Measurement of $k_{\text{eff}}$ with Neutron Flux Distribution Method Based on MC Simulation

Weiwei Wen*, Jinxing Cheng, Youpeng Wu, Qingbo Wang, Xianbo Chen, Lang Li, and Junjie Han

Beijing Institute of High Technology, Beijing, 100025, China

Abstract. In this work, the neutron flux distribution method to determine the effective multiplication coefficient $k_{\text{eff}}$ has been numerical analysis by MCNP program. The neutron flux distribution of four multi-sphere system models are calculated, and the characteristic parameter $c$ of each system are fitted with $k_{\text{eff}}$, so as to measure the $k_{\text{eff}}$ of multi-sphere system. And experiment based on reactor system has been carried out to prove the method. Experiment results show that the $k_{\text{eff}}$ obtained by the neutron flux distribution method are consistent with the experimental measurement results, indicating that the method is feasible and reliable.

1 Introduction

The $k_{\text{eff}}$ represents the safety margin of the nuclear system. Measure technologies of $k_{\text{eff}}$ include the source-hopping method[1], Rossi- $\alpha$ method[2], source multiplication method[3], pulsed neutron source method[4] and neutron spatial distribution method[5] and so on. These methods are mainly used in the reactor reactivity measurement, while rarely research has been made about multi-sphere system[6]. Under certain abnormal conditions, the multi-sphere system may be flooded, the scattering cross-section of water is relatively large, and the $k_{\text{eff}}$ of the multi-sphere system containing highly enriched uranium and plutonium fission material will change significantly. The neutron flux distribution method is simple and easy to obtain high measurement accuracy of $k_{\text{eff}}$. While the Monte Carlo method (MC) has the advantages of saving time and cost, simplicity and high accuracy. The MCNP program based on this method can be better applied to the study of neutron transport problems[7], which can effectively calculate the $k_{\text{eff}}$ of nuclear system. In this paper, the neutron flux distribution method is combined with Monte Carlo simulation to study the subcriticality monitoring of the multi-sphere system, combined with the reactor experimental device, the accuracy of the method is initially verified.

2 Calculation model

For different application purposes, nuclear systems often use complex structural models, such as reactor models, ADS system models, etc.[9]. In this paper, the multi-sphere system containing highly enriched uranium and plutonium fission materials is selected. The sphere model A is composed of uranium elements with radius $r_1$ of 0.06m, density $\rho_1$ of 19.09g/cm$^3$. The sphere model B is composed of plutonium elements, with radius $r_2$ of
0.03m, and density $\rho_2$ of 19.86g/cm$^3$. The height of the sphere from the ground is 0.5m, the room size is 6m$\times$6m$\times$4m, and the wall is 0.2m thick concrete. The density $\rho_3$ of thick concrete is 2.35g/cm$^3$.

Schematic diagram of multi-sphere system model is shown as Fig.1. When there is no water in the system (ie $l = 0$), calculate the neutron flux distribution and $k_{\text{eff}}$ of the system with the center distance of the sphere as 0.5m, 0.7m, 0.9m, 1.1m, 1.3m and 1.5m. While the different center distances are all situations where the sphere fills the entire storage, that is, the smaller the center distance, the more spheres. In some abnormal situations, when water enters the system (ie $l \neq 0$), calculate the neutron flux distribution and $k_{\text{eff}}$ of the system with the center distance of the sphere is 0.5m, and the thickness of the water layer is 0.1m, 0.3m, 0.5m, 0.55m, 0.6m, 0.7m, 0.8m.

3 Calculation result

3.1 Neutron flux distribution and $k_{\text{eff}}$

The MCNP program was used to calculate the neutron flux distribution and $k_{\text{eff}}$, with the detection point on the central axis of the storage space, and the detection range from the storage floor to the top (4m) increased at intervals of 0.3m. Fig.2 is the trend diagram of the $k_{\text{eff}}$ of different subcriticality systems under waterless and flooded conditions is shown as Fig.2, from which we can find out the $k_{\text{eff}}$ decreases with increasing of sphere distance, and water height.

![Figure 2. $k_{\text{eff}}$ trend of systems in the absence of water (a) and flooding (b).](image)

Distribution of neutron flux in U system and Pu system without water is shown as Fig.3, from which we can find out the spatial distribution of neutron flux increases firstly and then decreases as the detection height changes. The neutron flux value is the highest near the detection height of 0.5m.
Figure 3. Distribution of neutron flux in U system (a) and Pu system (b) without water.

Distribution of neutron flux in U system and Pu system under water flooding is shown as Fig.4, from which we can find out when the sphere is not submerged by the water layer, the maximum neutron flux appears near the detection height of 0.5m; when the thickness of the water layer reaches the height of the sphere, the maximum neutron flux appears near the detection height of 1m.

Figure 4. Distribution of neutron flux in U system (a) and Pu system (b) under water flooding.

4.2 Scale curve

The distribution of neutron flux in the four multi-sphere nuclear systems shows that the detection height at 1m and 2.8m is the sensitive point where the neutron flux density changes with the $k_{eff}$. Therefore, we choose the ratio of the detection height at 1m and 2.8m as the system Characteristic parameter $c$. Fig.5 shows the "characteristic parameter c-$k_{eff}$" calibration curves of the above four systems.
Figure 5. Scale curve of U ball (a) and Pu ball system (b), flooded U ball (c) and Pu ball system (d).

5 Experimental verification

The experimental has been taken using reactor critical device to verify MCNP calculation. The choice of detector position should with obvious difference in neutron flux distribution to characterize the difference in the shape of neutron flux with different $k_{eff}$. And, the detection position should keep away from the reflective layer, which can reflect the characteristics of the fundamental wave. The neutron detectors are arranged radially from inside to outside along the system. The measurement of neutron flux use Al-Lu-Mn (referred to as "Mn wire") containing 5% of Mn content, with size of $\phi 2\text{mm} \times 2\text{mm}$. The Mn wire is arranged on the measuring bar at a certain interval. Each Mn wire position represents a measuring point. The distribution of measuring points and the number of core measuring points are shown in Table 1.

| Height/m  | 1# | 2# | 3# | 4# | 5# | 6# | 7# | 8# |
|----------|----|----|----|----|----|----|----|----|
| 50       | 1  | 10 |    |    |    |    |    |    |
| 150      | 2  | 11 |    |    |    |    |    |    |
| 250      | 3  | 12 |    |    |    |    |    |    |
| 350      | 4  | 13 |    |    |    |    |    |    |
| 450      | 0  | 14 | 20 | 21 | 22 | 23 | 24 | 25 |
| 550      | 5  | 15 | 26 | 27 | 28 | 29 | 30 | 31 |
| 650      | 6  | 16 |    |    |    |    |    |    |
| 750      | 7  | 17 |    |    |    |    |    |    |
| 850      | 8  | 18 |    |    |    |    |    |    |
| 950      | 9  | 19 |    |    |    |    |    |    |

Fig.6 and Fig.7 show the comparison between the measured neutron flux and the MC calculation. It can be seen from the figure that the neutron flux calculated by MC method is basically the same as that measured by experiment, and MC method can be used to calculate the neutron flux in the reactor.
Figure 6. Longitudinal measurement point No.1(a), No.2(b) of neutron flux.

Figure 7. 450mm (a) and 500mm (b) horizontal measuring points of neutron flux.

The ratio of the two measuring points with height of 450 mm and 550 mm is selected as the characteristic parameter of neutron flux distribution to make the "scale curve c-keff", and compared with the MC calculation result, shown in Fig.8. It can be seen from Fig.8 that the scale curve obtained by MC calculation is basically consistent with the experimental.

Figure 8. MC calculation and experimental measurement.

5 Conclusion

In this paper, the neutron flux distribution method to determine the effective multiplication coefficient $k_{\text{eff}}$ has been numerical analysis by MCNP program. The neutron flux distribution and $k_{\text{eff}}$ of four kinds of multi sphere system models have been calculated, while the "scale curve c-keff" is established. And the accuracy of $k_{\text{eff}}$ measurement by neutron flux distribution method has been verified on the reactor experimental device. Result shows that the scale curve obtained by MC calculation is basically consistent with
the experimental, which means we can get the "scale curve c-k_{eff}" by MC calculation, and then get the k_{eff} by measurement of neutron flux.

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