ANALYSIS OF MASS FLOW AND COST FOR DOUBLE-STRATA FUEL CYCLE

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Abstract

In this study, the mass flow in double-strata nuclear fuel cycle is analysed based on mass inventory balance model, and the cost evaluation is carried out. As the commercial reactor fuel cycle, which is assumed to be sustainable in a significantly long term, the following different reactors and fuel cycles are considered: (1) Scheme of light water reactor (LWR-UOX and -MOX) based on sea water uranium resources, (2) Scheme of reduced-moderation water reactor (RMWR) with Pu breeding and (3) Scheme of fast breeder reactor (FBR).

Introduction

The double-strata nuclear fuel cycle consists of commercial reactor fuel cycle (the 1st stratum cycle) and nuclear transmutation fuel cycle (the 2nd stratum cycle) mainly based on accelerator-driven system (ADS) [1] which transmutes minor actinide (MA, that is, Np, Am and Cm) generated from the 1st stratum.

As the commercial reactor fuel cycle is assumed to be sustainable in a significantly long term, the following different reactors and fuel cycles are considered: (1) Scheme of light water reactor (LWR-UOX and -MOX) based on sea water uranium resources, (2) Scheme of reduced-moderation water reactor (RMWR) with Pu breeding and (3) Scheme of fast breeder reactor (FBR). Although the sea water contains a huge amount of uranium, collection technology [2] is in the stage of small-scale experiment which is examined by JAERI and the cost is ten times higher than that of mining uranium. However, it becomes an influential option in case that power generation is kept by the LWRs without breeding plutonium. The RMWR [3] researched by JAERI is a reactor designed for uranium utilisation with plutonium breeding based mainly on the present LWR technologies, which is positioned as a substitute reactor of FBR. As to the FBR, a MOX fuelled reactor is selected and the spent fuels are reprocessed with PUREX method. Although the many parts of technology for FBR are the future ones, it is most excellent from the viewpoint of the mass flow, that is, the fuel amount in the reactor is small and the breeding ratio is high. Mass flows at balanced state are calculated for six schemes consisting of one of the three commercial reactors.

In this study, the mass flow in double-strata nuclear fuel cycle is analysed in balanced state, and the cost evaluation is carried out. The generating costs of fuel cycles are obtained by multiplying the unit price to the mass flow or nuclear reactor generation capacity. Quoted is the database in OECD/NEA comparative study of ADS and FR in advanced nuclear fuel cycles, [4] which contains almost all unit prices necessary for the present examination. Unit prices related to sea water uranium and RMWR are not contained in the OECD database, and they are obtained from an analysis on the economics of plutonium recycle in JAERI. [5]

Since the database has been evaluated on various assumptions and the uncertainty is large, it is difficult to compare the existing technology with the future technology foreseeing future cost decrease. Therefore, in this study, most large consideration is put on quantifying the cost scale of the nuclear transmutation cycle.

Schemes

Table 1 shows the six schemes examined in the present study. They are divided as follows: (1) Three schemes of LWR based on sea water uranium resources, (2) A scheme of RMWR and (3) Two schemes of FBR.

Table 1. **Schemes**

Index	1st stratum	2nd stratum
LWR-GD	LWR, sea water uranium and 60GWd/HMt	SF are disposed geologically
LWR	LWR, sea water uranium and 60GWd/HMt	Pu and MAs are transmuted
LWR-M	LWR, sea water uranium and 60GWd/HMt. Pu is recycled only once	Pu and MAs are transmuted
RMWR	RMWR, Pu and Np multi-recycle	Am and Cm are transmuted
FBR	FBR, Pu and Np multi-recycle	Am and Cm are transmuted
FBR-MA	FBR, Pu and MAs multi-recycle	None

In the "LWR scheme", spent fuels (SFs) from LWRs are reprocessed and partitioned, then, Pu and MAs are transmuted by accelerator-driven system (ADS). In the "LWR-M scheme", Pu is recycled to LWRs only once, then, Pu in the mixed oxide fuel (MOX) and MAs are transmuted. The "LWR-GD" scheme is considered for the comparison, in which SFs are geologically disposed after interim storage during 50 years. In the "RMWR scheme", Pu is multi-recycled as MOX fuel and MAs are transmuted by ADS. Since Pu breading ratio of RMWR is beyond 1.0, uranium resources are efficiently used. In the "FBR scheme", Pu and Np are multi-recycled as MOX fuel, and Am and Cm are transmuted by ADS in the 2nd stratum. In the FBR and RMWR schemes, Np can be treated with MOX fuel in an advanced fuel system. In the "FBR-MA scheme", Am and Cm are also burned in the FBR. In the scheme, the 2nd stratum is not necessary.

Table 2. **Plants parameters**

	LWR [6]	RMWR [3]	FBR [7]	ADS [1]
Thermal power [MWt]	3 000	3 000	2 600	800
Plant capacity factor[%]	90	88	90	82
Thermal efficiency[%]	33	33	38	17*
Breading ratio	–	1.1	1.05	–
Core BU [GWd/HMt]	60	70	150	120
Blanket BU [GWd/HMt]	–	14	?	–
Time in core [y]	5	6	6	2
Time out of core [y]	5	3	3	3
HM core mass[HMt]	120	86	37	4
HM blanket mass [HMt]	–	110	41	–
Recycled HM core [HMt/y]	16.4	14.4	5.7	2
Recycled HM blanket [HMt/y]	–	18.1	6.3	–
Life of plant [y]	40	40	40	40

* Considering consumption in accelerator

Table 2 shows the parameters of the commercial power plants chosen for the burn-up (BU) data. The BU data for the LWR is obtained from Ref. 6, in which composition of SF from pressured water reactor (PWR) and boiled water reactor (BWR) were calculated in the case of BU of 33, 45 and 60 GW day per heavy metal ton (GWd/HMt) in a manner that one-group cross section is obtained by sell calculations with detail BU time steps. As a result of the calculation, the amount of MA decreases for high BU. In the LWR schemes, the result for 60 GWd/HMt is used with an assumption that ratio of PWR and BWR is 1:1. The BU data for the RMWR is calculated in the same manner as Ref. 6. The composition and operation plan is obtained from the high breading BWR in Ref. 3. The BU data for the FBR is obtained from Ref. 7, which presented two blanket arrangements for breading ratio of 1.05

and 1.2. The arrangement of 1.05 is adopted in the future balanced states, and the arrangement of 1.2 is adopted in a growth phase of FBR. In the FBR schemes, the result for breading ratio of 1.05 is used, because the balanced state is considered. The ADS mass flow for TRU transmutation of ADS in Ref.1 is such that; Pu and MA nitride fuels of 4 HMt are loaded to the ADS, TRU of 250 kg is burned annually and the SFs of 1.75 HMt unloaded from the ADS are reprocessed annually.

Mass flows

Figure 1 to 6 show mass flows of each scheme. The flows are normalised to an electric power so that total of electric generation is 1 GWe. The generations of the ADS can be neglected in the case of RMWR and FBR, though, in the case of LWR and LWR-M, the ADS generate 0.1 GWe and 0.06 GWe, respectively. Although the losses of HM in reprocessing are assumed to be 0.1 weight % per process, it does not effect to the present investigation. The scales of the ADS are presented in thermal powers, which mean the powers assigned to a commercial plant.

In the LWR-GD scheme, UOX-SFs of 14.4 HMt are geologically disposed after 50 years interim storage.

In the LWR scheme, UOX-SFs of 14.4 HMt are reprocessed and partitioned into Pu of 170 kg, MA of 25 kg and others. Then, Pu and MA are transmuted in the ADS. In the 2nd stratum, the TRU of 1 560 kg is fabricated and loaded to the ADS annually, and TRU of 1 370 kg and FP of 195 kg are unloaded after 2 years burning. The SFs from the ADS are reprocessed over a year after cooling term of 2 years, and reloaded to the ADS.

In the LWR-M scheme, the SFs from LWR include UOX-SFs of 12.7 t and MOX-SFs of 1.8 t. Pu of 149 kg in the UOX-SF is loaded to the LWR as MOX. MA in the UOX-SF and TRU in the MOX-SF are transmuted.

In RMWR scheme, the SFs from RMWR consist of MOX-SF of 10 t and blanket-SF of 20 t. The fuel pin of the RMWR has three blanket regions at top, middle and bottom. It is assumed that the MOX and blanket regions can be separately reprocessed and the unit cost is different between the two regions. In addition, SFs contains MA of 65 kg, 90% of which is produced in the MOX region.

In the FBR scheme, the SFs from FBR consist of MOX-SF of 5.7 t and blanket-SF of 6.3 t. MA production from blanket region is not presented in Ref.7 and is neglected. However, it is considered that the MA production in the blanket region is less than 10% in MOX region.

In the FBRMA scheme, because MAs are mixed to the MOX and loaded to FBR, the 2nd stratum does not exist.

The most significant amount in the present mass flow analysis is the total amount of TRU going down to the 2nd stratum. The amount determines the following indexes representing the scale of the 2nd stratum.

(Number of the ADS) = (TRU from the 1st stratum [kg/y]) / (Annual transmutation [250 kg/y]).

(Power of the ADS [MWt]) = (Number of the ADS) * (Unit power of the ADS [800MWt]).

(Support factor) = 1 / (Number of the ADS).

Table 3. **Scales of the 2nd stratum**

	LWR-GD	LWR	LWR-M	RMWR	FBR	FBR-MA
TRU from 1st stratum [kg/y]	–	195.3	118.0	61.8	26.0	–
Power of the ADS[MWt]	–	625	378	198	83	–
Support factor	–	1.28	2.12	4.05	9.60	–

The support factor means the number of commercial plants supported by an ADS. Table 3 shows the indexes of the present investigation. The LWR scheme has the largest 2nd stratum, in which the number of the ADS plants is almost same as that of LWR plants. Although MA going down to the 2nd stratum increases in the LWR-MA scheme, the scale of the 2nd stratum is reduced to 60%, because Pu decreases to a half. Moreover, the scale reduced to 32% to the LWR schemes in the RMWR scheme, in which Pu is multi-recycled. The scale of the FBR scheme is 13% to the LWR schemes, and an ADS supports 10 FBR plants.

Figure 1. **Mass flow in the LWR-GD scheme**

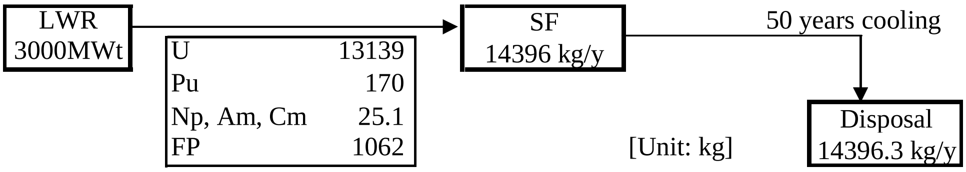


Figure 2. **Mass flow in the LWR scheme**

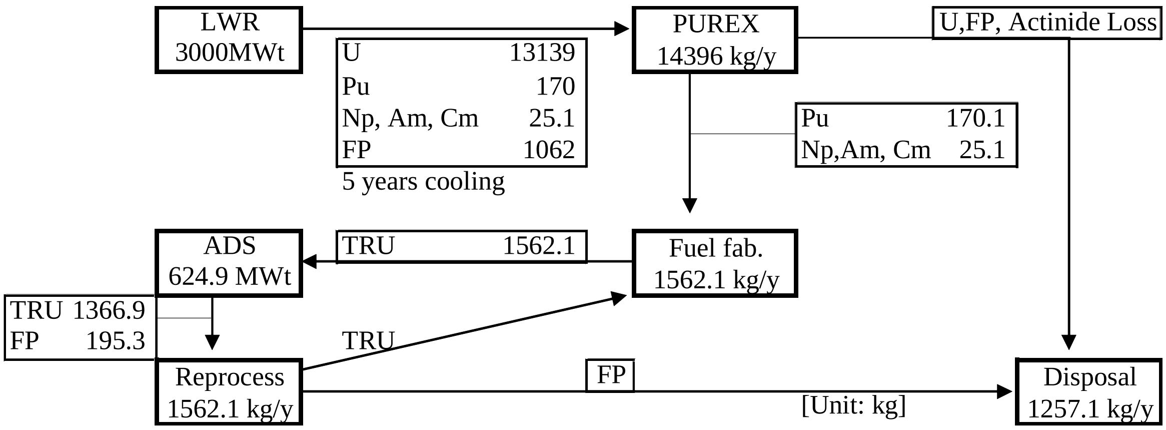


Figure 3. **Mass flow in the LWR-M scheme**

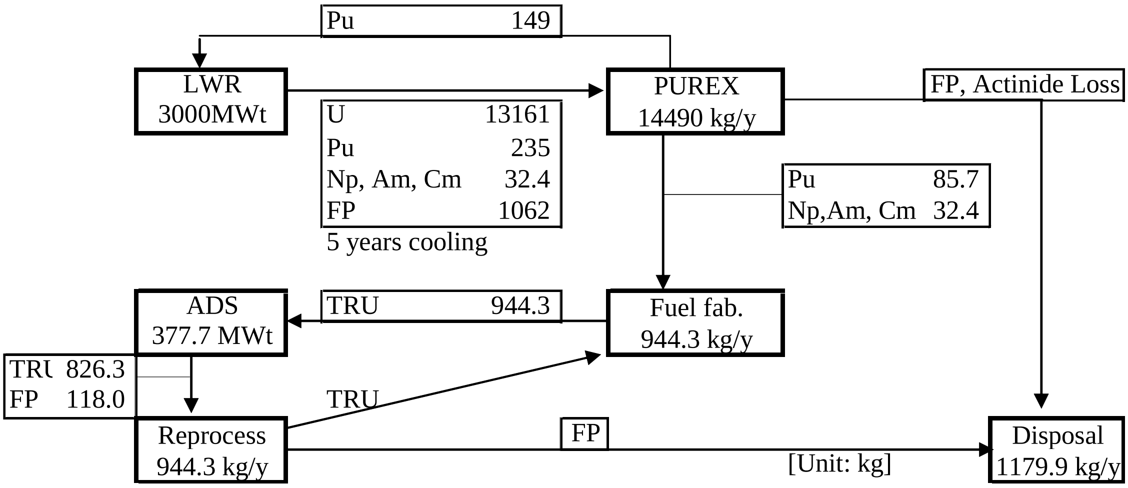


Figure 4. **Mass flow in the RMWR scheme**

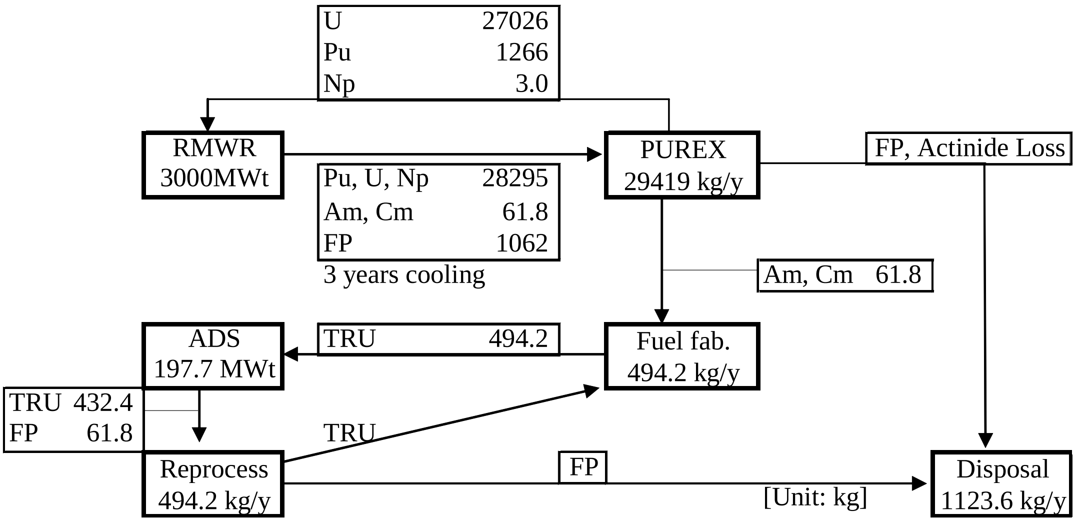


Figure 5. **Mass flow in the FBR scheme**

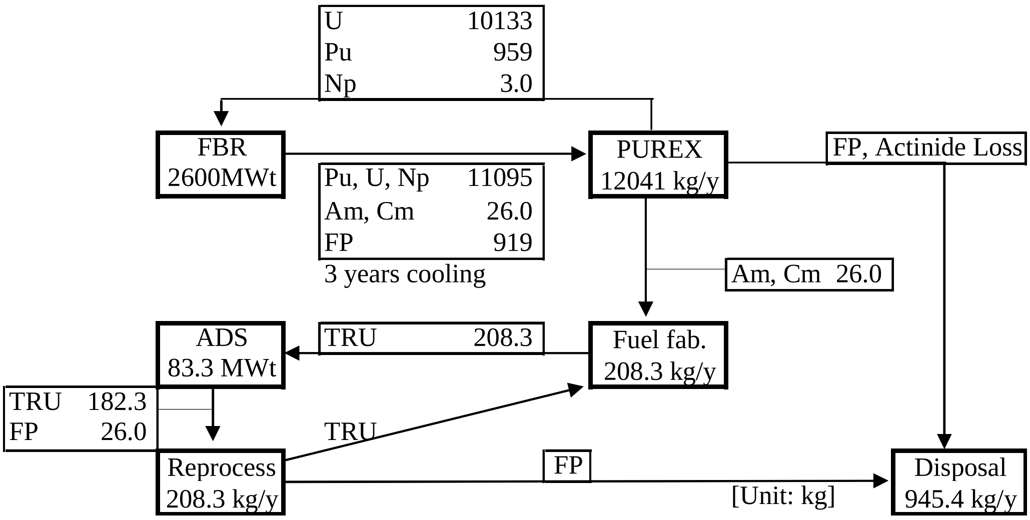
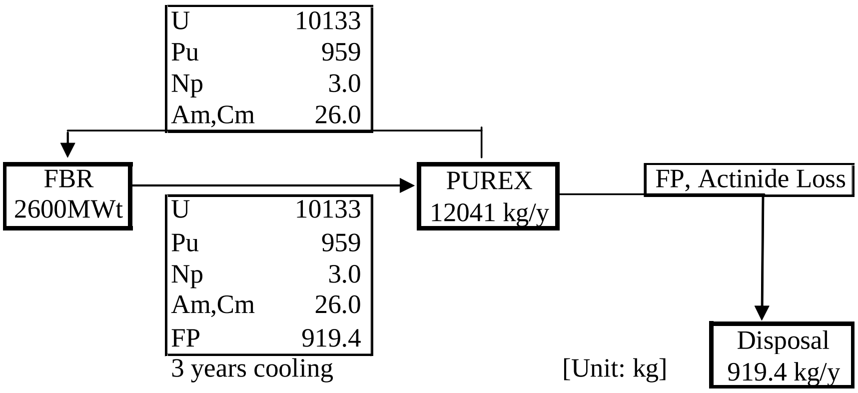


Figure 6. **Mass flow in the FBR-MA scheme**



Cost database and evaluation manner

Table 4 shows the cost database of OECD/NEA [4] mainly used in the present study and the database for Japanese costs collected by Tatematsu *et al.*, [5] which is used to supplement. The database of OECD/NEA presents nominal values and standard variations for existing techniques, and low, nominal and high values for future techniques. The costs for sea water uranium and RMWR are not given in the database of OECD/NEA, so they are supplemented by that of Tatematsu. The unit costs of Tatematsu are almost same or higher than the nominal value for the existing techniques and the high value for the future techniques. Especially, the costs for UOX fuel fabrication, UOX reprocessing and O&M for LWR and FBR are estimated higher than that of OECD/NEA data.

Table 4. **Cost database**

	OECD/NEA (ref. 4)			JR-2001-014(ref. 5)
Existing techniques	**Nominal**	**σ**		
Mining U [USD/kgU]	30	10		44.6
Sea water U [USD/kgU]	–	–		255
U conversion [USD/kgU]	5	2		6
U conversion from SF [USD/kgU]	24	5		–
U enrichment [USD/SWU]	80	30		125
UOX fabrication [USD/kgU]	250	50		727
UOX reprocessing [USD/kgHM]	800	100		1 818
MOX fabrication [USD/kgHM]	1 100	200		1 818
MOX reprocessing [USD/kgHM]	800	100		3 545
Capital cost of LWR [USD/kgWe]	1 700	100		1 818
Capital cost of RMWR [USD/kgWe]	1 870*	110		2 000
O&M annual charge [%/y/Capital cost]	4%			5.3%
Decommissioning cost of reactor [%/Capital cost]	8%			20%
SF short term storage [USD/kgHM]	60	10		–
SF interim storage [USD/kgU/50y]	300	150		–
Depleted U long-term storage [USD/kgHM]	3.6	1		–
Spent UOX disposal [USD/kgHM in SF]	420	100		–
HLW disposal [USD/kgHM in SF]	46	5.75		818
Future techniques	**Low**	**Nominal**	**High**	
FBR/RMWR driver fabrication [USD/kgHM]	650	1 400	2 500	2 091
FBR/RMWR Blanket fabrication [USD/kgHM]	350	500	700	727
FBR/RMWR driver reprocessing [USD/kgHM]	1 000	2 000	2 500	3 545
FBR/RMWR blanket fabrication [USD/kgHM]	900	1 500	2 500	1 818
FBR-MA driver fabrication [USD/kgHM]	1 400	2 600	5 000	–
FBR-MA blanket fabrication [USD/kgHM]	350	500	700	–
FBR-MA driver reprocessing [USD/kgHM]	1 000	2 000	2 500	–
FBR-MA blanket reprocessing [USD/kgHM]	1 000	2 000	2 500	–
ADS fuel fabrication [USD/kgHM]	5 000	11 000	15 000	–
ADS reprocessing [USD/kgHM]	5 000	7 000	18 000	–
Capital cost of FBR [USD/kgWe]	1 850	2 100	2 600	2 727
Capital cost of ADS without accelerator [USD/kgWe]	1 850	2 100	2 600	–
Capital cost of beam and target [USD /kWb]	5 000	15 000	20 000	–

* The cost is 1.1 times to LWR.

Follows are the preconditions and notes for the cost estimation.

- The UOX-SF is disposed after the interim storage of 50 years in the LWR-GD scheme.
- In the LWR schemes, the natural uranium is obtained from sea water uranium. The cost of the uranium accounts for 16% of total costs. If the mining uranium is available, the cost for the uranium becomes 1/8 times.

- The capital cost of RMWR is 1.1 times to that of LWR according to the estimation of Tatematsu. The reprocessing cost of MOX-SF from RMWR is supposed to be same as that of FBR.
- The decrease of HLW disposal cost brought by introducing the 2nd stratum is neglected. Since the cost accounts for only 0.1-0.2% of total costs, the effect is little, unless the cost of HLW disposal is reconsidered.
- 1 USD is exchanged to 130 yen.
- The lives of the all reactors are 40 years.

The annual escalation ratio is 3%. 0% and 5% are used for comparison.

Results of the cost estimation

Figure 7, 8 and 9 shows the generation cost in the cases for low, nominal and high cost data. Figure 10 shows the cost rate of the 2nd stratum. Results are discussed below.

- The costs of the LWR technology are same in the three cases, because the nominal values are applied.
- The disposal cost of the LWR-GD scheme is larger than others, because the unit cost of the UOX-SF disposal is 9 times larger than that of the HLW disposal.
- Since the power generation of the ADS can not be neglected in the LWR and LWR-M scheme, the costs of the commercial plant of the two schemes are less than that of the LWR-GD scheme.
- The cost of the LWR schemes is highest in the schemes based on LWR because of the large 2nd stratum. The next is the LWR-M scheme.
- The fuel cycle cost of the RMWR scheme is much larger than that of the FBR scheme, because the HM inventory of the RMWR is 2 times larger than that of the FBR.
- In the FBR schemes, since all technologies are future ones as shown in Table 4, the difference between cases are large.
- In the advanced fuel cycle, that is, the RMWR, FBR and FBR-MA schemes, the cost of the RMWR scheme is highest because of the large amount of reprocessing in the 1st stratum. The total costs of the FBR and FBR-MA scheme are almost same, because the cost of 2nd stratum in the FBR scheme cancels out the decrease of fuel fabrication cost in the FBR scheme.
- The cost rate of 2nd stratum in the FBR scheme changes little in the three cases as shown in Figure 10, because the unit costs of FBR and ADS similarly change in three cases. On the other hand, the cost rates of other cases greatly change because only the technologies of the ADS are future ones.

Figure 7. **Generation cost in the low case**

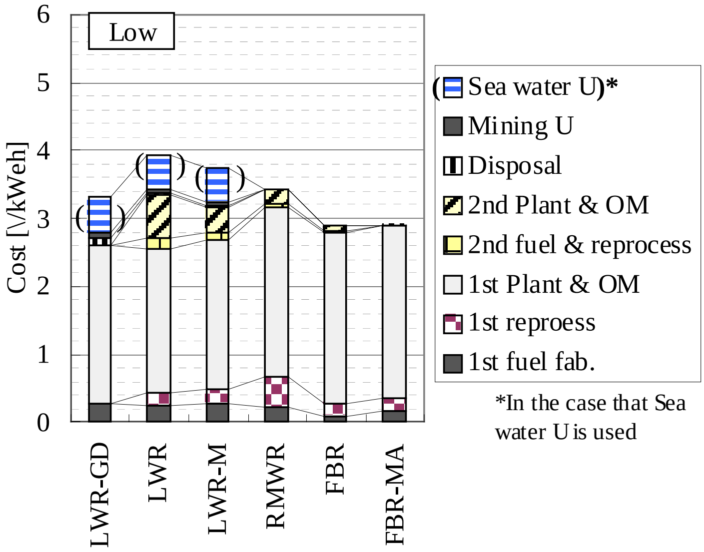


Figure 8. **Generation cost in the nominal case**

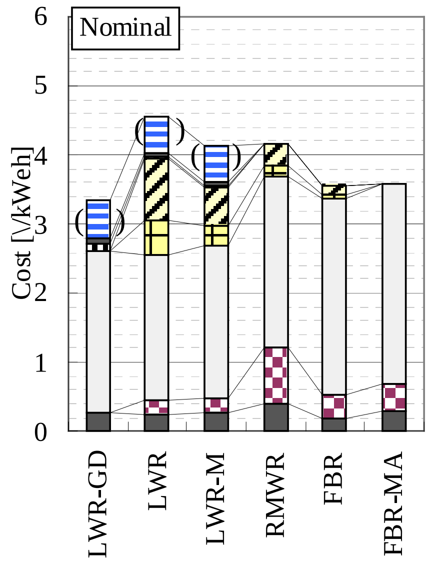


Figure 9. **Generation cost in the high case**

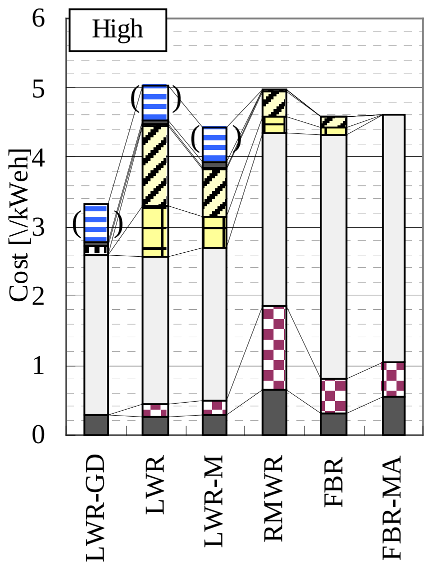


Figure 10. **Cost rate of the 2nd stratum**

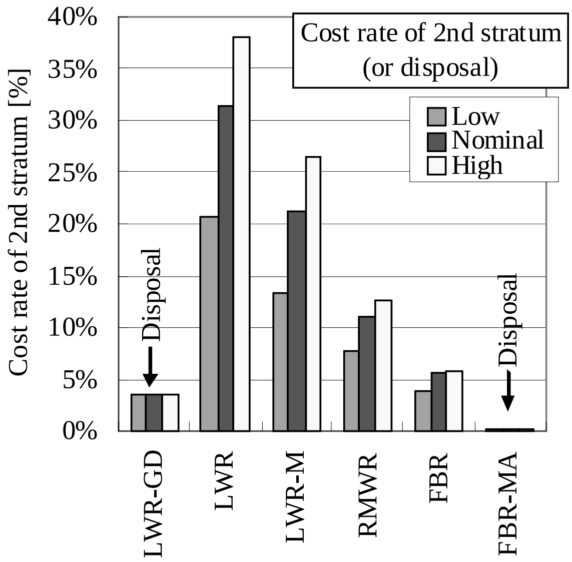
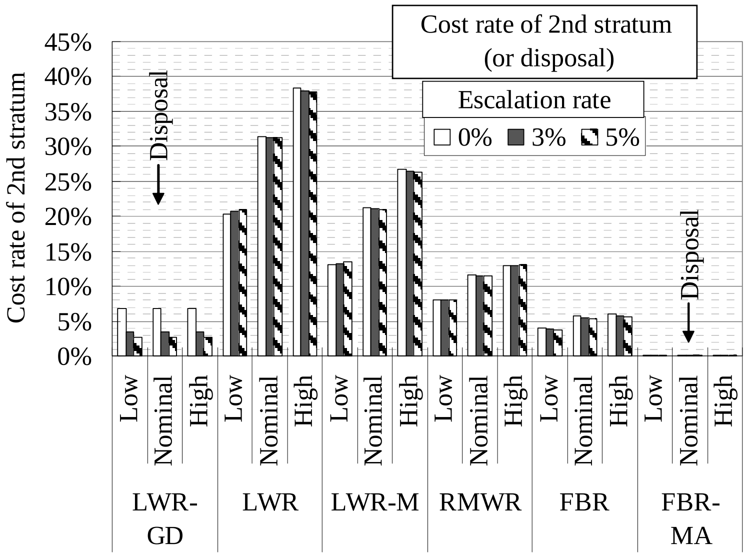


Figure 11 shows the effect of the escalation rate to the cost rate of the 2nd stratum. The escalation rate does not affect the cost rates of the 2nd stratum excepting for the LWR-GD scheme. This is because the ratio of the initial cost to cycle cost is same between the 1st and 2nd stratum. Only in the LWR-GD case, since the disposal cost occurs 50 years later, the escalation rate affects greatly.

Figure 11. **Cost rate of the 2nd stratum versus escalation rate**



Summary

Mass flows and costs were evaluated for the six sustainable schemes consisting of LWR, RMWR or FBR with the 2nd transmutation stratum. Two schemes do not have the 2nd stratum for comparative study. In the schemes consisting of LWR, since Pu is not breaded, the sea water uranium was chosen considering sustainability.

The scale of the 2nd stratum was quantified by mass flow analysis. As results of Table 3, the largest scheme was the LWR scheme in which Pu and MA are transmuted. The secondary largest scheme was the LWR-M scheme, in which Pu is recycled to LWR only once, and the third one was the RMWR scheme, in which Pu is multi-recycled. The smallest scheme was the FBR scheme.

The total costs of the schemes were quantified by multiplying unit cost to the mass flow. The OECD/NEA cost database was mainly quoted for the present cost estimation. The cost of the LWR schemes was highest in the schemes based on LWR technology because of the large 2nd stratum. The next one was the LWR-M scheme. In the advanced fuel cycles, that is, the RMWR, FBR and FBR-MA schemes, the cost of the RMWR scheme was highest because of the large amount of reprocessing in the 1st stratum. The total costs of the FBR and FBR-MA scheme were almost same.

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