Multi-Cycle Analysis on Spent Fuel Re-utilization in PWR Reload Core Design

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1. Introduction

Storage of spent nuclear fuel is an important matter either for short-term on-site storage or long-term interim storage in the aspect of both social and technical burden. In fact inside of spent fuel, there are large amount of precious fissile isotopes as well as many other minor actinides. Under the once-through cycle strategy, they are all to be dumped into waste repository. Recycling of spent fuel has been studied as only one option – recycling of separated isotopes after reprocessing. Recently, another option of recycling has been studied by our team in Kyung Hee University. Direct recycling can be done without reprocessing, when PWR spent fuels are dis-assembled, re-assembled and re-utilized at the next cycle [1]. This can be done only for part of spent fuel pins only if they are not burnt enough because of un-even power distribution in both radial and axial direction. Benefits of this re-utilization are expected in many ways.

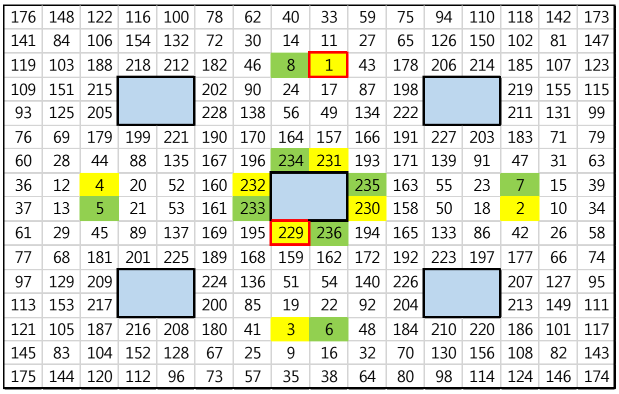
(1) Deep burning is achieved for low burnup fuel pins by letting them burn again.
(2) Cost of reprocessing is saved because this process do not need many procedures; such as de-cladding, dissolution, separation and fabrication.
(3) Required amount of fresh fuel loading is saved. After all, total amount of spent fuel to be disposed is reduced.

In the previous study, methodology and benefits of spent fuel recycling through re-assembling of spent fuel pins was shown. And thereafter, evaluation methodology for this procedure has been improved [2]. This paper shows the technical methodology for core design with recycled spent fuel pins in PWR application based on the methodology proposed in the previous studies. The scope of feasibility check was extended from single cycle to multi-cycle analysis, from replacement of 4 fuel assemblies to 12.

2. Spent Fuel Assembly Reconstruction

Spent fuel pin composition can be retrieved with detail operation history with extensive simulation for fuel pin depletion at each location. However, only few data can be available in reality; (1) Initial fuel pin enrichment, (2) Location inside of fuel assembly, and (3) Axially averaged pin-wise burnup. The reactivity of each fuel pin has to be known for the spent fuel assembly reconstruction for re-utilization, however, it is not easy to assess precise reactivity of each pins by lack of available data. Thus, in order to solve this problem, $(\eta_{pin})_{Burnup}$ can be used to assess pin-wise reactivity. $(\eta_{pin})_{Burnup}$ is able to be calculated additionally by HELIOS 1.8[3].

Spent fuel assembly reconstruction for re-utilization consists of a fuel pin with high reactivity, that is, fuel pins with high $(\eta_{pin})_{Burnup}$ value. These fuel pins are arranged to reduce the power peaking inside of the fuel assembly to be reconstructed as shown in Fig.1. The numbers in each cells represent the order of $(\eta_{pin})_{Burnup}$ value, and lower number means the pin with higher reactivity.



176	148	122	116	100	78	62	40	33	59	75	94	110	118	142	173	
141	84	106	154	132	72	30	14	11	27	65	126	150	102	81	147	
119	103	188	218	212	182	46	8	1	43	178	206	214	185	107	123	
109	151	215			202	90	24	17	87	198			219	155	115	
93	125	205			228	138	56	49	134	222			211	131	99	
76	69	179	199	221	190	170	164	157	166	191	227	203	183	71	79	
60	28	44	88	135	167	196	234	231	193	171	139	91	47	31	63	
36	12	4	20	52	160	232			235	163	55	23	7	15	39	
37	13	5	21	53	161	233			230	158	50	18	2	10	34	
61	29	45	89	137	169	195	229	236	194	165	133	86	42	26	58	
77	68	181	201	225	189	168	159	162	172	192	223	197	177	66	74	
97	129	209			224	136	51	54	140	226			207	127	95	
113	153	217			200	85	19	22	92	204			213	149	111	
121	105	187	216	208	180	41	3	6	48	184	210	220	186	101	117	
145	83	104	152	128	67	25	9	16	32	70	130	156	108	82	143	
175	144	120	112	96	73	57	35	38	64	80	98	114	124	146	174	

Fig. 1. Fuel pin arrangement for fuel assembly reconstruction

Spent fuel assembly reconstruction needs mainly five steps as shown in Fig. 2:

(1) 236 discharged fuel pins with relatively high reactivity is chosen from the spent fuel storage for reconstruction of new fuel assemblies. Information to be retrieved are; (1) Initial fuel pin enrichment, (2) Location inside of fuel assembly, (3) Axially averaged pin-wise burnup, and (4) evaluated $(\eta_{pin})_{Burnup}$.
(2) The fuel pins are relocated in the order of $(\eta_{pin})_{Burnup}$ in fuel assembly to have even distribution as shown in Fig. 1.
(3) Information of located fuel pins are divided into two parts which are (1) axially averaged burnup and (2) initial fuel pin enrichment and location inside of original fuel assembly.
(4) Burnup-isotope number density table should be prepared in ready by second part of fuel pin information; initial fuel pin enrichment and location inside of original fuel assembly.
(5) Compositions of each fuel pins are predicted with interpolation to the table set as a function of axially-averaged pin-wise burnup.

This whole procedure can be programmed with an aid of MATLAB software [4] without difficulty.

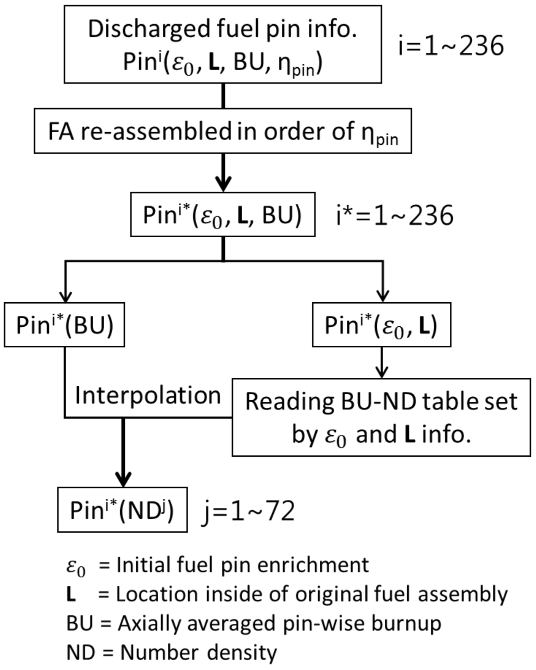


Fig. 2. Fuel assembly reconstruction procedure

3. Re-utilization in Single Cycle

Reconstructed fuel assembly is loaded instead of fresh fuel assembly. When reconstructed fuel assembly loaded, the core characteristics is changed considerably. Core average reactivity is dropped because of spent fuel pins are not equivalent to the fresh fuels. The purpose of the first step is to find how many reconstructed fuel assemblies can be replaced to the fresh fuel assemblies. The reference core is Ulchin unit-5 [5]. HELIOS-1.8/MASTER-2.2 [6,7] code were used for this calculation.

The targets of core design are as the followings:

- Cycle length reduction ≤ 7.5% of cycle length
- Fq ≤ 2.52, Fr ≤ 1.55
- AO ≤ ±10%
- MTC at HFP < 0 pcm/℃
- FTC at HFP < 0 pcm/℃
- SDM > 6500 pcm

Table 1. Spent fuel re-utilization in single cycle

	UCN5 CYC4	**4 FAs**	**8 FAs**	**12 FAs**
Reutilized FA location in core		[H, 1], [A, 8], [R, 8], [H,15]	[E, 2], [B, 5], [B,11], [E,14], [L,14], [P,11], [P, 5], [L, 2]	[H, 1], [A, 8], [R, 8], [H,15], [E, 2], [B, 5], [B,11], [E,14], [L,14], [P,11], [P, 5], [L, 2]
EFPD	419.12	409.09 (-2.4%)	394.48 (-5.9%)	381.59 **(-9.0%)**
Max. Fr	1.4765	1.5051	1.5687	1.6237
Max. Fq	1.8407	1.8810	1.9508	2.0113
AO (%)	-3.86 ~4.67	-3.95 ~4.49	-4.13 ~4.42	-4.10 ~4.04
MTC at HFP of BOC (pcm/℃)	-24.86	-25.73	-26.80	-28.04
FTC at HFP of BOC (pcm/℃)	-2.88	-2.91	-2.95	-3.00
SDM (BOC /EOC) (pcm)	7077 /6754	6971 /6678	7946 /7588	7780 /7558
Max. pin-wise BU_{xy} (MWD /kgHM)	-	42.48	47.01	47.96

Table 1 shows the location of reconstructed fuel assemblies in core and the following calculation results.

Reconstructed fuel assemblies are loaded into core periphery to increase neutronic economics such as reduce neutron leakage and less cycle length reduction. However, the peaking factor was increased by reactivity loss at core periphery.

The result shows that re-constructed fuel assemblies can be loaded for only one cycle because of burnup limit. In case of loading 8 and 12 fuel assemblies, the Fr value is slightly exceeded. However, Fr value is comparable to reference core. Cycle length reduction is over 35 EFPDs when 12 fuel assemblies were loaded. Therefore, up to 8 reconstructed fuel assembly can be loaded without difficulty in core design.

4. Extension to Multi-Cycle Analysis

Fresh fuel assemblies usually stay for three cycles in OPR-1000 core. However, reconstructed fuel assembly can be used only for one cycle as shown above. Therefore, the new reconstructed fuel assemblies should be supplied at the following cycles for the replacement to once-burnt and twice-burnt fuels. In this step, feasibility of spent fuel re-utilization is checked through 3 consecutive cycles. 4 re-utilization cases were chosen since 8 fresh fuel assemblies can be replaced in one cycle: (1) 4-4-4 re-utilization, (2) 8-4-4 re-utilization, (3) 8-4-8 re-utilization, and (4) 8-8-8 re-utilization. Table 2 shows the location of the fuel assemblies to be replaced in core during cycle 4 to cycle 6. Table 3 shows core performance of reference core.

Table 2. Location of the FAs to be replaced in core

(a) FA information to be replaced during 3 cycles

	Cycle 4	Cycle 5	Cycle 6
F0	A,8	B,8	J,9
	H,1	H,2	G,9

	H,15	H,14	J,7
	R,8	P,8	G,7
F0	P,11	C,6	A,7
	E,2	K,13	J,15
	L,2	F,13	G,15
	B,5	N,10	R,9
	L,14	F,3	G,1
	P,5	C,10	A,9
	B,11	N,6	R,7
	E,14	K,3	J,1

(b) FA information to be replaced during 2 cycles

	Cycle 4	Cycle 5	Cycle 6
G2	-	D,4	D,8
	-	D,12	H,12
	-	M,12	M,8
	-	M,4	H,4
G1	-	M,3	K,3
	-	C,4	C,6
	-	N,12	N,10
	-	C,13	F,13
	-	M,13	K,13
	-	N,4	N,6
	-	C,12	C,10
	-	D,3	F,3

(c) FA information to be replaced for 1 cycle

	Cycle 4	Cycle 5	Cycle 6
H6	-	-	M,12
	-	-	D,4
	-	-	D,12
	-	-	M,4
H0	-	-	P,11
	-	-	E,2
	-	-	L,14
	-	-	L,2
	-	-	B,5
	-	-	P,5
	-	-	B,11
	-	-	E,14

Table 3. Core performance of reference core

	Cycle 4	Cycle 5	Cycle 6
EFPD	419.12	459.25	408.03
Max. Fr	1.4765	1.5465	1.5356
Max. Fq	1.8407	1.9627	1.9196
AO (%)	-3.95 ~4.67	-3.86 ~3.40	-4.21 ~1.35
MTC at HFP of BOC (pcm/℃)	-24.86	-20.73	-26.12
FTC at HFP of BOC (pcm/℃)	-2.88	-3.27	-3.26
SDM (BOC /EOC) (pcm)	7077 /6754	7999 /7232	7557 /6922

4.1 4-4-4 Re-utilization

12 fresh fuel assemblies were replaced with 24 spent fuel assemblies in this case. Table 4 shows the core performance of 4-4-4 re-utilization. Cycle length reduction became maximum in cycle 5 because the reconstructed fuel assembly has lower reactivity than fresh fuel and once burnt fuel. However, the reactivity of reconstructed fuel assembly is higher than twice burnt fuel. It compensates reactivity loss from fresh and once burnt fuel assemblies in cycle 6.

The overall performance of this re-utilization case has good agreement with reference core performance. Thus, 4-4-4 re-utilization can be performed without any serious problem.

Table 4. Core performance of 4-4-4 re-utilization

	Cycle 4	Cycle 5	Cycle 6
EFPD	407.64 (-2.7%)	435.39 (-5.2%)	392.50 (-3.8%)
Max. Fr	1.5099	1.6472	1.5845
Max. Fq	1.8860	2.0855	1.9978
AO (%)	-3.95 ~4.45	-4.09 ~2.31	-3.94 ~-0.25
MTC at HFP of BOC (pcm/℃)	-25.9	-22.24	-26.84
FTC at HFP of BOC (pcm/℃)	-2.92	-3.27	-3.33
SDM (BOC /EOC) (pcm)	6957 /6665	7991 /7095	7454 /6917

4.2 8-4-4 Re-utilization

16 fresh fuel assemblies were replaced with 36 spent fuel assemblies in this case. Table 5 shows the core performance of 8-4-4 re-utilization. The cycle length reduction is minimal in cycle 6 due to the reactivity compensation from replacing twice burnt fuel.

The overall performance of this re-utilization case has good agreement with reference core performance except peaking factor. Especially, radial peaking factor was slightly exceed the design target. However, this exceeded radial peaking factor can be mitigated with core optimization. Thus, 8-4-4 re-utilization can be performed with core optimization.

Table 5. Core performance of 8-4-4 re-utilization

	Cycle 4	Cycle 5	Cycle 6
EFPD	392.63 (-6.4%)	425.87 (-7.3%)	396.96 (-2.7%)

Max. Fr	1.5752	1.7512	1.6166
Max. Fq	1.9579	2.2206	2.0124
AO (%)	-4.14 ~4.36	-4.26 ~1.39	-3.92 ~0.85
MTC at HFP of BOC (pcm/℃)	-26.97	-23.14	-26.14
FTC at HFP of BOC (pcm/℃)	-2.95	-3.25	-3.24
SDM (BOC /EOC) (pcm)	7921 /7648	7733 /7294	7282 /6851

4.3 8-4-8 Re-utilization

20 fresh fuel assemblies were replaced with 40 spent fuel assemblies in this case. Table 6 shows the core performance of 8-4-8 re-utilization. The cycle length reduction is minimal in cycle 6.

The overall performance of this re-utilization case has good agreement with reference core performance except peaking factor. Radial peaking factor of this case is a bit higher than 8-4-4 re-utilization case. However, this exceeded radial peaking factor value is not very high which can be mitigated with core optimization also. Thus, 8-4-8 re-utilization can be performed with core optimization.

Table 6. Core performance of 8-4-8 re-utilization

	Cycle 4	Cycle 5	Cycle 6
EFPD	391.79 (-6.5%)	424.81 (-7.5%)	389.99 (-4.4%)
Max. Fr	1.5788	1.7591	1.7194
Max. Fq	1.9613	2.2308	2.1380
AO (%)	-4.13 ~4.30	-4.27 ~1.30	-4.29 ~0.27
MTC at HFP of BOC (pcm/℃)	-27.06	-23.29	-27.61
FTC at HFP of BOC (pcm/℃)	-2.95	-3.25	-3.28
SDM(BOC /EOC) (pcm)	7908 /7668	7708 /7283	7056 /7081

4.4 8-8-8 Re-utilization

24 fresh fuel assemblies were replaced with 48 spent fuel assemblies in this case. Table 7 shows the core performance of 8-8-8 re-utilization.

The cycle length reduction is quite high, about 50 days. Maximum total peaking factor at cycle 6 was become higher than cycle 5 unlike other cases. Beside, radial peaking factor exceeded quite much. This exceeded radial peaking factor value is too high to mitigate with core optimization. Thus, 8-8-8 re-utilization cannot be performed.

Table 7. Core performance of 8-8-8 re-utilization

	Cycle 4	Cycle 5	Cycle 6
EFPD	391.04 (-6.7%)	409.90 **(-10.7%)**	377.02 **(-7.6%)**
Max. Fr	1.5813	**1.8754**	**1.9478**
Max. Fq	1.9639	2.3815	2.4167
AO (%)	-4.13 ~4.28	-4.34 ~0.13	-3.83 ~-0.20
MTC at HFP of BOC (pcm/℃)	-27.13	-25.39	-31.18
FTC at HFP of BOC (pcm/℃)	-2.95	-3.29	-3.27
SDM (BOC /EOC) (pcm)	7899 /7697	7558 /7072	6549 /6954

5. Conclusions

When the reconstructed fuel assemblies were replaced, a slight decrease in cycle length and an increase in radial peaking factor were observed due to the loss of reactivity. However, fresh fuel assemblies could be re-utilized with 2 to 2.25 times of spent fuel reloading in PWR core. It is not only reduced the number of fresh fuel requirement, but also reduces the number of discharged fuel assemblies.

In this study, the reconstructed fuel assemblies were placed at core periphery to compensate for the reactivity loss by increasing the neutron economics. As a result, the radial peaking factor was increased. In the future, if the optimization in reload core design is performed, cycle length loss and radial peaking will be minimized. Furthermore, a new equilibrium cycle core design with spent fuel re-loading is expected with a high feasibility for practice.

REFERENCES

[1] Aung Tharn Daing & Myung Hyun Kim (2014) Investigation into fuel pin reshuffling options in PWR in-core fuel management for enhancement of efficient use of nuclear fuel, Nuclear Engineering and Design, 273, 332-349

[2] Yun Seo Park & Myung Hyun Kim, (2016). Improved retrieval technique of pin-wise composition for spent fuel recycling, Korean Nuclear Society Autumn Meeting, Gyeongju, Korea.

[3] "HELIOS 1.9 User's Manuals", (2005) Studsvik Scandpower

[4] Duane Hanselman, Bruce Littlefield, (2012) Mastering MATLAB-1st ed., PEARSON

[5] "Nuclear Design Report for Ulchin Nuclear Power Plant Unit 5 Cycle 4," KNF-U5C4-07036, Rev. 00, KNFC, 2007.

[6] "PROLOG 1.1 User's Manual", KAERI/UM-4/99, September, 2004

[7] "MASTER 3.0 User's Manual", KAERI/UM-8m2004, March, 2004