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Evaluation of Spent Fuel Properties from a Conceptual PEACER Core

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Abstract

In this paper, a new conceptual core design, PEACER was evaluated in aspect of core performance and spent fuel properties. The core shape is like a pancake to increase axial neutron leakage. Square lattice array was applied which was suitable to decrease the flow speed of Pb-Bi coolant. Although over 30% TRU produced by pyroprocessing was loaded in U-Zr metal fuel, the cycle length of 1 year was achieved and the relative assembly power peaking was less than 1.3. In order to confirm nuclear performance of PEACER core design, several performance indices were adopted and developed. Simple indices such as FIR and FG were used to evaluate fissile breeding. BCM, TG, SNS, and OR calculated by plutonium composition vectors were chosen to distinguish the competency of proliferation resistance. For the estimation of transmutation capability, D-value and extended effective fission half-life time(T_{EX}) were used. According to these indices, the PEACER core had the better performance compared with other conventional reactor cores although fissile breeding was not acquired.

1. Introduction

The lead cooled fast reactor concept named as PEACER (Proliferation-resistant, Environment-friendly, Accident-tolerant, Continuable-energy, and Economical Reactor) was proposed by NUTRECK (Nuclear Transmutation energy Research Center of Korea) in 1998 based on the unique combination of proven technologies.[1)] The design objectives of this reactor are similar to that of GEN-IV and AFCI such as burning minor actinides and a good proliferation resistance potential and so on. For achieving those objectives, PEACER was designed with following features. The rated thermal power is 1,560 MWt and the core is cooled with lead-bismuth (Pb-Bi) primary coolant. Compared with other Pb-Bi cooled fast reactor concepts, operating coolant temperature is low (about 300°C ~ 400°C) in order to achieve corrosion-resistance condition. It is aimed for a longer reactor life-time. The square lattice is also applied which make coolant flow area large for Pb-Bi coolant. 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. 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 PEACER park. When the fuel volume fraction and the core aspect ratio(L/D) is optimized, it is found that the transmutation capability of PEACER for long-lived wastes from LWR spent fuels can exceed their production rate of two LWR's each at the same electric rating. In contrast with current power reactor design principles, the lower power density and the higher neutron leakage rate lead to the higher performance on the proliferation-resistance, and transmutation capability using a pancake type core.

The purpose of this paper is a reassessment of early designed PEACER core in core design and spent fuel properties. Firstly, the general performance of PEACER core was analyzed by REBUS-3 code system. With REBUS-3 output data, many performance indices were evaluated for PEACER core. The comparison with other commercial reactors was also done to confirm the achievement of nuclear design goals of PEACER in fissile breeding, proliferation resistance and transmutation capability.

2. PEACER Core Analysis

2.1 Core Configuration

The special features of PEACER core are Pb-Bi metal alloy coolant of low operation temperature and pancake type core with square lattice array. The fuel assemblies were made of 14x14 fuel rods in a square lattice to get large P/D ratio. Open lattice and spacer grid were adopted in contrast with Na-cooled LMR. The fuel type was a U-Zr metallic alloy form, which contained TRU separated from the spent fuel of conventional PWRs. The average fractions of U-TRU-Zr fuel were 57.2%-31.9%-10.9%. For fuel swelling, the smear density of fuel rod was selected as 67%. Fuel pin geometry is very similar to PWR fuel rod with 11 mm diameter and 1 mm cladding thickness. In order to flatten radial power distribution, PEACER core had two enrichment zones. A low enrichment zone with 15 w/o U-235 is at the inner core and 17 w/o zone at the outer core. The core regions consisted of inner reflector, inner core, outer core, outer reflector and shield. A blanket was not included because the breeding is not desirable in transmuter. The core dimension was decided as 0.5 meter of height, 2.5 meter of radius like a pancake. A short and wide core shape reduced the total fuel volume fraction and increased the neutron leakage to prohibit the production of TRU due to neutron capture. In safety aspect, a lot of neutron steaming effect from pancake type core led to a negative void coefficient. The design parameters of PEACER core were summarized at Table 1.

2.2 Calculation Method and Result

As a core design analysis tool, TRANSX / DANTSYS / DIF-3D / REBUS-3 code system was used in this paper. TRANSX code converts cross-sections of MATXS format to a format for discrete-ordinate code(TWODANT) considered with self-shielding effect, group collapsing, and region homogenization. DANTSYS(TWODANT) code produces a region flux table for R-Z geometry by S_N method to adjust self-shielding and region homogenization effect. Using the ISOTXS formatted cross-section, DIF3D/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. Master library is the modified KAFAX-F22, which is collapsed in 80 neutron groups and 24 gamma groups using JEF-2.2 and NJOY94 by KAERI.[2)] In order to assess the core performance, the equilibrium cycle behavior was determined using REBUS-3 code with a cycle length of 330 days and EOC k-effective of 1.002 in equilibrium cycle condition. 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 external fuel cycle calculation, all actinide isotopes in the chain were assumed to be extracted 100% by pyro-processing and recycled in the reactor repeatedly.

For equilibrium cycle, the excess reactivity was calculated by REBUS-3 as shown in Fig. 1. The excess reactivity at BOC was too high as about 5% Δk to accommodate control devices. A reactivity control design should be done for the 2nd design phase.

In an equilibrium state, the transmutation capability of PEACER core was assessed by subtracting the amounts of TRU in a discharged fuel by the amount in a charged fuel. When one third of core fuel was discharged, 1.19 ton of heavy metal remained in spent fuel and total amount of TRU was 440 kg which was reduced from 521 kg TRU in a charged fuel as shown in Table 2.

As shown in Fig. 2, higher relative power peaks were founded in areas between the inner core and the outer core. However, it was found that maximum power peaking was less than 1.3 without any control devices. It is predicted that maximum power peaking is controllable by locating control assemblies beside the hottest assembly.

3. Fuel Performance Indices

3.1 Breeding

In this paper, a conversion capability was evaluated by applying simple indices - overall fissile inventory ratio (FIR) and fissile gain(FG).

$$\mathrm{FIR} = \frac{\text{Fissile fuel amount at the end of a refueling period}}{\text{Initial fissile amount}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

$$FG = \frac{\text{Discharged fissile amout - Feed fissile amout}}{\text{Feed fissile amount}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(2)$$

It is easy to calculate these values by comparing the different fissile inventories between the starting point and the ending point of a specified period. However, the nuclear characteristics of fissile materials can not be shown and the effect of parastic absorptions of TRU is not considered.

In order to estimate the breeding capability of PEACER core, the comparisons were carried out for different reactor type - PWR, CANDU and Na-LMR. Table 3 shows that the PEACER core has not a goal for breeding gain, but for high conversion.

3.2 Proliferation Resistance Potential

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.[3)] 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. A large value of TG indicates the difficulty of weapon manufacturing due to the necessity of decay heat removal system in reprocessing plant. In this paper, a simple proliferation resistance index - Odd Ratio(OR) was also calculated. It is a ratio of total mass of odd number nuclides to total mass of chosen nuclide. Therefore, a small value of OR shows a good proliferation resistance in contrast with BCM, SNS, and TG.

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 a larger values in BCM, SNS and TG and a smaller value in OR, which means more favorable in proliferation resistance as shown in Table 4.

3.3. Transmutation

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. In this paper, two kinds of indices were considered and modified for exact transmutation behavior about major LLMAs which have long half-life time and large radioactivity impact.

One of them is D-value defined by Salvatorez.[4)] This value means the required number of neutron consumption for transmutation up to the final state in decay chain specified by user as shown in Fig. 3.

$$D_J = \sum_{J1_j} P_{J \to J1_j} \{R_{J1_j} + \sum_{J2_k} P_{J1_j \to J2_k} \times [R_{J2_k} + \sum_{J3_n} P_{J2_k \to J3_n}(....)]\} \quad \cdots\cdots (3)$$

$$where, \quad P_{J,X} = \frac{\sigma_X \phi}{(\sigma_c + \sigma_f + \sigma_{2n})\phi + \lambda_d} \qquad (X = c, \quad f, \quad or \quad 2n)$$

$P_{J \to J1}$ means the probability of transmutation from J to J1 isotope and can be calculated by one group cross-section, decay constant and neutron flux. Parameter R is defined by the consumed number of neutrons depending on the reaction types, such as 1 for neutron capture, 0 for decay, 1-ν for fission and -1 for (n,2n) reaction.

As shown in Table 5, the evaluations of D-values were performed for various reactor types. Because D-value is the required number of neutron, low value has a good transmutation capability. Under the fast neutron spectrum condition, all D-values were negative and lower values than that of LWR. In case of fissile materials such as Am-242m and Cm-243, D-values of LWR were similar to FR's because of higher fission cross-section in thermal spectrum.

The other transmutation indices is the effective fission half-life time(T_{EFHL}) defined by Mukaiyama.[5)] 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, there were large disagreement in order between D-value and T_{EFHL} 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 update, the modification of T_{EFHL} to an extended effective fission half-life time(T_{EX}) was accomplished in this paper. The decay constant that has large effects on the fission probability of daughter nuclides was added as the following equation.

$$T_{EX} = \frac{\ln 2}{\sigma_f^i \phi + \sum_j f_j \sigma_c^i \frac{\sigma_f^j \phi}{\sigma_t^j \phi + \lambda} \phi + \sum_k \lambda_i^{i \to k} \frac{\sigma_f^k \phi}{\sigma_t^k \phi + \lambda}} \quad \cdots\cdots (4)$$

According to the calculated results of T_{EX}, there was a little disagreement with that of D-value. The reason of disagreement was a different view point of each index value. The concept of D-value is concerned with amount of neutrons and the deconstruction time is major point in T_{EX}. The results of T_{EX} about Am-242m and Cm-243 isotopes showed best transmutation capability in CADNU reactor condition. Although the D-value of CANDU - required neutrons for transmutation - was similar to that of other reactors, T_{EX} – required time for transmutation - had the lowest value owing to the highest fission cross-section of these isotopes in thermal spectrum. In order to verify the compatibility between D-value and T_{EX} by different way, the normalization was performed that the maximum value and minimum value of each index were set to the 1 and –1 and compared with each normalized values. As shown Fig. 4, although normalized values of each isotope were different, the tendency of transmutation capability agreed with each other.

Therefore, it could be verified that PEACER core had a good transmutation capability for isotopes which have long half-life time or high activity even though T_{EX} values of PEACER core were not the best value for all isotopes.

4. Conclusions

In this paper the possibility of PEACER core that had unique design parameter was estimated as a fast reactor core and the accomplishment of design objectives such as proliferation resistance and transmutation was distinguished by fuel performance indices. Using the REBUS code system, the neutonic characteristics of PEACER core were verified. Namely, excess reactivity was maintained for cycle length of 1 year and relative power distribution was less than 1.3. Through three kinds of indices, it showed that fissile breeding of PEACER core could not be achieved because of large neutron leakage without blanket. It was also found that PEACER core had higher proliferation resistance than other commercial reactors and very high transmutation capability.

A design optimization of the core for large excess reactivity control will be done in a near future with safety analysis.

Acknowledgements

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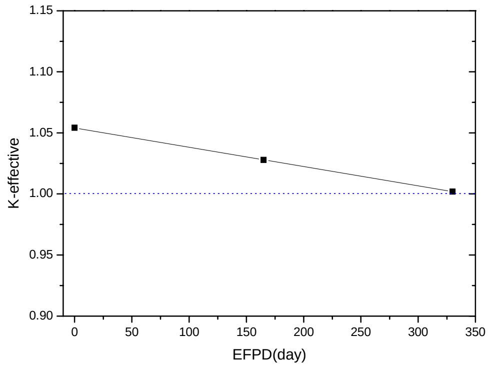

Fig. 1. Excess reactivity change of PEACER core

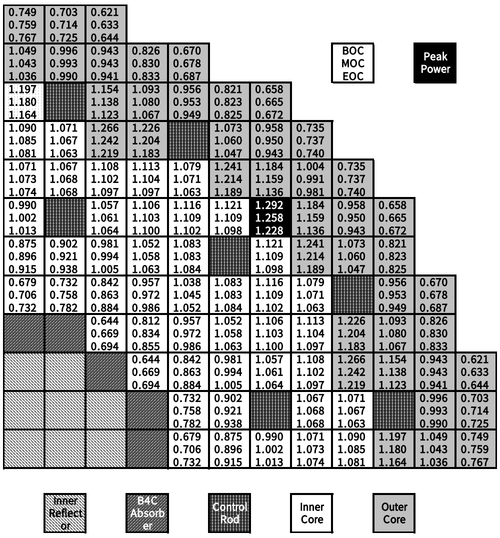

Fig. 2. Assembly power distribution in equilibrium state

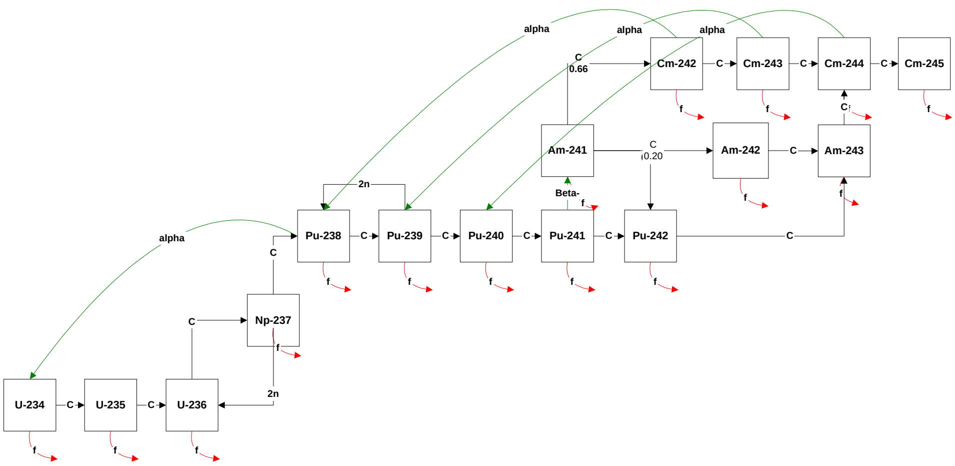

Fig. 3. User defined depletion chain for REBUS-3 calculation and transmutation indices

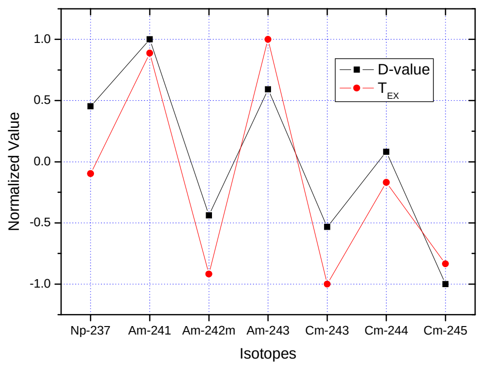

Fig. 4. Comparison with normalized D-value vs. T_{EX}

Table 1. Design parameters of PEACER core

Parameter	Values
Thermal Power	1,560 MWt
Electric Power	550 MWe
Thermal efficiency	35.3%
Coolant	Pb-Bi
Scram systems	B_4C control assembly
Effective Full Power Day	330 days
Cycle length	365 days
Capacity factor	90 %
Fuel composition	U-TRU-Zr (57.2-31.9-10.9)
Smeared density	67%
No. of enrichment zones	2
Cladding material	HT-9
Average power density	204.5 MW/m^3

Table 2. Initial actinides inventories and changes

Isotope	Heavy Metal Mass (kg)		
	Charged Fuel	Discharged Fuel after Cooling	Increased Mass
TH232	0.00	0.00	0.00
PA233	0.00	0.00	0.00
U-233	0.00	0.00	0.00
U-234	3.38	3.18	-0.20
U-235	1.88	1.41	-0.47
U-236	3.75	3.48	-0.27
U-238	799.76	744.22	-55.55
NP237	19.60	13.55	-6.05
PU238	16.74	15.12	-1.62
PU239	191.37	148.70	-42.67
PU240	177.19	159.13	-18.06
PU241	42.77	34.56	-8.21
PU242	46.83	43.97	-2.86
AM241	1.00	0.62	-0.39
AM242M	0.00	0.00	0.00
AM243	12.76	12.02	-0.73
CM242	0.01	0.01	0.00
CM243	0.01	0.01	0.00
CM244	9.83	10.14	0.31
CM245	1.89	1.87	-0.02
CM246	1.06	1.06	0.00

Table 3. Comparison of breeding performance

	PWR	CANDU	Na-LMR	PEACER
FIR	0.35	0.72	1.03	0.92
FG(%)	-64.61	-28.18	3.00	-8.00

Table 4. Comparison of proliferation resistance

	Weapon Grade	PWR	CANDU	Na-LMR	PEACER
BCM(kg)	10.51	13.88	12.22	12.02	36.76
SNS(Bq/kg)	52.9	258.2	167.9	183.0	439.1
TG(W/kg)	2.22	12.86	3.23	6.35	23.21
OR	0.999	0.692	0.726	0.787	0.457

Table 5. Comparison of transmutation – D-value

	PWR	CANDU	Na-LMR	PEACER	
			Driver	Inner	Outer
FLUX	2.99E+14	2.32E+14	18.94E+14	31.92E+14	27.45E+14
Np-237	0.86	0.89	-0.82	-0.72	-0.79
Am-241	0.54	0.31	-0.74	-0.75	-0.85
Am-242m	-1.91	-1.92	-1.93	-2.08	-2.17
Am-243	-0.45	-0.36	-0.86	-0.98	-1.07
Cm-242	-0.15	-0.54	-1.31	-1.23	-1.27
Cm-243	-2.16	-2.26	-2.26	-2.26	-2.33
Cm-244	-1.14	-1.34	-1.60	-1.67	-1.74

Table 6. Comparison of transmutation – T_{EX}(Year)

	PWR	CANDU	Na-LMR	PEACER	
			Driver	Inner	Outer
FLUX	2.99E+14	2.32E+14	18.94E+14	31.92E+14	27.45E+14
Np-237	28.29	41.22	10.30	6.02	7.04
Am-241	4.85	1.68	17.48	10.34	11.75
Am-242m	0.18	0.02	4.17	2.51	2.00
Am-243	139.56	474.79	18.81	12.66	15.11
Cm-242	4.46	4.73	0.62	0.64	0.64
Cm-243	1.05	0.23	3.56	2.21	1.87
Cm-244	44.16	49.06	9.42	6.18	7.21