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Investigation of the Shadowing Effect among Control Rods in China Experimental Fast Reactor Start-up Test

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1. Introduction

The China Experimental Fast Reactor (CEFR) [1] is China's first fast reactor, which uses sodium as a coolant and has a thermal power output of 65MW. During start-up tests, the worth of individual control rods and combined control rods was measured. The worth of each control rod was determined by measuring the differential rod worth of each rod, which was then used to obtain a reactivity worth curve (S-curve). The S-curve was used to estimate other reactivities, such as temperature, sodium-void, and sub-assembly swap.

During the measurement, the positions of the control rods were changed to compensate for the inserted reactivity. The change in the control rod positions was then converted into reactivity worth using the S-curves. By obtaining the S-curve for each control rod, the worth of each individual control rod was calculated, and the total control rod worth was obtained by adding up the worth of all individual control rods. However, there may be errors in the S-curve, depending on the position of the other control rods.

This work investigates the shadowing effect by calculating the total control rod worth using McCARD [2] Monte Carlo (MC) simulations. The simulation began by creating individual S-curves, which were also obtained from MC simulations. Then, the control rod worth for reactivity measurement was calculated and compared to those from the S-curves. It is important to note that the total control rod worth can be estimated in two different states: before reactivity insertion and after reactivity insertion. The introduced reactivity also affects the total control rod worth, so it was also compared in this study.

2. Control rod worth for reactivity calculation in CEFR start-up tests

In the CEFR core, a total of eight control rods are present, comprising three shim (SH) rods, two regulating (RE) rods, and three safety (SA) rods, as shown in Figure 1. During reactivity compensation, three SH rods and two RE rods were utilized, while all three SA rods were out of the core. By carefully controlling the positioning of the SH and RE rods, the overall reactivity of the core could be precisely adjusted, enabling safe and efficient operation of the reactor.

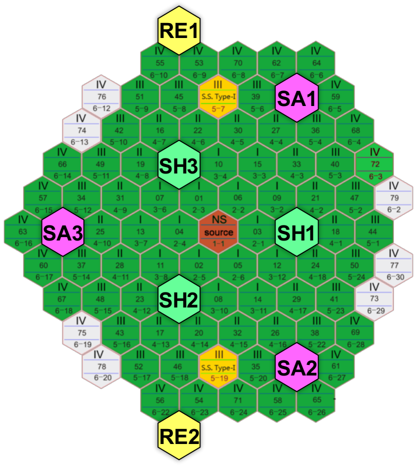

Fig. 1. Control rod positions in the CEFR for the start-up tests

The position change of SH and RE rods was converted to reactivity worth by S-curves. However, the reactor core may experience small off-criticality during the measurement, which needs to be corrected for the accurate estimation of reactivity. In this manner, the reactivity is calculated by the following equation:

$$\Delta\rho_m = \Delta\rho_{Cor} - \Delta\rho_{CR} \,, \qquad (1)$$

where m stands for the reactivity of interest, such as temperature, sodium void, or sub-assembly swap, while $\Delta\rho_{Cor}$ and $\Delta\rho_{CR}$ denote the reactivity correction and the reactivity compensation by the control rods, respectively. Eq. (2) defines $\Delta\rho_{CR}$, which is calculated by the control rod position sets for the base and perturbed state P_b and P_b as:

$$\Delta\rho_{Cor} = \left(\frac{1}{k_b(P_b)} - \frac{1}{k_p(P_p)}\right), \qquad (2)$$

where $k_b(P)$ and $k_p(P)$ stands for the criticality of core. As the control rod worth is the summation of individual rod worth, $\Delta\rho_{CR}$ can be written as:

$$\Delta\rho_{CR} = \sum_{k=1}^{N_{rod}} \Delta\rho_{CR,k} \,, \qquad (3)$$

where N_{rod} is the number of control rods for reactivity compensation, and k stands for the index for each control rod. The worth of control rod k, $\Delta\rho_{CR,k}$ of Eq. (3), is estimated from the S-curve in the numerical analysis as well as the actual measurement.

In the reactivity measurements, the control rod positions were different for each case, and they had to be distinct from the control rod positions used for obtaining the S-curves. Thus, the individual control rod worth in Equation (3) may slightly differ from the actual rod worth at each measurement because of the different control rod positions. Furthermore, the summation of individual rod worth does not ensure the combined rod worth, as inserted rods interact with each other. Although the total control rod worth was not measured for each reactivity measurement during the experiment, it can be calculated from MC simulations for both the base and perturbed state as:

$$\Delta\rho_{Cor,b} = \left(\frac{1}{k_b(P_b)} - \frac{1}{k_b(P_p)}\right) \text{ and} \tag{4}$$

$$\Delta\rho_{Cor,p} = \left(\frac{1}{k_p(P_b)} - \frac{1}{k_p(P_p)}\right). \tag{5}$$

The difference between $\Delta\rho_{Cor}$, $\Delta\rho_{Cor,b}$ and $\Delta\rho_{Cor,p}$ can provides insight into the shadowing effect in reactivity measurement

3. Numerical results for the shadowing effects

This study employed McCARD MC calculations to assess the influence of control rod shadowing on the start-up tests of the China Experimental Fast Reactor (CEFR) using the ENDF/B-VII.0 nuclear data library. The MC simulations were performed for a total of 250 active cycles, with 100,000 neutron histories per cycle. To ensure the accuracy of the fission source distribution, 50 inactive cycles were used to obtain full convergence. The estimated standard deviation of the criticality was found to be approximately 4 pcm.

3.1 Control rod worth measurements

In the CEFR start-up tests, prior to the reactivity measurement, the control rod worth was determined by the rod drop method for both individual and combined control rods. MC simulations were performed to analyze the measurement by comparing the criticality before and after the rod drop. Additional calculation results, namely the control rod worth obtained from the S-curves presented in Eq. (3), were also compared. The resulting values were plotted in Fig. 2. It can be observed from the figure that the rod worth estimated from S-curves tends to underestimate the actual control rod worth, and the difference becomes more significant with combined rod cases. The discrepancy between rod drop and S-curve approaches was estimated to be as high as –8.5% for the "2_RE+3_SH+3*SA" case.

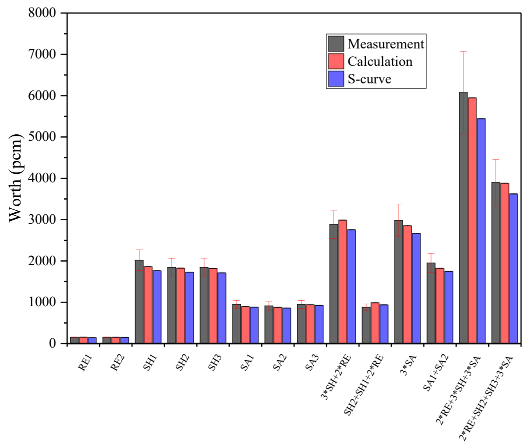

Fig. 2. Control rod worth by various approach

3.2 Sodium void reactivity measurements

Similar calculation was carried out for the sodium void reactivity measurements. where the control rod worth of each core configuration was not directly measured. Instead, the control rod worth obtained from the S-curves was compared to the calculated rod worth for both the base and perturbed states as given in Eqs. (4) and (5). The results of this comparison were summarized in Table I, where the CR worth A, B, and C represent the worth calculated by Eqs. (4), (5), and (3), respectively.

Due to the relatively large statistical uncertainty in Monte Carlo simulations, the CR worth A and B also showed some range of variations. However, it was evident that the worth obtained from the S-curves (C) was relatively smaller than the direct calculation obtained from different control rod positions. This difference became more pronounced in Fig. 3.

It is worth noting that the criticality of the CEFR core at all rod out case was estimated to be about 1.3, which can lead to a reduced worth from the S-curves. While the measurement also utilizes the S-curves for rod worth calculation, the curve can be different since the S-curves in the experiment were obtained at a critical core where some control rods were inserted. The different control rod configuration can introduce an additional error term in control rod worth, which can be considered the shadowing effects.

Although the error component in reactivity measurement was quantified in previous work [3], the shadowing effect can be an additional error component for the reactivity calculation in the CEFR start-up tests. Therefore, it is crucial to consider and account for the shadowing effect to accurately estimate the control rod worth and the reactivity measurement in the CEFR start-up tests.

Table I: Comparison of CR worths in the sodium void reactivity measurement

void position	CR worth			C/A-1 [%]	C/B-1 [%]
	A	B	C		
(2-4)	48.1	49	36.3	-24.5	-25.9
(3-7)	39	49.1	36.7	-6	-25.3
(4-9)	34.9	43.9	36.7	5.1	-16.5
(5-11)	46.1	43.3	36.9	-20.1	-14.9
(6-13)	21.7	23.7	17.7	-18.3	-25.3

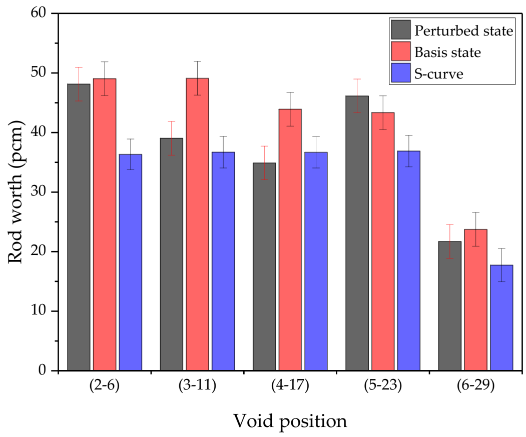

Fig. 3. Different CR worth for various approach in the sodium void reactivity measurement

3.3 Sub-assembly swap reactivity measurements

In the CEFR start-up tests, the reactivity compensation for sub-assembly swap was measured by two different control rod sets: a single SH rod and multiple SH rods. Two RE rods positions were changed for both measurements to control minor off-criticality. The measured reactivity values were compared to the calculated results obtained by Eqs. (4) and (5), which are referred to as case A and B, respectively. The worth obtained from the S-curves (C) was also compared to the calculated worth, and the results were summarized in Tables II and III for the measurements by a single rod and multiple rods, respectively. The results were also presented in Figs. 3 and 4.

Similar to the sodium void reactivity measurements, the worth calculated by the S-curve approach (C) was smaller than the worth calculated by Eqs. (4) and (5) (case A and B). However, the discrepancy was smaller than that of the sodium void cases, since the compensated control rod worth was greater than the sodium void cases.

One important observation is that the control rod worth was also affected by the sub-assemblies loaded in the core, as evidenced by the difference between case A and B. Additionally, the difference between A and B became greater for the single rod cases, as the large position change of a single rod could affect the power distortion greater than minor position changes of multiple rods.

Table II: Comparison of CR worths in the swap reactivity measurement – multiple rods

swap position	CR worth			C/A-1 [%]	C/B-1 [%]
	A	B	C		
(2-6)	888.8	899.2	869.8	-3.3	-2.1
(3-11)	772.4	778.1	767.4	-1.4	-0.7
(4-17)	710.7	710.2	693.5	-2.3	-2.4
(5-23)	548.6	559.5	528.6	-5.5	-3.6
(6-29)	578.5	603	572.2	-5.1	-1.1
(5-22)	-533.1	-537.1	-524	-2.4	-1.7
(7-31)	432.4	423.4	414.5	-2.1	-4.1
(5-19)	-197.5	-186.7	-184.3	-1.3	-6.6

Table III: Comparison of CR worths in the swap reactivity measurement – single rod

swap position	CR worth			C/A-1 [%]	C/B-1 [%]
	A	B	C		
(2-6)	885.2	924.9	857.1	-7.3	-3.2
(3-11)	769.3	807.8	758.3	-6.1	-1.4
(4-17)	697.7	738.8	687.8	-6.9	-1.4
(5-23)	534.8	560.2	527.7	-5.8	-1.3
(6-29)	590	596.5	560.6	-6	-5
(5-22)	-519.4	-523.8	-507.6	-3.1	-2.3
(7-31)	456.8	436.1	423.1	-3	-7.4
(5-19)	-199.6	-183.2	-173.4	-5.3	-13.1

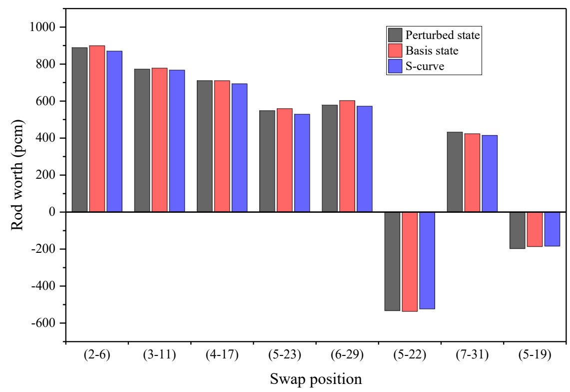

Fig. 3. Different CR worth for various approach in the swap reactivity measurement – multiple rods

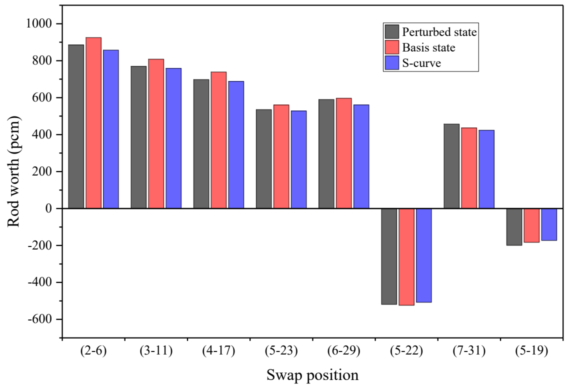

Fig. 4. Different CR worth for various approach in the swap reactivity measurement – single rod

4. Conclusions

In conclusion, this study investigated the shadowing effect among control rods in the CEFR start-up tests. By comparing the control rod worth measurement obtained from the rod drop method and MC simulation with that from the S-curve approach, significant error was observed for the combined rod worth measurement. For reactivity measurements, both sodium void and sub-assembly swap reactivity cases were analyzed. The results showed that the control rod worth estimated from the S-curve approach was generally smaller compared to the direct calculations, and the difference was greater for sodium void reactivity measurement due to smaller rod worth for reactivity compensation. Moreover, the shadowing effect was measured to be around 20% for sodium void reactivity and 5% for sub-assembly swap reactivity, which indicates the presence of an additional error component in the reactivity measurements of CEFR start-up tests.

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