Preliminary Design of 1000MW Nuclear Reactor

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Abstract: In order to verify the practicality of a software named NECP, which is used for physical design of the nuclear power reactor, a preliminary design of 1000MWe, PWR were carried out by using this software. After the conceptual design, fuel assembly design and the full core dispersion design, the main parameters were determined and the 8 kinds of fuel assemblies were arranged. The homogenization calculation of various types of fuel assemblies and the arrangement of core fuel assemblies were completed while the full core dispersion calculation was performed. The power results, reactivity curves and non-uniform coefficients were determined after simulated and compared with the preset expected values. According to the reactor design criteria, the results are analyzed and improved. By modifying parameters such as the fuel enrichment of different components, the reactor design that meets the requirements is finally obtained. The results show that the calculated values are in good agreement with the expected values and meet the reactor design criteria, and the NECP software can be applied to operate the reactor physical parameters in the nuclear power plant.

Key words: Nuclear reactor conceptual design; Core physical calculation; Homogenization; Diffusion calculation

1. Introduction

With the development of nuclear energy, various types of reactors have been developed in an endless stream. At present, pressurized water reactors have become the mainstream in the world. The pressurized water reactor has the characteristics of small size, light weight and good operating performance. It first appeared on ships as a mobile power reactor, most of it has been directly put into commercial use, and it is used in low-parameter industrial thermal reactors. It is easier to achieve inherent safety requirements, it is also easier to achieve technical and economic indicators, and is more suitable for playing the advantages of nuclear energy. Therefore, this project uses pressurized water reactor as a prototype for design work.

There is a software named NECP. It is in the core physics analysis module in the calculation analysis system. It receives the reactor design parameters provided by the user and obtained the physical parameters of the reactor core after simulation calculation, then provide the thermal and structural parameters of the core to the subsequent thermal-hydraulic analysis software of the reactor. This topic uses a self-developed reactor Nuclear design software, complete the preliminary nuclear design of 1000MW nuclear power plant reactor according to requirements.

The general procedure is to first set the two main parameters of reactor thermal power and core lifetime, and then use the empirical formula and empirical parameters obtained in the previous study to
determine the remaining program parameters, and enter these parameters into the software for the physical design part. In the meantime, component design and full-core diffusion calculation are carried out, and finally the core power distribution diagram and reactivity curve at the beginning of the lifetime are obtained. The conclusions are compared with the preset values, and the reasons for the numerical mismatch are analyzed. The optimization variables involve nuclear power plants. Therefore, we modify some of the main parameters to make the plan fit well, and conclude and determine a better plan under the constraints of physical design criteria.

This preliminary design of a reactor involves only the core design part. The core physical design, in addition to the core thermal hydraulic design and structural design, as well as safety evaluation and economic analysis, will be more complex and in-depth in the later more in-depth design.

2. Reactor concept design

2.1. Determination of basic fuel cell

The content of this section mainly introduces the tasks of the overall scheme design of the core, the method of determining the parameters, and the factors that need to be considered when determining each parameter. The task of this section is to determine some of the parameters in the 1000MW PWR nuclear power plant, such as core height, fuel enrichment, number of components, water to uranium ratio, etc. The selection of these parameters is often determined by engineering experience. The method is to refer to the previous experiment experience, consider the affected factors of each parameter, and calculate or select the empirical value under its constraint conditions, and the geometric size of the fuel pellet, the material characteristics in the core, and the geometric materials of other components. It refers to the design data of a certain nuclear power plant that has been put into operation, and carries out a multi-scheme design on the basis of the above. It provides the radius and height of the reactor core, the number of fuel assemblies loaded, the boundary limit of the core assembly layout, and the number of fuel rods.

2.2. Determines the size of the core geometry

Core geometry is generally determined under thermal conditions, the thermal core channel with the maximum allowable power level is generally linear power density maximum allowable value $q_{\text{max}}$ is represented, the temperature difference between the fuel element and the linear power density relationship using the following formula:

$$q = \frac{2\pi(T_{c} - T_{r})}{\left(\frac{1}{2k} + \frac{1}{R_{h}} + \frac{c}{k,R}\right)}$$  \hspace{1cm} (1)

At present, the limit of linear power density in PWRs using uranium dioxide fuel is about 660 W/cm, so in core design, the maximum allowable linear power density must be less than 660 W/cm. As long as the operating conditions of the hot aisle can meet the requirements of the core design criteria, the operation of the remaining channels in the core can be satisfied. The maximum allowable linear power density of the hot aisle is obtained above, in order to determine the core geometry, we also need to obtain the average linear power density of the core fuel elements:

$$\overline{q} = \frac{q_{\text{max}}}{F_{c}}$$  \hspace{1cm} (2)

In the case of known rod diameter, according to the actual cladding thickness, air gap thickness, and water-to-uranium ratio, the area $A$ occupied by the grid element can be obtained by geometric calculation:

$$A = (W_{r} + 1) \times \frac{\pi}{4} \times \frac{D^{2}}{100}$$  \hspace{1cm} (3)
The power peak factor determined by experience and the proportion of fuel heat release, the core height-to-diameter ratio $H/D$ eq can be determined by the following formula:

$$\frac{\pi D_{eq}^2}{4} = \frac{F_\mu N_T F_0}{q'_{max} H} A$$  \hspace{1cm} (4)

Through the analysis of the formula, for a uniform cylindrical core, the best height-to-diameter ratio $H/D$ eq is 1.08. For a real core, taking into account factors such as neutron leakage, manufacturing cost, and internal coolant pressure drop, this ratio is Approximately in the range of 0.9 to 1.5.

After the above calculation process, the geometric parameters of the core can be basically determined, and many specific parameters of the core design can be found in a large number of documents. As shown in Table 1, the program parameters obtained through the above calculations.

### Table 1. Scheme parameters

| name                          | unit       | Value       | Remarks       |
|-------------------------------|------------|-------------|---------------|
| Maximum line power density    | W/cm       | 634         | Less than 660W/cm |
| Total Hot Path Factor         |            | 2.548       | Around 2.5    |
| Core heat release rate        |            | 0.96        | Around 96%    |
| Maximum number of radial components |       | 15          |               |
| Number of components          |            | 15.3        |               |
| Core height                   | cm         | 370.89      |               |
| Core equivalent diameter      | cm         | 309.08      |               |
| Core height to diameter ratio |            | 1.2         | Around 1.2    |
| Grating period                | cm         | 1.43        |               |
| Core loading                  | kg         | 69,595.87   |               |
| Fuel consumption depth        | MWd/tU     | 17,242      |               |
| Initial enrichment            | %          | 3.39        |               |

### 3. Formatting the text

After completing the conceptual design of the core and obtaining the various parameters, we still need to evaluate the correctness of these parameters. The conditions of the evaluation are the reactor physical design criteria of the reactor. We hope that the designed core can last for the entire core life. It has a flat axial radial power distribution and sufficient residual reactivity. Among them, the reactor core has requirements for reactivity control. The reactivity in the reactor changes during core operation, and the reactivity can be controlled by different means. Therefore, we need to analyze the reactivity changes and adjust the way to control the reactivity. These include movable control rods, boric acid solutions, and combustible poisons. In this section, we perform reactive distribution of these three methods. The distribution method is to arrange the components of the component.

#### 3.1. Gate element design

For the design calculation of the fuel cell, the method of "mixing" is generally used to simplify. The fuel rods, cladding and moderators of a grid element are divided into different spatial regions according to the spatial geometric distribution, and the cross-sectional area is used as the weight to be equivalent to a one-dimensional cylindrical geometry composed of multiple concentric rings, that is, these the gate element can be regarded as composed of several concentric parts, since the software component calculated for each cell by claim material contains not exceed over 3 species, and require specific cell for the material region as a separate For example, the poison tube in the combustible
poison cell is used as a separate zone. In addition, the cladding zone and the moderator zone can be separated. Enter the corresponding zone radius, temperature and enrichment degree in the software. After equivalent treatment, the cell is up to three layers of concentric cylinders. In this design, the radius temperature and other data are automatically supplemented by the system. The enrichment degree needs to be modified during the design process, and finally selected according to the optimal scheme.

The components in this reactor are designed in a 15×15 square layout. The cell types mainly include fuel grid, control rod grid (placed in the guide tube), combustible poison grid (placed in the guide tube) and water hole (in the guide tube). There are four types of cells without cells. In addition to fuel elements, control rods and flammable poisons are placed in the positions of some cells. Neutron measuring tubes are generally placed in the center of the assembly. With reference to the design of Daya Bay Nuclear Power Station, according to the fuel enrichment of the components, the number and arrangement of combustible poison rods in the components are different, fuel components can be divided into 8 types. The specific conditions of these 8 types of components can be seen in Table 2.

### Table 2. Component Type

| Zone | Component Type | 1 | 16 | 2 | 8 | 16 | 8 | 16 |
|------|----------------|---|----|---|---|----|---|----|
| I    | Non-toxic stick | Zone I  | 16 poison sticks | Zone II | 8 poison sticks | Zone II | 16 poison sticks | Zone III | 8 poison sticks | Zone III | 16 poison sticks |

3.2. Gate element disposed

The components are arranged in the inner area of the core in an incomplete checkerboard format to flatten the radial neutron flux distribution of the core. Therefore, a non-uniform refueling scheme is usually used. The fuel components can be divided into three different degrees of enrichment, and the structure of the components with different degrees of enrichment is exactly the same. In Table 2 after the assembly of the various elements of the gate contained in the structure and materials required are defined, followed by arrangement of the gate element. This time we designed a 15*15 module. Since the modules are arranged symmetrically, it is only necessary to manually arrange the 1/8 area of the module. First select the required cell in the cell area, and then click on the corresponding position of the 1/8 component in the component area to arrange the cell. Different cells display different colors, and then arrange all the 1/8 components in order.

Referring to the design of GNPS core, we set the stack are arranged 153 fuel assemblies, each comprising 225 equal-pitch rod lattice, wherein 204 rods are rod lattice positions of the fuel rods placed in the gate, the center of the assembly. There is a measuring tube, which is generally used as a water hole, and the remaining 20 rod grids are used to hold control rods, combustible poison rods and guide tubes. Allocation grid element within the package can be found in Table 3.

### Table 3. Component layout

| Partition | Component code | Fuel rod | Control rod | Combustible poison | Water cave | Remarks |
|-----------|----------------|----------|-------------|--------------------|------------|---------|
| Zone I    | Component 1    | 204      | 16          | 0                  | 5          | Non-toxic |
| Zone I    | Component 2    | 204      | 4           | 16                 | 1          | 16 poisons |
| Zone II   | Component 4    | 204      | 12          | 8                  | 1          | 8 poisons |
| Zone II   | Component 5    | 204      | 0           | 16                 | 5          | 16 poisons |
| Zone II   | Component 6    | 204      | 16          | 0                  | 5          | Non-toxic |
| Zone III | Component 7 | Component 8 |
|----------|-------------|-------------|
|          | 204         | 204         |
|          | 12          | 0           |
|          | 8           | 16          |
|          | 1           | 5           |
|          | 8 poisons   | 16 poisons  |

Obtained by the software found in the gate arrangement of the fuel element assembly of figure 1.

**Figure 1.** Fuel assembly grid element arranged

### 4. Core Design

Referring GNPS core, the preliminary zoning form is shown in Figure 2. Inserting each assembly into different regions dispersed after the partition, it is shown in Figure 3.

**Figure 2.** Three-zone Loading

**Figure 3.** Three-zone mixed Loading

Then generate the input parameter data card and start the calculation to get the calculation result. Figure 4 - Figure 5 is the radial relative power distribution of the core at 0 and 15 burnup steps.

**Figure 4.** Radial relative power distribution of the core at 0 burnup

**Figure 5.** Radial relative power distribution of the core at 15 burnup
According to the axial power distribution of the core. It can be seen that with the increase in burnup, the radial power distribution of the core is gradually flattened, and the more uniform the number of components in the three fuel zones, the easier it is to flatten the radial power. The axial power distribution curve may be formed by the influence of the insertion of the control rods. In this design, the distribution of the control rods and the lifting rods are not involved. All components are considered to be inserted into the core. In this case, because the control rod is a strong absorber, its insertion will affect the neutron flux density of the core, and the power distribution will be distorted. The neutron flux density and power in the area with the control rod are relatively low. At the bottom of the control rod, the neutron flux density reaches its peak. In the actual reactor operation process, as the fuel burnup increases and the reactor operation time increases, the control rods must be continuously raised outwards. At the end of the core, the control rods have basically been raised to the core, and the peak value of the core axial power distribution graph should also gradually move to the right. The power distribution obtained by running the software also satisfies the distribution law of cosine function in axial direction and Bessel function in radial direction.

As the burnup deepens, the effective value-added factor gradually decreases. When the actual reactor core effective value-added factor $k_{\text{eff}}$ is less than 1, the reactor will be shut down. The deeper the burnup represents the more energy released by the fuel. It can be seen that the core completes the first cycle in about 14 to 15 steps.

Figure 6 shows the relationship between the core reactivity and the increase in burnup step length. The reactivity changes from 1.0094 to 0.9944 between the 14th and 15th steps. The burnup depth when the reactor shuts down is 417.5752, which is the same as the 400EFPD previously set has a certain deviation.

In order to select the optimal solution after running the program, we need to adjust the previously designed fuel enrichment. The above results are designed when the fuel enrichment of the three zones is 2.4%, 2.7%, and 3.1%.

By changing the degree of fuel enrichment, the change of the core reactivity curve with burnup and the change of core power distribution are obtained, then we can get the optimal solution.

5. Conclusions

By changing the fuel enrichment degree, it is found that the increase of the enrichment degree has little effect on changing the power peak factor of the module. However, as the core burnup continues to deepen, the radial power distribution of the core gradually flattens out. We use the axial power deviation to analyze the axial power, which is defined as the upper core power minus the lower core power and the stack. The ratio of the total power of the core, as the fuel consumption deepens, the axial power deviation approaches from a negative value to zero. By changing the component enrichment, it
can be seen that the core fuel enrichment will affect the axial power distribution of the core. The higher the enrichment, the later the axial power deviation tends to zero. When the reactor is initially loaded, it is necessary to ensure that the core has a certain residual reactivity. The new reactor fuel load is more than the critical fuel load, and the initial effective value-added factor is greater than 1. During the operation of the reactor core, with the deepening of burnup, the continuous accumulation of fission products, and the continuous decline of reactivity, the actual core value-added factor at the end of the reactor’s midlife cannot be completely 1, so we take the burnup depth value when $K_{\text{eff}}$ is less than 1 as the highest burnup depth. In this design, the core reaches a critical point within 14 to 15 burnup steps. The higher the core fuel enrichment, the greater the initial reactivity of the reactor, the faster the core reactivity decreases with burnup, and the greater the maximum burnup depth. Therefore, in order to approach the core life set earlier For the future value, we can appropriately adjust the enrichment degree of the fuel assembly.

In the component core design part, through the core physics calculation program NECP, the influence of different enrichment degrees on the physical properties of the components, such as reactivity and burnup, are analyzed separately, and their change laws are analyzed and studied by changing the fuel enrichment degree. However, the software lacks the research content of the core reactivity coefficient and the analysis of the influence of soluble boron solution, combustible poison, and control rod bundle on the reactivity of the core.

This design uses a uniform core, which simplifies the complexity of core layout. The reflective layer directly ignores problems such as neutron leakage and eliminates the influence of many factors. In fact, the operation of the reactor is much more complicated than this. The physical characteristics are also quite different. Therefore, to design a truly practical core solution, we need to consider many factors and make reference to the actual operating core. The previous experimental results show that increasing the fuel enrichment can meet the requirements of long fuel cycle and high unloading fuel consumption. However, due to the influence of the reactivity coefficient, the enrichment of fuel elements increases. In order to control the increase in the enrichment, the reactivity of the core and the need to add combustible poisons will also increase. If only the addition of combustible poisons is likely to lead to a large power peak factor and serious axial power deviation, in addition to adding combustible poisons for reactivity control, we can also add boron solution to adjust the remaining reactivity of the core, and reasonably select combustible poisons. Type, arrange multiple types of combustible poisons, and flatten the radial power distribution of the core and adjust the core reactivity curve with burnup depth through the partition loading of fuel and the reasonable arrangement of combustible poison rods.

6. Appendices
Appendix : The reactivity control requirements of each reactor and the approximate distribution of the total reactivity equivalent among various types of control elements

| Reactivity ( $\Delta k/k$ ) | Boiling water reactor | Pressurized water reactor | High temperature gas cooled reactor | Liquid metal block neutron value-added reactor |
|-----------------------------|----------------------|---------------------------|-----------------------------------|-----------------------------------------------|
| Remaining reactivity of clean core |                       |                           |                                   |                                               |
| At 20°C                     | 0.25                 | 0.293                     | 0.128                             | 0.5                                           |
| At operating temperature    | 0.218                |                           |                                   | 0.037                                         |
| Under the balance of samarium poison and xenon poison | 0.181                | 0.073                     |                                   |                                               |
| Total control equivalent    | 0.29                 | 0.32                      | 0.21                              | 0.071                                         |
Control rod reactivity value

|                     | 0.17  | 0.07  | 0.11  | 0.071 |
|---------------------|-------|-------|-------|-------|
| Combustible poison reactive equivalent | 0.12  | 0.08  | 0.1   |
| Chemical compensation reactivity equivalent | 0.17  |
| Shutdown margin     |       |       |       |
| Cold and clean pile | 0.04  | 0.03  | 0.082 | 0.024 |
| Heat and balance samarium and xenon poison | 0.14  | 0.137 | 0.037 |

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