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A Preliminary Design Study of Ultra-Long-Life SFR Cores having Heterogeneous Fuel Assemblies

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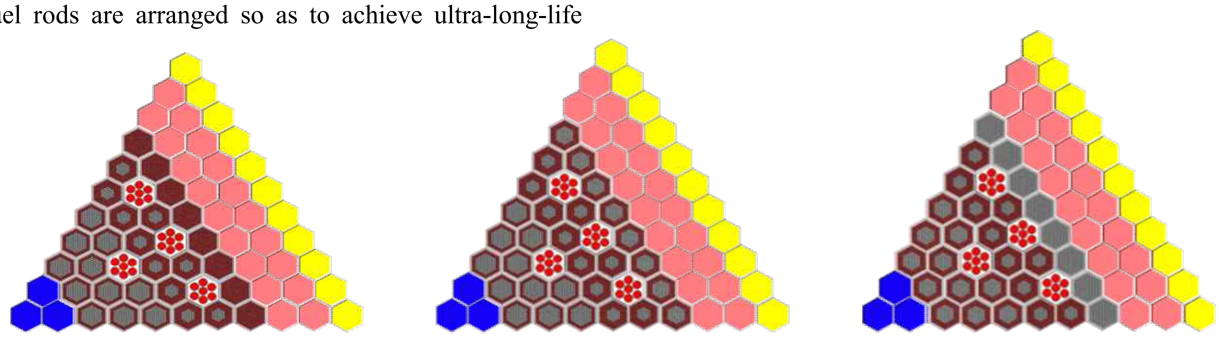
1. Introduction

The PWR and CANDU reactors have provided electricity for several decades in our country but they have produced lots of spent fuels and so the safe and efficient disposal of these spent fuels is one of the main issues in nuclear industry. On the other hand, it has been known that the ultra-long-life fast reactors can produce sustainably electricity over the several tens of years without refueling [1-5]. So, this type ultra-long-life cores are quite efficient in terms of the amount of spent fuel generation per electricity production and they can be used as an interim storage for PWR or CANDU spent fuel over several tens of years if they use the PWR or CANDU spent fuel as the initial fuel. So, there have been lots of interests in designing the ultra-long-life fast reactors [1-5]. Typically, the previous works have considered radially homogeneous fuel assemblies in which only blanket or driver fuel rods are employed and they considered axially or radially heterogeneous core configurations with the radially homogeneous fuel assemblies. These core configurations result in the propagation of the power distribution which can lead to the significant temperature changes for each fuel assembly over the time.

In this work, the radially heterogeneous fuel assemblies are employed in new ultra-long-life SFR (Sodium-cooled Fast Reactor) cores to minimize the propagation of power distribution by allowing the power propagation in the fuel assemblies. In the heterogeneous fuel assemblies, the blanket and driver fuel rods are arranged so as to achieve ultra-long-life and to minimize the propagation of the power distribution over the core. The objective of this preliminary neutronic study is to explore the possible core configurations with the radially heterogeneous fuel assemblies.

2. Core Design and Results

The core power is 222.24MWt (85MWe) for consideration of the small modular reactor. The fuel is the binary metallic fuel of U-5Zr and its density was assumed to be 17.3g/cm^3 with the smear density of 75% for coping the fuel swelling. The blanket fuel is depleted uranium (DU) while the driver fuel is the enriched uranium of which the initial uranium enrichment was determined to have initial k_{eff} of ~1.004. The active fuel length is 100cm and 150cm tall upper fission gas plenum was considered to reduce the fission gas pressure. The relative short active core was considered to have a small coolant void reactivity and a low linear heat generation rate of 95.3 W/cm was considered to achieve ultra-long-life cores. The heterogeneous Monte Carlo neutron transport and depletion calculations with the MCNP6 code [6] and ENDF/B-VIIr0 nuclear data were performed to analyze the core performances with high accuracy. As the results of the exploration study, three candidate cores shown in Fig. 1 were found to have ultra-long-life longer than 40 EFPYs (Effective Full Power Year). The design parameters for these cores are summarized in Table I.



Core I **Core II** **Core III**

Fig. 1. Configuration of the reference core (1/6)

As shown in Fig. 1, the cores consist of the central sodium duct assemblies and the fuel assemblies. These fuel assemblies are successively surrounded by the reflector and radial shield assemblies. In the present work, the duct filled with lead was considered as the reflector assembly for reducing the neutron leakage. The inner most two rings are occupied by the sodium duct assemblies that were considered to provide a way for reducing coolant void reactivity. The active core region is divided into the inner, middle, and outer core regions. Each core region has its own fuel assembly type. For the reference core (Core I), the inner core fuel assembly has 91 blanket fuel rods in the inner rings which are followed by 78 driver fuel rods in the outer rings and the middle core fuel assembly has 37 blanket and 132 driver fuel rods in the inner and outer rings, respectively, while the outer core fuel assembly has only driver fuel rods. The second core (Core II) has the same number of fuel assemblies and the same fuel assembly types in the inner and middle core regions as the reference core but its outer core fuel assembly has 61 blanket and 108 driver fuel rods in the inner and outer rings, respectively. The last core (core III) has the same middle core as the previous two cores while its inner core fuel assembly has a large number of driver rods and its outer core fuel assembly has only blanket rods. This core was selected to show the effect of the increased amount of blanket in the outer core region on the cycle length.

Table I Comparison of the design parameters of the cores

Design parameter	Core I	Core II	Core III
Fuel rod diameter (cm)	1.4	1.4	1.4
Cladding thickness (mm)	0.55	0.55	0.55
Fuel type			
Driver fuel	U-5Zr	U-5Zr	U-5Zr
Blanket fuel	DU-5Zr	DU-5Zr	DU-5Zr
Fuel density (g/cm^3)	17.3	17.3	17.3
Initial uranium enrichment (%)	14.7	17.06	16.49
Active Core volume (m^3)	50.8	50.8	50.8
Actinide inventory (kg) in driver fuels	4613.1	3924.5	3093.6
Actinide inventory (kg) in blanket fuels	1649.8	2337.6	3168.7
Volume fractions (%) per FA			
Inner core	[a]26.1/30.4/16.9/26.5	26.1/30.4/16.9/26.5	36.1/20.4/16.9/26.5
Middle core	44.2/12.3/16.9/26.5	44.2/12.3/16.9/26.5	44.2/12.3/16.9/26.5
Outer core	56.6/NA/16.9/26.5	36.1/20.4/16.9/26.5	NA/56.6/16.9/26.5
Number of fuel rods / FA			
Driver	[b]78/132/169	78/132/108	108/132/0
Blanket	91/37/0	91/37/61	61/37/169
Average linear power density (W/cm)	95.3	95.3	95.3
Average power density (W/cc)	72.9	72.9	72.9

[a]Driver fuel/blanket fuel/structure/coolant, [b]Inner core/middle core/outer core

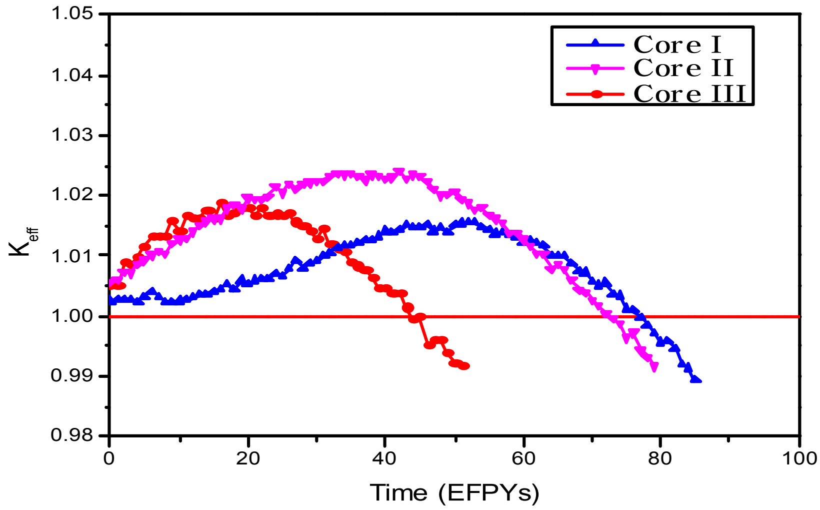


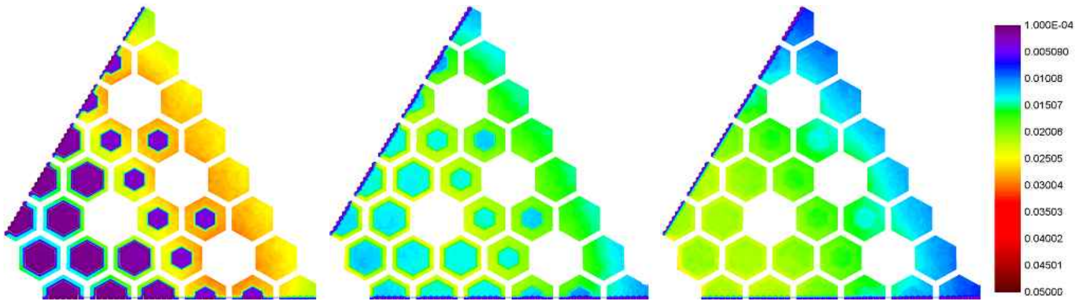
Fig. 2 Comparison of the eigenvalue evolutions

Table II Comparison of the basic core performance parameters

Parameter	Core I	Core II	Core III
Fuel type	U-5Zr	U-5Zr	U-5Zr
Cycle length (EFPY)	77	72	48
Actinide mass (ton, Driver/Blanket)			
Inner core	0.95/1.11	0.95/1.11	1.32/0.74
Middle core	1.61/0.45	1.61/0.45	1.61/0.45
Outer core	1.81/NA	1.15/0.65	1.41/0.40
Average discharge burnup (MWD/kg)	166.3	155.5	103.6
Burn up reactivity swing (pcm)	1590	2399	1878
Sodium void worth (pcm, BOC/EOC)	-396.0/1341.7	-289/1333	-497/936
Fuel Doppler coefficient (pcm/K, 900K, BOC/EOC)	-0.635/-0.399	-0.46/-0.22	-0.63/-0.47
Fuel axial expansion coefficient (pcm/K, BOC/EOC)	-0.275/-0.254	-0.353/-0.370	-0.497/-0.356

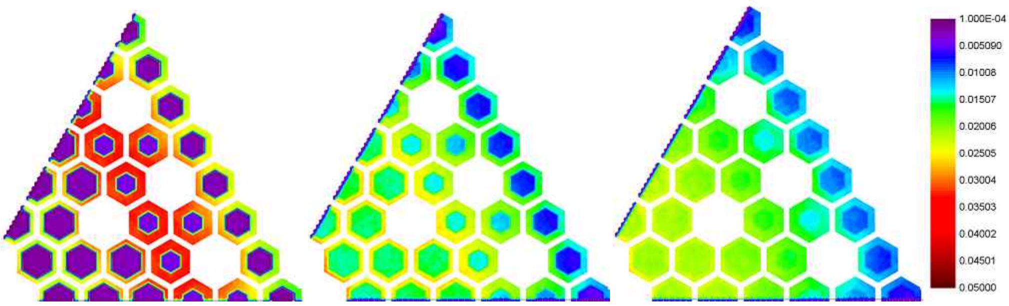
The main performances are summarized in Table II. The evolutions of the effective multiplication factors over the time are compared in Fig. 2. For the Depletion calculations using MCNP6, each of the inner, middle, and outer regions is sub-divided into axially five depletion zones. The depletion calculations were performed using 4000 particles for each of 300 cycles in MCNP6. In addition, each fuel assembly is divided into two depletion zones (i.e., blanket and driver zones). Therefore, if all the fuel assemblies have driver and blanket fuel rods, the total number of depletion zones for the core is 30. Fig. 2 shows that core I and core II have longer cycle lengths than 70 EFPYs while Core III has much shorter cycle length than these cores. In particular, it is noted that Core III has the largest initial breeding but its k_{eff} rapidly decreases after ~20 years. The reference core (i.e., core I) has the longest cycle length of 77EFPYs with the smallest burnup reactivity swing of 1590pcm. The second core (i.e., core II) has slightly reduced cycle length of 72 EFPYs and a slightly larger burnup reactivity swing of 1878pcm than the reference core. All the cores have initial uranium enrichment of driver fuel rods lower than 20wt%.

Table II shows that all the cores have negative sodium coolant void reactivity at BOC while they have positive ones at EOC. However it is considered that the sodium coolant void reactivity (SVR) worth of Core I and Core II at EOC is acceptable because these levels of SVR would correspond to 4~5$. The smallest SVR of Core III at EOC is resulted from the lowest discharge burnup.



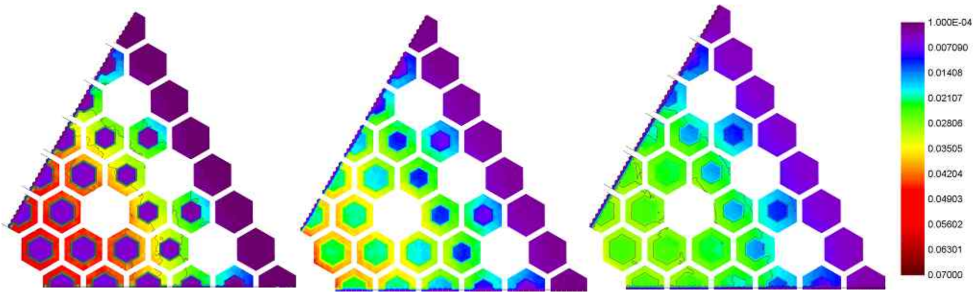
(BOC) **(MOC)** **(EOC)**

(a) Core I



(BOC) **(MOC)** **(EOC)**

(b) Core II



(BOC) **(MOC)** **(EOC)**

(c) Core III

Fig. 3. Comparison of the pin-wise power distributions at BOC, MOC, and EOC

Fig.3 compares the pin-wise power distributions of the cores at BOC, MOC, and EOC. This figure shows that the propagations of the power occur in the fuel assembly level (propagation from driver to blanket in each fuel assembly) for Core I and Core II but the blanket assemblies in the outer most rings of Core III is not effective because the burnup is very low in the outermost rings.

3. Conclusions

In this work, new small ultra-long life SFR cores were designed with heterogeneous fuel assemblies having both blanket and driver fuel rods to minimize the propagation of power distribution over the core by allowing power propagation from driver rods to blanket rods in fuel assemblies. In particular, high fidelity depletion calculation coupled with heterogeneous Monte Carlo neutron transport calculation was performed to assess the neutronic feasibility of the ultra-long-life cores. The results of the analysis showed that the candidate core has the cycle length of 77 EFPYs, a small burnup reactivity swing of 1590 pcm and acceptably small SVRs both at BOC and EOC.

ACKNOWLEDGMENT

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