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Optimization of conceptual Design on the Lead-based Modular Nuclear Power Reactor Core Loaded with U-10Zr Alloy Fuel

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Abstract:As one of the forth-generation nuclear energy system reactor types, lead fast reactor has good safety and economical properties due to the stable chemical properties of the coolant and the proliferation characteristics of the fuel, and modular nuclear power faster reactor designed for nuclear plant can further improve the economics of the reactor. In this article, the conceptual design of the lead-based modular power reactors with different power levels loaded with uranium alloy fuel is found to be found that when reactor core size increased to a certain level, the proliferation performance is too high due to the increase of the reactor core size under a specific core life such as 2000EFPD, so at the end of core life, the reactor core still has a large remaining reactivity.The proliferation advantage of the core can't be fully released during the current core life time. Based on this phenomenon, in this article, we optimized the conceptual design of lead-based modular nuclear power reactor core loaded with uranium alloy fuel, and proposed to choose the appropriate rod to diameter ratio and effective density of fuel based on the power level and life time of the core. By adjusting the amount of uranium and ^{235}U per unit volume, the proliferation performance of the core can be changed to match the power level and life time of the core. Sothe reactivity of core during the life period does not change, which not only reduce the difficulty of the reactivity control, but alsomake full use of the proliferation performanceof the core.And at the same time, the reasonable rod to diameter ratio can provide safety and design margin for the analysis of thermal and hydraulic safety, and effectively improve the economy and safety of the core.

Keywords: Lead-based modular reactor; Uranium alloy fuel; optimization of reactor core conceptual design; Effective density of fuel pin; Therod to diameter ratio

1. Introduction

Lead-based fast reactors[1-3], as one of the fourth-generation nuclear energy systems, mainly benefit from the chemical stability of lead-based coolants and the breeding performance of fast reactor fuels. Compared with active metals such as sodium, lead-based coolants hardly react with water and air, so they are safer than sodium-cooled fast reactors. The core energy spectrum of lead-based fast reactors is harder than that of the commonthermal spectrum reactors such as Pressure Water Reactor (PWR), and the share of fast neutrons is high, which can convert fissionable nuclides such as ^{238}U in the fuel into fissile nuclides such as ^{239}Pu, etc., which can effectively improve the utilization rate of uranium resources. Therefore, it is more economical than the thermal spectrum core.

Modular nuclear power design is to use a certain number of single reactors with a specific power level to be combined to meet the power level requirements of nuclear power plants. The use of modular design can make the core design easier and make the power combination of nuclear power plants more flexible. The improved design also reduces design and production costs, further improving core economics.

In this paper, uranium-zirconium alloy fuel is used to carry out the conceptual design of the modular nuclear power reactor core, and the basic characteristics of the core under different power levels are analyzed. For example, the end-of-life reactivity of 2000EFPD cannot be fully released, and the reactivity and breeding characteristics of the core cannot be effectively released and utilized in the current core power and lifetime due to excessive breeding characteristics. Based on this, this paper puts forward the optimization ideas and directions. The optimal design of the core with different power levels finally makes the change of the core reactivity basically match the core power and life, and effectively improves the safety and economy of the core.

2. Calculation Program

The calculation in this paper is done by the RMC program, and the Reactor Monte Carlo code RMC (Reactor Monte Carlo code) [4]is a three-dimensional transport Monte Carlo program for the calculation and analysis of the reactor core developed by the Reactor Engineering computation and Analysis Laboratory (REAL Team, Institute of Nuclear Energy Science and Engineering Management, Department of Engineering Physics, Tsinghua University). The RMC program is developed for the basic requirements in the calculation and analysis of the reactor, and is developed in combination with the flexible geometric structure, complex neutron energy spectrum, diverse material components, anisotropy and strong leakage in the design of the new concept reactor system, and can handle complex geometric structures, and it uses se continuous energy point section to describe complex energy spectrum and materials, and can calculate critical problem eigenvalues, eigenfunction calculation, system burnup simulation, transient process analysis, etc. according to the needs of practical problems.

3. Preliminary Conceptual Reactor Design

3.1. Assembly Design

The type of assemblies used in the core refer to the assembly design of the lead-based research reactor SLBR-50 (Small Lead-Based Reactor - 50MWt) [5] of Nuclear Power Institute ofChina (NPIC). The schematic diagram of the assemblies is shown in Figure 1. The main design parameters are shown in Table 1.

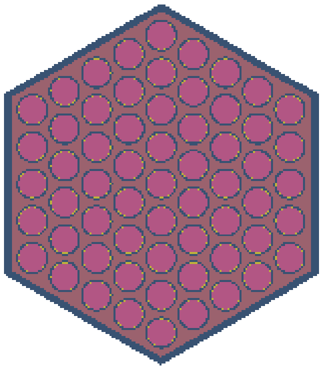


Figure 1 Schematic diagrams of fuel assemblies

Table 1 main design parameters of assembly

Parameter	Value	Parameter	Value
Fuel pin diameter / mm	8.0	Assembly center distance / mm	93.5
Air gap thickness / mm	0.1	Assembly box inner distance / mm	88.0
Clad thickness / mm	0.5	Assembly box outer distance / mm	93.0
Clad Outer diameter / mm	9.2	Assembly box thickness / mm	2.5
Fuel rod center distance / mm	10.9	Assembly fuel rod number	61
Fuel effective temperature / K	900	Clad material	SS
Coolant temperature / K	700	Coolant material	Lead-based

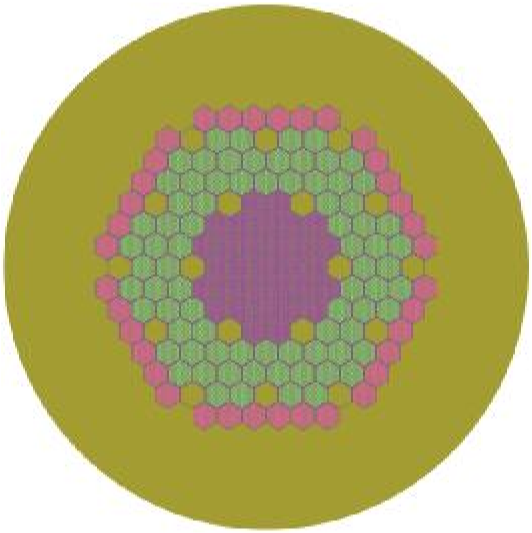
3.2. Core Design

According to the above assembly structure design, U-10Zr fuel core is used for core design of different power levels, and the core life time meets 2000EFPD [3], main design parameters of each scheme is shown in Table 2.

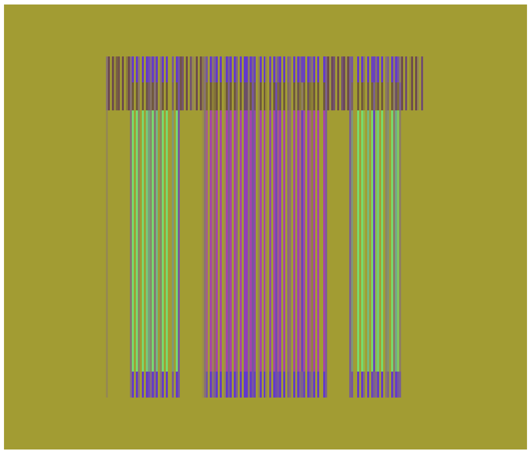
Schematic diagrams of radial and axial arrangements of the five core schemes with different power levels are shown in Figures 2, 3, 4, 5 and 6. The design parameters of each scheme of the core are shown in Table 3.

Table 2 main design parameters of each scheme

Core schemes	Core power / MW	Core life / EFPD	Fuel type
Scheme 1	100	≥2000	U-10Zr
Scheme 2	300	≥2000	U-10Zr
Scheme 3	500	≥2000	U-10Zr
Scheme 4	700	≥2000	U-10Zr
Scheme 5	1000	≥2000	U-10Zr

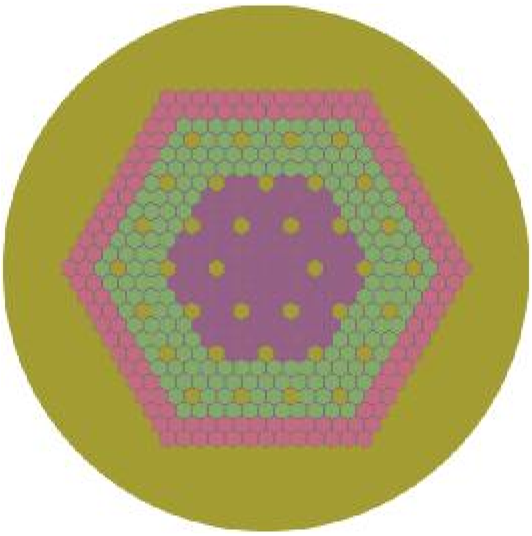


（a）Radial layout

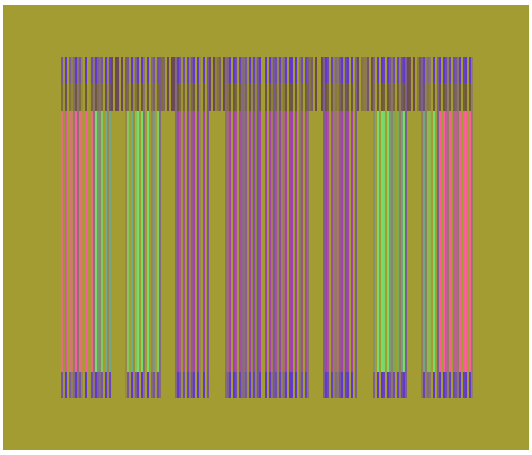


（b）Axial layout

Figure 2 Schematic diagram of 100MW core

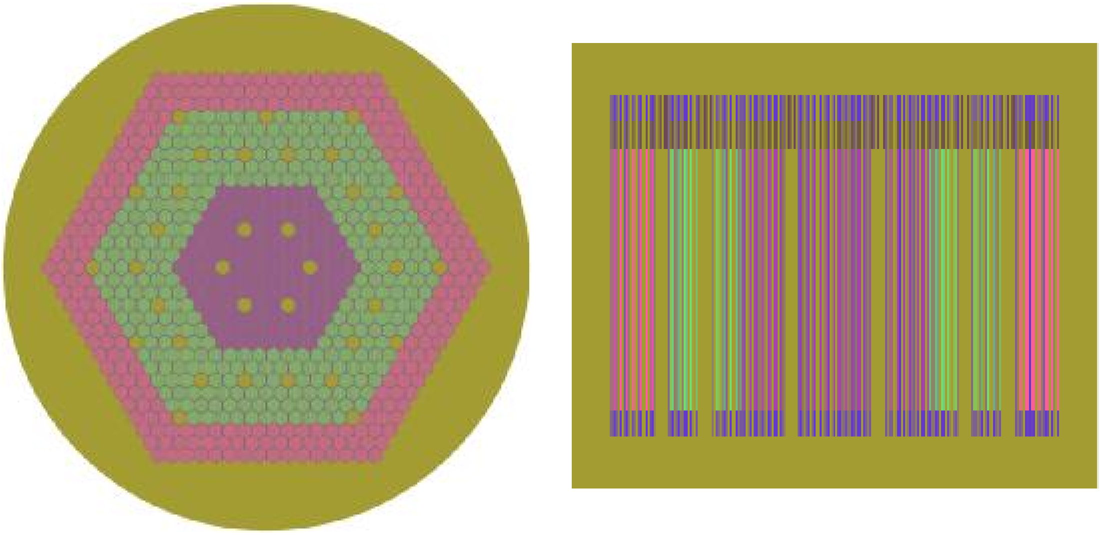


（a）Radial layout



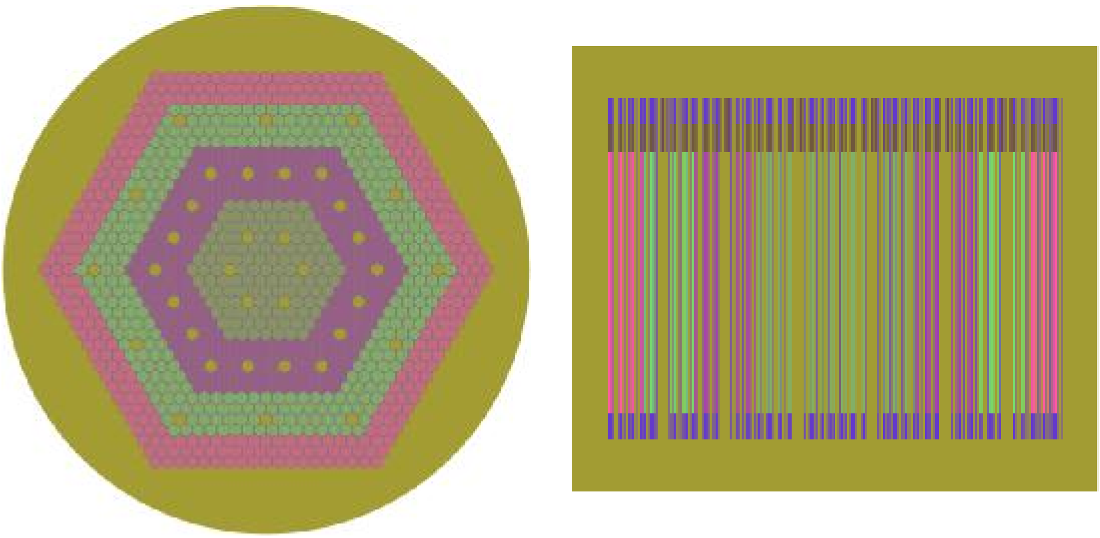
（b）Axial layout

Figure 3Schematic diagram of 300MW core



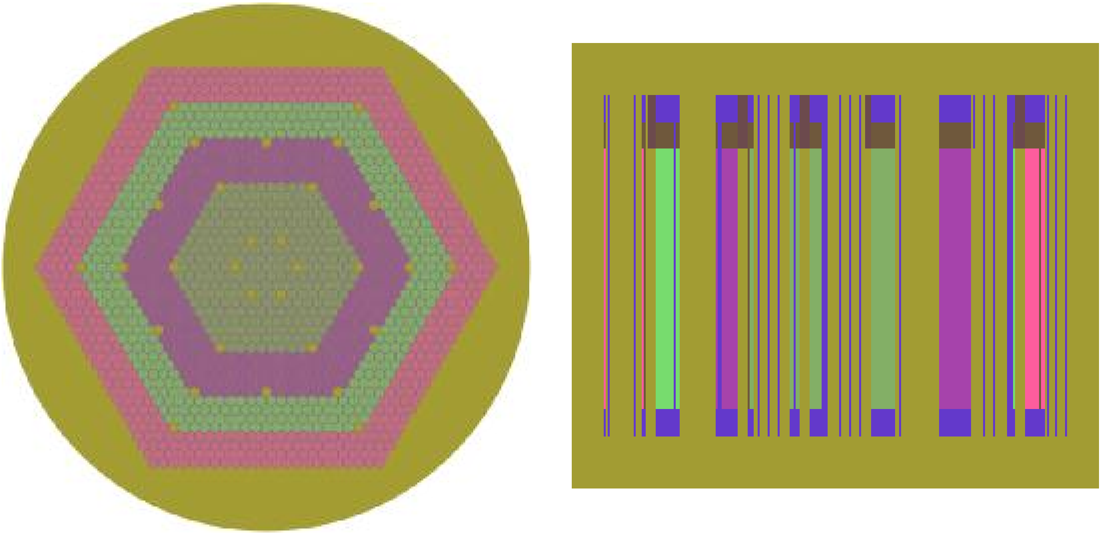
（a）Radial layout （b）Axial layout

Figure 4 Schematic diagram of 500MW core



（a）Radial layout （b）Axial layout

Figure 5 Schematic diagram of 700MW core



（a） Radial layout （b） Axial layout

Figure 6 Schematic diagram of 1000MW core

Table 3 Design parameters of each core scheme

Core schemes	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 5
Core thermal power /MWt	100	300	500	700	1000
Core life / EFPD	2000	2000	2000	2000	2000
Fuel pin density / (g/cm^3)	11.94	11.94	11.94	11.94	11.94
Fuel type	U-10Zr	U-10Zr	U-10Zr	U-10Zr	U-10Zr
Mass of ^{235}U at BOL /kg	882	2025	2930	4143	5952
Mass of ^{238}U at BOL /kg	3895	12242	19673	28510	42912
Mass of ^{235}U at EOL /kg	668	1425	1970	2782	3955
Mass of ^{238}U at EOL /kg	3762	11714	18711	27008	40605
Mass of ^{239}Pu at EOL /kg	94	372	667	964	1441
Utilization rate of ^{235}U / %	24.32	29.64	32.77	32.85	33.55
Utilization rate of ^{238}U / %	3.42	4.32	4.89	5.27	5.38
Fuel enrichment /%	19.50	15.00	14.00	14.00	13.50
	18.50	14.00	12.50	13.00	12.50
	17.50	13.50	12.00	12.00	11.50
	/	/	/	10.00	10.00
Number of fuel assemblies	344	433	686	991	1483
Number of control assemblies	18	36	35	36	30
Active core height /mm	1000	1000	1000	1000	1000
Outer reflector diameter / mm	≈1300	≈2200	≈2700	≈3300	≈3900
Average fuel enrichment /%	16.62	12.77	11.67	11.42	10.96

Core line power density / (W/cm)	11.31	11.36	11.95	11.58	11.05
Core body power density / (W/cm^3)	91.09	91.51	96.27	93.30	89.06
k_{eff} at BOL	1.059786	1.027194	1.009590	1.012693	1.012008
k_{eff} at EOL	1.008881	1.005588	1.009543	1.017490	1.023341

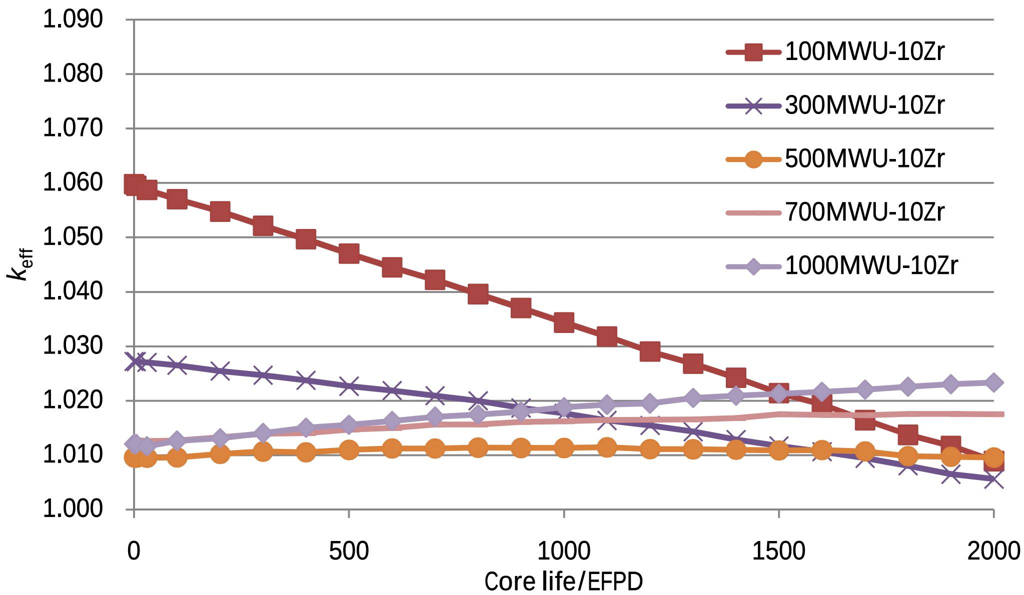


Figure 7Reactivity curves along core life time of each core scheme

From the comparison of the parameters of each core scheme in Table 3 and Fig. 7, it can be seen that the core design is carried out on the premise that the power density of the cores is not much different. When the core power level is 100MW and 300MW, the core k_{eff} curve increases with the decrease of lifetime monotonically, but the decreasing rate of the k_{eff} curve of the 300MW core is smaller than that of the 100MW core. When the core power is 500 MW, the k_{eff} curve rises and then decreases in a very small range during the core life. Due to the extremely small amplitude, it can be considered that there is almost no change in k_{eff} during the life of the core. When the core power is 700MW and 1000MW, the k_{eff} curve in the core life has an upward trend with the burnup, and the k_{eff} at the end of the life is larger than the beginning of the life. If the burnup is further deepened, the k_{eff} will show a downward trend to the end of the life. The core life has far exceeded the required 2000EFPD, which may not meet the core refueling cycle and fuel burnup limit requirements.

For the above-mentioned core schemes, the breeding performance of the 500MWt core has a good match with the core power and life. The breeding characteristics of the core during the 2000EFPD life are effectively utilized, and the reactivity fluctuation during the core life is very small. It is beneficial to the control of the core reactivity, and the core economy and safety are relatively high. The breeding characteristics of the 100MWt and 300MWt core schemes are relatively weak, while the breeding characteristics of the 700MWt and 1000MWt cores are relatively strong, both of which are not conducive to the improvement of fuel utilization and the control of core reactivity. Therefore, it is necessary to optimize the design of the cores with different power levels, and the core schemes of other power levels can also achieve the reactivity variation characteristics of the 500MWt coreby changing the core parameters.

4. Optimization Route Analysis

From the calculation and analysis results of the above schemes, it can be seen that when the uranium-zirconium alloy fuel is designed with different powers under the given assembly structure, power density level and core life, and the core power level is proportional to the core size, andthe breeding performance of the core is also proportional to the core power level and core size. At low power level, the core size is relatively small, the core breeding performance is weak, and the core reactivity curve shows a monotonically decreasing trend with burnup. And at high power level, the core size is larger and the core breeding performance is stronger, the core reactivity curve first increases and then decreases with burnup. When the core power level matches a given assembly structure, power density level and core lifetime, the core reactivity slightly increases firstly and then decreases throughout the lifetime. Due to the small fluctuation, it can be considered that the core reactivity hardly changes throughout the core life.

According to the above analysis, if it is necessary to design lead-based modular nuclear power reactor cores with different power levels in the project, it is necessary to design the assembly structure according to the core power level and lifetime, and at the same time, it is necessary to limit the volume power density level to meet the requirements of thermal safety analysis. This paper only qualitatively analyzes the power density level, focusing on the influence of the assembly structure on the physical performance of the core.

In addition to the size of the core, the breeding performance of the uranium-zirconium alloy fuel core is mainly affected by the uranium loading per unit volume. Therefore, the effective density of the uranium-zirconium alloy fuel core and rod to diameter ratio in the assembly can be changed as required. Two factors change the amount of uranium per unit volume.

Since the uranium-zirconium alloy fuel core needs to consider its radiation swelling effect, the effective density of 75% is generally used in the engineering design, that is, 15.92 g/cm^3×0.75=11.94 g/cm^3 above.

The rod to diameter ratio is the ratio of the center-to-center distance between the two fuel rods in the assembly to the fuel rod diameter. In the above analysis, the fuel rod center-to-center distance is 1.09 cm, and the fuel rod diameter is 9.2 cm. In addition to the parameters in the assembly, the center distance of the assembly also affects the uranium content per unit volume. And the center distance of the assemblies is 9.35cm. Since the center distance of the fuel rods in the assemblyand the center distance of the assembly need to be changed adaptively,so in this paper it's considered that the rod to diameter ratio as the main representative influencing factor.

5. Design Optimization

This section will take the 700MW and 1000MW cores as the research objects. By optimizing the effective density of the uranium-zirconium alloy fuel core and the ratio of the pitch distanceand the rod diameter, the corresponding optimized core schemes can be obtained respectively, so that the core reactivity can be improved. There is almost no change during the life cycle, so as to reduce the difficulty of controlling the reactivity of the core and make the breeding performance of the core match the power and life of the core, so as to improve the safety and economy of the core.

5.1. Assembly Optimization

According to the above optimization ideas, the parameter optimization is mainly carried out from the assembly level. Through calculation and verification, the fuel core density and the ratio of the pitch distanceand rod diameter used after optimization are shown in Table 4.

Table 4 main design parameters of assembly before and after optimazation

Parameters	Values（Before）	Values（After）
Fuel pin diameter / mm	8.0	8.0
Fuel pin density fraction/(%)	75%	**70%/65%**
Fuel pin density / (g/cm^3)	11.94	**11.144/10.384**
Air gap thickness / mm	0.1	0.1
Clad thickness / mm	0.5	0.5
Clad Outer diameter / mm	9.4	9.4
Fuel rod center distance / mm	10.9	**11.2/12.0/12.5**
Fuel effective temperature / K	900	900
Coolant temperature / K	700	700
Assembly center distance / mm	93.5	**96.5/103.5/105.5**
Assembly box inner distance / mm	88.0	**91.0/98.0/100.0**
Assembly box outer distance / mm	93.0	**96.0/103.0/105.0**
Assembly box thickness / mm	2.5	2.5
Assembly fuel rod number	61	61
Clad material	SS	SS
Coolant material	Lead-based	Lead-based

5.2. Core Optimization

Firstly, the core optimization design is carried out according to the assembly parameters after the optimized the rod to diameter ratio. By adjusting the fuel enrichment, two optimization schemes are proposed for Scheme 4 and Scheme 5, namely Scheme 4-O1, Scheme 4-O2, Scheme 5-O1 and scheme 5-O2.The design parameters of each core scheme are shown in Table 5, and the variation curve of reactivity with life of each core scheme is shown in Figure 8.

It can be seen from Table 5 that during the optimization of the scheme, by increasing the center distance of the fuel rods, the center distance of the assemblies, the inner-to-edge distance and the outer-to-edge distance of the assembly boxes are adjusted accordingly, and the average fuel enrichment of the core is appropriately increased. The diameter increases and the core power density decreases. This change is beneficial to thermal safety. The core power can be increased by appropriately increasing the core power densityin theory. But in this articlethe core power is not changedto show the optimization effect brought by it.

It can be seen from Fig. 8 that after optimizing the rod to diameter ratio of scheme 4-O1 and scheme 5-O1 match the core power and lifetime, and the reactivity of the core increases firstly and then increases during the lifetime. There is a downward trend, but the change range is very small, and it can be considered that the core reactivity hardly changes during the whole lifetime. Scheme 4-O2 and Scheme 5-O2 further increase the center distance of fuel rods on the basis of Scheme 4-O1 and Scheme 5-O1, and the reactivity curve shows a monotonically decreasing trend during the core lifetime, which is the similar to that of Scheme 1 and Scheme 2with core powers of 100 MW and 300 MW in Fig. 7, indicating that the breeding performance of the core is not enough to compensate for the reactivity loss caused by the core burnup.

From the above analysis and calculation results, it can be seen that the breeding performance of the core can be changed by adjusting the rod to diameter ratio, and the power and life of the core can match with the appropriate rod to diameterratio, and finally the reactivity of the core hardly changes with the life, or the reactivity of the core can be monotonically decreased with the lifetime by further increasing the rod to diameter ratio. Similarly, Schemes 1 and 2 with power levels of 100 MW and 300 MW should theoretically be able to make the core reactivity almost unchanged with life by reducing the rodtodiameter ratio. However, it can be seen from Table 5 that the disadvantageous factor brought by increasing the rodtodiameter ratio is that the average fuel enrichment of the core needs to be increased, thereby increasing the ^{235}U inventory of the core, and it is not conducive to the breeding performance of the core, and ultimately reduce the core fuel utilization rate.

Table 5 Design parameters of each core scheme before and after optimization of the rod to diameter ratio

Scheme NO of the cores	Scheme 4	Scheme 4-O1	Scheme 4-O2	Scheme 5	Scheme 5-O1	Scheme 5-O2
Thermal power /MWt	700	700	700	1000	1000	1000
Core lifetime / EFPD	2000	2000	2000	2000	2000	2000

Fuel pin theoretical density/ (g/cm^3)	15.92	15.92	15.92	15.92	15.92	15.92
Fuel pin type	U-10Zr	U-10Zr	U-10Zr	U-10Zr	U-10Zr	U-10Zr
Effective fraction of fuel pin density /%	75%	75%	75%	75%	75%	75%
Fuel pin density/(g/cm^3)	11.94	11.94	11.94	11.94	11.94	11.94
Fuel rod distance /mm	10.9	**11.2**	**12.5**	10.9	**12.0**	**12.5**
Assembly center distance /mm	93.5	**96.5**	**105.5**	93.5	**103.5**	**105.5**
Assembly inner distance /mm	88.0	**91.0**	**100.0**	88.0	**98.0**	**100.0**
Assembly outer distance /mm	93.0	**96.0**	**105.0**	93.0	**103.0**	**105.0**
Mass of ^{235}U at BOL /kg	4143	4183	4633	5952	6441	6579
Mass of ^{238}U at BOL /kg	28510	28470	28020	42912	42423	42285
Mass of ^{235}U at EOL /kg	2782	2884	3212	3955	4448	4568
Mass of ^{238}U at EOL /kg	27008	27153	26765	40605	40509	40402
Mass of ^{239}Pu at EOL /kg	964	914	901	1441	1379	1362
Utilization rate of ^{235}U / %	32.85	31.05	30.67	33.55	30.94	30.57
Utilization rate of ^{238}U / %	5.27	4.63	4.48	5.38	4.51	4.45
Fuel enrichment /%	14.00	14.00	**15.5**	13.50	**14.5**	**14.7**
	13.00	13.00	**14.5**	12.50	**13.5**	**13.7**
	12.00	12.00	**13.5**	11.50	**12.5**	**12.7**
	10.00	**11.00**	**11.5**	10.00	**11.0**	**11.7**
Number of fuel assemblies	991	991	991	1483	1483	1483
Number of control assemblies	36	36	36	30	30	30
Active core height /mm	1000	1000	1000	1000	1000	1000
Outer reflector	≈3300	**≈3390**	**≈3780**	≈3900	**≈4300**	**≈4470**

diameter / mm						
Average fuel enrichment /%	11.42	**11.53**	**12.77**	10.96	11.86	12.12
Core line power density / (W/cm)	11.58	11.58	11.58	11.05	11.05	11.05
Core body power density / (W/cm^3)	93.30	**87.59**	**73.28**	89.06	**72.69**	**69.96**
k_{eff} at BOL	1.012693	1.008185	1.022413	1.012008	1.009678	1.014986
k_{eff} at EOL	1.017490	1.007989	1.005618	1.023341	1.006486	1.008197

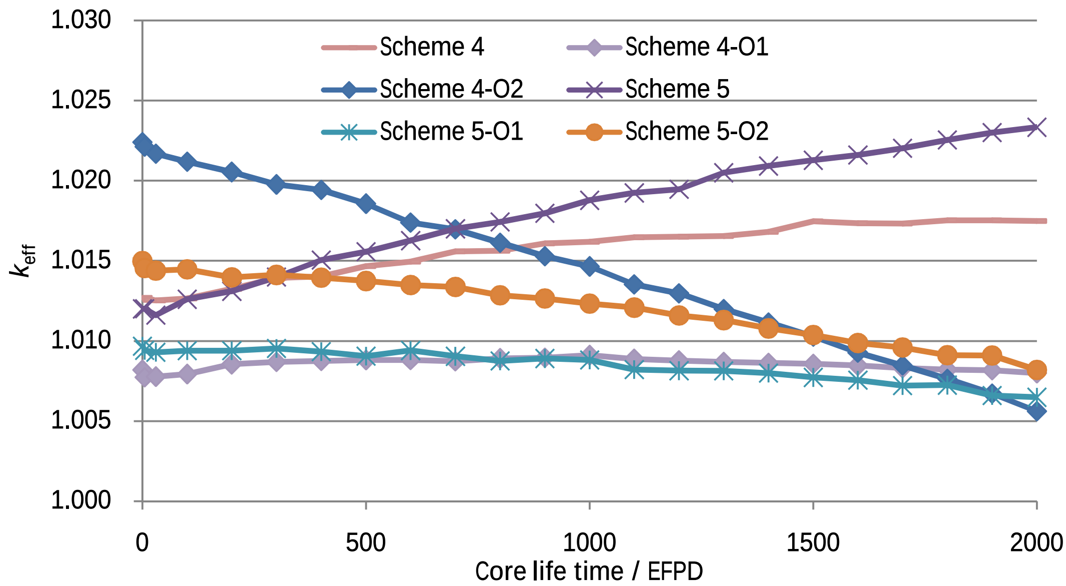


Figure 8 Reactivity curves along core life time of each core scheme before and after optimization of the rod to diameter ratio

This section continues to use the method of optimizing the fuel core density above to optimize the core design. Taking Scheme 4 as an example, the design parameters of each core scheme before and after optimizing the fuel core density are shown in Table 6. The change curve of core reactivity with life is shown in Figure 9.

It can be seen from Table 6 that by reducing the effective density of the fuel from 75% to 70% and 65%, the required inventoryof U and ^{235}U of the core will be reduced, and the uranium resource utilization at the end of the core life will be appropriately improved.

It can be seen from Fig. 9 that the reactivity of scheme 4-O3 hardly changes during the lifetime after the fuel core density is optimized, while the reactivity of the core of scheme 4-O4 decreases with the lifetime due to the further reduction of the effective density of the fuel core, and the reduction is a monotonous downward trend.

By adjusting the fuel core density, the change trend of the core reactivity with life can be adjusted. When the effective density of the fuel core matches with the core power and life, the core reactivity can hardly change during the life. At the same time, by adjusting the density of the fuel core, the inventory of U and ^{235}U in the core at the beginning of the life can also be reduced, and the utilization rate of uranium resources can be appropriately improved.

Table 6 Design parameters of each core scheme before optimization of the density of fuel pin

Scheme NO of the cores	Scheme4	Scheme4-O3	Scheme4-O4
Thermal power /MWt	700	700	700
Core lifetime / EFPD	2000	2000	2000
Fuel pin theoretical density / (g/cm^3)	11.94	11.94	11.94
Fuel pin type	U-10Zr	U-10Zr	U-10Zr
Effective fraction of fuel pin density /%	75%	**70%**	**65%**
Fuel pin density /(g/cm^3)	11.94	**11.144**	**10.384**
Fuel rod distance /mm	10.9	10.9	10.9
Assembly center distance /mm	93.5	93.5	93.5
Assembly inner distance /mm	88.0	88.0	88.0
Assembly outer distance /mm	93.0	93.0	93.0
Mass of ^{235}U at BOL /kg	4143	3965	3908
Mass of ^{238}U at BOL /kg	28510	26511	24391
Mass of ^{235}U at EOL /kg	2782	2616	2542
Mass of ^{238}U at EOL /kg	27008	25112	23095
Mass of ^{239}Pu at EOL /kg	964	937	886
Utilization rate of ^{235}U / %	32.85	34.02	34.95
Utilization rate of ^{238}U / %	5.27	5.28	5.31
Fuel enrichment /%	14.00	**14.2**	**15**
	13.00	**13.2**	**14**
	12.00	**12.2**	**13**
	10.00	**11.2**	**12**
Number of fuel assemblies	991	991	991
Number of control assemblies	36	36	36
Active core height /mm	1000	1000	1000
Outer reflector diameter / mm	≈3300	≈3300	≈3300
Average fuel enrichment /%	11.42	**11.71**	**12.43**
Core line power density / (W/cm)	11.58	11.58	11.58
Core body power density / (W/cm^3)	93.30	93.30	93.30
k_{eff} at BOL	1.012693	1.008178	1.018577

k_{eff} at EOL	1.017490	1.008019	1.005044

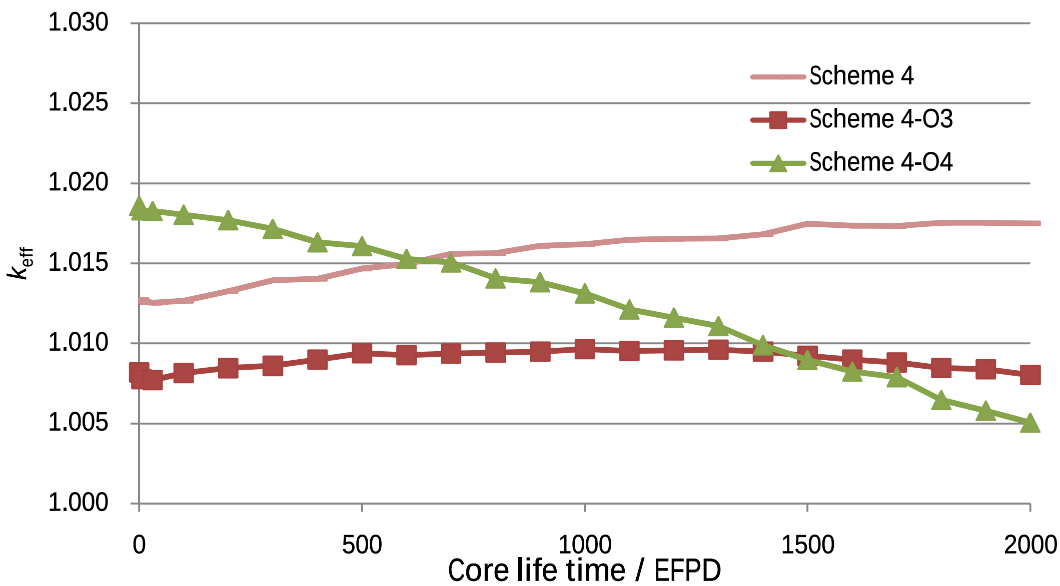


Figure 9Reactivity curves along core life time of each core scheme before optimization of the density of fuel pin

6. Conclusion

In this paper, by studying the uranium-zirconium alloy fuel core scheme at different power levels, it is found that with the increase of the core power level and the increase of the core size, the reactivity of the core will increase firstly and then decrease with the life cycle, andat the end of the core life, the core reactivity cannot be effectively released. Based on this phenomenon, an optimization idea is proposed in this paper. By optimizing the rod to diameterratio and the density of the fuel, the reactivity of the core hardly changes during the lifetime, or the reactivity of the core decreases monotonically with the lifetime. It can effectively improve the safety and economy of the core. The main conclusions of the above research are as follows:

(1) With the increase of thecore size with uranium-zirconium alloy fuel, the breeding performance of the core gradually increases, and the reactivity of the core will increase firstly and then decrease with the life.

(2) By adjusting the rodtodiameter ratio, the breeding performance of the core can be adjusted, so that the reactivity of the core hardly changes during the lifetime, but it will reduce core fuel utilization.

(3) By adjusting the density of the fuel, the breeding performance of the core can also be adjusted, and the reactivity of the core can also be almost unchanged during the life cycle, which can not only effectively reduce the inventory ofU and ^{235}U at the beginning of the life, but also it can improve the utilization rate of core fuel.

(4) The thermal performance of the core will be changed by adjusting the rod to diameter ratio. The design

optimization of increasing the rod to diameterratioin this paperis conducive to thermal safety. In the subsequent consideration of the physical and thermal coupling, both the rod to diameterratio and fuel density can be adjusted, which ultimately improves the safety and economy of the core.

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