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Application of the Spectral-Shift Effect in the Small Lead-Based Reactor SLBR-50

Chen Zhao, Lei Lou, Xingjie Peng, Bin Zhang and Lianjie Wang*

Science and Technology on Reactor System Design Technology Laboratory, Nuclear Power Institute of China, Chengdu, China

In the design of a nuclear reactor, improving fuel utilization and extending burnup are two of the most important goals. A concept design of spectral-shift control rods is presented to extend cycle length and fuel utilization. First, a small lead-based reactor, SLBR-50, is preliminarily designed, and the design rationality is proved. Next, the concept design of spectral-shift control rods is presented and analyzed. Finally, numerical results of the small reactor design show that the burnup depth is extended by 73.3% and the fuel utilization rate for ^{235}U and ^{238}U is improved by 66.6 and 68.4%. All results are calculated using a Monte-Carlo code RMC. These results show advantages of the concept design for the spectral-shift control rod.

Keywords: spectral-shift effect, SLBR-50, RMC, fuel utilization, extending burnup

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****Correspondence:***
Xingjie Peng
pengxingjiets@126.com

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INTRODUCTION

Improving fuel utilization, extending burnup depth, and improving the nuclear plant economy are several important reactor design targets (Zhang et al., 2020a; Zhang et al., 2020b). It is still an open question when it comes to extending burnup depth with certain fuel weights. The spectral-shift effect is one of the solutions for the problem.

The spectral-shift effect was studied and the spectral-shift control concept was first proposed in 1961 in the Babcock and Wilcox company report (Mars and Gans, 1961). After that, the spectral-shift effect was studied in the pressurized water reactor design (Ronen and Galperin, 1980; Ronen and Fahima, 1984; Martin, 1988) and extended to the boiling water reactor design (Yokomizo et al., 1993). In the 21st century, the spectral-shift effect research was applied in the new-type advanced reactor. In the ABWR-II core design, spectral-shift rods were adopted and analyzed (Anegawa et al., 2001; Moriwaki et al., 2004). Results show that the average discharge burnup was improved by 5% and uranium weight was saved by 6~7%. Recently, the spectral-shift control design was applied in other advanced reactors, such as SmAHTR (Greene, 2010; Ilas et al., 2014; Kotlyar et al., 2017; Mehta and Kotlyar, 2019), small modular reactors (Lindley and Parks, 2016), and molten salt reactors (Betzler et al., 2018). SmAHTR is a small advanced high-temperature graphite-moderator reactor designed by Oak-Ridge. The cycle length can be extended by up to 20% or coated particle (TRISO) fuel can be reduced by 15% while maintaining the cycle length with the spectral-shift effect (Kotlyar et al., 2017; Mehta and Kotlyar, 2019). In these new-type advanced reactor analyses, a reactor design with spectral-shift effect shows good improvements of the fuel utilization rate and cycle length extension. However, few research studies have been carried out on spectral-shift lead-based reactors (LBRs) or the spectral-shift for extending cycle length and the fuel utilization rate.

In this study, a 50-MWt small lead-based fast reactor, SLBR-50, is conceptually designed at the Nuclear Power Institute of China (NPIC) for research. Besides, detailed parameters of the SLBR-50 are introduced. Based on the SLBR-50, the concept design of control rods with the spectral-shift

TABLE 1 | Basic parameters of the SLBR-50.

Items	Parameter	Items	Parameter
Reactor power	50 MWt	Fuel diameter	8.0 mm
Hot-condition average temperature	700 K	Air gap thickness	0.1 mm
^{235}U enrichment	19.95%	Clad thickness	0.6 mm
U total weight	3,835.3 kg	Clad outer diameter	9.4 mm
CR absorber material	B_4C	Fuel rod distance	10.9 mm
Reflector material	BeO	Assembly box thickness	2 mm
Clad material	Stainless steel	Assembly center distance	93.5 mm
Coolant material	Lead	Assembly inner distance	88.0 mm
Barrel material	Stainless steel	Assembly outer distance	92.0 mm
Fuel assembly amount	144	Active core height	95 cm
Control rod assembly amount	18	Outer reflector diameter	82 cm
Reflector assembly amount	48	—	—

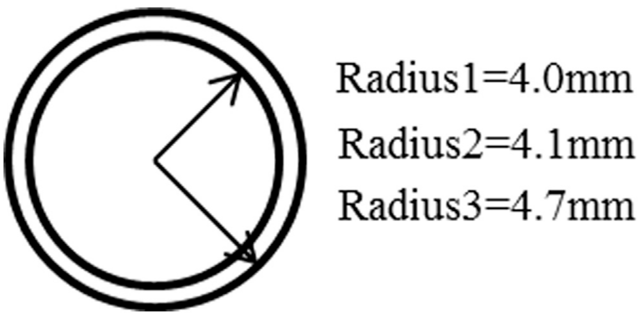

FIGURE 1 | Pin cell geometry of the SLBR-50; **(A)** fuel assembly, **(B)** reflector assembly, and **(C)** control rod assembly.

effect are proposed and analyzed, including the spectral-shift effect analyses and reactor performance improvement.

A continuous-energy Monte-Carlo reactor physics code, RMC (She et al., 2013; Wang et al., 2015; Liu et al., 2017), is adopted for the small reactor design. RMC has been developed by the Department of Engineering Physics, Tsinghua University, from 2010 as a tool for a reactor core analysis platform. It has several functions, such as complicated geometry modeling, criticality calculation, burnup calculation, and critical position searching calculation. Until now, RMC has already been used for reactor design and validation. In this study, all geometry modeling and calculation results are provided using RMC.

DESIGN OF SLBR-50

Design of SLBR-50

The SLBR-50 is conceptually designed for research. Several basic parameters of the reactor are shown in **Table 1**. Thermal power of the SLBR-50 is 50 MW. The hot-condition average temperature is 700 K. As for materials, 19.95% enrichment UO_2 is applied as the fuel. The uranium total weight is 3835.3 kg in the SLBR-50. B_4C is chosen as the control rod absorber material. In each pin cell, stainless steel is conducted as the clad material. Outside of the active core, BeO is applied as the reflector and stainless steel is conducted as the barrel. Heavy metal lead is adopted as the coolant in the lead-based reactor SLBR-50. Other parameters will be introduced in geometry modeling.

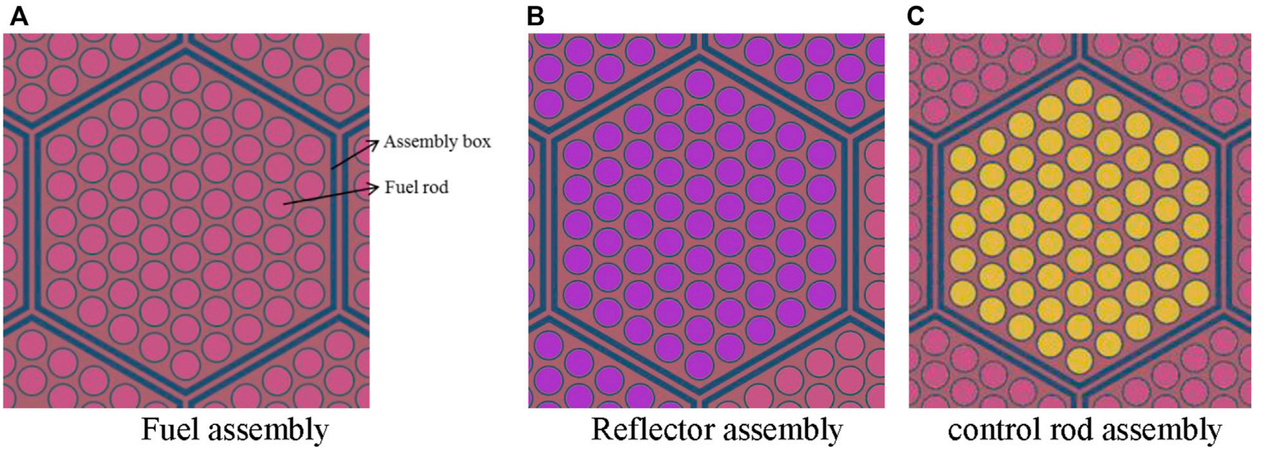

FIGURE 2 | Hexagonal assembly geometry of the SLBR-50.

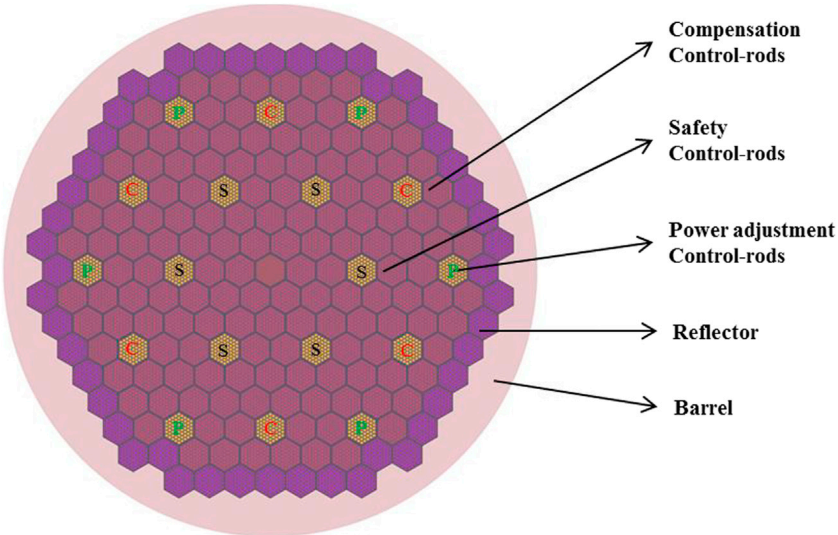

FIGURE 3 | Radial cut of the SLBR-50.

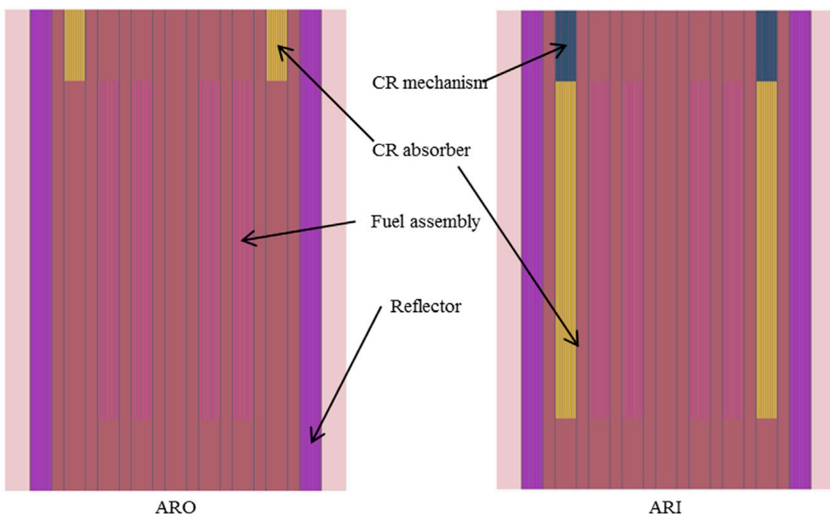

FIGURE 4 | Axial cut of the SLBR-50.

The geometry modeling of the SLBR-50 is divided into the pin cell, the lattice, and the whole core. The basic pin cell geometry is shown in **Figure 1**. The radius of the fuel region is 4.0 mm. The thickness of the air gap between the fuel and the clad is 0.1 mm, which is hard to show in the figure. The 0.6-mm-thick clad lies outside of the pin cell.

The hexagonal assembly geometry of the fuel, reflector, and control rod lattice are shown in **Figure 2**. The basic geometry is totally the same for these assemblies. 61 rods are arranged in regular matrix form. The thickness of the stainless steel assembly box is 2 mm. The assembly inner and outer distances are 88.0 and 92.0 mm separately. The assembly center distance is 93.5 mm.

The radial cut of SLBR-50 whole-core modeling is shown in **Figure 3**, and axial cuts of all rods out (ARO) and all rods in (ARI) cases are shown in **Figure 4**. The whole core consists of 144 fuel assemblies, 48 reflector assemblies, 18 control rod assemblies, and center guide tube assembly. Control rod assemblies are divided into three groups, including compensation, safety, and power adjustment. Besides, reflector assemblies are located outside of the active core. The barrel is explicitly modeled and the diameter of the barrel is 82 cm. In the axial cut, the height of the active core is 95 cm. On the top and the bottom of the active core, a 20-cm-high coolant reflector is arranged.

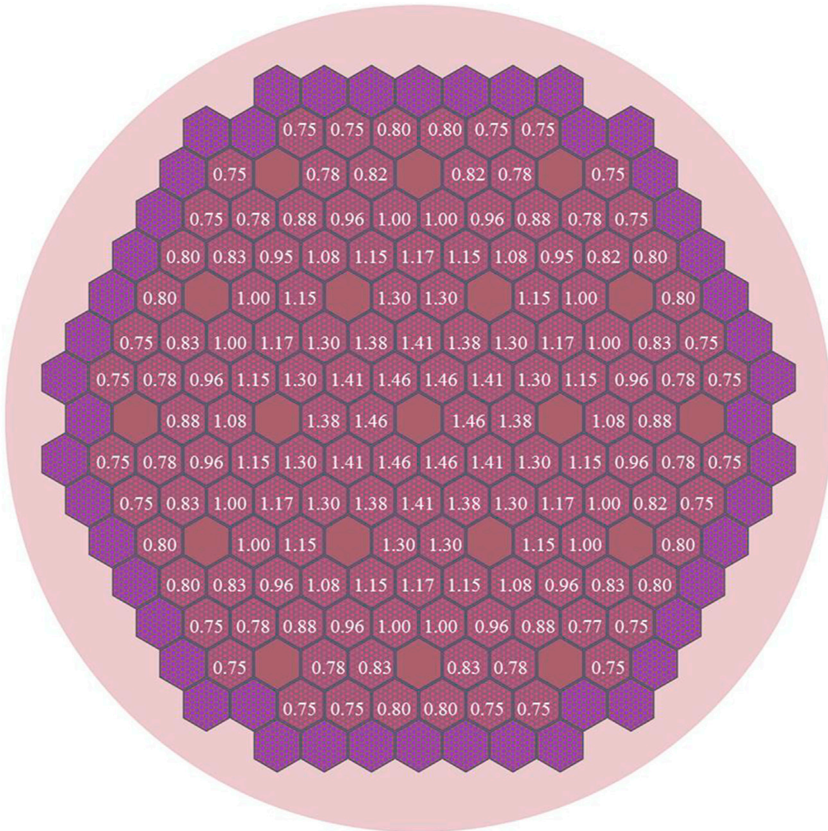

FIGURE 5 | Radial assembly power result of the SLBR-50.

Nuclear Design Results of SLBR-50

Nuclear design calculations for the power distribution and control rod worth were conducted using the Monte-Carlo code RMC. In the calculation, the ENDF-VII.0 library was adopted. 10 layers were divided in the axial direction of the active core. To obtain the detailed power distribution results, a relatively refined calculation condition was applied in the calculation. 8 billion active particles were used (800 generations consisting of 10 million neutrons per generation, of which 300 generations were skipped). Normalized radial assembly power and axial power distribution results of the ARO case are shown in **Figures 5**, **6**. In the radial assembly power result, the maximum assembly power is 1.46, which lies in the center of the reactor. In the axial power distribution, the maximum power is 1.268.

In the control rod worth calculation, 60 million active particles are used (600 generations consisting of 100 thousand neutrons per generation, of which 200 generations are skipped). The control rod worth results are shown in **Table 2**. Three sets of control rods are calculated. Integral rod worth (IRW) results are 6,915, 4,114, and 16,022 pcm for compensation, power adjustment, and safety control rod sets separately. Both differential rod worth (DRW) and integral rod worth (IRW) results show the shutdown depth is adequate for reactor control.

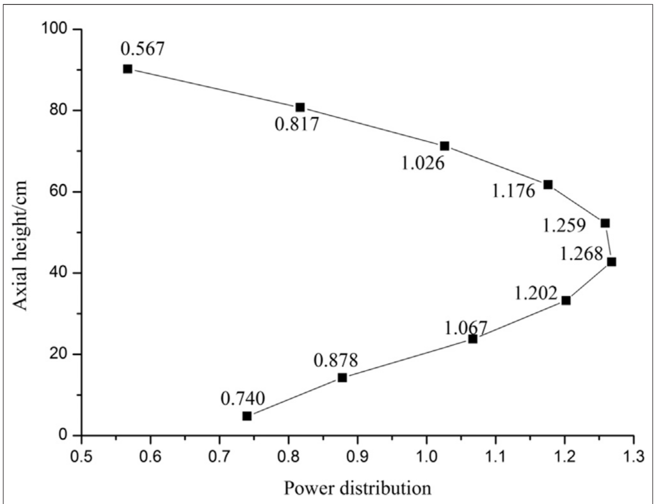

FIGURE 6 | Axial power distribution result of the SLBR-50.

Rationality of the primary design for the SLBR-50 is confirmed by these nuclear design results. Apparently, parameters in the reactor design need to be researched to improve the reactor characteristic. In this study, the spectral-shift effect is researched and analyzed based on the SLBR-50.

TABLE 2 | Control rod worth of the SLBR-50.

CR insert depth/cm	Compensation CR			Power adjustment CR			Safety CR		
	Eigenvalue	DRW/pcm	IRW/pcm	Eigenvalue	DRW/pcm	IRW/pcm	Eigenvalue	DRW/pcm	IRW/pcm
0	1.02244 ± 9pcm	/	/	1.02244 ± 9pcm	/	/	1.02244 ± 9pcm	/	/
9.5	1.01985 ± 9pcm	259	259	1.02101 ± 9pcm	143	143	1.01667 ± 9pcm	577	577
19	1.01505 ± 9pcm	480	739	1.01770 ± 9pcm	331	474	1.00639 ± 9pcm	1,028	1,605
28.5	1.00769 ± 9pcm	736	1,475	1.01332 ± 9pcm	438	912	0.99156 ± 9pcm	1,483	3,088
38	0.99858 ± 9pcm	911	2,386	1.00766 ± 9pcm	566	1,478	0.97255 ± 9pcm	1901	4,989
47.5	0.98803 ± 9pcm	1,055	3,441	1.00132 ± 9pcm	634	2,112	0.94940 ± 9pcm	2,315	7,304
57	0.97704 ± 9pcm	1,099	4,540	0.99477 ± 9pcm	655	2,767	0.92328 ± 9pcm	2,612	9,916
66.5	0.96689 ± 9pcm	1,015	5,555	0.98900 ± 9pcm	577	3,344	0.89761 ± 9pcm	2,567	12,483
76	0.95947 ± 9pcm	742	6,297	0.98472 ± 9pcm	428	3,772	0.87743 ± 9pcm	2018	14,501
85.5	0.95480 ± 9pcm	467	6,764	0.98201 ± 9pcm	271	4,043	0.86563 ± 9pcm	1,180	15,681
95	0.95329 ± 9pcm	151	6,915	0.98130 ± 9pcm	71	4,114	0.86222 ± 9pcm	341	16,022

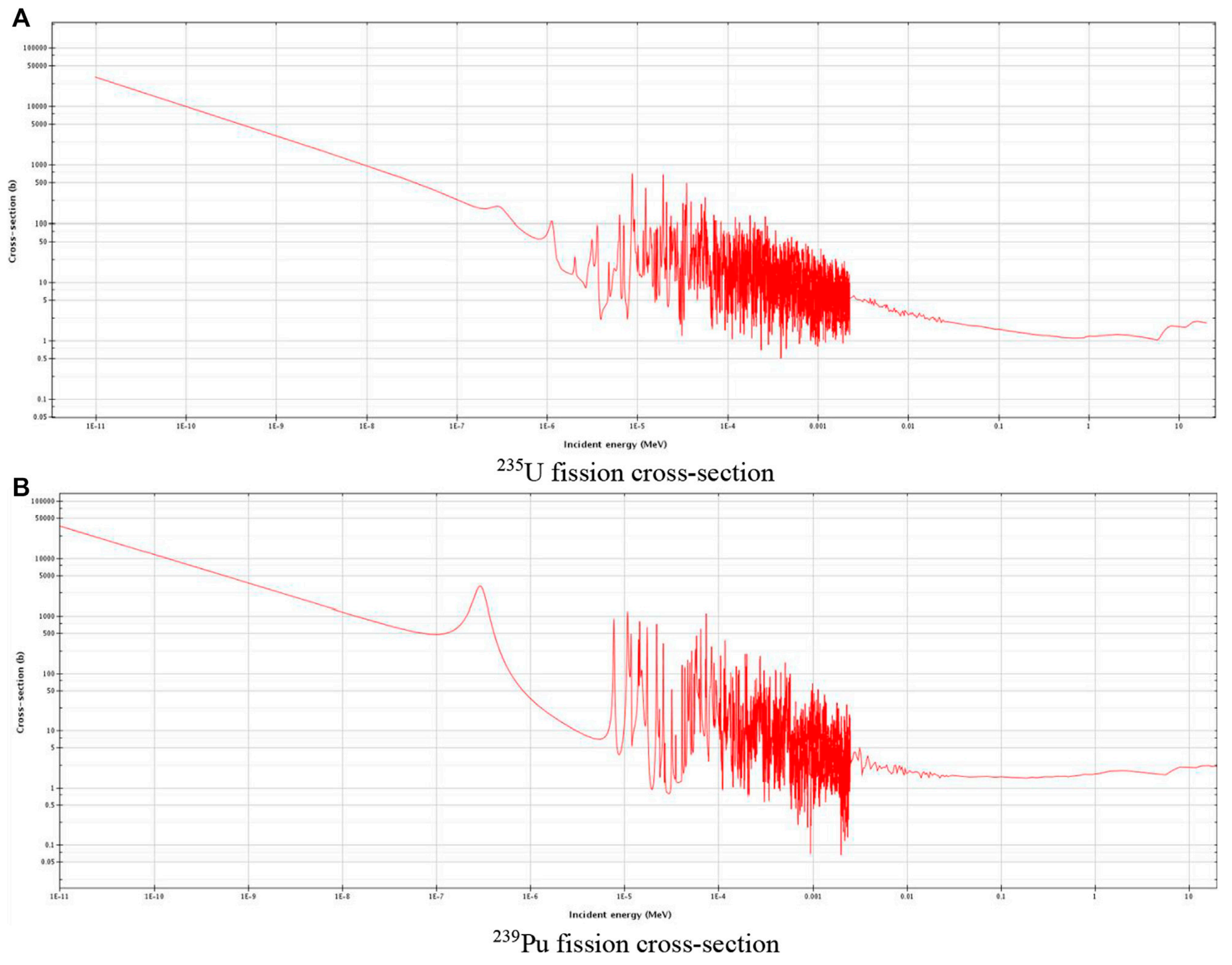

FIGURE 7 | Diagram of the fission cross-sections for typical fuel nuclides. **(A)** ^{235}U fission cross-section. **(B)** ^{239}Pu fission cross-section.

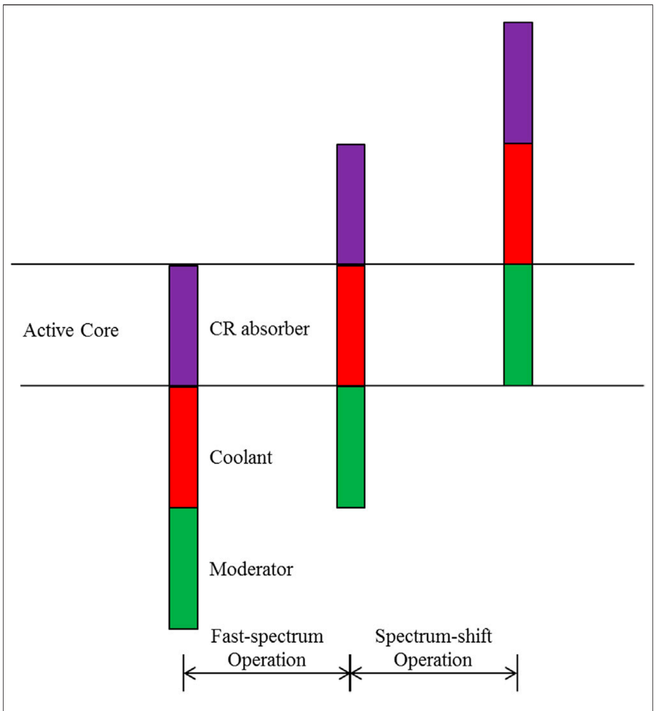

FIGURE 8 | Concept design of the control rod for the spectral-shift scheme.

THE CONCEPT DESIGN OF SPECTRAL-SHIFT CONTROL RODS

The basis of the spectral-shift effect is the difference of the fission absorption capacity in different energy ranges. ^{235}U and ^{239}Pu are dominant fission nuclides. As is shown in **Figure 7**, fission cross-sections of ^{235}U and ^{239}Pu show a similar pattern; the cross-section in the thermal energy region is larger than that in the fast energy region. Besides, ^{238}U can absorb fast neutrons and convert to ^{239}Pu. In this way, fuel breeding happens in the fast-spectrum reactor. Based on the fuel nuclides analysis of the different energy ranges, it can be concluded that the spectral-shift effect can balance the fuel breeding in the fast energy range and fission absorption in the thermal energy range. As a result, the fuel utilization rate will increase by the spectral-shift effect.

In this study, a concept design of a control rod with the spectral-shift effect is analyzed to realize the spectral-shift effect in the small lead-based reactor SLBR-50. The concept design of spectral-shift control rods is shown in **Figure 8**. Three sections are divided axially, including the control rod absorber, coolant, and moderator from the top to the bottom. Compared to the traditional control rod, the spectral-shift rod adds coolant and moderator sections. In the beginning of the spectral-shift scheme, the absorber section is inserted into the core active region. Spectral-shift control rods are withdrawn in the burnup procedure. With all absorbers withdrawn outside of the active core and the coolant section raised into the core, the fast-spectral operation procedure is finished. In the fast-spectrum operation, the reactor is operated in the fast spectrum to realize fuel proliferation. After that, spectral-shift rods continue withdrawing and moderators are moving to the core. In the spectrum-shift operation, neutrons will be moderated and the energy spectrum is softened. In this way, fuel utilization can be improved with the spectral-shift effect. The control rod moving procedure is shown in **Figure 9**. In the SLBR-50, YH_2 is applied as the moderator material.

THE SPECTRAL-SHIFT EFFECT ANALYSES AND NUMERICAL RESULTS

Cycle Length Results

The burnup depth and critical rod position results for the small reactor design are shown in **Table 3**. Three sets of control rods are withdrawn in the order of safety rods, power adjustment rods, and compensation rods. The initial rod position is −95 cm, where the control rod absorbers are totally inserted. The fast-spectrum operation is from the beginning of life to 1500 EFPD. In

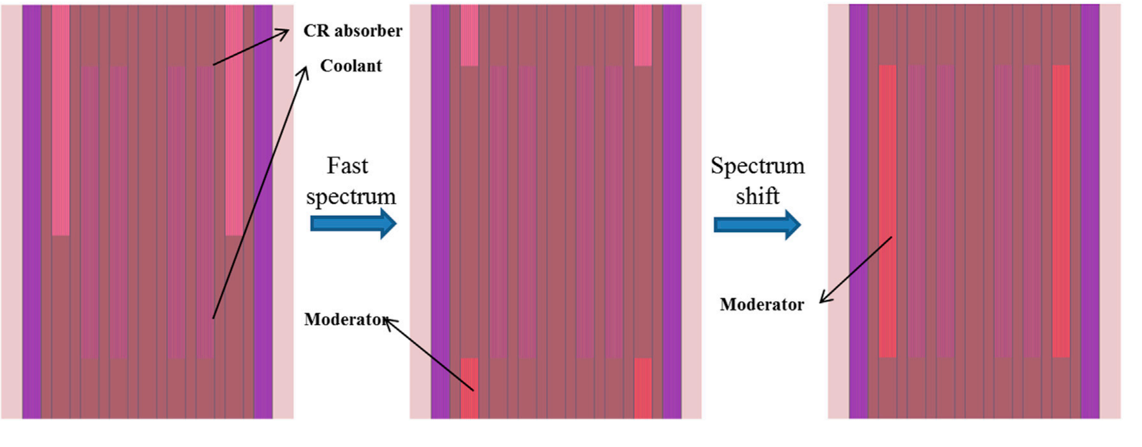

FIGURE 9 | Detailed axial cut in the spectral-shift rod withdrawing procedure.

TABLE 3 | Results of the critical rod position for the SLBR-50 spectral-shift control rod design.

Operation	Burnup/EFPD	Rod position/cm		
		Compensation CR	Power adjustment CR	Safety CR
Fast-spectrum operation	0	−44.79	0	0
	5	−43.81	0	0
	30	−43.4	0	0
	100	−45.07	0	0
	200	−41.87	0	0
	300	−39.58	0	0
	400	−37.28	0	0
	500	−34.72	0	0
	600	−32.3	0	0
	700	−29.82	0	0
	800	−27.35	0	0
	900	−24.82	0	0
	1,000	−20.75	0	0
	1,100	−19.06	0	0
	1,200	−14.89	0	0
	1,300	−9.51	0	0
	1,400	0	0	0
	1,500	0	0	0
Spectral-shift operation	1,600	0	0	7.38
	1700	0	0	24.31
	1800	0	0	23.86
	1900	0	0	23.27
	2000	0	0	64.75
	2,100	0	0	67.97
	2,200	0	0	95
	2,300	0	0	95
	2,400	30.66	95	95
	2,500	60.42	95	95
	2,600	95	95	95
—	2,700	Subcritical		

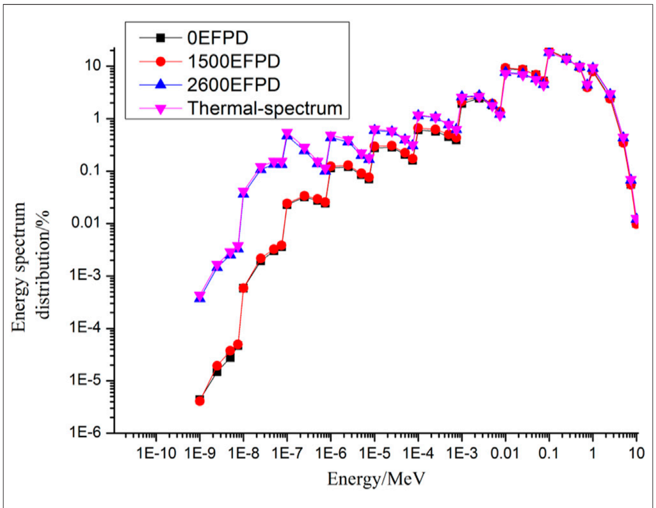

FIGURE 10 | Energy spectrum results of the spectral-shift scheme in the SLBR-50.

1500 EFPD, all control rod absorbers are withdrawn and the spectrum-shift operation begins. The spectral-shift effect can extend the cycle length from 1500 EFPD to 2600 EFPD, which has a 73.3% improvement for the cycle length with the same fuel weight. Besides, the spectral-shift design has the same shutdown margin as the fast-spectrum design.

Energy Spectrum Results

The kernel of the spectral-shift effect is the energy spectrum shift. Therefore, the energy spectrums are analyzed in typical burnup steps, shown in **Figure 10**. Energy sections are divided by an order of magnitude, from 1.0e-9 to 10 MeV. Each line shows the energy spectrum along all energy sections for the certain burnup. The energy spectrum analyses need to match with the spectral-shift rod withdrawal procedure. Besides, the thermal-spectrum result is provided in the beginning of life with all moderator rods inserted. The thermal-spectrum result can be shown as a reference in the spectrum-shift analysis. In the fast-spectrum operation from 0 EFPD to 1500 EFPD, energy spectrums are similar. Control absorber insertion has little influence on the energy spectrum. In the spectral-shift operation from 1500 EFPD to 2600 EFPD, moderators are inserted, and the spectrum-shift phenomenon can be observed in the energy spectrum analyses. The energy spectrum distribution of 2600 EFPD is similar to the thermal spectrum. It can be concluded that the spectrum-shift control rod design takes advantage of the spectrum-shift effect sufficiently in the SLBR-50.

TABLE 4 | Density of typical nuclides in the spectral-shift scheme.

Operation	Burnup/EFPD	Nuclide density/b−1cm−1			Utilization rate[a]/%	
		^{235}U	^{238}U	^{239}Pu	^{235}U	^{238}U
Fast-spectrum operation	0	1.960E+03	7.767E+03	0.000E+00	/	/
	5	1.960E+03	7.766E+03	2.130E-01	0.00	0.00
	30	1.956E+03	7.764E+03	2.418E+00	0.20	0.13
	100	1.945E+03	7.756E+03	8.756E+00	0.77	0.13
	200	1.929E+03	7.746E+03	1.774E+01	1.58	0.26
	300	1.913E+03	7.736E+03	2.653E+01	2.40	0.39
	400	1.898E+03	7.725E+03	3.518E+01	3.16	0.51
	500	1.882E+03	7.715E+03	4.370E+01	3.98	0.77
	600	1.867E+03	7.705E+03	5.209E+01	4.74	0.90
	700	1.852E+03	7.694E+03	6.033E+01	5.51	1.03
	800	1.837E+03	7.684E+03	6.845E+01	6.28	1.16
	900	1.822E+03	7.674E+03	7.647E+01	7.04	1.29
	1,000	1.807E+03	7.663E+03	8.437E+01	7.81	1.42
	1,100	1.793E+03	7.653E+03	9.214E+01	8.52	1.54
	1,200	1.778E+03	7.643E+03	9.976E+01	9.29	1.67
	1,300	1.764E+03	7.633E+03	1.073E+02	10.00	1.80
	1,400	1.750E+03	7.622E+03	1.147E+02	10.71	1.93
	1,500	1.735E+03	7.612E+03	1.220E+02	11.48	2.06
Spectral-shift operation	1,600	1.721E+03	7.602E+03	1.292E+02	12.19	2.19
	1700	1.707E+03	7.591E+03	1.363E+02	12.91	2.32
	1800	1.693E+03	7.581E+03	1.432E+02	13.62	2.45
	1900	1.680E+03	7.571E+03	1.499E+02	14.29	2.57
	2000	1.666E+03	7.561E+03	1.565E+02	15.00	2.70
	2,100	1.652E+03	7.551E+03	1.628E+02	15.71	2.83
	2,200	1.639E+03	7.541E+03	1.688E+02	16.38	2.96
	2,300	1.625E+03	7.531E+03	1.748E+02	17.09	3.09
	2,400	1.612E+03	7.522E+03	1.804E+02	17.76	3.22
	2,500	1.599E+03	7.513E+03	1.857E+02	18.42	3.35
	2,600	1.585E+03	7.503E+03	1.909E+02	19.13	3.47

[a]*Utilization rate = Consumed nuclides/Total nuclides*100%*

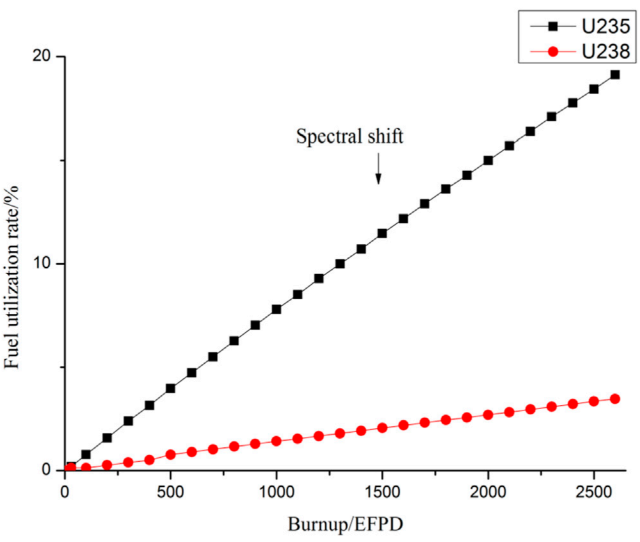

FIGURE 11 | Nuclide density variation in 200 EFPD for several typical fuel nuclides in the burnup.

Fuel Utilization Rate Results

Nuclide density variation is an important result for the spectral-shift effect. In the nuclide density analysis, only the spectral-shift scheme is conducted because that is the only scheme influenced by the spectral-shift effect. Considering the breeding of ^{238}U to ^{239}Pu, the fission reaction of ^{235}U, ^{238}U, and ^{239}Pu is the dominant nuclear reaction in the burnup. ^{235}U, ^{238}U, and ^{239}Pu are analyzed as the typical nuclides. The nuclide densities for these three nuclides are listed in **Table 4**, and the utilization rate variations in the burnup are shown in **Figure 11**.

As is shown in the table, the nuclide density of ^{235}U and ^{238}U is decreasing both in the fast-spectrum operation and the spectrum-shift operation, and the nuclide density of ^{239}Pu is increasing. The phenomenon is caused by the relatively hard energy spectrum. In the burnup procedure, even though the spectrum-shift effect makes the energy spectrum softer than the original fast spectrum, the spectrum-shift effect is unable to change the harder energy spectrum in the SLBR-50. Therefore, the breeding of ^{239}Pu is stronger than the fission absorption in the burnup procedure. All in all, the spectral-shift improves the fuel utilization of ^{235}U and ^{238}U from 11.5 to 19.1% and from 2.06 to 3.47%.

CONCLUSION

A 50-MWt small lead-based reactor, SLBR-50, is conceptually designed at the NPIC for research. The detailed design parameters are provided, as well as power distribution and control rod worth calculation results. These results verify the rationality of the preliminary design for the SLBR-50.

Based on the SLBR-50, the concept design of the spectral-shift control rod is analyzed for extending the burnup depth and improving fuel utilization. The basic configuration of the spectral-shift control rod is introduced in detail. Three sections are divided axially, including the control rod absorber section, the coolant section, and the moderator section. In the burnup procedure, the first section is the fast-spectrum operation. Control rod absorbers are withdrawn in this section and it is totally the same as the traditional control rod design. The second section is the spectral-shift operation with moderators inserted into the active core. The spectral-shift effect is realized in this section, and the burnup depth can be extended.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

CZ: main researcher in the group and writer of the manuscript. LL: main researcher in the group. XP: leader in the group. BZ: researcher in the group. LW: main adviser and director.

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