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# A Core Design for a Single Fuel Enrichment in a Self-Sustaining Lead-Cooled Reactor

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Reactor physics studies have been done to achieve single fuel enrichment (SFE) in a 900 MWth lead-cooled breakeven reactor with a burnup reactivity swing smaller than the $\beta_{eff}$ value. For the single fuel enrichment in an identical fuel rod type, new fuel assembly designs have been introduced: a combination of $B_4C$ burnable absorber rods, neutron streaming tubes, and moderator rods are utilized to control power distribution. The burnable absorber rods are designed to have top and bottom cutback regions to reduce the peak fast fluence and enhance overall boron depletion rate. An 18-month cycle core has been designed and its various physics characteristics are analyzed. Additionally, subchannel thermal-hydraulic analyses have been performed for the peak power assembly.

***KEYWORDS: lead-cooled reactor, breakeven, single fuel enrichment (SFE), burnable absorber, neutron streaming tube, moderator rod, cutback***

## 1. Introduction

For the sustainable nuclear energy development, it is well perceived that fast spectrum reactors should play an important role. Recently, lead- or lead-alloy-cooled fast reactors have been actively studied worldwide due to their potential advantages over the conventional sodium coolant. Nowadays, fast reactors are not required to breed fissile materials such as Pu-239. Instead, studies are mainly focused on the breakeven self-sustaining reactors or transmutation of radioactive nuclides. This paper is concerned with core physics studies of a lead-cooled breakeven reactor.

In the conventional fast reactor design, the reactor core is divided into a few zones and the fuel enrichment is adjusted in each zone to control the power distribution. The zone-wise different enrichment leads to a zone-wise different conversion ratio. Consequently, the fissile elements generally need to be separated from the discharged fuel and this makes the related fuel cycle costly and susceptible to the proliferation concern. Also, in this fuel cycle, fabrication and management of fuel are quite complicated and costly, hampering the competitiveness of fast reactors.

In the Russian BREST[1] breakeven reactor using a nitride fuel, a single fuel enrichment (SFE) concept was adopted in order to mitigate the above-mentioned problems resulting from the conventional zone-dependent fuel enrichment. For the SFE, zone-dependent fuel rod diameters were used in the BREST design: the core was partitioned into 3 zones and a different rod diameter with a different pitch-to-diameter (P/D) ratio was adopted in each zone. It was shown that the core provides a good neutronic performance. However, the

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design is subject to a complicated coolant flow pattern and also, three types of fuel rods are required in the core.

In this paper, new design measures have been studied to achieve a single fuel enrichment (SFE) in a lead-cooled breakeven reactor with a burnup reactivity swing smaller than the $\beta_{eff}$ value, in which depleted uranium is only fed. In a previous work, we have introduced burnable absorbers (BA) and neutron streaming tubes (NSTs) to design a lead-cooled reactor with the SFE based on an identical rod type.[2] In this paper, a detailed evaluation of the concept is provided for a modified core design and another SFE scheme of using BA and moderator rods is proposed, too.

## 2. Reference Core Design

In this paper, a 900 MWth lead-cooled reactor is considered. The reference reactor core is divided into 3 zones of different enrichments: inner core (IC), middle core (MC), and outer core (OC), as shown in Fig. 1. No blanket assemblies are loaded to exclude production of weapon-grade plutonium. The core is comprised of 192 ductless hexagonal fuel assemblies containing 204 fuel rods and 13 tie rods (TRs) for grid spacers. Locations of TRs are symmetrical and 6 hexagonal corner points are occupied by TRs due to small coolant flow rate there. Fuel is the conventional metallic alloy of U-TRU-10Zr with a lead bonding. Unlike the fuel assemblies, the reflector and shield assemblies have a duct to control the coolant flow rate in the non-active zone. The reflector material is lead and a steel shield is utilized in the design. A large gas plenum and an HT9 shield are placed above and below the active core, respectively. The core is equipped with two sets of control rods and the shutdown rods are placed in the reflector zone. In the control and shutdown systems, a 90%-enriched $B_4C$ is utilized as absorber.

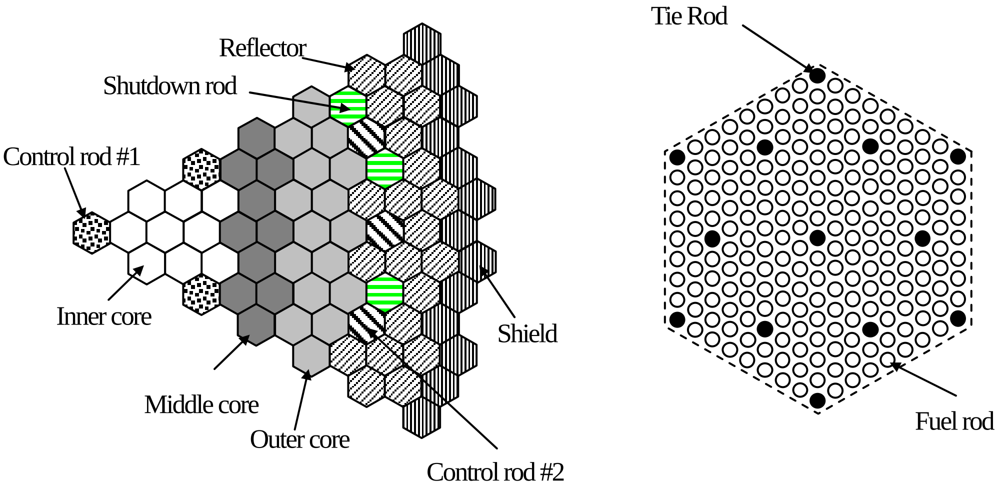

Fig. 1 Configurations of core and ductless fuel assembly

Accounting for the relatively small void reactivity and the high boiling temperature of the lead coolant, the height of the active core is determined to be 124 cm. In general, the maximum permissible coolant speed is known to be about 2 m/sec due to the corrosion and erosion effects of lead. Consequently, a relatively open lattice is used in the core: the pitch-to-diameter (P/D) ratio of fuel rods is 1.41 in the fuel assembly. The coolant inlet temperature is set at 420 °C since the melting temperature of lead is high (327 °C), and the coolant outlet temperature is 540 °C, resulting in ~1.67 m/sec average coolant speed. Design data for the fuel assembly are given in Table 1.

Since a breakeven core produces self-sufficient fissile materials, only depleted uranium is fed to the core. Figure 2 shows the schematic concept of the fuel cycle in this work. The spent fuel is reprocessed by a pyrotechnology which is considered to be proliferation-resistant and economically competitive. It is worthwhile to note that, in the closed fuel cycle, the transuranics (TRU) are not separated from the spent fuel. The fission products are only removed from the spent fuel and all the remaining actinides are recycled into the core in a single stream. Among the fission products, it is assumed that only 95% of the rare earth (RE) elements are removed from the spent fuel. The remaining RE elements are recycled into the core. The recovery factor for actinides is assumed to be 99.9% in the reprocessing.

**Table 1** Ductless fuel assembly design (reference design)

| | |
|---|---|
| Cladding and TR material | HT9 |
| No. of fuel pins | 204 |
| No. of TRs | 13 |
| Pin diameter, cm | 0.88 |
| Cladding thickness, cm | 0.057 |
| P/D ratio | 1.41 |
| Diameter of TR, cm | 0.96 |
| Tube thickness of TR, cm | 0.13 |
| Active length, cm | 124 |
| Interassembly gap, cm | 0.32 |
| Assembly pitch, cm | 18.393 |

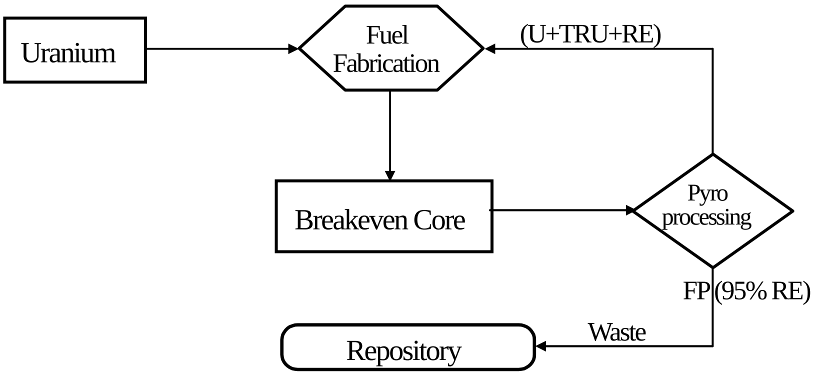

Fig. 2 Concept of fuel cycle for SFE breakeven core

All the neutronic analyses have been done with the REBUS-3[3]/DIF3D[4] code system and the ENDF-B/VI cross section data. In the DIF3D calculations, a diffusion nodal option is used with 9-group cross sections. The multi-group cross sections are obtained with the TRANSX[5]/ TWODANT[6] codes.

## 3. Design Concepts for Single Fuel Enrichment

In nuclear reactors loaded with identical fuel assemblies throughout the core, the power peaking is unacceptably high in the core center. It is required to suppress the power in the central region for a reasonable power distribution. There are several ways for the SFE in lead-cooled reactors and they could be categorized into two groups, one is using several types of fuel rods and the other is with an identical fuel rod. The BREST concept corresponds to the former. From the viewpoint of fuel fabrication, a single rod type concept would be preferable, thus we focus on the latter concept in this study.

Two methods have been considered for the SFE: a burnable absorber (BA) inside the TRs and replacing some fuel rods with a neutron streaming tube (NST). In the BA approach, a $B_4C$ absorber is loaded into the TRs in the inner and (or) middle cores. The BA option provides a relatively short cycle length due to the relatively poor neutron economy. It makes the coolant void reactivity less favorable since the neutron absorbing power of $B_4C$ is reduced when neutron spectrum is hardened. Meanwhile, in the NST option, some fuel rods are replaced by empty tubes, so it is very simple and easy to implement. A potential advantage of this scheme is that it may reduce the coolant void reactivity due to the enhanced neutron leakage. However, it is subject to several drawbacks such as an increased linear power and higher fast neutron fluence.

To make best use of the two concepts, they have been combined in the following way. In the inner core, the $B_4C$ BA is loaded into TRs and 24 NSTs are placed and 15 NSTs are only applied to the middle core without BAs, and the standard fuel assemblies (no NSTs and no BAs) are loaded in the outer core. Fuel assemblies for the inner and middle cores are depicted in Fig. 3. It is worthwhile to note that top/bottom cutback zones are applied to the absorber rods to reduce the fast neutron fluence, which is a limiting design constraint in a lead-cooled reactor with a hard neutron spectrum. The BA rod with cutbacks also enhances the depletion rate of $B_4C$. Outer diameter of NST is the same as that of TR. However, the tube thickness of NST is 0.057 cm as in fuel rods.

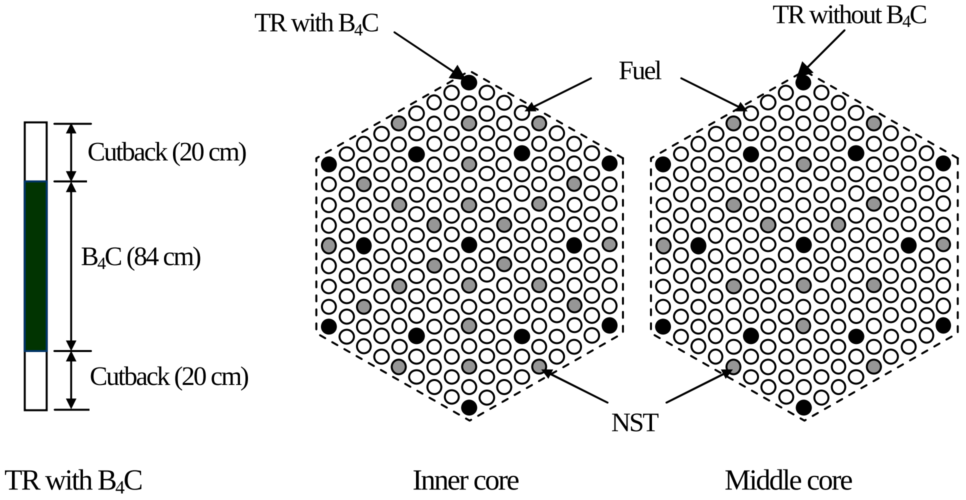

Fig. 3 Configurations of fuel assemblies for single fuel enrichment

In the design with the BAs and NSTs, we have found that the zone-wise conversion ratios (CRs) are slightly different: CRs in the inner and middle cores are slightly lower than that of the outer core due to the presence of the $B_4C$ absorbers. In an SFE core, it is desirable that the CR values are constant throughout the whole core such that a discharged fuel might be reprocessed independently regardless of its origin. To resolve this problem, a variant of the above SFE concept is also considered: NSTs in the inner and middle cores are simply replaced by moderator (graphite) rods. Actually, 24 moderator rods per assembly are introduced in the inner and middle cores. Note that 9 TRs per assembly are filled with a moderator in the middle core since a middle core assembly has only 15 NSTs. The volumetric fraction of the graphite moderator in an assembly is only about 3.0%. Another purpose of the moderator is to mitigate the less favorable coolant void reactivity caused by the $B_4C$ BA.

## 4. Core Characteristics

With the aforementioned design concepts, an 18-month-cycle core has been designed to have 492 effective full power days. The scattered reloading scheme is used in a 4-batch fuel management in each zone. A 47%-enriched $B_4C$ is loaded into TRs in the inner core. For the two SFE cores, the REBUS-3/DIF3D equilibrium cycle analyses have been performed. In addition, for a comparison purpose, a reference core design was also done with the conventional enrichment splitting scheme. Table 2 shows major neutronic parameters of equilibrium cycles of the three cores. The breakeven condition was determined by adjusting the fuel smear density in each core.

**Table 2** Equilibrium cycle performance of the breakeven cores

| Parameter | | Conventional | With BA & NST | With BA and Mod. |
|---|---|---|---|---|
| Fuel composition (U/TRU/Zr), w/o | | 80.0/10.0/10.0 1)<br>77.4/12.6/10.0 2)<br>75.3/14.7/10.0 3) | 77.0/12.9/10.0 | 76.6/13.4/10.0 |
| Active core height, cm | | 124 | 124 | 124 |
| Effective full power day (EFPD) | | 492 | 492 | 492 |
| Fuel smear density, % | | 63.25 | 74.15 | 74.63 |
| Core conversion ratio | | 1.005 | 1.004 | 1.004 |
| Zone-wise conversion ratio (IC/MC/OC) | BOC | 1.203/1.014/0.907 | 1.000/1.003/1.027 | 1.014/1.011/1.013 |
| | EOC | 1.123/0.990/0.907 | 0.984/0.984/1.008 | 0.995/0.991/0.997 |
| Reactivity swing, pcm | | 90 | 178 | 223 |
| $\beta_{eff}$, neutron generation time, μsec | | 0.00342, 0.60 | 0.00338, 0.54 | 0.00337, 0.54 |
| Core-average power density, kW/l | | 133 | 133 | 133 |
| Average linear power, W/cm | | 191 | 197 | 197 |
| Power peaking factor (BOC/EOC) | | 1.47/1.48 | 1.42/1.40 | 1.44/1.41 |
| Average fuel discharge burnup, a/o | | 9.25 | 8.30 | 8.25 |
| Peak fast fluence (>0.1MeV), n/cm$^2$ | | $4.65\times10^{23}$ | $3.96\times10^{23}$ | $3.68\times10^{23}$ |
| BOC B-10 inventory, kg | | --- | 8.3 | 8.1 |
| B-10 discharge burnup, a/o | | --- | 61.1 | 61.7 |
| Heavy metal inventory (BOC/EOC), Kg | | 19,047/18,591 | 21,312/20,856 | 21,455/20,999 |
| Active core void reactivity, pcm | | 2,788 | 3,312 | 3,286 |

1) Inner Core, 2) Middle Core, 3) Outer Core

The cycle-averaged CRs are slightly larger than unity for the three cores to compensate for the loss in reprocessing. Table 2 shows that the CR values are significantly different in the three zones for the conventional design. On the other hand, the CRs in the three zones are quite similar in the SFE core with BAs and NSTs. Furthermore, the SFE concept using both BA and moderator provides almost identical CRs for the three zones. Consequently, the fissile inventory in each zone is well balanced in the BA and moderator case, as shown in Table 3. Fig. 4 compares the 9-group neutron spectrums of the three cores. Note that neutron energy decreases with the group index. One can see that introduction of the graphite moderator softened the spectrum marginally. As a result, its impacts on the TRU vectors and local power peakings are negligibly small. Figures 5 and 6 indicate that the discharged fuels have very similar TRU compositions regardless of their origin for the two SFE cores. Regarding the fuel composition, the core with moderator shows a slightly higher minor actinide accumulation due to the softened spectrum.

**Table 3** Fissile mass in the breakeven cores (kg)

| BA & NST | | | | |
|---|---|---|---|---|
| | IC | MC | OC | Total |
| BOC | 504.948 | 595.518 | 1074.084 | 2174.544 |
| EOC | 503.790 | 594.216 | 1077.060 | 2175.126 |
| BA & Mod. | | | | |
| | IC | MC | OC | Total |
| BOC | 521.742 | 614.232 | 1099.830 | 2235.798 |
| EOC | 522.054 | 613.992 | 1100.400 | 2236.434 |

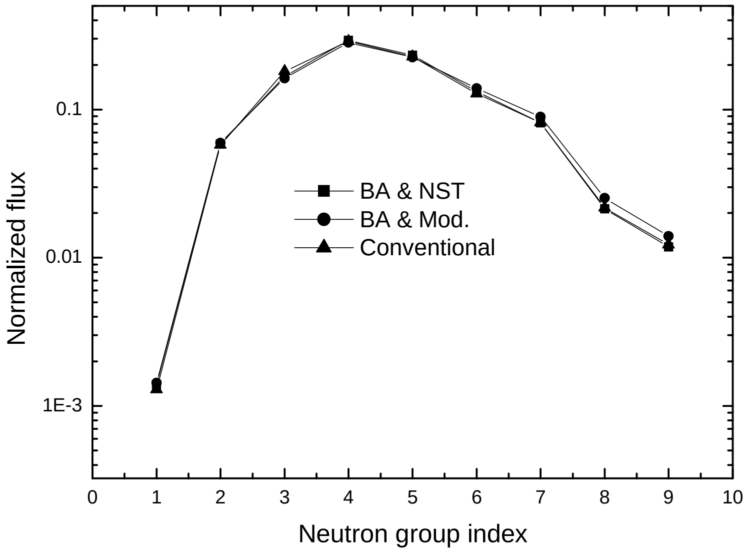

Fig. 4 Comparison of neutron spectrums in the cores

The burnup reactivity change over a cycle is significantly smaller than $\beta_{eff}$ in the three designs. Consequently, it is very unlikely that a malfunction of the control system will lead to a power excursion accident (prompt critical accident) in the cores. The conventional design has the smallest reactivity swing and the moderator-containing core reveals the largest value. This is because depletion of $B_4C$ results in an increase of the reactivity in the SFE cores and the $B_4C$ depletion rate is a little faster in the core with moderator. The evolutions of k-eff over a cycle are shown in Fig. 7. The k-eff value monotonically increases with time in the two SFE cores, while the conventional core has a maximum k-eff in the middle of cycle.

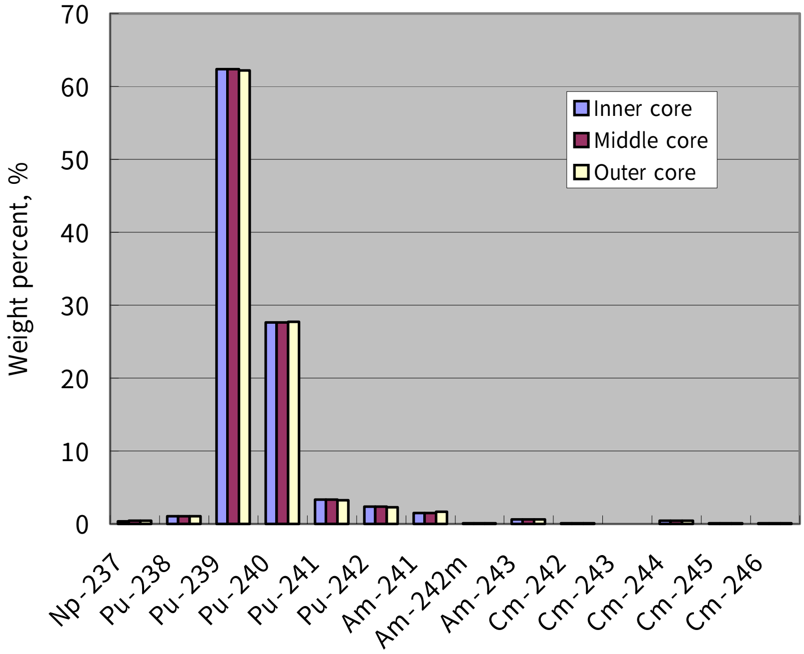

Fig. 5 Compositions of discharged fuels for the core with BA & NST

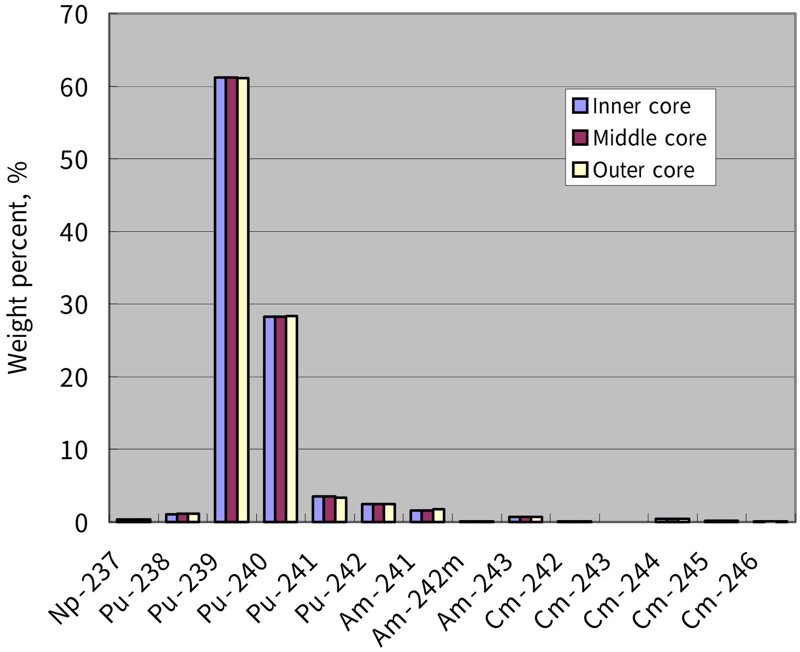

Fig. 6 Compositions of discharged fuels for the core with BA & Moderator

Fraction of the delayed neutrons is quite comparable for the three cores. It is noteworthy that the neutron generation time is a little shorter in the SFE cores than in the conventional core. This is because of the neutron absorption in the $B_4C$ BA.

The peak fast neutron fluences in the new SFE designs satisfy the generic design limit of $4.0 \times 10^{23}$ n/cm$^2$ for the HT-9 steel, while the conventional core design violates the fluence limit. The reduced fast neutron fluence in the SFE cores is first attributed to the BA rods with top and bottom cutback. A BA rod without top/bottom cutbacks cannot effectively reduce the fast fluence. It is noted that the fast fluence is further reduced in the moderator-loaded core due to the softened neutron spectrum.

Table 2 indicates that TRU fraction in the metallic fuel is less than 14%. In Table 4, the fuel compositions are provided for the SFE cores. From Table 4, it is observed that the minor actinide fraction is quite small (less than 1%) in the two cases. Thus, it is expected that the conventional metallic fuel technologies could be applied to the SFE cores. However, compatibility between the fuel and bonding material (Pb) needs to be investigated. It is shown that fuel inventories in the SFE cores are slightly larger than that of the conventional core. The increased fuel inventory in the SFE cores is mainly attributed to the introduction of the $B_4C$ absorbers. Consequently, the fuel discharge burnup is also decreased a little in the SFE cores. In general, the depletion rate of $B_4C$ is quite slow in fast reactors. Consequently, the discharge burnup of the B-10 isotope is about 61% in spite of the long residence time (about 5.4 years). Table 2 indicates that introduction of the $B_4C$ BA make the core void reactivity less favorable. This is because the neutron absorption of the BA is reduced when the spectrum is hardened. It is worthwhile to note that the moderator-containing SFE core shows a smaller coolant void reactivity compared with the BA and NST case. In the three cores, the active core height is larger than those of the conventional fast reactors, resulting in a relatively large coolant void reactivity. However, taking into account the high boiling temperature of the lead coolant, we think that the coolant void reactivity would not be a big concern in the three designs.

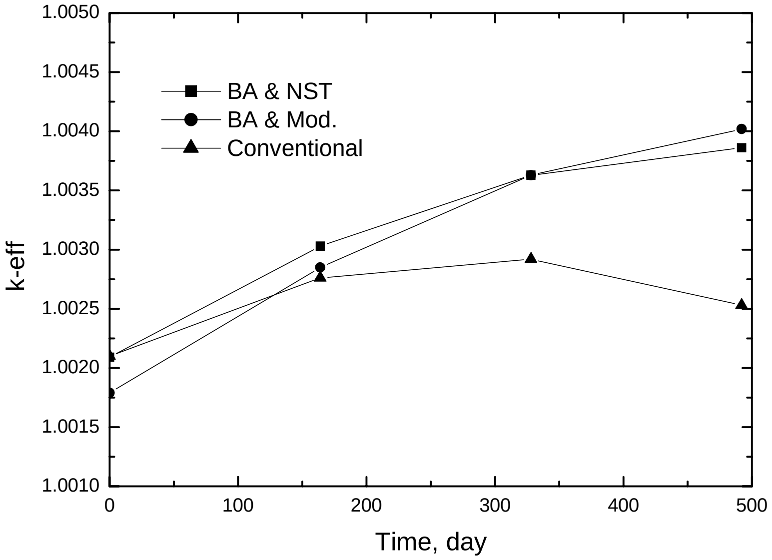

Fig. 7 Evolution of the effective multiplication factors

**Table 4** Fuel compositions (w/o) in an equilibrium cycle

| Isotope | Feed | Charge | | Discharge | |
|---|---|---|---|---|---|
| | | BA & NST | BA & Mod. | BA & NST | BA & Mod. |
| U-234 | -- | 2.714E–2 | 3.010E–2 | 2.507E–2 | 2.783E–2 |
| U-235 | 0.2 | 3.801E–2 | 3.890E–2 | 2.104E–2 | 2.203E–2 |
| U-236 | -- | 4.504E–2 | 4.705E–2 | 4.436E–2 | 4.633E–2 |
| U-238 | 99.8 | 8.542E+1 | 8.491E+1 | 7.710E+1 | 7.664E+1 |
| Np-237 | -- | 5.769E–2 | 5.829E–2 | 5.706E–2 | 5.761E–2 |
| Pu-238 | -- | 1.587E–1 | 1.730E–1 | 1.523E–1 | 1.661E–1 |
| Pu-239 | -- | 8.969E+0 | 9.113E+0 | 8.975E+0 | 9.120E+0 |
| Pu-240 | -- | 3.986E+0 | 4.220E+0 | 3.986E+0 | 4.219E+0 |
| Pu-241 | -- | 4.345E–1 | 4.694E–1 | 4.714E–1 | 5.093E–1 |
| Pu-242 | -- | 3.331E–1 | 3.656E–1 | 3.333E–1 | 3.659E–1 |
| Am-241 | -- | 2.641E–1 | 2.857E–1 | 2.284E–1 | 2.472E–1 |
| Am-242m | -- | 1.680E–2 | 1.837E–2 | 1.694E–2 | 1.853E–2 |
| Am-243 | -- | 8.864E–2 | 9.884E–2 | 8.872E–2 | 9.893E–2 |
| Cm-242 | -- | 6.881E–4 | 7.478E–4 | 9.332E–3 | 1.014E–2 |
| Cm-243 | -- | 6.395E–4 | 7.320E–4 | 6.671E–4 | 7.637E–4 |
| Cm-244 | -- | 5.650E–2 | 6.410E–2 | 6.037E–2 | 6.849E–2 |
| Cm-245 | -- | 1.790E–2 | 2.045E–2 | 1.792E–2 | 2.047E–2 |
| Cm-246 | -- | 1.077E–2 | 1.255E–2 | 1.078E–2 | 1.256E–2 |
| RE | -- | 7.790E–2 | 6.756E–2 | 1.558E+0 | 1.546E+0 |
| FP* | -- | 0.0 | 0.0 | 6.842E+0 | 6.795E+0 |

* without RE

In Figs. 8 and 9, planar and axial power distributions are given for the SFE cores. It is noted that the assembly power distributions show small changes over the long depletion period. The relatively large change in the inner core is due to the depletion of the BA. From the figures, one can clearly see that the axial power peaking is substantially reduced in the inner core because of the $B_4C$ BA with cutbacks. This results in a reduced fast neutron fluence in the inner core where the peak fast fluence usually occurs in fast reactors.

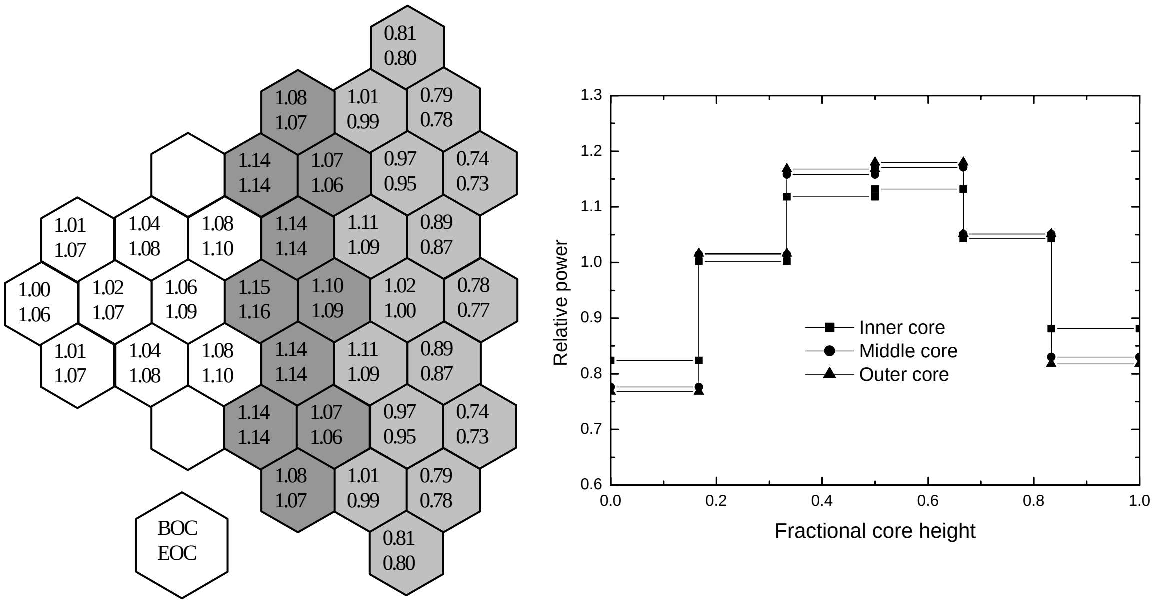

Fig. 8 Planar and axial power distributions in core with BA and NST

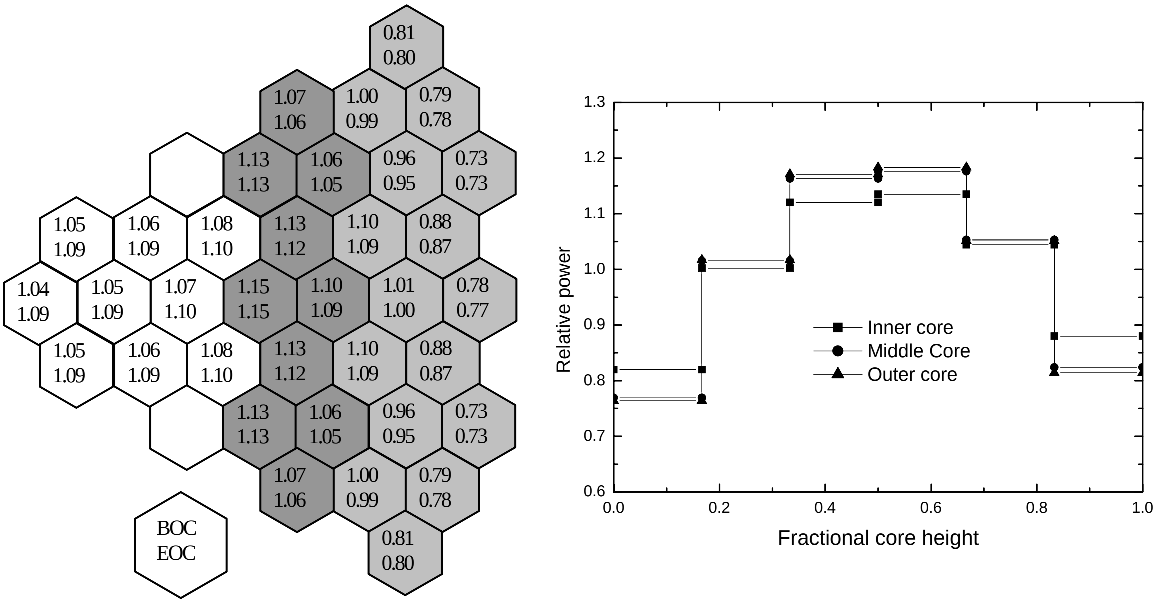

Fig. 9 Planar and axial power distributions in core with BA and moderator

A preliminary subchannel thermal-hydraulic (TH) analysis was performed with the MATRA[7] code for the peak power assembly in each zone and the results are shown in Table 5. The results in Table 5 are for the breakeven core with BA and graphite moderator. In the case of BA and NST, the peak assembly powers turned out to be a little smaller than those in Table 5. In the current TH analysis, it was assumed that the coolant flow rate was uniformly distributed over all the assemblies. It is observed that the peak temperature of cladding outer surface is 603 °C in the core design. It is expected that the peak temperatures could be further reduced if the core design is optimized. In the actual design, the coolant flow could be adjusted such that the flow rate is a little larger in the inner and middle cores than in the outer core, leading to a reduced cladding and coolant temperature in the inner and middle cores.

**Table 5** TH analyses for peak power assemblies in core with BA and moderator

| Parameter | Inner core | Middle Core | Outer core |
|---|---|---|---|
| Peak power, MW | 5.13 | 5.41 | 5.07 |
| Coolant speed (avg./max), m/sec | 1.69/1.84 | 1.69/1.82 | 1.66/1.78 |
| Coolant exit temperature (avg./max.), °C | 552/578 | 560/581 | 551/561 |
| Peak cladding outer surface temperature, °C | 596 | 603 | 580 |
| Peak fuel temperature, °C | 703 | 709 | 669 |
| Pressure loss, Mpa | 0.196 | 0.196 | 0.193 |

## 5. Conclusion

Two schemes have been proposed to design a single enrichment lead-cooled core using an identical fuel rod type, one is a combination of $B_4C$ BAs and NSTs and the other one is based on the same BA and graphite moderator rods. It has been demonstrated that an

18-month cycle metal-fueled breakeven core can be designed with the proposed concepts such that the burnup reactivity swing is less than the effective delayed neutron fraction.

The proposed single enrichment design measures are effective ways to design a long-cycle, high-burnup breakeven lead-cooled core with a single fuel enrichment and an identical rod type. A $B_4C$ absorber rod with top/bottom cutbacks substantially reduces the peak fast neutron fluence, which is a limiting design criterion in fast reactors. It has been found that, in the core with BA and NST, the conversion ratios of the inner and middle cores are slightly smaller than that of the outer core. We have shown that the zone-wise conversion ratios can be equalized by loading a small amount of a graphite moderator into the inner and middle cores. The introduction of the moderator softens the neutron spectrum just a little and further reduces the peak fast neutron fluence, with a little sacrifice in the neutron economy. Introduction of the $B_4C$ absorber into the core slightly increases the coolant void reactivity. However, we think that the increased void reactivity is not a big concern in a lead-cooled reactor when we consider the high boiling temperature of the coolant. A subchannel analysis indicates that the new approaches could be viable options from the thermal-hydraulic point of view.

The proposed single enrichment concepts may improve the proliferation-resistance of the related fuel cycle. Also, the fuel reprocessing/fabrication processes could be significantly simplified with the proposed design approach.

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