Ultra Long Cycle MMLFR (Micro Modular Lead-cooled Fast Reactor) Cores using PWR Spent Fuel TRU

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1. Introduction

At our recent previous study, a 60 MWt reactor core with U-Zr metallic fuel was proposed [1]. In this VSMLFR (Very Small Modular Lead-cooled Fast Reactor) core, ultra-long cycle is obtained using small fuel regions and high breeding performance of metallic uranium fuel. The objective of this work is to design a smaller MMLFR (Micro Modular Lead-cooled Fast Reactor) of 35 MWt (~10 MWe) using low enrichment uranium (LEU) nitride fuel mixed with TRU from PWR spent fuels enabling to make better breeding performance to achieve longer cycle length and discharge burnup. Also, we targeted a compact core having ~1 m active core diameter.

In particular, we considered not only a homogeneous single region core loaded with ^{Depl}U-TRU-N but also radially two-region cores where the inner and outer cores are loaded with UN and ^{Depl}U-TRU-N fuels, respectively.

2. Computational methods and core design

2.1 Computational methods

The TRU compositions from PWR spent fuel to be loaded in the MMLFR core was estimated using the ORIGEN module in SCALE 6.2 code system which was developed at Oak Ridge National Laboratory [2].

The depletion analysis of the core was done using the Serpent2 continuous-energy Monte Carlo reactor physics burnup calculation code which was developed by VTT [3]. The ENDF/B-VII.r0 point-wise cross section library was used for all the depletion calculations and for the evaluation of the core physics parameters. Full-core 3-D analysis was performed with preserving fuel pin level heterogeneities and Chebyshev Rational Approximation Method (CRAM) option is used for burnup depletion modeling. We used 100 inactive and 500 active cycles with 50000 histories each for depletion calculation giving ~12 pcm statistical standard deviation. Each assembly was treated as a radial depletion zone and the active core was divided into eight axial depletion zones. The depletion time step size is one year.

2.2 Core design model

We considered a reference MMLFR core of which thermal power is 35 MWt. This reference core uses nitride fuels (U-TRU-N) containing depleted uranium and TRU, where TRU is from PWR spent fuel and 99% ^{15}N enriched nitrogen was used. To achieve an ultra-long cycle, the 2664 fuel rods arranged with a triangular lattice structure without the assembly duct and these fuel rods are hold through grid spacers, which eliminates potential flow blockage by allowing crossflow paths. An 87% smear density was used to consider swelling of the fuels. The active fuel length is 130 cm and a 100cm fission gas plenum above fuel is considered to reduce fission gas pressure. The fuel outer diameter of 1.60 cm and P/D ratio of 1.18 are adopted for achieving high breeding ratio. The reactivity controls are achieved using 12 outer peripheral control assemblies and one central control assembly. The combination of B_4C and W is considered by 40 vol% B_4C + 60 vol% W for control material, where W is used to make the density of the control elements exceed the density of the heavy liquid coolant, to enable scramming by gravity [4]. The boron is enriched to 92% ^{10}B. Each control assembly is comprised of a single control rod within a 3.5mm thick hexagonal HT9 duct. This core does not use solid reflector but the liquid lead surrounding active core plays a role as reflector. The liquid reflector thickness is 40 cm to compensate the high neutron leakage of small size core. The average linear heat rate and volumetric power density are 104.23 W/cm and 31.6 W/cm^3, respectively. Fig. 1. and Fig. 2 show the radial and axial core layouts, respectively. Table I summarizes the main design parameters.

We considered the following four different burnups of PWR spent fuels to show the sensitivity of the TRU composition on the core performances: 25 MWd/kg (Case 1), 30 MWd/kg (Case 2), 35 MWd/kg (Case 3), and 40 MWd/kg (Case 4). All the cases have 15 years cooling time.

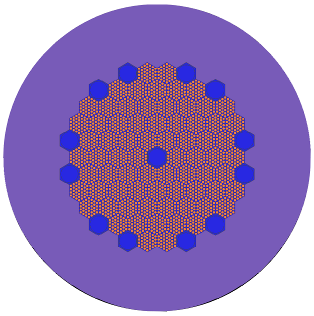

Fig. 1. Radial Core Layout of the reference core

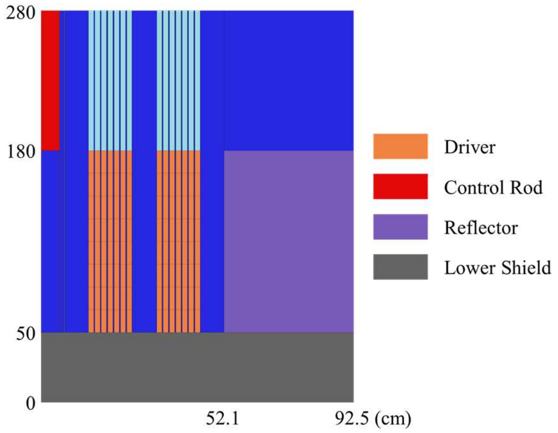

Fig. 2. Axial Core Layout of the reference core

Table I. Main design parameters of the core

Design parameter	***Value***
Power (MWt)	35
Active core height (cm)	130
Active core diameter (cm)	104.23
Average LPD (W/cm)	101.06
Average PD (W/cc)	31.55
Fuel type	0.2 wt% U-TRU-N
Number of rods per core	2664
Smear density of fuel (%)	87
Fuel pin outer diameter (cm)	1.60
Cladding thickness (mm)	0.55
Control assembly duct wall thickness (mm)	3.5
Volume fraction (%) (fuel/coolant/structure)	54.3/37.2/8.5
Number of control rods	13
Thickness of reflector (cm)	40
Control rod type	40 vol% B_4C + 60 vol% W

3. Core Performance Analysis and Results

In this section, the results of the parametric study are described on the TRU compositions depending on the discharge burnup of the PWR spent fuels. In addition to the homogeneous reference core, we suggested the two-region cores where the inner and outer cores are loaded with UN and $^{\mathrm{Depl}}$U-TRU-N fuels, respectively, to enhance the neutronic performances. The initial TRU contents of the cores are adjusted to give the initial effective multiplication factor (k_{eff}) of 1.004 and the cycle length is considered as the time interval over which k_{eff} is maintained over 1.002 with a margin of reactivity of 200 pcm.

3.1 Reference core design

The TRU contents were estimated to be 12.36, 12.95, 13.54 and 13.78wt% for the Cases A-1, 2, 3 and 4, respectively, due to their different TRU nuclide compositions. The evolutions of k_{eff} as depletion time for TRU feed compositions depending on the discharge burnup of PWR spent fuels are compared in Fig. 3. As shown in Fig. 3, the Cases A-1, 2, 3 and 4 have higher breeding performances leading to the ultra-long cycle lengths of 57, 57, 58, and 58 EFPYs, with corresponding to the average fuel burnups of 102.7, 102.7, 104.5 and 104.5 MWd/kg, respectively. The Case A-1 core having higher initial ^{239}Pu contents in TRU feed gives only very small drop of the reactivity at the initial depletion while the other cases give higher drops less than 200 pcm. Table II summarizes the main performance parameters of the different cases for the reference core configuration. The Case A-1, 2, 3 and 4 cores have higher burnup reactivity swings of 1133, 1073, 1082 and 1088 pcm, respectively, due to the high breeding performances than the previous VSMLFR [1]. These cores have relatively smaller effective delayed neutron fractions (β_{eff}) of ~ 390 pcm due to the addition of TRU than the previous VSMLFR. So, all the cores have higher burnup reactivity swings than 1$.

The Cases A have the positive lead void worths at BOC, while they have considerably negative lead void worth at EOC. The Case A-1 has lower lead void worth of 157.4 and -2006.0 pcm, respectively at BOC and EOC for lead voiding both in active core and upper gas plenum regions. For additional lead voiding in the liquid lead reflectors, the Case A-1 core has significantly lower lead void worth of -9371 and -15224 pcm at BOC and EOC, respectively. The lead void worths considered the voided case with the liquid reflectors are greatly reduced, due to the high reflective power of lead.

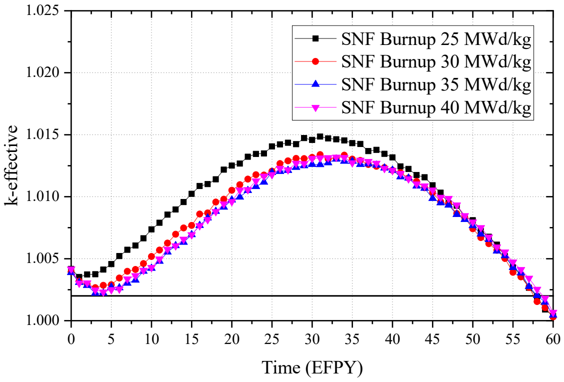

Fig. 3. Comparison of the k_{eff} evolutions of the reference cores

Fig. 4 compares the pin-wise power distributions at BOC and EOC, plotted using C# winform with ScottPlot package. Fig. 4 shows that the Case A-1, 2, 3, and 4 cores have similar power distributions to each other and power peakings occur near the center of the cores. Representatively, the Case A-1 has the maximum linear power densities of 146.2 W/cm and 141.6 W/cm at BOC and EOC, corresponding to the maximum radial power peaking factors of 1.446 and 1.402, respectively. However, it is noted that the radial power distribution becomes flat as depletion proceeds.

3.2 Two-region core design

The above reference cores have ultra-long cycle lengths and high breeding performances but quite higher burnup reactivity swings than 1\$. To reduce the burnup reactivity and to increase β_{eff}, we considered alternative two-region cores, where the inner and outer cores are loaded with UN and ^{Depl}U-TRU-N fuels, respectively, as shown in Fig. 5. In the inner core, enriched uranium nitride fuel is loaded and the initial uranium enrichment is fixed to 10wt%. The TRU contents for ^{Depl}U-TRU-N fuels in outer core region are adjusted to achieve initial effective multiplication factor (k_{eff}) of 1.004. The inner and outer core regions have 666 and 1998 fuel rods, respectively. We also considered the same TRU feed composition as those of the reference cores (i.e, Cases A).

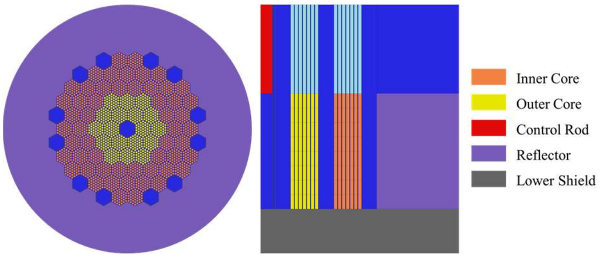

Fig. 5. Radial/Axial Core Layout of the two-region core

The initial TRU contents for the Cases B-1, 2, 3 and 4 are estimated to be 13.68, 14.34, 14.98 and 15.25wt%, respectively, due to their different TRU feed compositions. Fig. 6 compares the evolutions of k_{eff} as depletion time for the Cases B. The reactivity drops for the Cases are 108, 188, 288 and 262 pcm, which are higher than those of the corresponding cases of the reference cores. Table III summarizes the main performance parameters of the two-region cores. The Cases B-1, 2, 3 and 4 cores have cycle lengths of 50, 49, 48 and 48 EFPYs, respectively. The burnup reactivity swings are estimated to be 516, 502, 490, and 507 pcm, respectively, which are considerably lower than the Cases A (reference cores). Effective delayed neutron fractions (β_{eff}) for the Cases B are estimated to be ~ 480 pcm which are also higher than those of the reference cores. The Cases B-1, 2, 3 and 4 cores have average burnup of 90.1, 88.3, 86.5 and 86.5 MWd/kg, respectively. The cores have high burnups by ~25 MWd/kg in the inner cores than the outer cores.

For lead voiding both in active core and upper gas plenum regions, the Case B-1 has lower lead void worth of 30.7 and -1432.8 pcm, respectively at BOC and EOC. For additional lead voiding in the reflectors, the Case B-1 core has significantly lower lead void worth of -12479 and -14679 pcm at BOC and EOC, which are considerably lower than the Cases A (reference cores).

Fig. 7 compares the pin-wise power distributions at BOC and EOC. The Cases B-1, 2, 3, and 4 core have flatter power distributions than the corresponding reference cores. For example, the Case B-1 has the maximum linear power densities of 127.8 W/cm and 131.2 W/cm at BOC and EOC, corresponding to the maximum radial power peaking factors of 1.264 and 1.298, respectively.

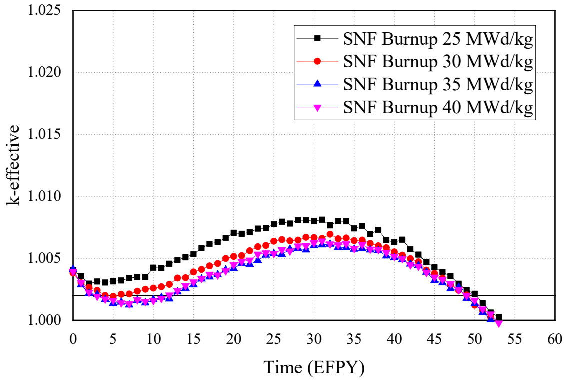

Fig. 6. Comparison of the k_{eff} evolutions of the two-region cores

4. Conclusions

In this work, new ultra-long life micro lead cooled fast reactor cores were designed using nitride fuels containing TRUs from PWR spent fuels. In particular, we considered not only a homogeneous single region core loaded with ^{Depl}U-TRU-N but also radially two-region cores where the inner and outer cores are loaded with UN and ^{Depl}U-TRU-N fuels, respectively. From the results of the neutronic analysis, it can be concluded that the new micro lead cooled fast reactors have ultra-long cycle lengths longer 48 EFPYs. In particular, the two-region cores have much smaller burnup reactivity swings, higher β_{eff}, and flatter power distributions than the homogeneous cores. Also, each cores have considerable negative lead void worth under ~14000 pcm at EOC, which can enhance the inherent safety under the unprotected accidents.

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Table II. Summary of performance parameters of the reference cores

Parameters	***Case A-1***	***Case A-2***	***Case A-3***	***Case A-4***
Spent fuel burnup (MWd/kg)	25	30	35	40
Cycle length (EFPY)	57	57	58	58
Burnup reactivity swing (pcm)	1133	1073	1082	1088
Effective delayed neutron fractions (pcm)	390	388	387	388
TRU contents (%)	12.36	12.95	13.54	13.78
Burnup (MWd/kg)	102.66	102.66	104.46	104.46
Maximum LPD (W/cm, BOC/EOC)	146.2/141.6	145.6/141.8	146.7/142.0	146.5/142.0
Radial power peaking factor (BOC/EOC)	1.446/1.402	1.440/1.403	1.451/1.405	1.450/1.405
Voided case (pcm, BOC/EOC)				
With upper plenum	157.4/-2006.0	220.8/-2022.6	333.3/-2034.4	309.4/-2050.2
And with lead reflector	-9371/-15224	-9201/-14994	-8984/-14996	-8880/-14950

Table III. Summary of performance parameters of the two-region cores

Parameters	***Case B-1***	***Case B-2***	***Case B-3***	***Case B-4***
Spent fuel burnup (MWd/kg)	25	30	35	40
Cycle length (EFPY)	50	49	48	48
Burnup reactivity swing (pcm)	516	502	490	507
Effective delayed neutron fractions (pcm)	478	480	479	480
TRU contents (%)	13.68	14.34	14.98	15.25
Burnup (MWd/kg)				
Total core	90.05	88.25	86.45	86.45
Inner core	109.97	107.56	105.28	105.11
Outer core	83.49	81.82	80.17	80.23
Maximum LPD (W/cm, BOC/EOC)	127.8/131.2	124.2/131.3	124.0/130.5	124.7/130.6
Radial power peaking factor (BOC/EOC)	1.264/1.298	1.229/1.300	1.227/1.291	1.234/1.292
Voided case (pcm, BOC/EOC)				
With upper plenum	30.7/-1432.8	58.5/-1384.1	84.2/-1396.4	122.9/-1310.0
And with lead reflector	-12479/-14679	-12333/-14493	-12260/-14378	-12134/-14258

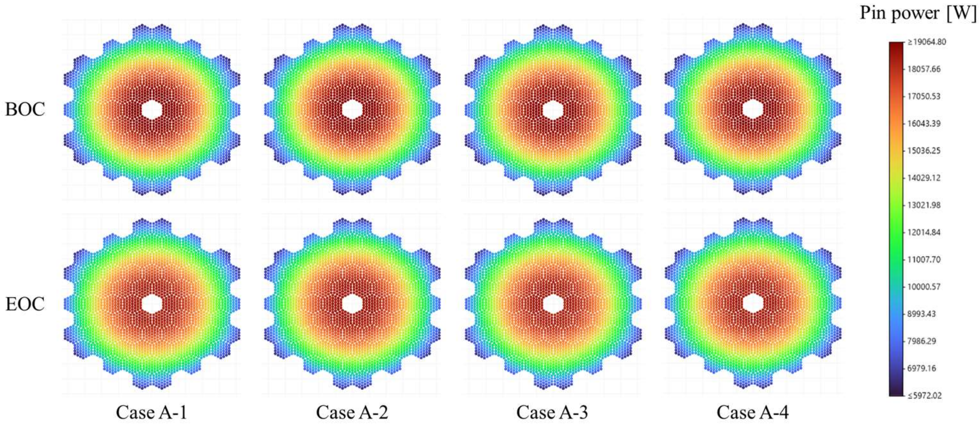

Fig. 4. Configuration of power distribution of the reference cores

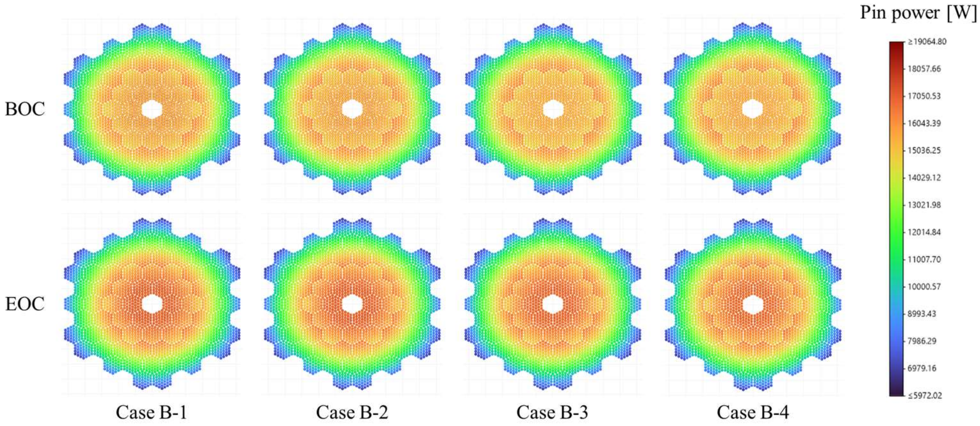

Fig. 7. Configuration of power distribution of the two-region cores