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The feasibility study of the minimum-shuffling reloading strategy for PWR

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Abstract: The minimum-shuffling (MS) reloading strategy for PWRs is proposed as a fuel shuffling method to increase the load factor. In general, the full core shuffling is performed for PWRs, in which all fuel assemblies are once discharged and then reloaded with fresh fuel assemblies to make a next core. In the MS method, short intermediate shutdown just for fuel shuffling is performed. In this period, only highly burnt fuel assemblies are discharged and fresh fuel assemblies are inserted into the vacant positions. The other fuel assemblies are fixed during intermediate shutdown. This fuel reloading method can make the outage time shorter, and improvement of the load factor is expected. The MS method is applied to the 24 months cycle operation with intermediate shutdown. Loading patterns to satisfy various safety limitations are designed assuming the MS method. Economics analyses were carried out and it is confirmed that economics of the MS method is better than that of the conventional reloading strategy i.e. the full core shuffling.

KEYWORDS: load factor, discharge burnup, design of equilibrium cycles, economic effect.

1. Introduction

In general, economics of nuclear power plants is improved by increasing the load factor. Though longer cycle leads to improvement of the load factor, it degrades the fuel cycle cost since discharge burnup becomes lower. Therefore in the extended cycle operation, some operation techniques are desired, which increase the discharge burnup. The intermediate shutdown for fuel shuffling is regarded as effective way to increase the discharge burnup. However, the load factor becomes lower by the intermediate shutdown. To keep the load factor high, shutdown period should be as short as possible. In order to resolve this issue, we propose the minimum-shuffling (MS) method which minimize fuel reloading period. In this paper, feasibility study of the MS method is carried out mainly from technical viewpoint, and economics of the MS method is evaluated.

In the MS method, only highly burnt fuel assemblies are discharged from the core to a spent fuel pool and then fresh fuel assemblies are inserted in the vacant positions in the core. Positions of irradiated fuel assemblies used in subsequent cycle are fixed. Duration of reloading can be shorter than that of ordinary reloading, i.e. the full core shuffling. A similar study was carried out for BWRs in which once-burnt fuel assemblies are fixed (Ref.1). However, the present study is more innovative since only highly burnt fuel assemblies are replaced by fresh ones.

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2. Concept of the MS method

In case of extending the operating cycle and performing a periodic inspection per 24 months, following operation methods can be considered.

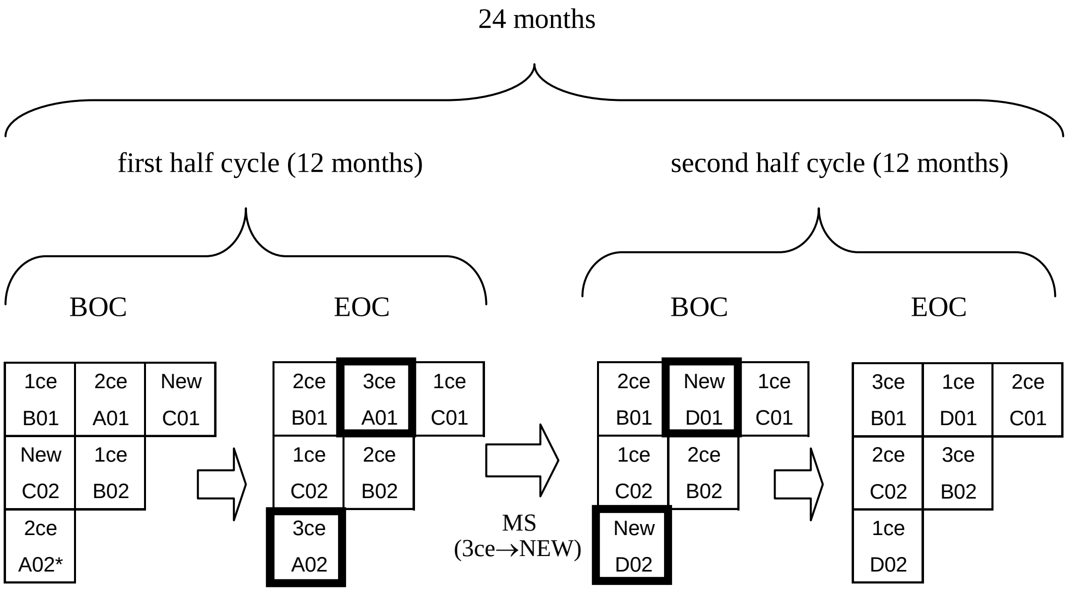
(1) Continuously operate 24 months without intermediate shutdown.

(2) Perform intermediate shutdown with the full core shuffling after 12 months operation, and then operate 12months.

Obviously, in view of the discharge burnup, the method (2) is superior to the method (1). On the other hand, the load factor of the method (2) is lower than that of the method (1) since intermediate shutdown is carried out. If the intermediate shutdown in the method (2) can be shorter, both discharge burnup and load factor can be higher. Therefore, economical reactor operation and fuel management can be achieved.

As a concrete example of it, the MS method is considered. This method is the fuel shuffling strategy which can be performed in short term. Concept of the MS method is shown in Fig.1. In Fig.1, we assume a simple core which consists of six fuel assemblies. Spent fuel assemblies (A01 and A02) at end of cycle (EOC) of the first half cycle are discharged during the intermediate shutdown, and they are replaced by fresh fuel assemblies (D01 and D02). In the second half cycle, positions of other fuel assemblies are not changed.

The load factor of the MS method can be higher similar to that of the method (1), because period of intermediate shutdown can be shortened by the MS method. Furthermore, the discharge burnup of the MS method can be also higher similar to that of the method (2), because batch number of the MS method is same as that of the method (2).



*)example of fuel label that suggest fuel loading

Fig.1 Concept of fuel shuffling in the minimum-shuffling

3. Calculation conditions for loading pattern design

Assuming 24 months operation, we evaluated the feasibility of the MS method. Calculation cases are the following.

method (1): Continuously operate 24 months without intermediate shutdown.

method (2): Perform intermediate shutdown just for the full core shuffling after 12 months operation, and then operate 12 months.

MS method: Perform intermediate shutdown just for the minimum-shuffling after the first half cycle (12 months), and then operate the second half cycle (12 months).

The calculation conditions are listed below. Loading patterns for the methods (1) and (2) were also designed under the following calculation conditions to make a comparison with the MS method.

- Core type: Three-loop PWR with 17×17 type fuel assemblies
- Cycle length: MS method: 13.1GWd/t×2 (12months×2)
  method (1): 26.2GWd/t (24months)
  method (2): 13.1GWd/t ×2 (12months×2)
- Fuel enrichment: 4.8wt%
- Maximum burnup: ≤ 55.0Gwd/t
- Radial power-peaking factor (FxyN): ≤ 1.52
- Moderator temperature coefficient: < 0($\times 10^{-5}\Delta k/k/°C$)
- Shutdown margin: ≥ 1.8(%dk/k)

Core characteristics were evaluated in equilibrium cycles. Therefore each case was iteratively calculated (depleted) until the core characteristics of them reached the equilibrium state. Calculation flow of equilibrium cycles in each method are shown in Figs.2~4.

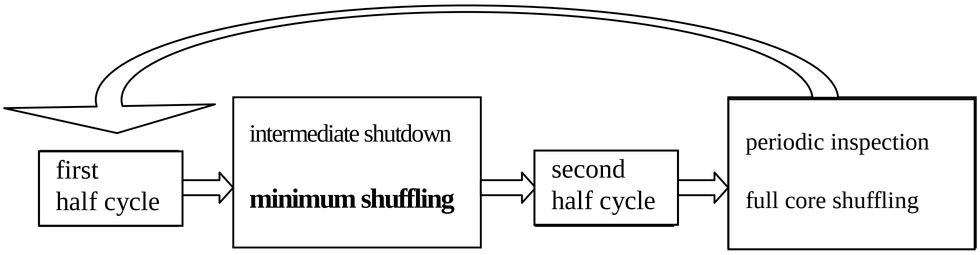


Fig.2 Calculation flow of equilibrium cycle in the MS method

As shown in Fig.2, in the MS method, the intermediate shutdown is performed after the first half cycle (12 months), and the minimum-shuffling is performed during the intermediate shutdown. Then the second half cycle (12 months) is operated. Finally full core shuffling is performed during the periodic inspection. This process is repeated in this method. Every first half cycle has the same fuel location, and every second half cycle has the same fuel location. However, fuel location of the first half cycle and that of the second half cycle are different.

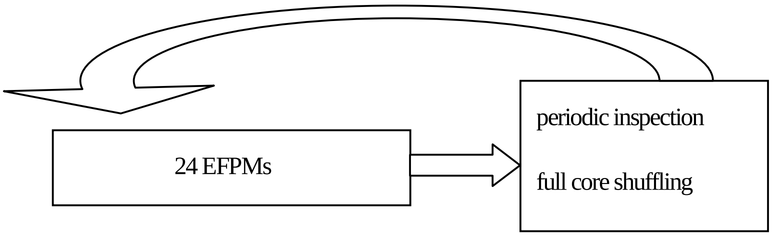


Fig.3 Calculation flow of equilibrium cycle in the method (1)

As shown in Fig.3, in the method (1), reactor operation is performed for 24 months continuously without intermediate shutdown. Then full core shuffling is performed during the periodic inspection. Every 24 EFPMs cycle has the same fuel location.

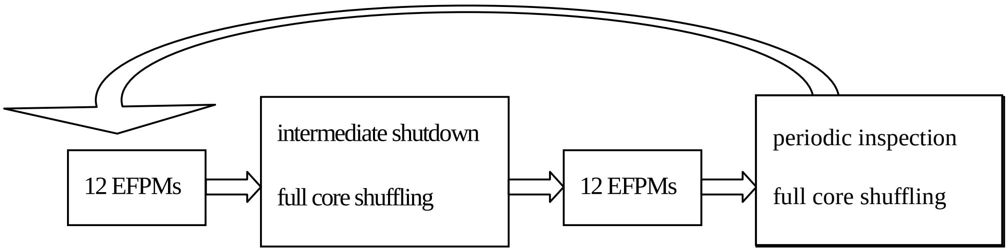


Fig.4 Calculation flow of equilibrium cycle in the method (2)

As shown in Fig.4, in the method (2), the intermediate shutdown is performed after 12 months operation, and full core shuffling is performed during the intermediate shutdown. Then after the next 12 months operation, the full core shuffling is performed during the periodic inspection. Every 12 EFPMs cycle has the same fuel location.

When we design fuel loading patterns in the MS method, some provisions are needed to satisfy various safety limitations, because movable fuel positions in the MS method is less than that in the full core shuffling.

Some safety limitations which are especially difficult to be satisfied in above calculation conditions are FxyN and maximum burnup. It is easy to understand that limitation for FxyN is difficult to be satisfied, because we cannot change positions of irradiated fuel assemblies in fuel reloading by the minimum-shuffling.

Most fuel assemblies loaded at beginning of cycle (BOC) of the first half cycle are not discharged during the intermediate shutdown in the MS method. These fuel assemblies are irradiated at same positions for 24 months. Therefore burnup of fuel assemblies loaded inside of the core at BOC of the first half cycle is expected to be much higher at EOC of the second half cycle, because burnup of these fuel assemblies increase much more quickly than that of other fuel assemblies. From this reason, some fuel assemblies are quite difficult to satisfy the limitation for maximum burnup.

4. Results and discussions

4.1 Results of the loading pattern calculations

Firstly, fuel inventories in each method were decided by try-and-error method. The result is shown in Table 1. Schematic diagram of fuel reloading in the MS method is shown in Fig.5

Table 1 Fuel inventory of each method

Number of irradiated cycle	Number of fuel assemblies			
	method (1)	method (2)	MS method	
			first half cycle	second half cycle
0 (Fresh)	100	40	40	40
1 (Once burned)	57	40	40	40
2 (twice burned)	0	40	37	40
3 (thrice burned)	0	37	40	37

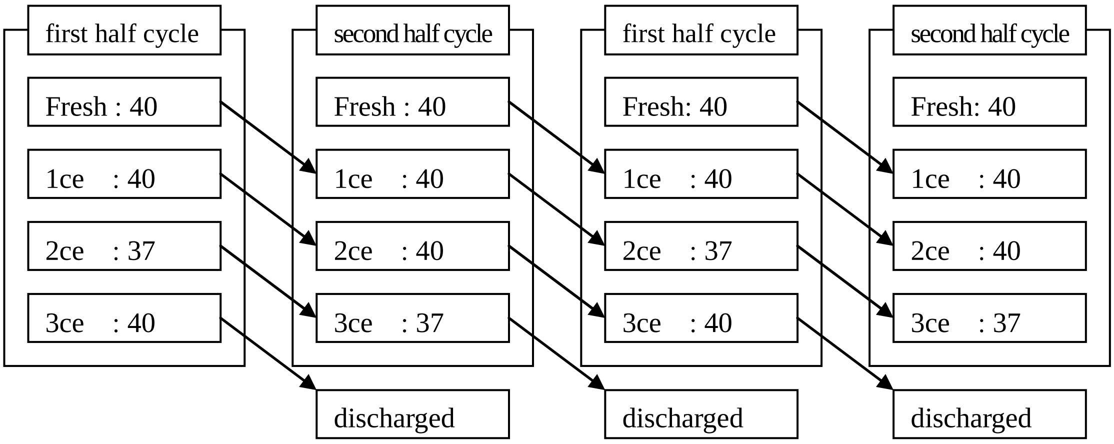


Fig.5 Schematic diagram of fuel inventory in the MS method

Secondary, we designed loading patterns of equilibrium cycle in the MS method. Loading patterns of equilibrium cycle in the methods (1) and (2) were also designed to compare with the MS method. These loading patterns are shown in Figs.6~8. Since each case is iteratively calculated, 13 cycles of depletion calculations were needed to reach equilibrium state in any methods. As shown in Fig.8, in equilibrium cycle of the MS method, burnup of every position at EOC of the first half cycle is completely identical to that at BOC of the second half cycle except the fresh fuel assemblies.

Core characteristics for these equilibrium cycles are shown in Table 2. Core feasibility in case of applying the MS method to fuel shuffling can be confirmed from Table 2.

<burnup distribution of fuel assemblies>

	H	G	F	E	D	C	B	A
8	3G 39.1 51.2	2G 29.1 42.9	3G 39.0 51.5	3G 42.8 54.2	3G 39.1 51.5	NG 0.0 15.4	3 38.7 50.1	1G 15.4 24.8
9	2G 29.1 42.9	1G 12.5 29.1	1 15.4 32.1	2G 24.2 39.1	1 10.4 27.2	2 28.4 42.2	1 13.8 28.4	N 0.0 10.4
10	3G 39.0 51.5	1 15.5 32.1	3 38.7 52.3	NG 0.0 16.2	3 40.5 52.6	3 42.1 53.5	N 0.0 13.8	
11	3G 42.8 54.2	2G 24.2 39.1	NG 0.0 16.2	2G 24.8 39.1	2 27.2 40.5	N 0.0 15.4	2 32.1 38.8	
12	3G 39.1 51.5	1 10.4 27.2	3 40.5 52.6	2 27.2 40.6	NG 0.0 12.5	1G 16.2 24.2		
13	NG 0.0 15.4	2 28.4 42.2	3 42.4 53.5	N 0.0 15.4	1G 16.2 24.2			
14	3 38.7 50.1	1 13.8 28.4	N 0.0 13.8	2 32.1 38.8				
15	1G 15.4 24.8	N 0.0 10.4	-- Fuel type ID -- Burnup at BOC(GWd/t) -- Burnup at EOC(GWd/t)					

<Fraction distribution of BPRs>

	H	G	F	E	D	C	B	A
8								
9								
10								
11								
12								
13								
14								
15			-- BPR type -- Fraction at BOC -- Fraction at EOC					

N	Fresh fuel without Gd
1	1ce burned fuel
2	2ce burned fuel
3	3ce burned fuel
NG	Fresh fuel with Gd
1G	1ce burned fuel with Gd
2G	2ce burned fuel with Gd
3G	3ce burned fuel with Gd

Fig.6 Loading pattern of the method (1)

<burnup distribution of fuel assemblies>

	H	G	F	E	D	C	B	A
8	1G 31.6 52.9	1G 23.2 48.2	NG 0.0 32.5	1G 25.1 53.9	NG 0.0 34.0	NG 0.0 32.3	1G 25.1 47.0	1G 29.8 42.1
9	1G 23.2 48.2	1G 23.2 49.8	NG 0.0 33.3	NG 0.0 33.6	1 15.1 47.3	NG 0.0 32.2	NG 0.0 25.1	N 0.0 15.1
10	NG 0.0 32.5	NG 0.0 33.3	NG 0.0 33.5	1 23.2 52.4	NG 0.0 32.6	NG 0.0 29.8	N 0.0 23.2	
11	1G 25.1 53.9	NG 0.0 33.6	1 23.2 52.4	NG 0.0 31.6	1 16.6 43.7	NG 0.0 23.2	1G 32.2 42.6	
12	NG 0.0 34.1	1 15.2 47.3	NG 0.0 32.6	1 16.6 43.7	1G 29.8 48.9	N 0.0 16.6		
13	NG 0.0 32.2	NG 0.0 32.1	NG 0.0 29.8	NG 0.0 23.2	N 0.0 16.6			
14	1G 25.1 47.0	NG 0.0 25.1	N 0.0 23.2	1G 32.1 42.6				
15	1G 29.8 42.2	N 0.0 15.2	-- Fuel type ID -- Burnup at BOC(GWd/t) -- Burnup at EOC(GWd/t)					

<Fraction distribution of BPRs>

	H	G	F	E	D	C	B	A
8								
9								
10								
11								
12								
13								
14								
15			-- BPR type -- Fraction at BOC -- Fraction at EOC					

N	Fresh fuel without Gd
1	1ce burned fuel
2	2ce burned fuel
3	3ce burned fuel
NG	Fresh fuel with Gd
1G	1ce burned fuel with Gd
2G	2ce burned fuel with Gd
3G	3ce burned fuel with Gd

Fig.7 Loading pattern of the method (2)

<burnup distribution of fuel assemblies>

first half cycle

	H	G	F	E	D	C	B	A
8	2G 32.5 45.0	2G 27.7 41.4	1 17.0 33.3	1 17.5 34.2	3 40.7 53.9	1 11.0 28.2	2G 32.5 42.8	3 48.4 52.2
9	2G 27.7 41.4	1 17.1 32.4	3 40.9 53.3	NG 0.0 16.9	2 25.5 40.8	1 17.0 33.9	NG 0.0 12.6	3 47.2 50.8
10	1 17.0 33.2	3 40.9 53.3	2G 27.6 41.5	2 20.8 36.8	2G 26.1 40.9	1 10.9 27.8	N 0.0 13.4	
11	1 17.4 34.2	NG 0.0 17.0	2 20.9 36.9	1 11.0 28.2	3 42.6 54.5	NG 0.0 13.2	3 46.1 51.5	
12	3 40.7 53.9	2 25.5 40.8	2G 26.0 40.9	3 41.4 53.4	1 13.2 27.2	N 0.0 10.8		
13	1 11.0 28.2	1 17.0 33.9	1 10.9 27.8	NG 0.0 13.2	N 0.0 10.7			
14	2G 32.5 42.8	NG 0.0 12.6	N 0.0 13.4	3 46.1 51.5				
15	3 48.4 52.2	3 45.4 49.1	-- Fuel type ID -- Burnup at BOC(GWd/t) -- Burnup at EOC(GWd/t)					

<Fraction distribution of BPRs>

first half cycle

	H	G	F	E	D	C	B	A
8								
9								
10								
11								
12								
13								
14								
15			-- BPR type -- Fraction at BOC -- Fraction at EOC					

N	Fresh fuel without Gd
1	1ce burned fuel
2	2ce burned fuel
3	3ce burned fuel
NG	Fresh fuel with Gd
1G	1ce burned fuel with Gd
2G	2ce burned fuel with Gd
3G	3ce burned fuel with Gd

second half cycle

	H	G	F	E	D	C	B	A
8	3G 45.0 54.0	3G 41.4 52.1	2 33.3 47.2	2 34.2 48.4	N 0.0 17.5	2 28.2 41.4	3G 42.8 53.7	N 0.0 13.2
9	3G 41.4 52.0	2 32.4 45.4	N 0.0 17.0	1G 16.9 32.5	3 40.8 52.8	2 33.9 46.1	1G 12.6 26.0	N 0.0 11.0
10	2 33.2 47.2	N 0.0 17.0	3G 41.5 53.7	3 36.8 49.1	3G 40.9 52.6	2 27.8 40.9	1 13.4 25.5	
11	2 34.2 48.4	1G 17.0 32.5	3 36.9 49.2	2 28.2 42.6	N 0.0 17.1	1G 13.2 27.7	N 0.0 10.9	
12	N 0.0 17.4	3 40.8 52.7	3G 40.9 52.6	N 0.0 17.0	2 27.2 40.7	1 10.8 20.9		
13	2 28.2 41.4	2 33.9 46.1	2 27.8 40.9	1G 13.2 27.6	1 10.7 20.8			
14	3G 42.8 53.7	1G 12.6 26.1	1 13.4 25.5	N 0.0 10.9				
15	N 0.0 13.2	N 0.0 11.0	-- Fuel type ID -- Burnup at BOC(GWd/t) -- Burnup at EOC(GWd/t)					

second half cycle

	H	G	F	E	D	C	B	A
8					12BP 1.00 0.11			
9			20BP 1.00 0.12					
10		20BP 1.00 0.12						
11					20BP 1.00 0.12			
12	12BP 1.00 0.11			20BP 1.00 0.12				
13								
14								
15			-- BPR type -- Fraction at BOC -- Fraction at EOC					

N	Fresh fuel without Gd
1	1ce burned fuel
2	2ce burned fuel
3	3ce burned fuel
NG	Fresh fuel with Gd
1G	1ce burned fuel with Gd
2G	2ce burned fuel with Gd
3G	3ce burned fuel with Gd

Fig.8 Loading patterns of the MS method

4.2 Evaluations of the economic effect of the MS method

Economics of the above three cases were compared with each other. At first, we consider the intermediate shutdown period. In the method (1), the intermediate shutdown period is 0 day, since the intermediate shutdown is not performed in this method. Period and cost needed for the partial shuffling in the MS method are assumed to be 40/157 of these in the full core shuffling, because number of reloaded fuel assemblies during the intermediate shutdown is 40 (total number of fuel assemblies in the core is 157).

On the other hand, as shown in Table 2, critical boron concentrations at EOC are surplus and they depend on methods. In these cases, fuel enrichment can be lower, since surplus of the critical boron concentration at EOC correspond to excess reactivity. On evaluating the economics, fuel enrichment in each method are lowered according to the surplus of critical boron concentration at EOC, since critical boron concentration at EOC in each method must be made the same value to evaluate the economics. The correction is carried out based on the equation shown in the Appendix. It should be noted that the critical boron concentrations at EOC in the MS method are different between the first half cycle and the second half cycle. We adopted lower critical boron concentration at EOC of the second half cycle to correct fuel enrichment of first half cycle.

The number of fresh fuel assemblies, the intermediate shutdown period, and the corrected fuel enrichment have great influence on economics. These parameters in each method are shown in Table 3. The intermediate shutdown period consists of core cooling time and fuel reloading time. In Table 3, core cooling time was assumed to be 5 days, and fuel reloading time for the full core shuffling was assumed to be 8 days.

Table 3 Important parameters for economics in each method

	method (1)	method (2)	MS
Number of fresh fuel assemblies per 24months	100	80	80
Period of intermediate shutdown (days)	0.00	13.0	7.04
Corrected fuel enrichment (wt%)	4.66	4.52	4.65

The fuel cycle cost and the power generation cost were evaluated based on Ref.2. The cost parameters used in the calculations for them are shown in Appendix. The calculation results are shown in Table 4.

Table 4 Power generation cost in each method

	method (1)	method (2)	MS method
Generated electricity (kWh)	1.52E+10	1.52E+10	1.52E+10
Fuel cycle cost ($)	3.14E+08	2.60E+08	2.63E+08
Periodic inspection ($)	1.16E+08	1.16E+08	1.16E+08
Intermediate shutdown ($)	0.00E+00	2.26E+07	1.19E+07
Total power generation cost ($)	4.30E+08	3.99E+08	3.91E+08
Total power generation cost ($/kWh)	2.84E-02	2.63E-02	2.58E-02

From Table 4, it is found that there is much difference between the fuel cycle costs of the methods (1) and (2). This difference comes from the number of fresh fuel assemblies, which has great effect on the fuel cycle costs. The fuel cycle costs of the MS method and the method (2) are almost the same value, since the number of fresh fuel assemblies in each method are the same. A little difference between them comes from the corrected fuel enrichment.

On the other hand, the intermediate shutdown cost of the MS method is about 53% less than that of the method (2), since 6 days less the intermediate shutdown period in the MS method.

Consequently, overall power generation cost of the MS method is lower than that of others. Total power generation cost is less than those of the methods (1) and (2) by about 9.0% and 2.5% respectively. Therefore we could confirm that economics of the MS method is better than those of other methods.

5. Conclusion

In this paper, the MS method is proposed, which can shorten the period of intermediate shutdown and be expected the improvement of economics. The feasibility of the core which satisfies the safety limitations in the MS method was conformed. In case of adopting the MS method, economics are improved by 2.5% compared with the conventional methods.

Further study will be desired on the following things.

- Feasibility of more practical fuel shuffling (mechanical aspect and so on)
- Investigation of optimum fuel types for the MS method
- Development of calculation codes for optimization of the MS method

Appendix

Some calculations and parameters used in this study is described in this appendix.

(1) Correction of the fuel enrichment according to the critical boron concentration at EOC

The fuel enrichment is corrected by the following equation:

the fuel enrichment reduction [wt%] =

$\Delta$of the critical boron concentration at EOC [ppm] / B [ppm/wt%],

where,

B: Difference of the critical boron concentration at EOC when fuel enrichment is changed by 1wt% on same cycle length and same loading pattern.

(2) Fuel cycle cost and power generation cost

The parameters used in calculations of the fuel cycle cost are following:

Items	Cost	Unit
Natural UF6	9.48E+01	$/kgU
Enrichment	1.30E+02	$/kgU*SWU
Fabrication	8.80E+02	$/kgU
Transportation	3.49E+02	$/kgU
Reproccessing	1.75E+03	$/kgU
Final Disposal	3.90E-03	$/kWh

The power generation cost in this study consists in fuel cycle cost, replacement power cost and periodic inspection cost. The parameters used in the calculations of the generation cost are following:

Items	Cost	Unit
Replacement power cost	4.00E-02	$/kWh
Inspection cost	5.00E+07	$

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