Performance Analysis of a Pb-Bi Cooled Fast Reactor – PEACER-300 in Proliferation Resistance and Transmutation Aspects

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Abstract

A design study of 850 MWt lead-bismuth cooled reactor cores is performed to maximize the transmutation of both TRU nuclides in homogeneous fuel pin and long-lived fission products in separate target pins. Transmutation of minor actinide under a closed recycling was analyzed with assumption that decontamination factors in pyro-reprocessing plant data be reasonably high. The optimized design parameter were chosen as of a flat core shape with 50 cm in active core height and 5 m in core diameter, loaded with 17 x 17 arrayed fuel assemblies. A pitch to diameter ratio is 2.2, operating coolant temperature range is 300°C ~ 400°C, and core consists of 3 different enrichment zones with one year cycle length. In safety aspects, this core design satisfied large negative temperature feedback coefficients, and sufficient shutdown margin by primary shutdown system with 20 B_4C control assemblies and by secondary shutdown system with 40 w/o enriched 12 B_4C control assemblies. Performance of designed core showed a high transmutation capability with support ratio of 2.085 and less T_{EX} values than other reactor types. Better proliferation resistance could be achieved than other reactor types.

KEYWORDS: Pb alloy cooled fast reactor, Proliferation Resistance, Transmutation, Flat Core

1. Introduction

One of the critical issues in the nuclear industry is how to treat the nuclear waste such that it has no significant effects on the natural environment. The nuclear waste is comprised of spent fuel from operating nuclear power plants – PWR, CANDU in Korea. It is well known that if the transuranic isotopes and long lived fission products which have small fraction in spent fuels are removed from the spent fuel destined for disposal, the toxicity of the spent fuel are dropped that of the natural uranium ore within several hundred years. Therefore, GEN IV reactors are aimed for improvement in sustainability as well as reactor safety, reliability, proliferation resistance, economics. A university research center was formed in 2002 for Gen-IV reactor research, named as NUTRECK (Nuclear Transmutation energy Research Center of Korea) as a consortium center of three university members in Korea. As a long term option, a concept of integral system of transmutation fast reactor with collocated pyro-processing plants was proposed as PEACER (Proliferation-resistant, Environment-friendly, Accident-tolerant, Continuable-energy, and Economical Reactor) park.[1]

Since the transmutation of long-lived minor actinides (LLMA) under the safety criteria is the prime goal of PEACER reactor, the core design was focused on the maximization of transmutation capability. For this prime objective, the most important and unique design concept of PEACER was introduced, which was the flat core shape. It could increase the transmutation performance by inducing large neutron leakage under the high flux level. Because of this core shape, few special features were induced. For transferring large heat in short heat transfer section, lead-bismuth coolant which had large heat capacity was used. It brought the other advantage in plant economics by eliminating an intermediate heat exchanger. When the core is flattened in radial direction, radial power distribution caused a power peak at the center of core without zoning. To solve this problem, enrichment zoning was applied with three different enrichments. To allow a cross-flow between assemblies open lattice structure was chosen just like PWR. It would be compatible in lead cooled reactor core with high P/D ratio.

In order to achieve good corrosion-resistance condition for a longer reactor life-time, low operating coolant temperature was adopted by comparing with other Pb-Bi cooled fast reactor concepts and HT-9 structure material was used instead of stainless steel which was chosen in general SFR. The proliferation resistance of PEACER is built by installing both institutional barrier through multi-national operation and technical barrier. The former is a transmutation complex named by a PEACER-Park which is consisted of four PEACERs and two reprocessing plants. According to the control and observation about all material produced in PEACER-Park, any kinds of fuel and residual material can not be escape to outside of PACER-Park. The latter includes denaturing of fissile materials, Pu in particular, as well as the intense radiation field associated with the pyro-chemical partitioning method. After reprocessing procedure, only low level wastes is disposed in the repository located in PEACER-Park.

The detail reactor design has been started under maintaining aforementioned PEACER design concepts. Several research teams were composed about neutonics, thermal hydraulics, pyro-processing, 3-dimensional visualization, materials and waste disposal. After neutonics calculation was preceded, the results were provided to the teams of thermal hydraulics, pyro-processing and waste disposal. Hence, PEACER plant design study is concentrated in neutronics firstly and the optimized core design has to be finished as soon as possible. In order to find the best design condition about safety and transmutation performance in neutronics concerns, several parametric studies were performed. Based on the analysis results of parametric studies, one of the optimized REACER core design was proposed and proliferation resistance and transmutation performance of optimized design were evaluated in this paper.

2. Design Concepts and Calculation Methods

Before starting parametric studies, basic design parameters had been fixed in order to keep characteristics of PEACER concept. The basic design features of PEACER-300 core were the same with previous PEACER design which was designed for commercial application but did not have natural cooling capability after HCDA. Those were the use of Pb-Bi metal alloy coolant at a low operation temperature band, the use of square lattice fuel assemblies like as PWR fuel assemblies and flat core shape like a pancake. A flattened core design lead to a large neutron leakage and increased requirement of TRU loading, resulting in enhanced burning of LLMA but loss of neutron economics. The fuel assemblies were designed to be a square lattice to have a large

P/D ratio under the enough coolant mass flow. Open lattice structure with spacer grid was adopted just like a PWR in contrast with Na-cooled LMR where core compactness was wanted. The characteristics of open lattice and spacer grid were checked through heat transfer calculation and stress analysis.[2][3]

The selection of metallic fuel as a U-Zr alloy which bearing TRU was aimed for safety satisfaction and compatibility to pyro-reprocessing. TRU was assumed to be separated from the LWR spent fuels. The reference composition data of U-TRU-Zr fuel were fraction of about 60%-30%-10%. Against the fuel swelling, the smeared density of fuel pellets was selected as 70%.

For the goals of this reactor core and its safety limit, which were described in the previous study as the following four kinds of criteria:

1) Excess reactivity at beginning of equilibrium cycle is not need to exceed 0.4 Δk to be able to guarantee shutdown capability during whole reactor operation time.

2) The maximum relative pin power peaking is not need to exceed 1.5 because this value is safety limit of fuel melting accident in this study.

3) TRU amount is needed to be able to transmute two times than produced TRU amount in LWR because the transmutation plan using 4 PEACER-Park was set to be able to burn out the total TRU amounts produced from 20 PWR plants.

4) Proliferation resistance is better than commercial reactors or sodium cooled fast reactor.

As a core design analysis tool, TRANSX / DANTSYS / REBUS-3 code system was used in this study. TRANSX code converts cross-sections of MATXS format to a format for a discrete-ordinate code.[4] This new format is also considered with self-shielding effect, group collapsing, and region homogenization by TRANSX. DANTSYS code produces a region flux table for R-Z geometry by S_N method to adjust self-shielding and region homogenization effect.[5] Using the ISOTXS formatted cross-section, REBUS-3 solves a multi-group steady-state neutron diffusion equation in 2-D or 3-D geometries and also performs a fuel cycle analysis.[6] Master library is based on KAFAX-F22, which is collapsed in 80 neutron groups and 24 gamma groups by KAERI.[7] Additionally, three kinds of master library depend on JEFF and ENDF, JENDLE were rebuilt by adding omitted isotopes which were needed for exact transmutation calculation.

In order to evaluate the third criterion, two kinds of transmutation indices were used in this paper. In case of the support ratio (SR), transmutation speed is measured based on the ratio TRU destruction rate to TRU production rate in LWR. The calculated TRU transmutation rate is scaled linearly with the electrical power and cycle length of corresponding LWR. The other transmutation index is the effective fission half-life time(T_{EFHL}) and extended effective fission half-life time (T_{EX}). This value is defined for each isotope as half-life time which is required for reduction to a half of initial amount by fission of themselves and associate destruction of their daughters.

A PEACER-300 core design was evaluated by three indices for a different point a view – proliferation resistance. Bare critical mass (BCM), thermal generation rate (TG), and spontaneous neutron source rate (SNS) calculated by plutonium composition vectors were chosen to compare the characteristics of proliferation resistance. Larger index values of BCM, TG, SNS indicate that a spent fuel has better proliferation resistance.

3. Performance Check of Optimized Core

3.1 Safety Check

In order to assess the performance of optimized core, the equilibrium cycle behavior was determined using REBUS-3 code under the parametric study results. Fuel assembly consists of 17 x 17 arrays with 2.2 of pitch to diameter ratio. Fuel cycle strategy with a cycle length of 330 days and 3 batches is adopted. As LWR feed spent fuel composition, the PWR spent fuel after 30 year cooling is used. However, following several assumptions were made for simplification of calculation procedures. Fission products were grouped into four lumped fission products by originating fissiles. In constructing the burnup chains, actinides heavier than Cm-245 and lighter than Th-232 were ignored and a few reactions which has short half-life were omitted. For a equilibrium cycle, the excess reactivity was calculated by REBUS-3 and it was not exceed about 2.5% Δk at BOEC and 0.09% Δk at EOEC.

Table 1: Optimized Core Design Parameters

Core Design Parameter	
Power (MWe/MWt)	300 / 850
Cycle length (irrad./refuel.) (day)	330 / 35
Refueling batch	3
Active core height (cm)	50.0
Core equivalent diameter (cm)	365.4
Core materials (fuel/cladding)	(U,TRU)Zr / HT-9
Fuel pins / assembly (#)	280
Pitch to diameter	2.2
Fuel pellet diameter (cm)	0.548
Clad. Outer diameter/thickness (cm)	0.832 / 0.1
Enrichment (inner/middle/outer)	14.8 / 17.0 / 19.2
Burnup reactivity swing (%Δk)	2.41
Assembly power peaking	1.347

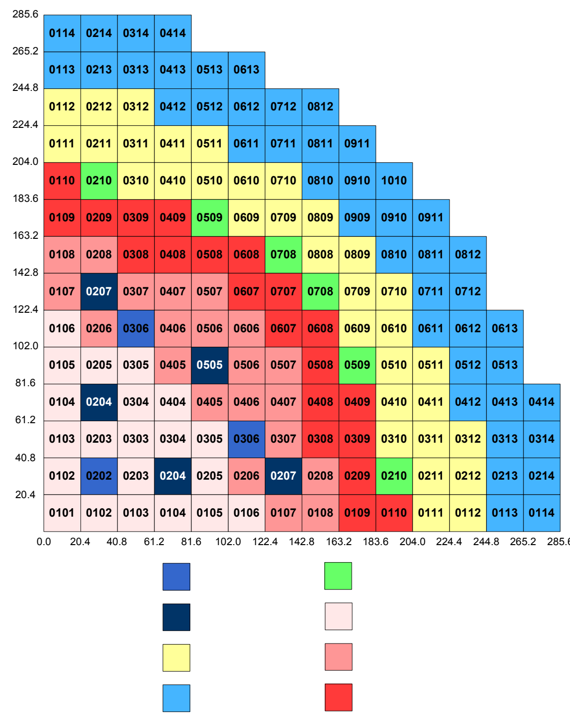

Figure 1: PEACER-300 Core Layout

Since REBUS-3 code is based on assembly-wise nodal calculation, maximum assembly peak power which is 1.347 in middle core at BOEC can be acquired. However, maximum pin power peaking is required for assessment of fuel centerline temperature and safety aspect. Therefore, Monte Carlo code – MCNP-4c which could describe pin configuration in detail was applied.[8] By MCNP-4c results, maximum pin power peaking was 1.421 at BOEC. For comparison with relative errors of assembly power between REBUS-3 and MCNP-4c, the MCNP-4c results were normalized by the summation of pin powers about each assembly. The difference of relative errors were lower than 5% and the position where had maximum power peaking was same, it was confirmed that the results of two codes showed good agreements.

A lot of neutron leakage by flat core shape of PEACER-300 should induce a large reactivity swing to satisfy fuel cycle length than tall core shape. The excess reactivity at BOEC has a large value of over 3% Δk. Therefore, the reservation of enough shutdown margin is one of major issues to design a PEACER core. In order to overcome this disadvantage, two kinds of shutdown system were proposed and evaluated.

Firstly, primary shutdown system was configured with 20 control assemblies with motor-driven control element driving mechanism. 8 control assemblies are located in inner core and 12 control assemblies located in middle core that give higher power generation was occurred relatively. Control assembly has a same configuration with fuel assembly to maintain thermal hydraulic condition and consists of 208 absorber rods and 81 structure rods. Absorber rods are sintered B_4C pellet with natural enrichment of B-10. Due to large core size, a lot of control assemblies were used to prevent local power peaking. However, the use of 20 control assemblies and natural enriched B_4C could be maintain a flat power distribution in operating control assemblies. When all control assemblies are inserted, reactivity of over 6,000 pcm can be restrained and subcriticality of under 0.98 can be maintain during the whole fuel cycle length.

Using a new driving concept by buoyancy force between heavy Pb-Bi coolant and light B_4C absorber, secondary shutdown system was developed with diversity and independency. 12 control assemblies are located under the core bottom in normal operation and they are inserted from bottom to core inside by emergency signal only. To get similar reactivity worth with primary shutdown system using less control assemblies, control assemblies are designed by 280 absorber rods with 40 w/o enriched B_4C and 9 structure rods

In order to check the inherent safety feature of PEACER-300 core, three kinds of reactivity coefficients were calculated as shown in table 2. Calculations were done for the reference states with DIF-3D.[9]

From DIF-3D calculation results, it was found that all temperature feedback coefficients were negative except coolant void coefficient which is not a crucial objective in lead-bismuth coolant reactor. However, the positive void coefficients could be compensated by the large negative effect by coolant expansion. A flat core which has a larger radial expansion coefficient has better inherent safety than a tall core. Additionally, the quantities of void coefficients are smaller than those of sodium cooled fast reactor due to its lower capture cross-section even though coolant voiding coefficients were all positive. The creation of voiding is impossible since the boiling temperature of Pb-Bi is 1,670°C which is higher 1,270°C than normal operation temperature.

Table 2: Reactivity Coefficient of PEACER300 Core

Parameters	PEACER-300
Doppler Coefficient ($d\rho/dT$)	-3.60×10^{-6}
Radial Expansion Coefficient (dk/K)/(R/dR) (pcm/%)	-733.91
Axial Expansion Coefficient (dk/K)/(H/dH) (pcm/%)	-106.84
Coolant Void Coefficient ($)	
10% voiding in active fuel region	+0.39
50% voiding in active fuel region	+1.97
100% voiding in active fuel region	+4.02
Total β_{eff}	0.00298
Total Control Rod Worth ($)	20.94

4.2 Proliferation Resistance Check

The parameters which determine an intrinsic proliferation resistance are a quantity and a quality of plutonium in a spent fuel. Therefore, several performance indices which were calculated by isotope fractions of plutonium were evaluated in this paper. In aspect of criticality and shielding of neutron and heat, three indices - BCM, SNS, TG - were proposed by Beller in LANL.[10] Bare Critical Mass(BCM) is defined a minimum plutonium mass which is able to make a bare critical sphere and calculated by MCNP. Spontaneous Neutron Source(SNS) means the emission rate of unit mass which was composed by plutonium fractions in spent fuel. The spontaneous fission might make the quality of nuclear weapon degrade and the treatment of spent fuel be difficult for the manufacture of nuclear weapon. Thermal Generation rate(TG) also means that the heat production rate per unit mass which is calculated by ORIGEN-2.[11] A large value of TG indicates the difficulty of weapon manufacturing due to the necessity of decay heat removal system in reprocessing plant.

Because the fuel cycle option of PEACER reactor is a recycling of spent fuel from both PWR and PEACER, the quality of plutonium in a PEACER spent fuel is degraded than other reactors. It was shown that PEACER had larger values in BCM, SNS and TG which means more favorable in proliferation resistance as shown in table 3.

Table 3: Comparison with indices in various reactor types

Proliferation Resistance Indices	Plutonium Grade		Reactor Type			
	W-Grade	R-Grade	PWR	CANDU	Na-LMR	PEACER
BCM(kg)	10.510	13.430	13.647	12.223	11.745	16.862
TG(W/BCM)	23.931	220.79	183.14	39.479	74.416	396.92
SNS(μBq/BCM)	1.1308	9.9557	8.6452	3.0349	4.1283	18.649

4.3 Transmutation Performance Check

A measurement of transmutation capability of long-lived minor actinide (LLMA) can not be simplified due to the complexity of depletion chain including successive fission and decay chains. Several approaches have been tried to quantify the transmutation of LLMA using the effective fission half-life time(T_{EFHL}) defined by Mukaiyama.[12] This value is obtained as half-life time which is required for reduction to a half of initial minor actinides amount by fission of themselves and their daughters. However, T_{EFHL} has disadvantage because only the ratio of fission cross-section to total cross-section was adopted in order to get the probability of fission reaction.

In order to overcome, the modification of T_{EFHL} to an extended effective fission half-life time(T_{EX}) was accomplished like following equation. The decay constant that has large effects on the fission probability of daughter nuclides was added.

$$T_{EX} = \frac{\ln 2}{\sigma_f^i \phi + \sum_j f_j \sigma_c^i \dfrac{\sigma_f^j \phi}{\sigma_t^j \phi + \lambda} \phi + \sum_k \lambda_i^{i \to k} \dfrac{\sigma_f^k \phi}{\sigma_t^k \phi + \lambda}}$$

Because T_{EX} values can be calculated by each LLMA isotopes, transmutation tendency of each LLMA was compared with various reactor types as shown in table 4. Fissile isotopes – Am-242m and Cm-243 can be burnt easily in thermal reactor by large fission cross-section. Therefore, T_{EX} values of these isotopes was very low than that of fast reactor systems. However, the performance of fast reactor system was superior than thermal reactor about the other isotopes because of smaller capture to fission ratio and higher neutron flux. In comparison with Na-LMR and PEACER, PEACER showed better performance by following two kinds reasons. First one is harder neutron spectrum by heavier coolant and bigger flux amount in core region is second reason to compensate a large neutron leakage.

Table 4. Comparison with isotopes in various reactor types

	Isotopes	Reactor Type			
		PWR	CANDU	Na-LMR	PEACER
T_{EX}(Year)	Np-237	28.29	41.22	10.30	7.85
	Am-241	4.85	1.68	17.48	14.19
	Am-242m	0.18	0.02	4.17	2.16
	Am-243	139.56	474.79	18.81	13.55
	Cm-242	4.46	4.73	0.62	0.62
	Cm-243	1.05	0.23	3.56	2.02
	Cm-244	44.16	49.06	9.42	7.91

5. Conclusion

In this paper, the performance of optimized PEACER-300 core which was decided previous study were evaluated in aspect of safety, transmutation and proliferation resistance. For verifying the safety of this core design, 4 kinds of factor – excess reactivity, maximum pin power peaking, shutdown margin and temperature coefficients - were calculated. Using Dy burnable poison, excess reactivity should be controlled under 2.5% Δk at BOEC. Pin power peaking could be reduced by 3 enrichment zoning. For diversity and independency of shutdown system, two kinds of shutdown system with different driving mechanism were designed and were satisfied with shutdown margin. A small positive coolant void coefficient might be compensated with a large negative expansion coefficient and negative Doppler coefficient.

In order to compare with proliferation resistance performance of PEACER-300, 3 kinds of indices – BCM, SNS and TG - were used. Because performance of proliferation resistance is dominated with plutonium isotope contents, PEACER-300 which could burn Pu fissile isotopes largely showed good proliferation resistance.

The major objective of this reactor is twice destruction rate of TRU than production rate of PWR. To satisfy this objective, support ratio was used in core design change and 2.085 of SR was achieved. As a different comparison method, extended effective fission half-life time was used and was compared with various reactor types. By flat core shape and Pb-Bi coolant, PEACER-300 could be acquired high neutron flux, hardened neutron spectrum and low capture to fission ratio. It leads smaller T_{EX} values of LLMA.

Acknowledgements

This work was financially supported by the Korean Ministry of Commerce, Industry and Energy and KEPRI (KEPCO Electric Power Research Institute) through the IERC program.

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