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Uranium Enrichment Reduction in the PGSFR Core Design

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1. Introduction

It is essential to handle the spent nuclear fuel for sustaining the nuclear power utilization in Korea. In fact, the problematic TRU (transuranics) from spent nuclear fuel can be transmuted quite effectively in a fast reactor. Thus, Korea is currently developing the so-called Prototype Gen-IV Sodium-cooled Fast Reactor (PGSFR) to investigate and demonstrate the capability of TRU transmutation [1,2]. However, since fuel recycling technology is still at early development in Korea and also due to lack of experience in burning TRU in a fast reactor, the initial core of PGSFR is loaded with low-enriched uranium (LEU) fuel. Several test assemblies containing TRU fuels are supposed to be irradiated and tested for future TRU fuel developments. The uranium enrichment in the LEU PGSFR core is high, about 19.20%, due to large neutron leakage and low conversion ratio.

In this paper, the required uranium enrichment is reduced by replacing the reflector material and modifying the reflector geometry in order to decrease the fuel cost of the LEU PGSFR core. PbO is chosen as the reflector material to replace the current HT9 and an inverted reflector assembly is also investigated in this study. The impacts of these design modifications are analyzed by using Monte Carlo code SERPENT2 [3] in conjunction with ENDF/B-VII.0 nuclear data library

2. Current PGSFR Core Design

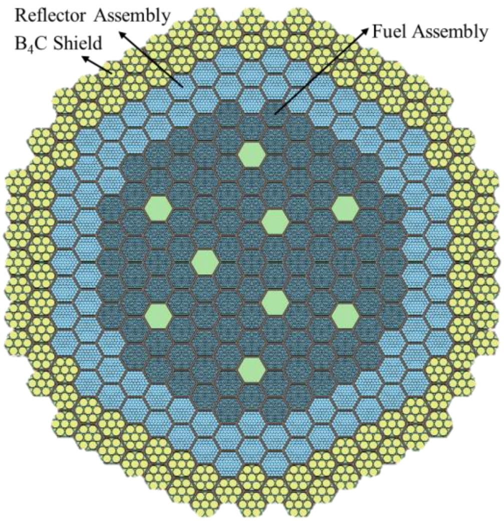

Fig. 1. PGSFR core radial layout [1].

PGSFR is a pool type sodium-cooled fast reactor with 392.2 MWth power. Figure 1 shows the radial core configuration. The core consists of 112 fuel assemblies, 90 reflector assemblies, 102 B_4C shield assemblies and 9 control assemblies. PGSFR core design parameters and performance parameters are shown in Tables I and II.

Table 1. PGSFR Core Design Parameters [1]

Design Parameters	Value
Power, MWth	392.2
Coolant temp., ℃ (inlet/outlet)	390 / 545
Fuel form	U-10%Zr
Cycle length(EFPD), day	290
Cladding material	HT9M
Structural Material	HT-9
Number of batches (IC/OC)	4 / 5
Active core height, cm	90.0
Upper gas plenum length, cm	125.0
Overall bundle length, cm	371.7
Number of drivers (IC/OC)	52 / 60
Fuel pin diameter, cm	0.74
Assembly pitch (cold), cm	13.636
P/D ratio	1.14
Number of fuel pins per assembly	217
Fuel volume fraction, %	32.5

Table II. PGSFR Core Performance Parameters [1]

Core Performance Parameters	Value
Enrichment, wt. %	19.20
Heavy metal loading, MT	7.33
Charge HM mass, T/yr	1.68
Burnup (avg./peak), MWd/kg	66.1 / 104.7
Burnup reactivity swing, pcm	2,176
Fast neutron flux, #/cm^2-sec	1.44E+15
Peak fast neutron fluence, #/cm^2	2.88E+23
Ave. linear power density, W/cm	159.7
Peak linear power density, W/cm	323.7
Ave. power density, W/cm^3	213.4
Peak power density, W/cm^3	432.5
Bundle Pressure Drop, Mpa	0.429
Flow Rate, kg/sec (included 2% flow leakage)	1989.8

3. Reflector Modification Strategies

3.1 PbO Reflector Assembly

In terms of neutronics, Pb is considered as a good reflector material for fast neutrons since it has a large scattering cross section and also a small capture cross section [4]. These nuclear properties of Pb, combined with its heavy mass, can effectively improve the neutron economy in fast reactor cores such as SFR. In this work, the geometry of PbO reflector assembly is basically the same as current HT9 reflector geometry and it is shown in Figure 2. As revealed in Ref. 4, a pure Pb is superior to PbO in view of the neutron economy. However, PbO is considered to be very compatible with the HT9 clad, while the corrosive behavior of liquid Pb can be an engineering problem. The melting point of PbO is 888℃, which is much higher than the coolant operating temperature of the PGSFR core.

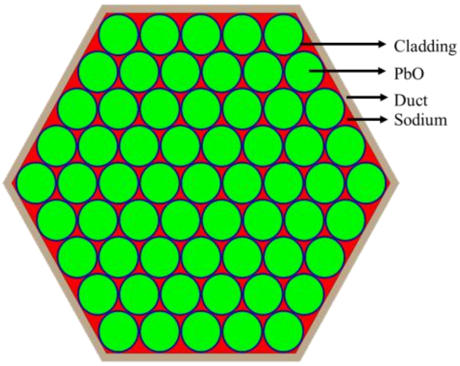

Fig 2. PbO reflector assembly geometry

Due to its small capture cross section, performance of the PbO reflector is relatively sensitive to the geometry of the core or reflector assembly. In the case of HT9 reflector, geometry does not affect to the core performance since HT9 absorbs a noticeable number of neutrons regardless of core assembly design. Moreover, because of less neutron absorption, the fast flux in the PbO reflector region is increased and thus, neutron leakage from the reflector surface is expected to be enhanced comparing to HT9 reflector.

3.2 Radial Reflector Arrangement

Because PbO reflector is relatively sensitive to the geometry comparing to HT9, it is important to optimize the radial core configuration to improve the core performance and to reduce the neutron leakage. Figure 3 is a core configuration suggested by this research which has 3 reflector assembly rings and 1 shielding assembly rings. The reason for the core configuration modification is that by increasing the number of radial reflector assembly rings, reflection of neutron to the core and neutron economy can be improved. However, since number of radial shielding assembly rings is decreased from 2 to 1, neutron leakage is expected to be increased. Considered PbO reflector assembly has the same geometry with the original HT9 reflector assembly to analyze the impact of modified core configuration with PbO reflector on the core performance independent to the assembly geometry. However, to improve the performance of PbO reflector, it is better to increase the volume fraction of PbO in the reflector assembly by reducing the number of reflector pins and increasing the reflector pin radius in the assembly.

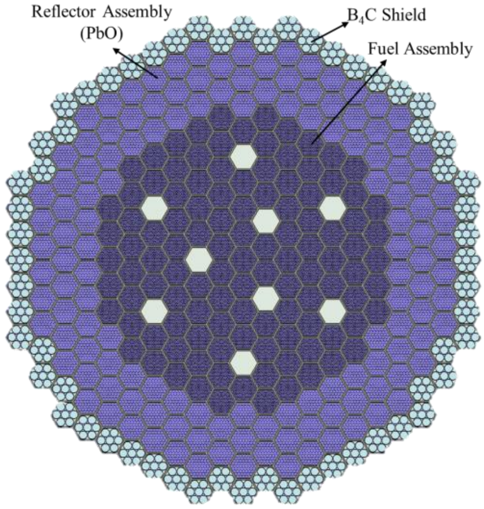

Fig 3. Modified PGSFR core axial layout

3.3 Inverted PbO Reflector

Main motivation of inverted geometry is reducing the neutron leakage by maximizing the volume fraction of reflector material in reflector assembly. Figure 4 shows the suggested inverted PbO reflector. The inverted reflector assembly is filled with bulky PbO and flow path for the coolant exists to remove the heat from the neutron capture reaction of reflector or structure material.

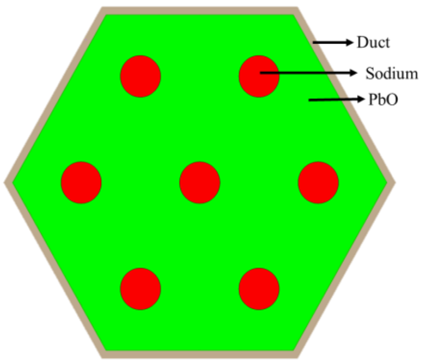

Fig 4. inverted reflector geometry

4. Core Performance Analysis Results

4.1 Single Batch Depletion Calculation

To analyze the impact of reflector material and geometry modification, single batch depletion calculation was carried out. The axial growth of the fuel was also accounted for in the depletion calculation.

Figure 5 shows the fuel length increase in various metallic fuels as a function of burnup. It is shown that fuel elongates rapidly at initial 1~2% burnup and grows slowly after that. To simplify the analysis, it is assumed that active core is already grew 8% from initial stage.

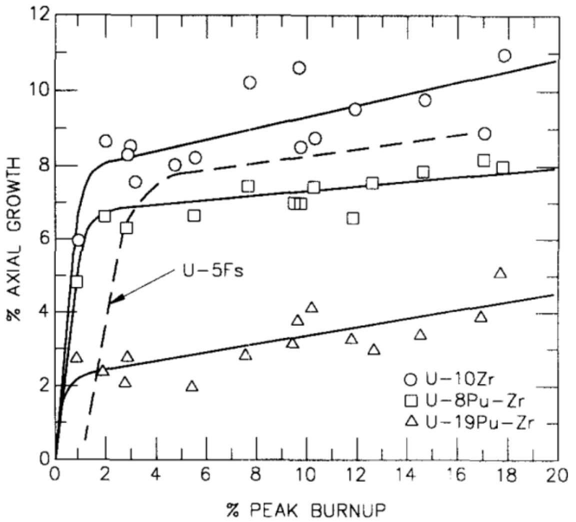

Fig. 5. Fuel Length Increases in Various Metallic Fuels as a Function of Burnup [5]

Figure 6 shows the result of single batch depletion calculation and Table III shows the required uranium enrichment. The required enrichment is estimated by balancing the reactivity increase by reflector modification and reactivity decrease by enrichment reduction. Also shown in Fig. 5, reactivity is decreased if elongation is considered because of enhanced neutron leakage.

With radial 3 rings of PbO reflector assemblies and U-10Zr fuel, required uranium enrichment is 18.2% which is 1% lower than that of original PGSFR and cycle length is also longer than that of original PGSFR. This is because of good characteristics of PbO as a neutron reflector. If inverted PbO reflector is used, then required enrichment is much lowered and obviously the core cycle length is expected to be longest because of larger PbO volume fraction in the reflector assembly.

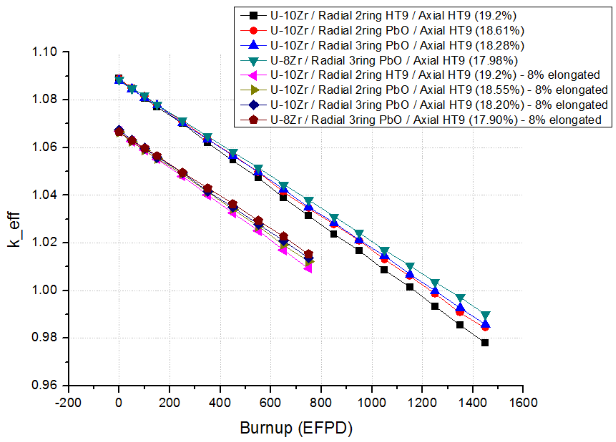

Fig 6. Single batch depletion calculation results

Table III. Required uranium enrichment of each PGSFR reflector design modification

Reflector	U-10Zr (%)	U-8Zr (%)
2 rings HT9	19.20	18.90
2 rings PbO	18.55	18.32
3 rings PbO	18.20	17.98
2 rings inverted PbO	18.44	N/A
3 rings inverted PbO	18.05	N/A

4.2 Multi-batch Fuel Management Analysis

The fuel management scheme of PGSFR is a 4 batch for the inner core and 5 batch for the outer core [2]. However, to simplify the analysis, the discharge burnup and cycle length for each of 4 batch fuel management and 5 batch fuel management was calculated and the average of 4 batch case and 5 batch case is used as a representative value. The linear reactivity theory [6] is used to approximately predict the discharge burnup and cycle length of 4 and 5 batch fuel managements.

Linear reactivity theory is the method which can approximately but quite nicely predict the discharge burnup and cycle length of multi-batch fuel management using discharge burnup and cycle length from single batch fuel management. Especially, the linear reactivity theory shows good accuracy in the fast reactor whose reactivity decrement tendency as a function of fuel burnup is almost linear. Formula (1) shows the basic equation of linear reactivity theory.

$$\mathrm{Bu_d} = n \cdot Bu_c = \frac{2n}{n+1}\mathrm{Bu_1} \qquad (1)$$

Where:
$\mathrm{Bu_d}$: Discharge Burnup (MWd/kgU)
Bu_c : Cycle Burnup (MWd/kgU)
n : Number of batches
$\mathrm{Bu_1}$: Single batch Burnup (MWd/kgU)

Table IV shows the results of 4/5-batch discharge burnup and cycle length prediction results. With radial 3 rings of PbO reflector, discharge burnup is about 10% higher than that of original PGSFR and if inverted PbO reflector is used, discharge burnup becomes higher and cycle length becomes longer.

Table IV. 4/5-batch burnup prediction results based on linear reactivity theory

Reflector	U-10Zr	U-8Zr
2 rings HT9 - $\mathrm{Bu_d}$, MWd/kgU - Cycle length, days	 74.53 / 77.64 348 / 290	 75.79 / 78.94 362 / 302
2 rings PbO - $\mathrm{Bu_d}$, MWd/kgU - Cycle length, days	 78.67 / 81.95 367 /306	 83.05 / 86.51 397 / 331
3 rings PbO - $\mathrm{Bu_d}$, MWd/kgU - Cycle length, days	 80.60 / 83.96 376 /313	 84.63 / 88.15 404 / 337

4.3 Neutron Leakage

Since PbO reflector hardly absorbs the neutrons, the fast flux in the reflector region is increased with PbO reflector. To evaluate how much the neutron leakage increases with PbO, fast flux at the periphery of the core was tallied. Table V shows the results of fast flux tally. The 2 rings of HT9 assembly with 2 rings of B_4C shield showed best results and the 3 rings of HT9 assembly with 1 ring of B_4C shield is the worst in view of neutron leakage among cases with pin type reflectors. And different from expectation, just because of so low neutron absorption of PbO, inverted PbO reflector showed similar or slightly larger neutron leakage than the conventional pin type reflector. In spite of the leakage enhancement, total number of shielding and reflector assemblies are kept to be 4 to keep the size of the core same as original PGSFR design.

Table V. Fast flux at the core periphery region

Reflector and Shield	Fast Flux (E>0.1 MeV)
2 rings HT9 + 2 rings of B_4C	
-Natural B_4C	1.97E+12
- 50% enriched B_4C	1.16E+12
2 rings PbO + 2 rings of B_4C	
-Natural B_4C	1.99E+12
- 50% enriched B_4C	1.18E+12
3 rings HT9 + 1 rings of B_4C	
-Natural B_4C	3.46E+12
- 50% enriched B_4C	2.50E+12
2 rings inverted PbO + 2 rings of B_4C	
-Natural B_4C	2.00E+12
3 rings inverted PbO + 1 rings of B_4C	
-Natural B_4C	3.47E+12

To deal with the enhanced neutron leakage, enriched B_4C is considered as a shielding material while original shielding material was natural B_4C. By using 50% enriched B_4C, fast flux with 3 PbO reflector rings is decreased about 30% from that of case with natural B_4C. Although leakage is still higher comparing to the case which uses 2 rings of HT9 reflectors and 2 rings of natural B_4C shielding, leakage can be reduced more by using more highly enriched B_4C or by modifying the core structure.

4.4 Power Distribution

If reflector does not reflect neutrons effectively, neutron flux in the outer region of the core is expected to be decreased and the power difference between inner and outer of the core becomes larger. Since PbO is considered as better reflector than HT9, it is natural to expect flatter power distribution with the PbO reflector than with HT9 reflector. Table VI shows the result of power distribution evaluation according to the numbering of the core region shown in Fig. 2. Although the power distribution of fuel assemblies of a ring are not exactly the same, the value in Table VI is an average ring-wise value. It is shown that the power in the outer region of the core is increased due to enhanced neutron reflection so that the power distribution is more flattened. Same tendency is observed with the U-8Zr fuel.

Table VI. Ring-wise core power distribution
(1: innermost / 7: outermost)

Ring	2 rings HT9	2 rings PbO	3 rings PbO
1	1.25	1.22	1.20
2	1.23	1.20	1.18
3	1.17	1.14	1.13
4	1.07	1.05	1.04
5	0.94	0.94	0.94
6	0.75	0.78	0.80
7	0.58	0.67	0.72

5. Cost Reduction Evaluation

The influence of uranium enrichment to the fuel cost is represented as SWU factor [7]. The cost for the uranium enrichment is calculated by multiplying the cost per SWU and SWU factor. SWU cost is 88$ us$/kgSWU and UF_6 cost is 100.5$/kgU in December 2014 [8]. In the previous section, it is shown that 1% of enrichment reduction is possible with 3 radial reflector rings using conventional pin type PbO reflector. The inverted PbO reflector is not included since it needs optimization of coolant path geometry and it also has to be investigated more. In this regard, the impact of 1% enrichment reduction to the fuel cost is evaluated and is shown in Table VII. Not only enrichment but also increment of cycle length and discharge burnup can affect to the fuel cost since fuel can be burned more in the core if discharge burnup is higher and cycle length is longer.

Table VII. Fuel cost reduction estimation corresponding to 1% enrichment reduction

	2 rings HT9	3 rings PbO	3 rings inverted PbO
Total fuel Cost, Million Korean Won	61,162	57,795	57,290
4.5 batch cycle length, days	319	344	347
Refueling period, days	60	60	60
4.5 batch fuel cost per year, Million Korean Won	13,089	11,603	11,417
Cost reduction per year, Million Korean Won	-	1,485	1,672
Initial core cost reduction, Million Korean Won	-	3,367	3,871

3. Conclusions

It is evaluated that 1% uranium enrichment reduction can be achieved by increasing the number of radial reflector assembly rings from 2 to 3 and changing reflector material from HT9 to PbO. In aspect of fuel cost, 1% reduction of uranium enrichment can save about 3.37 billion Korean won. Also, it is shown that longer cycle length, higher fuel burnup and flattening power distribution can be achieved with PbO reflector and enhanced neutron leakage can be handled by the optimization of shielding material or core geometry. PbO reflector with inverted geometry is suggest in this research and by using inverted PbO reflector, core performance can be improved while leakage is negligibly enhanced than conventional pin type reflector assembly. Research about reducing the uranium enrichment more by increasing the uranium content in the uranium fuel which is U-10Zr now or increasing the smeared density which is currently 75% can be considered as a future work. Detailed analysis about multi-batch fuel management should be carried out since currently it is done approximately by using linear reactivity theory. Also, analysis for PGSFR with various reflector materials like LME, liquid lead will be carried out and the chemical reaction of those materials including PbO with sodium should be carefully investigated. Finally, although lead hardly absorbs neutrons, the nuclides which can be made from the neutron capture reaction of lead should be analyzed.

REFERENCES

[1] Y. I. Kim et al., “Status of SFR Development in Korea”, *Proceedings of International Conference on Fast Reactors and Related Fuel Cycles: Safe Technologies and Sustainable Scenarios (FR13)*”, IAEA, Paris, France, March 4-7(2013)

[2] J. H. Lee, “Preliminary Conceptual Design Report of Gen-IV Prototype SFR”, SFR-010-DA-307-001, KAERI, Daejeon, Korea (2013)

[3] J. Leppänen, Serpent – a Continuous-energy Monte Carlo Reactor Physics Burnup Calculation Code User’s Manual, VTT Technical Research Centre of Finland, 2013.

[4] D. Hartanto, Y. Kim, Alternative Reflectors for a Compact Sodium-cooled Breed-and-Burn Fast Reactor, Annals of Nuclear Energy 76, pp. 113-124 (2015).

[5] G. Hofmann et al., “Metallic Fast Reactor Fuels”, Progress of Nuclear Energy, 31, pp. 83-110 (1997).

[6] M.J. Driscoll, T.J. Downar, E.E. Pilat, The Linear Reactivity Model for Nuclear Fuel Management, American Nuclear Society Press, La Grange Park, Illinois, 1990.

[7] Lamarsh, John R. *Introduction to Nuclear Engineering*. 2nd ed. pp. 203-205 (1983)

[8] "UxC Nuclear Fuel Price Indicators (Delayed)." *Ux Prices*. Web. Dec. 2014.
<http://www.uxc.com/review/UxCPrices.aspx>.