PERFORMANCE EVALUATION OF A PB-BI COOLED FAST REACTOR, PEACER-300

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1. Introduction

Many concepts of reactor and fuel cycle are proposed to decrease the production of high radioactive nuclear wastes and satisfy the future demand of electricity like concepts in AFCI and GEN IV. Major goals of AFCI are the reduction of spent fuel volume and the separation of long-lived, highly toxic isotopes that present the most difficult disposition challenge. The objectives of GEN IV reactors are the improvement of reactor safety and reliability, proliferation resistance, economics and sustainability. In order to design a power plant with purposes above mentioned, lead-bismuth cooled fast reactor(LFR) 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).[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. 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 PEACER power plant and reprocessing plant in same site. According to the control and observation about all material produced in PEACER-Park, any kinds of fuel and residual material should 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 which should be satisfied with Korean regulation is disposed in the repository located in near of PEACER-Park.

Several research teams were composed about neutronics, thermal hydraulics, pyro-processing, 3-dimensional visualization, materials and waste disposal in NUTRECK. After neutronics calculation was preceded, the results were provided to the teams of thermal hydraulics, pyro-processing and waste disposal. 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. Those were the use of Pb-Bi metal alloy coolant at a low operation temperature band, the use of square lattice 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 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 by CFX code and stress analysis by ANSYS code.[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 $\Delta k$ 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 10 PWR plants.
4) Proliferation resistance of PEACER-Park is better than commercial reactor site 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 ($T_{\text{EFF}}$) and extended effective fission half-life time ($T_{\text{EX}}$). 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. Fuel cycle strategy of PEACER is based on multi-recycling to burn LLMA and LLFP. Therefore, the most of high activity materials are reloaded into a core repeatedly and unrecovered actinides and fission products in pyroprocessing process are only disposed. Since the radiotoxicity of tailed material is important to a disposal site design and vitrified waste, the radioactivity of PEACER spent fuel and tailed material are calculated by ORIGEN-2.[8]

3. Performance check of optimized core

3.1 Safety evaluation

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
confirmed that the results of two codes showed good agreements. The MCNPV4c results were normalized by the summation of pin powers about each assembly. The difference was 1.42 at BOEC. For comparison with relative errors of assembly power between REBUSV3 and MCNPV4c, could describe pin configuration in detail was applied.[9] By MCNPV4c results, maximum pin power peaking is 1.347 in middle core at BOEC can be acquired. However, maximum pin power peaking is required for core materials (fuel/cladding) (U,TRU)Zr/HTV Clad. Outer diameter/thickness 0.832/0.1

| Enrichment (inner/middle/outer) | 14.8/17.0/19.2 |
| Assembly power peaking | 1.347 |

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.[9] 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% $\Delta k$. 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$_4$C 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$_4$C 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$_4$C 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$_4$C 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.[10]

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>
<thead>
<tr>
<th>Parameters</th>
<th>PEACER-300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doppler Coefficient (dp/dT)</td>
<td>-3.60 x 10^6</td>
</tr>
<tr>
<td>Radial Expansion Coefficient (dk/K)/(R/dR) (pcm/%)</td>
<td>-733.91</td>
</tr>
<tr>
<td>Axial Expansion Coefficient (dk/K)/(H/dH) (pcm/%)</td>
<td>-106.84</td>
</tr>
<tr>
<td>Coolant Void Coefficient ($)</td>
<td></td>
</tr>
<tr>
<td>10% voiding in active fuel region</td>
<td>+0.39</td>
</tr>
<tr>
<td>50% voiding in active fuel region</td>
<td>+1.97</td>
</tr>
<tr>
<td>100% voiding in active fuel region</td>
<td>+4.02</td>
</tr>
<tr>
<td>Total $\beta_{eff}$</td>
<td>0.00298</td>
</tr>
<tr>
<td>Total Control Rod Worth ($)</td>
<td>20.94</td>
</tr>
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</table>

### 4.2 Proliferation resistance evaluation

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.[11] 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.

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.

### 4.3 Transmutation performance evaluation

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 1. The decay constant that has large effects on the fission probability of daughter nuclides was added.

$$T_{EX} = \frac{\ln 2}{\sigma_f^r/\phi + \sum_j f_j \sigma_f^j/\phi + \sum_k \sigma_f^k/\phi + \lambda}$$

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. $T_{EX}$ Comparison with isotopes in various reactor types**

<table>
<thead>
<tr>
<th>Isotopes</th>
<th>Reactor Type</th>
<th>PWR</th>
<th>CANDU</th>
<th>Na-LMR</th>
<th>PEACER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Np-237</td>
<td>28.29</td>
<td>41.22</td>
<td>10.30</td>
<td>7.85</td>
<td></td>
</tr>
<tr>
<td>Am-241</td>
<td>4.85</td>
<td>1.68</td>
<td>17.48</td>
<td>14.19</td>
<td></td>
</tr>
<tr>
<td>Am-242m</td>
<td>0.18</td>
<td>0.02</td>
<td>4.17</td>
<td>2.16</td>
<td></td>
</tr>
<tr>
<td>Am-243</td>
<td>139.56</td>
<td>474.79</td>
<td>18.81</td>
<td>13.55</td>
<td></td>
</tr>
<tr>
<td>Cm-242</td>
<td>4.46</td>
<td>4.73</td>
<td>0.62</td>
<td>0.62</td>
<td></td>
</tr>
<tr>
<td>Cm-243</td>
<td>1.05</td>
<td>0.23</td>
<td>3.56</td>
<td>2.02</td>
<td></td>
</tr>
<tr>
<td>Cm-244</td>
<td>44.16</td>
<td>49.06</td>
<td>9.42</td>
<td>7.91</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 2. Radioactivity change of discharged fuel**

4.4 Radiotoxicity evaluation

In order to increase the transmutation rate, PEACER was designed with high TRU loading. However, it might also be increased the remained TRU amount in spent fuel even though the TRU transmutation amount can be increased. It caused the radioactivity of PEACER spent fuel to be larger than that of general SFR. That is against one of PEACER objective which is keeping the quality of waste under low level waste. To overcome disadvantage, ideal decontamination factors (DF) which have around 10 for F.P. and $10^4$ for Actinide are adopted in pyroprocess.[13]

After reprocessing with these DFs, only 7.6 % of spent fuel mass was disposed and the radioactivity of unrecovered material could be reduced in inverse proportion. However, because most of actinides in discharged fuel are recycled, high radioactive recycled actinides might be a burden to radioactivity shielding in reprocessing process.

Figure 2 is the time-dependent radioactivity changes of actinides which delivered to reprocessing plant. The most of total radioactivity is depend on plutonium and curium isotopes. Fortunately, these isotopes are alpha particle emitter and a few percent of gamma-ray are produced in same time. Therefore, it is expect that the sustainability of reprocessing plant can be maintained for lifetime because the radioactivity of fission products is similar to that of SFR and shielding about increased gamma-ray is considered.
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

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References