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Evaluation of Spent Fuel Recycling Scenario using Pyro-SFR related System

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1. Introduction

Pyro-SFR related system is being studied as the best way to reduce amount of the spent fuels(SF). Thus, it is needed to validate whether the recycling scenario connecting pyro-processing and sodium-cooled fast reactor(SFR) is promising or not. The latest technologies of pyro-processing are applied to SFR and the recycling scenario is evaluated through the SFR's performance analysis. The analyzed SFR is KALIMER-600 TRU burner [1] which purpose is to transmute transuranics (TRU).

National policy of CANDU SF management has not been decided yet. However, the stored quantity of this SF is large enough not to be neglected. So this study includes additionally the recycling scenario of CANDU SF.

2. Recycling scenario

2.1 Pyro-processing key technical factors

2.1.1 TRU and RE recovery factor

The target value of TRU recovery factor is 99.9%. Since Rare Earth elements (RE)'s electrochemical characteristic is similar to TRU's, They are recovered simultaneously with TRU, resulting in a specific mass ratio of TRU and RE. In this study, the ratio is set to 4 to 1.

2.1.2 I, Tc and Cs, Sr separation efficiency

There is a plan that I, Tc, Cs and Sr are separated from SF during pyro-processing.

I and Tc are long-lived fission product (LLFP). These nuclides are volatilized and collected in the filter at head end process. The separation efficiency is 99%.

Cs and Sr have a very high decay heat and short half-life. Most of Cs is volatilized by high temperature treatment at head end process and the remainder and Sr are separated from the molten salt waste. The separation efficiency of Cs and Sr are 99.9% and 99% on each.

The daughter nuclides of Cs-137 and Sr-90 are Ba-137mand Y-90. They also have a high decay heat and the same separation efficiency with their parent nuclide because each of their half-life is much shorter than each parent nuclide.

2.2 Process of Pyro-SFR system

Commonly assumed period of processes are pyro-processing for 8 months, fuel fabrication for 8 months, preloading before fuel charging in the core for 2 months, and cooling the discharged fuel(SFR SF) for 1 year [1]. A merit of pyro-processing is that the process can be operated no matter how highly SF's decay heat generates. So SFR SF's cooling time is assumed only 1 year. But PWR SF should be stored at least 10 years to facilitate the transportation from PWR site to SFR site.

2.2.1 PWR SF recycling

In the initial stage of SFR introduction, only PWR SF may be recycled to manufacture the SFR fuel, not self-recycling like figure 1.

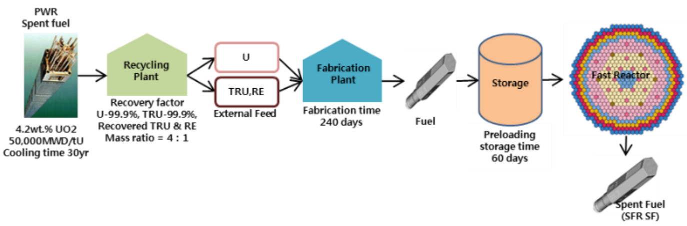

Fig. 1 PWR SF recycling scenario – no self-recycling

After 4 or 5 operating cycles, SFR will be self-recycling. The mass ratio of recovered TRU and RE is 4 to 1 in case of PWR SF pyro-processing. But SFR SF's pyro-processing technologies have not been fully developed yet, so the same mass ratio of 2.1.1 and the same factors of 2.1.2 applies to the case of SFR SF.

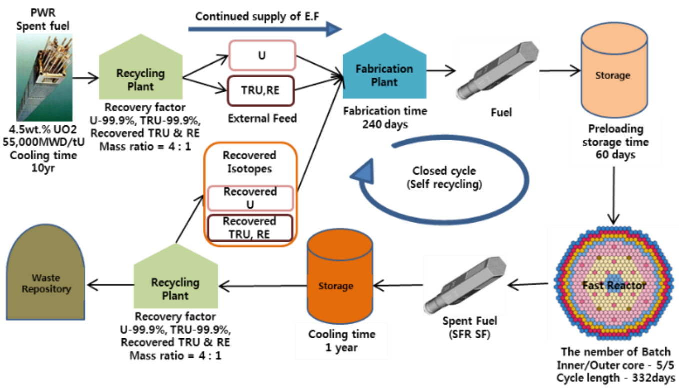

Fig. 2 PWR SF recycling scenario –self-recycling

2.2.2 CANDU SF recycling

There are a few merits and demerits for pyro-processing CANDU SF. Use of natural uranium fuels lead to a short discharge burn-up (~7,500MWD/tU) and

TRU contents in the SF about 0.41%. Thus, large capacity of pyro-processing will be needed to recover sufficient amount of TRU from CANDU SF for making the SFR's fuel, which renders the pyro-processing not economical.

Because of short discharge burn-up, total heat generation of CANDU SF is smaller than PWR SF. If the volume of high-level radioactive waste disposal is proportional to heat generation of the waste, the volume of CANDU SF disposal is estimated to about 63% of PWR SF disposal after cooling for 100 years.

Table 1. Heat density and total heat of the SFs in one of PWR and CANDU unit

	Cooling time (yr)	10	30	60	100	300	500
PWR SF	Actinide(W/t)	539.80	464.10	384.70	318.60	180.80	129.20
	FPs (W/t)	1363.5	737.31	357.93	139.63	1.33	0.04
	Sum (W/t)	1903.3	1201.4	742.63	458.23	182.13	129.24
	Amount of SF(t)	19					
	Total (W)	36163	22827	14110	8706	3460	2456
CANDU SF	Actinide(W/t)	24.57	32.42	35.12	34.42	27.88	23.36
	FPs (W/t)	200.56	114.66	56.12	21.93	0.21	0.01
	Sum (W/t)	225.13	147.08	91.24	56.35	28.09	23.37
	Amount of SF(t)	97					
	Total (W)	21838	14267	8850	5466	2725	2267
Volume ratio for disposal (CANDU SF /PWR SF)		0.604	0.625	0.627	0.628	0.787	0.923

The recycling of CANDU SF should be strategically determined considering safety of long-term storage, final disposal site, social, environmental and political issues, etc...

The key factors of pyro-processing CANDU SF are assumed to be the same as those of PWR SF. And the cooling time of CANDU SF is 60 years on the supposition that the longest cooled SF will be recycled for making the SFR fuel.

3. The SFR performance analysis

The parameters are divided into four main classes; recycling conditions, core performance, sodium void reactivity(SVR), and the fuel mass flow.

The SVR is sodium void reactivity coefficients, one of the most important core design values in assuring safety of SFR core loaded with TRU. The limit values of 7~8$ are taken as the design basis for metal fuel. This is the reason why the SVR was evaluated.

The minimum capacity of pyro-facility in mass flow class means that how much external feed(PWR or CANDU SF) must do pyro-processing to charge the SFR core at the beginning of equilibrium cycle.

Table 2. and Table 3. show the SFR performance summary in each case of PWR SF and CANDU SF recycling.

TRU transmutation performance of PWR SF recycling is better than the case of CANDU SF because of nuclides composition ratio.

Fissile Pu composition ratio in TRU of CANDU SF is higher than PWR SF, So the required amount of TRU to satisfy the excess reactivity for one cycle is smaller in CANDU SF recycling. This is the reason why TRU transmutation performance in CANDU SF recycling is worse than the case of PWR SF.

Table 2. The SFR performances in case of PWR SF recycling

parameter		PWR SF recycle	
		No self-recycle	Self-recycle
Condition	Cooling time of PWR SF (yr)	30	10
	Cooling time of SFR SF (yr)	-	1
	TRU recovery factor (PWR/SFR, %))	99.9 / 0	99.9 / 99.9
	RE recovery factor (PWR/SFR, %)	20 / 0	20 / 58
Performance	Burnup reactivity swing (pcm)	3530	4531
	Average conversion ratio	0.59	0.65
	TRU Trasmutation (kg/cycle)	262.56	282.61
	TRU Support Ratio	1.798	1.933
	Average discharged burnup (In/Out, MWD/kg)	198.3 / 129.2	197.1 / 131.4
SVR	Sodium Void Reactivity BOEC/EOEC (pcm)	2393 / 2530	2587 / 2897
	Beta-effective BOEC/EOEC (supposed value, pcm)	~315 / ~315	~310 / ~310
	Sodium Void Reactivity BOEC/EOEC ($)	7.60 / 8.03	8.35 / 9.34
Mass flow	Amount of U External Feed (kg/cycle)	2137.64	248.71
	Amount of TRU External Feed (kg/cycle)	1102.71	283.98
	TRU/RE Content in U-TRU-Zr (charged, %)	26.74 / 6.40	29.41 / 6.92
	TRU : RE ratio in U-TRU (charged fuel)	4.18 : 1	4.21 : 1
	Minimum capacity of pyro-facility (tHM)	16.60	18.18

Table 3. The SFR performance in case of CANDU SF recycling

parameter		CANDU SF recycle	
		No self-recycle	Self-recycle
Condition	Cooling time of PWR SF (yr)	60	60
	Cooling time of SFR SF (yr)	-	1
	TRU recovery factor (PWR/SFR, %))	99.9 / 0	99.9 / 99.9
	RE recovery factor (PWR/SFR, %)	45 / 0	45 / 58
Performance	Burnup reactivity swing (pcm)	4747	4272
	Average conversion ratio	0.65	0.70
	TRU Trasmutation (kg/cycle)	178.65	206.89
	TRU Support Ratio	0.829	0.960
	Average discharged burnup (In/Out, MWD/kg)	177.3 / 110.7	179.5 / 110.7
SVR	Sodium Void Reactivity BOEC/EOEC (pcm)	1308 / 1618	1903 / 2187
	Beta-effective BOEC/EOEC (supposed value, pcm)	~325 / ~325	~320 / ~320
	Sodium Void Reactivity BOEC/EOEC ($)	4.03 / 4.98	5.95 / 6.84
Mass flow	Amount of U External Feed (kg/cycle)	2805.04	323.96
	Amount of TRU External Feed (kg/cycle)	871.03	207.83
	TRU/RE Content in U-TRU-Zr (charged, %)	20.15 / 4.95	23.47 / 5.46
	TRU : RE ratio in U-TRU (charged fuel)	4.07 : 1	4.30 : 1
	Minimum capacity of pyro-facility (tHM)	212.45	50.69

Table 4. Compositions of PWR and CANDU SF

Nuclides	PWR SF (4.5wt.%, 55,000MWD/tU, 10yr cooling)			CANDU SF (0.71wt.%, 7,500MWD/tU, 60yr cooling)		
	Composition (gram/ton)	Composition ratio in SF(%)	Composition ratio in U, TRU(%)	Composition (gram/ton)	Composition ratio in SF(%)	Composition ratio in U, TRU(%)
U-234	213.4	0.0213	0.02	45.7	0.0046	0.005
U-235	7119.5	0.7120	0.77	2186.0	0.2186	0.221
U-236	6368.7	0.6369	0.69	748.0	0.0748	0.076
U-238	915405.0	91.5405	98.53	985200.0	98.5200	99.698
Total U	929106.6	92.9107	100	988179.7	98.8180	100
Pu-238	413.8	0.0414	2.95	-	-	-
Pu-239	6345.1	0.6345	45.24	2745.0	0.2745	67.445
Pu-240	3004.8	0.3005	21.43	1038.0	0.1038	25.504
Pu-241	1175.1	0.1175	8.38	11.5	0.0012	0.284
Pu-242	1020.0	0.1020	7.27	49.2	0.0049	1.209
Total Pu	11958.7	1.1959	85.27	3843.8	0.3844	94.441
Np-237	866.9	0.0867	6.18	40.3	0.0040	0.991
Am-241	791.9	0.0792	5.65	184.2	0.0184	4.526
Am242m	1.5	0.0001	0.01	-	-	-
Am-243	303.1	0.0303	2.16	1.7	0.0002	0.042
Cm-243	0.8	0.0001	0.01	-	-	-
Cm-244	93.8	0.0094	0.67	-	-	-
Cm-245	6.3	0.0006	0.05	-	-	-
Cm-246	1.3	0.0001	0.01	-	-	-
Total MA	2065.6	0.2066	14.73	226.2	0.0226	5.559
Total TRU	14024.3	1.4024	100	4070.0	0.4070	100
RE		1.72		2236.6	0.2237	
FP		3.23		5537.8	0.5538	

In case of CANDU SF recycling, the SVR is less than the design basis of metal fuel. PWR SF recycling case show higher SVR than 7$, meaning adverse safety implications.

4. Conclusions

Adopting the mass ratio of TRU and RE recovered in pyro-processing is 4 to 1 on PWR SF recycling, the sodium void reactivity is higher than design basis of metal fuel. So the current pyro-processing technology is may not be acceptable.

If pyro-processing technology of CANDU SF is assumed to be the same as PWR's case, CANDU recycling scenario is acceptable. Transmutation performance is worse than PWR's, while the sodium void reactivity is within design limit.

Therefore, it is needed to minimize the RE mass ratio in recovered materials to reduce SVR for recycling PWR SF. The next plan is to search for the mass ratio of TRU and RE to satisfy the design basis.

REFERENCES

[1] Y.I.Kim, et.al, “Establishment of Advanced SFR Concept”, KAERI/TR-4063/2010, Korea Atomic Energy Research Institure, Daejeon, Korea, 2010