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Core physics calculation study of miniature lead-bismuth cooled nuclear reactor

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Abstract. Aiming at the application environment of small marine nuclear power platform, a 1MW Lead-Bismuth cooled nuclear reactor design scheme was proposed. The Monte Carlo method was used to calculate the reactor core physical parameters. 469 core fuel rods were arranged in 13 turns and 90% enriched UO₂ fuel loading meet the power operation of nearly 10 years, and the core size meets the environmental requirements. The calculation results of fuel consumption show that after each loading, the reactor can run continuously for 1 year at 1 MW power. The radial density and axial flux density distribution and power distribution gradient trend of the core are reasonable, indicating that the design scheme can meet the requirements of small ships. Nuclear power platform use requirements.

1. Introduction

It is generally believed that the Lead-Bismuth cooled reactor has the following characteristics. 1) Compared with the sodium-cooled fast reactor, the lead-bismuth cooling fast reactor has a simplified structure and high economy. The liquid lead-bismuth cooled fast reactor is a direct circulation system, and the LBE does not change the phase state in the reactor. In addition, due to the simplification of the structure, the entire system is miniaturized, and the volume of the containment is correspondingly reduced. 2) Although the melting point of LBE is slightly higher than that of sodium, its chemical activity is weak, and it is inert with water. 3) Under the same geometric conditions, the LBE cooling system is better at using neutrons than sodium. Since the density of LBE is much larger than that of liquid sodium, the average free path of neutrons in LBE is less than that of sodium. And LBE has a good reflective ability to prevent neutrons from escaping the core. 4) The fuel cycle is closed, which can realize the effective conversion of U-238 and the effective management of actinides. 5) The LBE cooled fast reactor has good inherent safety and passive safety features.

In the early 1990s, Russia proposed the SVBR-75/100 design concept, which deciphered Russia's unique LBE development technology, which attracted widespread attention from the international nuclear science community and booms the research of reactor using lead and lead alloys as coolant [1]. A large number of studies have been carried out in Korea, Japan and EU countries [2-6].

In this paper, a 1 MW Lead-Bismuth cooled nuclear reactor scheme is proposed for the marine nuclear power platform application environment. The Monte Carlo method is used to calculate the core physical parameters. The results show that the design scheme can meet the needs of marine nuclear power platform.

2. Miniature lead-bismuth cooled reactor core solution



Miniature Lead-Bismuth cooled reactors need to be compact and inherently safe, and the core can run for a long life while achieving high maneuverability and flexibility.

Space reactor core design The TOPAZ-II reactor is a small, zirconium hydride-moderated space reactor using highly enriched uranium 235 fuel, low temperature thermal design, including 37 single cell systems, combined with fission heat source heat exchangers [7]. The reactor contains 37 individual fuel elements with a 90% enrichment of fuel U235 surrounded by a moderator package. The fuel element is placed in an axially stacked five zirconium hydride moderator block surrounded by a beryl (Be) reflective layer. The reactor is cooled by sodium-potassium eutectic (NaK), and the coolant enters the reactor core through the lower supercharger and then passes through the upper space from the outer surface of the fuel element and the outlet. The fuel elements are evenly distributed throughout the moderator and the exterior is surrounded by an outer reflective layer. 12 drums are uniformly distributed in the outer reflection layer to control the reactivity of the reactor, 9 of which are control drums, 3 are safe drums, and the outer surface of each drum is made of boron carbide with a center angle of 120°. The absorber controls the reactor core by changing the angular change of the drum and the drum shaft to introduce different reactivity. Figure 1 is the top view and cross-sectional view of the core of the TOPAZ-II reactor.

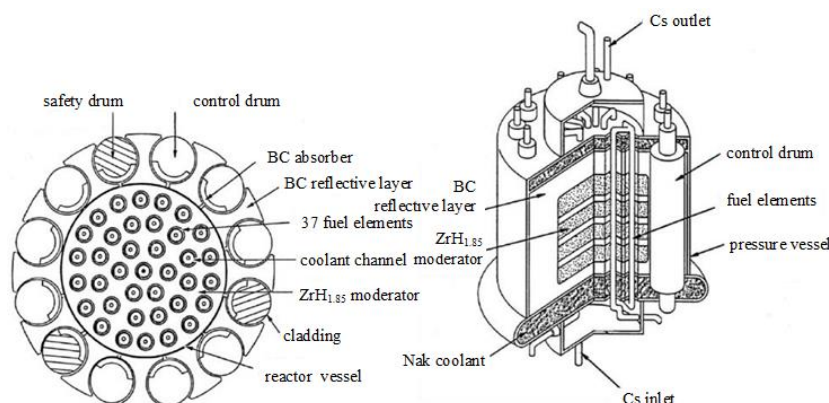


Figure 1. Top view and a cross-sectional view of the TOPAZ-II reactor core.

The TOPAZ-II reactor has a design life of 3 years and the reactor unit has a mass of approximately 1000 kg. The reactor has a thermal power of 115 kW at full power operation, a maximum output power of 5.5 kW, and a thermoelectric conversion efficiency of approximately 4.78%. The reactor power supply output voltage is 27 V, which is a DC power supply. The design advantages of Lead-Bismuth cooled reactors are combined with the compact arrangement of space reactors to design the miniature Lead-Bismuth cooled reactor core.

3. Calculation of core physics

3.1. Monte Carlo program

The Monte Carlo method can use accurate continuous energy spectra to calculate reactor physical parameters of any complex geometry and material. Because of these advantages, the Monte Carlo method has been used in recent years for the calculation of physical parameters of different types of reactors. MCNP (Monte Carlo N-Particle transport code) is one of the most versatile three-dimensional Monte Carlo programs in the world. The Re-section library is provided to the MCNP program for calculating the effective value-added factor and neutron flux density, as shown in figure 2.

The calculation of fuel consumption requires the solution of the radionuclide density equation given the neutron flux and the conversion cross section. The Origen program calculates the accumulation and decay of radioactive material during the nuclear fuel cycle and simulates the radiological characteristics of the fuel assembly during post-processing. The program is equipped with

a comprehensive single-group equivalent conversion section Library and a decay bank for PWR, boiling water reactor, liquid metal block heap and heavy water reactor, and the fission yield of five kinds of important fission nuclides is given for each heap type. Because Monte Carlo program can match point continuous cross section, the Energy variable processing of transport equation is more accurate, and has powerful geometric processing function, so the use of Montessori program in the research of advanced nuclear energy system has unique advantages. The common characteristic of these coupling programs is to obtain the various conversion sections needed for flux and fuel consumption calculation with MCNP, and then use Origen to obtain the kernel density for the next transport calculation.

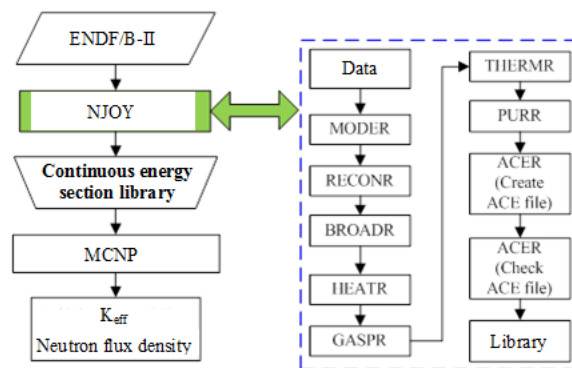


Figure 2. Generation of MCNP program.

Therefore, it is feasible to use the coupling program of three-dimensional transport and fuel consumption to accurately simulate the change of neutron flux distribution and radionuclide density in the miniature lead bismuth reactor. MCNP can not only solve the problem of anisotropic neutron transport, but also greatly relax the limitation of geometric shape. The Origen includes data such as a more complete decay chain, fission yield, various nuclear reaction sections and their release energy. The calculation process is shown as following. (1) Read the initial information entered by the user and generate the initial input file of Origen; (2) The initial flux is obtained by running MCNP; (3) Use the initial flux to update the input file of the Origen and run to the midpoint of the fuel-draining step; (4) Read the Origen output file, update the material nuclear density information and counting card of the MCNP input file, and run the MCNP; (5) Read the MCNP output file (flux, fuel consumption material single Group section, etc.), update the Origen program input file and database, and run ORIGEN to the end of the fuel consumption step.

3.2. Design parameters

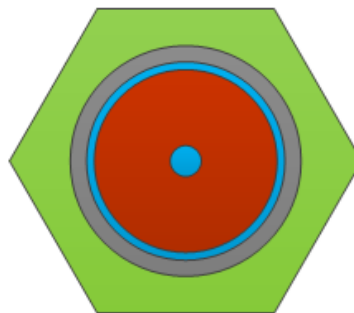


Figure 3. Schematic diagram of the geometric structure of the fuel rod grid element.

The core refers to the geometrical arrangement of the existing lead bismuth reactor, and the fuel rods are arranged in a triangular manner. The fuel cores in the fuel rods are UO_2 as fuel, and the reflectors and enclosures are BeO and T91 steel, respectively.

The fuel rods are arranged in a positive triangle, with a LBE coolant between the rods, as shown in figure 3. The fuel rod parameters are shown in table 1.

In order to make the core small and run for a long time, high-enriched UO_2 is used as fuel. At the same time, according to the design scheme of the space reactor, the stop heap and control the residual reactivity are realized by rotating the control drum on the outside of the core.

Table 1. Main design parameters of fuel rods.

Parameter	Value
Total length of fuel rods/mm	1040
Fuel rod Active section long/mm	500
Fission gas cavity length/mm	300
Reflection Layer Thickness/MM	100
End Plug Length/mm	20
Fuel rod Diameter D/MM	9.4
Grid distance P/MM	10.9
Fuel Core block diameter/mm	8
Air gap thickness/MM Shell thickness/mm	0.2
Total length of fuel rods/mm	0.5

The core layout is shown in figure 4. The core is a fuel assembly, the fuel rod bundle is triangular distribution, and the lead bismuth coolant flows up from the bottom of the core between the rods. The perimeter of the core is 12 control drums made of BC materials to regulate reactivity, radial and axial reflection layers for beo materials.

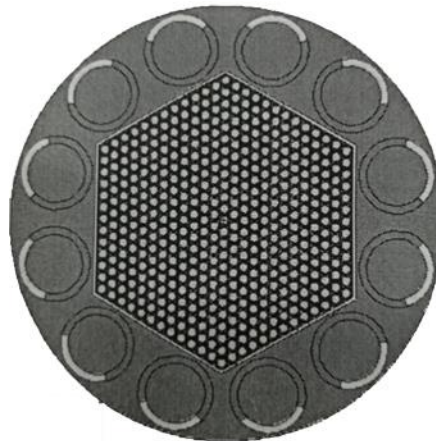


Figure 4. Radial layout of the reactor core.

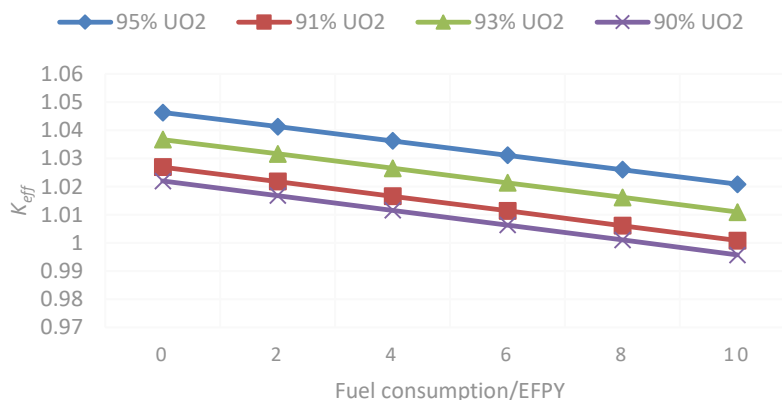
4. Results and discussions

When the number of core fuel rods is 469 (13 laps). The MCNP and Origen coupling program is used to calculate the UO_2 fuel load with different enrichment degrees, and the calculated results are shown in table 2 and figure 5.

As a result, 90% enriched UO_2 fuel loads can be selected to meet nearly 10 years of power operation.

Table 2. Calculation results of combustion consumption after UO_2 fuel loading with different enrichment degree.

Operation years	95% UO_2	93% UO_2	91% UO_2	90% UO_2
0	1.0463219	1.0367268	1.0269557	1.0219932
2	1.0413039	1.0316533	1.0218154	1.0168294
4	1.0362473	1.0265332	1.0166333	1.0116144
6	1.0311544	1.0213783	1.0114205	1.0063654
8	1.0260308	1.0161932	1.0061649	1.0010750
10	1.0208679	1.0109659	1.0008765	0.9957578

**Figure 5.** Comparison of fuel consumption results of miniature lead bismuth reactors loaded with different enrichment UO_2 fuels.

When the enrichment degree of the fuel is determined, different quantities of fuel rods are selected for the calculation of combustion consumption. 10-lap fuel rods, or 271 fuel rods; 11-lap fuel rods, or 331 fuel rods; 12-lap fuel rods, or 397 fuel rods; 13-lap fuel rods, or 469 fuel rods; 14-lap fuel rods, or 547 fuel rods. The calculated results are shown in table 3 and figure 6. According to the calculation results, the selection of 13 laps (469) fuel rods, 90% UO_2 fuel load, can meet the power operation of nearly 10 years, but also can make the core size is small. Therefore, this study will be used as the final geometric and fuel composition design scheme of miniature lead bismuth reactor core.

At the beginning of the core life, the control drum is fully opened and the core K_{eff} is 1.022, and when the control drum is completely closed, the K_{eff} is about 0.97, and the total value of all control drums at the beginning of the life period is 5200 PCM, and the value of a single control drum is 433 PCM. After each loading, the reactor can operate continuously for about 8 years at 1 MW power.

Table 3. Calculation results of combustion consumption of different quantities of fuel rods after loading.

Operation years	10ring	11 ring	12 ring	13 ring	14 ring
0	0.7722355	0.8576732	0.9411025	1.0219932	1.0999415
2	0.7645134	0.8509614	0.9352327	1.0168294	1.0953733
4	0.7566999	0.8441849	0.9293026	1.0116144	1.0907681
6	0.7488117	0.8373441	0.9233231	1.0063654	1.0861338
8	0.7408463	0.8304467	0.9173051	1.001075	1.0814707
10	0.7327992	0.8234877	0.9112371	0.9957578	1.0767800

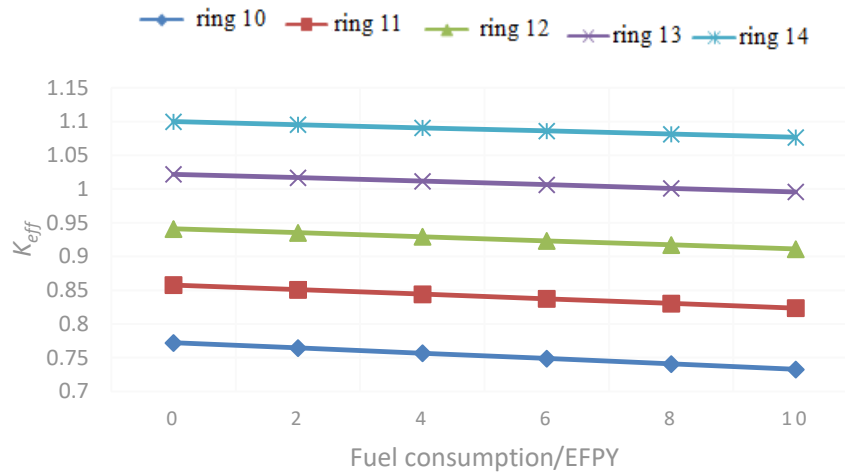


Figure 6. Comparison of combustion results of miniature lead bismuth reactors loaded with different quantities of fuel rods.

Monte Carlo program is used to calculate the radial and axial flux of the core, and the results are shown in figure 7. The calculation results of the power distribution are shown in figure 8.

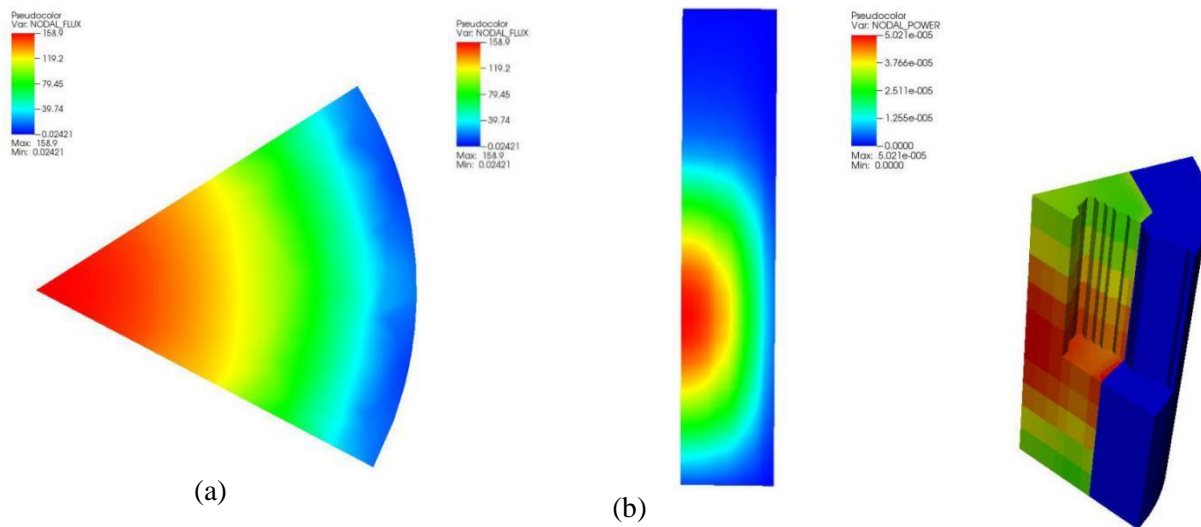


Figure 7. Results of neutron flux density distribution. (a) radial flux density distribution and (b) axial flux density distribution.

Figure 8. Core power distribution of the lead-bismuth cooled nuclear reactor.

5. Conclusions

A 1 MW Lead-Bismuth cooled nuclear reactor solution is proposed and the core physics parameter as fuel consumption efficiency and neutron flux density distribution as well as power distribution was calculated.

MCNP (Monte Carlo N-Particle transport code) is used in the work and the results show that the scheme with 469 core fuel rods arranged in 13 turns and 90% enriched UO_2 fuel loading meet the power operation of nearly 10 years and a reasonable neutron flux density distribution and power distribution of the core. The presenting Lead-Bismuth cooled nuclear reactor can be applied in a marine nuclear power platform.

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