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Study of Control rod worth in the TMSR

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Abstract Control rod is a primary control part of emergency control and power regulation in nuclear reactor. The main application of it is to control fast change of the reactivity. The theoretical analysis for the worth of control rod is necessary in the stage of design. Based on design requirements, some results are calculated. Firstly, control rod worth with different density of neutron absorber is calculated by MCNP here. Secondly, the study of integral and differential control rod worth is presented in this paper while the control rod is inserted into reactor core and total worth of three rods with different positions are also calculated. Finally, the effect of the axial and radial neutron flux in reactor core which is caused by the control rods is simulated. The simulation results of the control rods meet design requirements for TMSR.

Key words Neutron absorber, Reactivity, Control rod worth, Neutron flux

1 Introduction

The abbreviation of thorium molten salt reactor is TMSR. The TMSR is the first start implementing strategic guide for technology special in the Chinese Academy of Sciences. Control rod is an important control part of the reactivity in TMSR. Due to the high importance of the control rods' reactivity worth, methods for its measurement have been proposed by Shimazu[1]. Many efforts have been made for the choice of the right absorber materials by Saji[2], tested also with calculations. Control rod worth calculations have also been reported by Bretscher[3] for best simulation method. The features of control rod are summarized: fast movement speed, reliable operation, flexible use and high accuracy for the control of reactivity[4]. The worth of one and multiple control rods for the TMSR is calculated in this paper, and that the control rod worth with different density of neutron absorber is shown. In addition, the integral and differential control rod worth is presented, finally, the effect of the axial and radial neutron flux in reactor core which is induced by control rods is also analyzed.

2 Position, structure and size of control rod in the TMSR

The TMSR which is composed of standard hexagonal lattice cells has three control rods. The total of cells is 168. Each side of the lattice cell is 6 cm. The design requirements of control rods are: the worth of each control is between 2700 pcm and 2800 pcm and the total worth is between 6800 pcm and 8100 pcm. The initial positions of the control rods are shown in Fig.1.

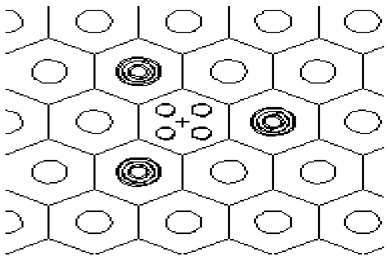

Fig.1 Positions of control rods in reactor core.

In Fig.1, the single circle in the center of hexagonal lattice stands for fuel molten salt which is composed of $LiF\text{-}BeF_2\text{-}ZrF_4\text{-}UF_4$ and the rest of hexagonal lattice stands for the graphite. The molar ratio of $LiF\text{-}BeF_2\text{-}ZrF_4\text{-}UF_4$ and $^{235}U\text{-}^{238}U\text{-}^{234}U\text{-}^{236}U$

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are 650:292:50: 8 and 1.02: 6.94: 0.02: 0.02, respectively. The densities of fuel and graphite are 2.312 g·cm^{-3} and 1.86 g·cm^{-3}, respectively. There are four circles standing for the sample pipelines in a hexagonal lattice. Concentric circles in three hexagonal lattices stand for three control rod guideline. The neutron absorbers are made of B_4C. The length of reactor core is 1600 mm. The detail for the compositions and sizes of the control rod are shown in Table 1.

Table 1 Structural parameters of the control rod

From the inner to the outer	Material	Inner radius / mm	Outer radius / mm
Cooling gas (enter)	nitrogen	_____	9
Guide tube	Stainless steel	9	12
Inner cladding (neutron absorbers)	Stainless steel	12	12.5
Neutron absorbers	B_4C	12.5	17.5
Outer cladding(neutron absorbers)	Stainless steel	17.5	18.5
Cooling gas (out)	nitrogen	18.5	23
Cladding (control rod)	Hastelloy	23	25

3 Control rod worth with different density of neutron absorbers

The neutron absorbers of control rod are B_4C in the TMSR. The abundance of B-10 is 19.8%, which means natural boron. The critical reactor is simulated by MCNP. The worth of control rod is the difference of the reactor's reactivity between the control rod is inserted into the reactor or not. Generally speaking, the total worth of several control rods inserted into the reactor is not equal to the sum when each of them is inserted into the reactor respectively because of the mutual interference between control rods[5,6]. The theoretical density of B_4C is 2.52 g·cm^{-3}. Since the density of B_4C varies with the processing condition, so that control rod worth is different even if the rods are of the same size. The mass ratios of ^{10}B and ^{11}B are 19.8% and 80.2%, respectively. The positions of control rod channel are shown in Fig.1. The values of control rod worth at different density are shown in Table 2.

Table 2 Control rod worth with different density

Density / g·cm^{-3}	2.0		2.1		2.2		2.3	
Atomic density (Atom/barn-cm)	0.018576		0.0195048		0.0204336		0.0213624	
The mass of one neutron absorber / kg	1.5		1.582		1.658		1.733	
The control rod worth	K_{eff}	$(\Delta k/k)_{eff}$（%）	K_{eff}	$(\Delta k/k)_{eff}$（%）	K_{eff}	$(\Delta k/k)_{eff}$（%）	K_{eff}	$(\Delta k/k)_{eff}$（%）
No control rod	1.00590							
One control rod	0.97955	2.62	0.97866	2.71	0.97870	2.72	0.97884	2.69
Two control rods	0.95698	4.86	0.95692	4.87	0.95636	4.92	0.95623	4.94
Three control rods	0.93833	6.72	0.93812	6.74	0.93743	6.81	0.93732	6.82

*K_{eff} is the effective multiplication factor.

The relationship between the reactivity and K_{eff} is:

$$\rho = \frac{K_{eff} - 1}{K_{eff}} \tag{1}$$

The error of the simulation is ±20 pcm. From Table 2, it can be seen that one control rod worth varies with the density, but the worth does not always rise when the density increases. It could be due to strong self-shielding effect of neutron absorbers. When clubbed control rod is inserted into the core, the effective absorption cross sections decrease. The result that the total worth of multiple control rods inserted into the reactor is not equal to the sum when each of them is inserted into the reactor respectively is shown.

4 Integral and differential worth of one control rod

The change of reactivity when control rod moves from one initial position to another is the integral control rod worth for the displacement distance, and the rate of change is the differential worth. The control rod inserts gradually the core from the top to the bottom when the initial condition of reactor is critical. The simulation is on the assumption that the integral worth is zero when the control rod is completely withdrawn. The calculation step is 20 cm[7,8]. The results of the integral and differential worth are shown in Fig.2 and Fig.3, respectively.

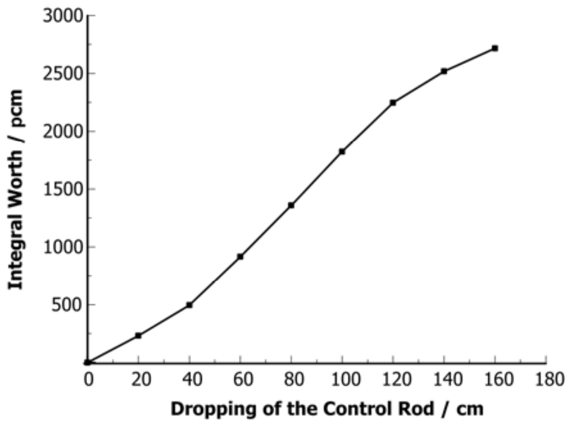

Fig.2 Integral worth of one control rod in TMSR (2 MW).

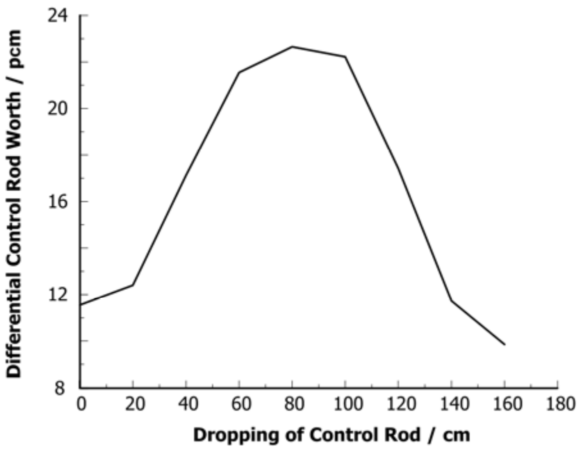

Fig.3 Differential worth of one control rod in TMSR (2 MW).

The integral worth of one control rod is about 2716 pcm in Fig.2. Fig.3 shows that the maximum value of differential worth is about 23 $pcm\cdot cm^{-1}$ when the control rod reaches the nearby center of core and the minimum one is about 10 $pcm\cdot cm^{-1}$ when the control rod is just inserted into the core. The curve of Fig.3 is not exactly symmetrical because of asymmetrical distribution for the fuel in simulation. That the differential worth is different when the control rod is on the top and the bottom of core is due to the fuel and graphite's asymmetrical distribution.

5 Worth of rod changes with the position

The worth of control rod varies with its position. The reactivity caused by inserting control rod completely in different position is simulated for searching suitable control rod channel. The simulation step is a hexagon lattice cell which is about 10 cm. The effective multiplication factor varies with the position of control rod channel, shown in Fig.4. The relationship between the total worth of three control rods and the position is shown in Fig.5.

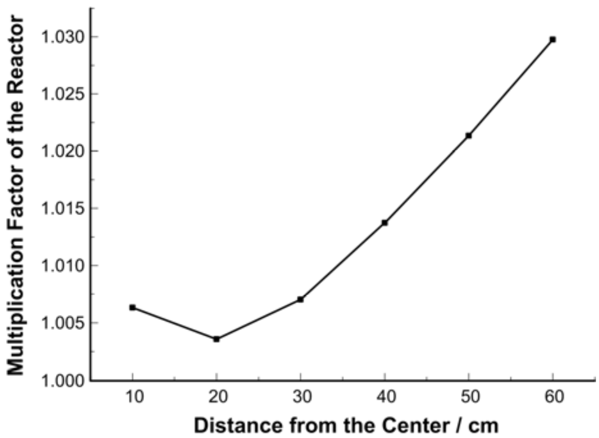

Fig.4 Multiplication factor varies with the radial position of control rods.

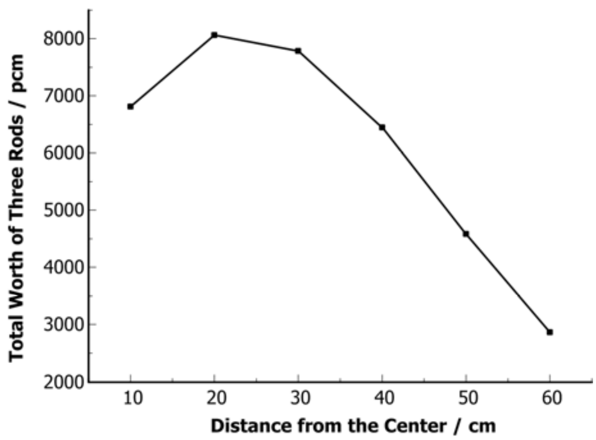

Fig.5 Total worth of three control rods varies with the radial position of control rods.

From Fig.4, it can be seen that the effective multiplication factor K_{eff} ≥1.00704 when the distance of channel from the center ≥30 cm, that means the reactor reaches prompt criticality which is a dangerous situation. When the distance is 20 cm, K_{eff} reaches the minimum value 1.00358. When the distance is 60 cm, K_{eff} (three control rods are inserted into the core completely) which is 1.03 is bigger than 1.00590 (no control rods inserted) when the positions of control rod channel are shown in Fig.1. K_{eff} is affected by the positions of control rod channel from the simulation results. From Fig.5 one can see the total worth of three rods reaches the maximum value 8062 pcm when the distance is 20 cm. The total worth of three rods reaches the minimum value 2863 pcm when the channel of control rod is close to the edge of reactor. If one wants to get the maximum worth, the suitable distance for the channel is 20 cm based on the simulation result and the design requirements, which is in accord with Fig.8, shown in Fig.6.

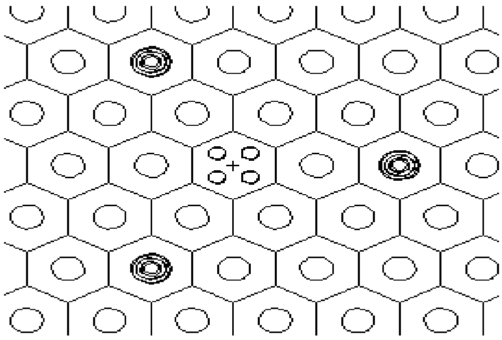

Fig.6 Positions of control rods after optimizing.

6 Effect of control rod to neutron flux in reactor

Estimated neutron source strength: Average power of fission is about 180 MeV and average neutron number of fission is 2.439. If the TMSR is operating at a power level of 2 MW, the neutron source strength would be n=1.69×10^{17} n·s^{-1}.

That control rods are completely inserted into the core will affect the axial and radial neutron flux. The relationship between axial neutron flux and control rod is simulated by MCNP5, shown in Fig.7 (step is 10 cm). The relationship between radial neutron flux and control rod is shown in Fig.8 (step is 5 cm).

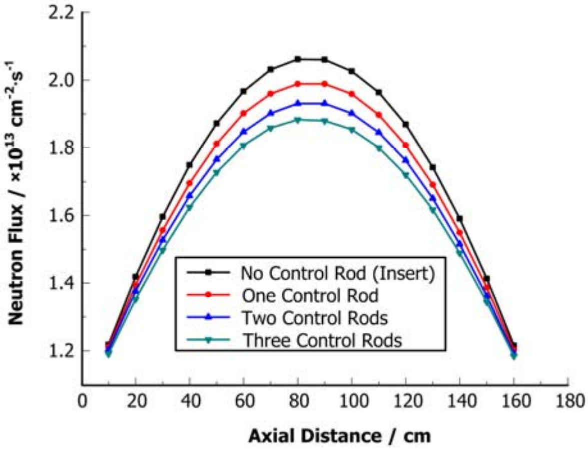

Fig.7 Axial neutron flux effect by the control rod.

From Fig.7 one can see that the one or multiple control rod affect the axial neutron flux slightly when it is on the top and the bottom of reactor core, but the axial neutron flux would be effect greatly when the control rod locates at the central of the core. If there is no control rod inserted, the neutron flux at the central position would be about 2.062×10^{13} n·cm^{-2}·s^{-1}. If there is one control rod inserted, the maximum of neutron flux is about 1.989×10^{13} n·cm^{-2}·s^{-1} at the central position. If there are two control rods inserted, the maximum of neutron flux is about 1.931×10^{13} n·cm^{-2}·s^{-1}. The maximum of neutron flux is 1.883×10^{13} n·cm^{-2}·s^{-1} with three control rods inserted. From the simulation results one can see that the neutron density and the position with the maximum neutron flux will be affected by inserting control rod. The total effect of many control rods inserting the reactor is less than the sum when each of them inserts the reactor respectively because of mutual interference between the control rods.

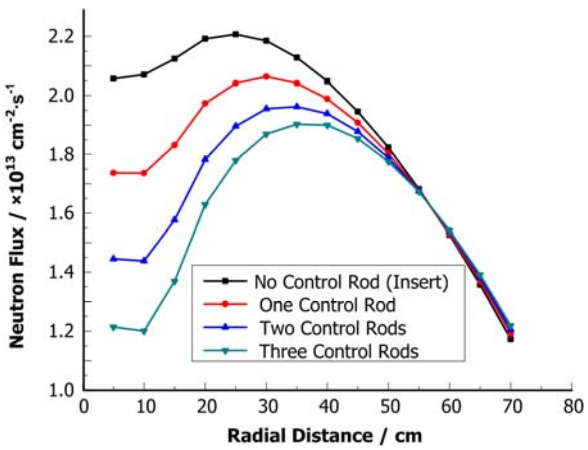

Fig.8 Radial neutron flux effect by the control rod.

From Fig.8 one can see: firstly, the maximum of radial neutron flux density is not at the center of reactor core due to sample pipeline. Figs.8, 4, 5 and 6 are consistency. The position of the maximum for power density is 20 cm in radial and 80 cm in radial from Fig.7 and Fig.8. Secondly, radial neutron flux density is affected seriously by the control rod at the center and nearby, and radial neutron flux density is affected slightly by the control rod close to the edge of reactor core. In addition, the radial neutron flux density is flattening effect by several control rods inserting the reactor core.

7 Conclusion

Control rod worth with different density of neutron absorber is calculated using MCNP5. The simulation results are necessary for process. The integral and differential control rod worth and the total worth of three rods with different position are also simulated. The effect of control rods to the axial and radial neutron flux is analyzed here. The simulation results are necessary for the control rod's process and applications in the TMSR more or less.

References

1 Shimazu Y, Okazaki K, Tsuji M. J Nucl Sci Technol, 2006, **43:** 1718−1725.

2 Takahashi S E. J Nucl Sci Technol, 1986, **23:** 745−751.

3 Bretscher M. ANL-RERTR-TM, 1997, 29−29.

4 Xie Z S, Wu H C, Zhang S H. Nuclear Reactor physical Analysis. Xi'an: Xi'an Jiaotong University Press, 2004, 244−245.

5 Glasstone E. Nuclear reactor engineering principles. Beijing: Science Press, 1959, 235−235.

6 Glasstone E. Nuclear reactor theoretical outline. Beijing: Science Press, 1958, 227−228.

7 Engel J R, Prince B E. ORNL-TM, 1967, **1796:** 5.

8 U.S.Department of Energy. DOE-HDBK-1019, 1993, **2:** 50−56.