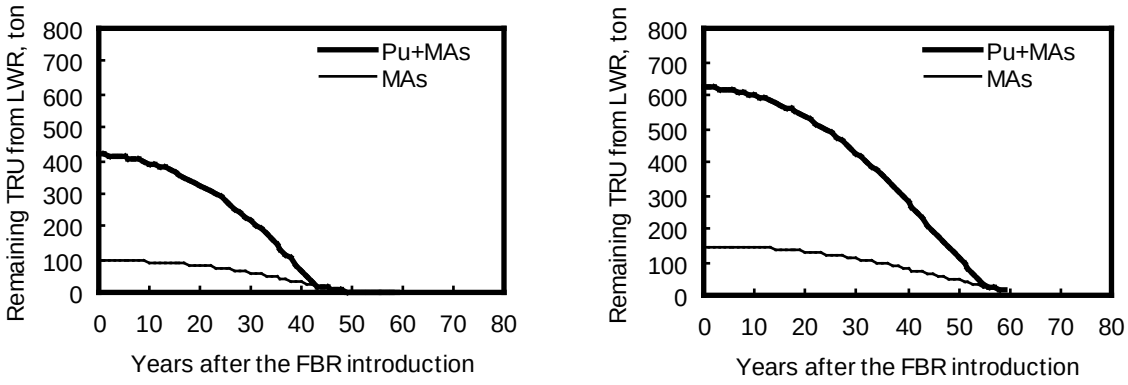
These results indicate that further delay of the FBR introduction causes no significant problem in terms of the consumption of the accumulated transuranic.

Figure 5. **The remaining transuranic from the LWRs. The impact of the LWR burnup**

•The LWR discharge burnup is 60GWd/t.

• 1/40 of the 50GWe of LWRs are replaced per year.

•The minor actinides content of the FBR fuel is 2 weight percent.




(a) The period before the FBR introduction = 50 years

(b) The period before the FBR introduction = 75 years.

## Conclusion

The mass flow of Plutonium and minor actinides is calculated for a future LWR-FBR fuel cycle model, in which a certain scale of power generation by LWRs is continued for 50 to 75 years before the replacement by FBRs begins. The averaged discharge burnup of the LWR spent fuel is set to be 48 GWd/t or higher considering the current goals for high burnup. It is assumed that all the Plutonium and minor actinides recovered from LWRs are kept and used to startup and feed metal fuel commercial FBRs. All the heavy metals discharged from the FBR cores are reprocessed and recycled.

The results show that the Plutonium and minor actinides from LWRs can be consistently consumed without further accumulation, by establishing the same scale of FBR power generation and its fuel cycle. The optimum content of the minor actinides in the standard FBR fuel is about 2 weight percents. The consumption may take longer when the period before the FBR introduction is longer, due to the increased amount. But still it is possible to consume the accumulated transuranic by simply introducing FBRs. The best way to consume the transuranic of the LWR origin is the recycle into the FBRs. It can be concluded that the extended LWR era causes no significant problem in terms of the consumption of the accumulated transuranic, if the FBR era is to come in the future.

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