Study on Reactor Core Physics Calculation of Marine Nuclear Power Platform

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Abstract: The marine nuclear power platform is an organic combination of small nuclear reactor and ship engineering technology. It has the characteristics of good manoeuvrability, long on-time charging operation cycle, high power density, low operating cost, energy saving and environmental protection. In this paper, The core geometry model is built based on the design of the marine nuclear power platform reactor core. The core reactivity and control rod worth are calculated by a Monte Carlo code MCNP for this core design at first cycle, initial loading, normal temperature, and normal pressure condition. The results of the calculation are compared with nuclear design values. It shows that MCNP code is suitable for marine nuclear power platform core design calculation, and can be verified with nuclear design values.

1. Introduction
The marine nuclear power platform is an organic combination of small nuclear reactors and ship engineering technology. It is a floating nuclear power plant (FNPP) with complex system engineering features that can continuously provide power, fresh water and other resources to the outside world. It has the characteristics of good manoeuvrability, long one-time charging operation cycle, high power density, low operating cost, energy saving and environmental protection. It does not occupy precious land resources. It has obvious advantages in the development of marine resources, construction of islands and reefs, and future deep-sea exploration and other energy security programs to meet the needs of sustainable development. Therefore, it has broad application prospects. The marine nuclear power reactor is the central component of the marine nuclear power platform, and it is the energy source that produces external electricity, fresh water output, or as a power to propel ships to sail.

Nuclear design calculations have always played an important role in the safety analysis of marine nuclear power platform reactors, and the accuracy and reliability of their calculations have always been the focus of security reviews. In this paper, the MCNP program is used to establish an accurate MC model of the reactor core of the marine nuclear power platform. The reactive distribution and control rod value under the cold state and normal pressure of the initial charge in the first cycle are calculated. It provides guidance for the safety analysis of marine nuclear power platform reactors.

2. Marine nuclear power platform core
The marine nuclear power platform reactor core is the central device that provides fission heat for the system. As an important part of the marine nuclear power platform, the reactor core of the marine nuclear power platform uses a thermal neutron pressurized water reactor with light water as the coolant and moderator. The fuel element uses UO₂ sintered pellets with a $^{235}$U enrichment of about 3%. The reactor core consists of 283 fuel assemblies, 77 solid combustible poison rods and 25 control rods.
The core radial reflector mainly includes water, a basket and a pressure vessel. The axial reflection layer mainly includes fuel rod air cavity, end plug, tube seat, grid plate, water and so on. The core fuel assemblies are arranged in a hexagonal grid, as shown in Figure 1. Every 7 or 6 control rods form a bunch, 25 control rod bunches are divided into 8 groups: A, C1, C2, E1, E2, F1, F2, N. Each group of control rods realizes reactive control through joint action.

There are three types of fuel assembly in the core of the marine nuclear power platform reactor [5], including pure assemblies, control rod assemblies, and combustible poison assemblies. The material of the assembly box and the centred guide tube are both Zr-4 alloy. Two circles of fuel elements are evenly arranged at an angle, 12 in the inner ring and 18 in the outer ring, a total of 30 fuel elements are arranged. The fuel element is composed of Zr-4 alloy cladding, helium gas gap and uranium dioxide fuel pellets. The combustible poison rod structure is in the form of a ring-shaped pellet sleeve, and the middle interlayer is a B4C-Zr-2 absorber. The control rod is a ring-shaped hafnium absorber with a total length of 1300 mm. The main parameters of the marine nuclear power platform fuel assembly are listed in Table 1.

![Schematic diagram of core layout](image)

**Fig.1. Schematic diagram of core layout**

| Table 1. Parameters of fuel assembly for marine nuclear power platform |
|-----------------|-----------------|-----------------|
| Item            | Physical parameter | Value           |
| Fuel rod        | Outer diameter / mm | 8.00            |
|                 | Inner diameter / mm | 6.70            |
|                 | UO₂ pellets diameter / mm | 6.55 |
|                 | Cladding wall thickness / mm | 0.65 |
| Fuel rod bundle | Layout            | Double concentric circles |
|                 | Number of fuel rods in outer ring | 18 |
|                 | Number of fuel rods in inner ring | 12 |

3. Methods

The MCNP code is a large-scale multifunctional Monte Carlo program developed by the Alamos Laboratory in the United States. Different from deterministic numerical methods, this code uses statistical numerical methods, which can be used to calculate neutron transport problems and eigenvalue problems. The MCNP code can handle more complex geometric structure problems with its powerful three-dimensional description capabilities. Since MCNP is an internationally recognized neutron and photon transport program, this software is often chosen for reference and comparison when modelling the core. MCNP simulation is based on appropriately simplifying the supporting components of the reactor, modelling from the inside to the outside, from building the fuel rods to the...
core, and finally the core components. MCNP is used to establish a whole-core calculation model, as shown in Figure 2 and Figure 3.

The calculation ignores the influence of the positioning grids arranged in the axial direction of the components. The top and bottom reflective layers of the component axis are homogenized. The outer surface of the reflection layer at the top and bottom of the calculation model adopts vacuum boundary conditions, and the outside of the pressure vessel is also vacuum. In this study, the eigenvalues of the reactor core are calculated, and the neutron flux rate of the core is high and the distribution is relatively uniform. Therefore, the neutron importance IMP of each cell in the core is set to 1; the neutron importance of the area outside the reactor is set to 0, which means that the neutron will be automatically annihilated when leaving the reactor. When establishing the calculation model, use the KCODE card to define the critical source. Each generation has 200,000 neutrons and 500 generations are calculated, of which 100 generations are skipped. The nuclear database used and evaluated is ENDF/B-VI [6].

4. Numerical results

4.1. Reactivity calculation

The reactor should have enough initial residual reactivity to compensate for the loss of reactivity during operation caused by temperature effects, poisoning, fuel consumption, so as to ensure the
expected burnup depth and core life. In all operating modes of the reactor, assuming that the bundle of control rods with the greatest reactivity value is stuck outside the core (sticking rod criterion), the $k_{\text{eff}}$ is required to be less than 0.99 to ensure safe shutdown and have a certain shutdown margin \cite{7}. When the fuel assembly has been loaded into the pressure vessel and the top cover of the vessel is opened, all control rods are put into the core, and the $k_{\text{eff}}$ should be less than 0.95. The initial cold critical calculation results of the core are shown in Table 2.

The calculation results show that the reactor has sufficient initial residual reactivity and shutdown margin to meet the requirements of the clamping rod design criteria. Secondly, the maximum reactivity deviation between the nuclear design value and the MCNP calculation result occurs when the control rods are fully inserted, which may be caused by the superposition of multiple control rod deviations.

Table 2. $k_{\text{eff}}$ and reactivity values in different states of the initial core

| Calculation status                                     | $k_{\text{eff}}$ | Deviation /pcm | Reactivity | Deviation/pcm |
|--------------------------------------------------------|------------------|----------------|------------|--------------|
| Cold, no control rods, no burnable poisons             | 1.29750          | -248           | 22929      | -148         |
| Cold, no control rods, burnable poisons                | 1.21157          | -192           | 17462      | -131         |
| Cold, the control rod is fully inserted, burnable poison | 0.93112         | -332           | -7397      | -384         |
| Cold, a bank of maximum control rods worth are stuck, burnable poison | 0.97944         | -77            | -2099      | -80          |

4.2. Control rod worth calculation

Control rod worth calculation is the reactivity calculation when a certain control rod is inserted or withdrawn in the core. The different reactivity in the two cases is the control rod worth. The control rod worth is often related to the constantly changing state of the core, such as the core neutron spectrum, the moderator density, and the neutron flux rate at the position of the control rod.

Table 3 shows the calculation results of the reactivity value of each control rod group in the cold state at the beginning of the lifetime. It can be seen that the total value of each control rod group inserted separately is 14578pcm, which is less than the value when the control rods are fully inserted (24860pcm), and the total interference effect between the control rod groups is positive. In addition, when the control rod is inserted alone, the deviation between the core design value and the MCNP calculation result is less than 100pcm.

Because of the strong interference effect between the control rods, there is a big difference in the value when there are control rods in the stack and when they are inserted separately. Since the central neutron flux rate is high when the net reactor has no control rods, the central rod has a high value. When the control rods are fully inserted, the neutron flux peak moves to the periphery, and the value of the peripheral control rods will increase relatively. The value of each group of control rods is proposed in turn according to the rod raising procedure, which is of reference significance for the operation of the reactor. Therefore, Table 4 and Table 5 respectively show the value of control rods when E1 and C1 are used as the regulating rods, and the other rod groups are successively proposed to the core according to the corresponding rod raising procedures. It can be seen that the deviation between the nuclear design value and the MCNP calculation result is less than 100pcm.
### Table 3. Calculation results of control rod worth

| Calculation status                  | Control rod bank position | Control rod worth /pcm | Design value | MCNP | Deviation |
|------------------------------------|---------------------------|------------------------|--------------|------|-----------|
| All control rods are withdrawn     | A C1 C2 E1 E2 F1 F2 N    | - - - - - - - -       | -            | -    | -         |
| Insert the A bank                  | I O O O O O O O         | 1352 1397 45          | 1352         | 1397 | 45        |
| Insert the C1 bank                 | O I O O O O O O         | 3931 3978 47          | 3931         | 3978 | 47        |
| Insert the C2 bank                 | O O I O O O O O         | 3930 3997 67          | 3930         | 3997 | 67        |
| Insert the E1 bank                 | O O O I O O O O         | 1442 1536 94          | 1442         | 1536 | 94        |
| Insert the E2 bank                 | O O O O I O O O         | 1484 1548 64          | 1484         | 1548 | 64        |
| Insert the F1 bank                 | O O O O O I O O         | 989 985 -4            | 989          | 985  | -4        |
| Insert the F1 bank                 | O O O O O O I O         | 928 969 41            | 928          | 969  | 41        |
| Insert the N bank                  | O O O O O O O I         | 520 557 37            | 520          | 557  | 37        |
| All control rods are inserted      | I I I I I I I I         | 24860 25113 253       | 24860        | 25113| 253       |

### Table 4. Calculation results of control rod worth

| Calculation status                  | Control rod bank position | Control rod worth /pcm | Design value | MCNP | Deviation |
|------------------------------------|---------------------------|------------------------|--------------|------|-----------|
| Adjust E1 to 600                    | A C1 C2 E1 E2 F1 F2 N    | 3713 3717 4            | 3713         | 3717 | 4         |
| Propose N in order                 | I I I I 600 I I I I O   | 4232 4328 96          | 4232         | 4328 | 96        |
| Propose F1 in order                | I I I I 600 I O I O O   | 3574 3638 64          | 3574         | 3638 | 64        |
| Propose F2 in order                | I I I I 600 I O O O O   | 2193 2174 -19         | 2193         | 2174 | -19       |
| Propose A in order                 | O I I I 600 I O O O O   | 358 317 -41           | 358          | 317  | -41       |
| Propose E2 in order                | O I I I 600 O O O O O   | 2525 2602 77          | 2525         | 2602 | 77        |
| Propose C1 in order                | O O I I 600 O O O O O   | 3241 3248 7           | 3241         | 3248 | 7         |
| Propose C2 in order                | O O O O 600 O O O O O   | 4164 4188 24          | 4164         | 4188 | 24        |

### Table 5. Calculation results of control rod worth

| Calculation status                  | Control rod bank position | Control rod worth /pcm | Design value | MCNP | Deviation |
|------------------------------------|---------------------------|------------------------|--------------|------|-----------|
| Adjust C1 to 600                    | A C1 C2 E1 E2 F1 F2 N    | 6444 6426 -18         | 6444         | 6426 | -18       |
| Propose N in order                 | I I I I 600 I I I I O   | 1707 1782 75          | 1707         | 1782 | 75        |
| Propose F1 in order                | I I I I 600 I O I O O   | 2883 2926 43          | 2883         | 2926 | 43        |
| Propose F2 in order                | I I I I 600 I O O O O   | 2294 2310 16          | 2294         | 2310 | 16        |
Propose E2 in order

| Order | Position/mm | Design value /pcm | MCNP/pcm | Deviation /pcm |
|-------|-------------|-------------------|----------|----------------|
| O     | I           | 600               | 3233     | 3258           |
| I     | 0           |                   | 3233     | 3258           |
| I     | 600         |                   |          | 25             |

Propose E1 in order

| Order | Position/mm | Design value /pcm | MCNP/pcm | Deviation /pcm |
|-------|-------------|-------------------|----------|----------------|
| O     | I           | 600               | 2164     | 2192           |
| I     | 0           |                   | 2164     | 2192           |
| I     | 600         |                   |          | 28             |

Propose C2 in order

| Order | Position/mm | Design value /pcm | MCNP/pcm | Deviation /pcm |
|-------|-------------|-------------------|----------|----------------|
| O     | O           | 600               | 3118     | 3109           |
| O     | O           |                   | 3118     | 3109           |
| I     | 600         |                   |          | -9             |

Propose A in order

| Order | Position/mm | Design value /pcm | MCNP/pcm | Deviation /pcm |
|-------|-------------|-------------------|----------|----------------|
| O     | O           | 600               | 1182     | 1219           |
| O     | O           |                   | 1182     | 1219           |
| O     | 600         |                   |          | 37             |

Table 6 shows the integral value curve of the regulating rod E1 in the cold state. The positions of other rod groups are: N, F1, F2, A/1400mm, E2, C1, C2/100mm. The nuclear design value and the calculated total integral value of the E1 rod group are 3288 pcm and 3313 pcm, respectively, with a deviation of 25 pcm. The nuclear design value and calculation are around 600 mm of the rod position. The differential value of the E1 rod group is 4.6 pcm/mm and 4.3 pcm/mm, respectively, with a deviation of -0.3 pcm/mm. In short, for the value of the control rod, the core design value and the calculated result are in good agreement with each other.

Table 6. Calculation results of integral control rod worth for E1 bank

| E1 bank position/mm | Design value /pcm | MCNP/pcm | Deviation /pcm |
|---------------------|-------------------|----------|----------------|
| 100                 | 0                 | 0        | -              |
| 200                 | 111               | 139      | 28             |
| 300                 | 359               | 341      | -18            |
| 400                 | 766               | 759      | -7             |
| 500                 | 1246              | 1261     | 15             |
| 600                 | 1709              | 1690     | -19            |
| 700                 | 2099              | 2102     | 3              |
| 800                 | 2460              | 2444     | -16            |
| 900                 | 2700              | 2713     | 13             |
| 1000                | 2928              | 2929     | 1              |
| 1100                | 3086              | 3095     | 9              |
| 1200                | 3189              | 3220     | 31             |
| 1300                | 3247              | 3276     | 29             |
| 1400                | 3288              | 3313     | 25             |

5. Conclusion

In this paper, the core calculation model of the marine nuclear power platform reactor is established based on the MCNP code, and the numerical results such as the reactivity distribution and the control rod worth in the cold state are calculated. By comparing the calculation results with the nuclear design values, it can be seen that the whole core calculation results based on the MC method are basically consistent with the nuclear design values.

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