

An Appropriate Application of Three-Step Method for Estimating Temperature Coefficient in CEFR Start-up Test

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1. Introduction

Chinese Experimental Fast Reactor (CEFR) [1] is a sodium-cooled fast reactor with power of 20 MWe. In the CEFR start-up tests, any reactivity insertion, such as temperature or sodium void, is accompanied by control rod insertion to keep the reactor core critical because of safety issues. Therefore, the reactivities in the CEFR Start-up test were measured by the inserted rod worth. In the experiments, pre-calculated control rod worth table, so-called S-Curve, is utilized to estimate the inserted rod worth. In simulation, however, the inserted rod worth can be directly calculated by adjusting control rod positions, which is called 3-Step method. The 3-Step method is beneficial for neutronics analysis since it is relatively free from the S-Curves' uncertainties issues, and improved accuracy is expected in numerical calculation. However, we found that the conventional 3-step method results in unintended error in temperature reactivity estimation, and the error is analyzed in this paper.

2. Temperature Reactivity with 3-Step Method

The reactivities in CEFR start-up tests were measured by control rod worth, that were evaluated from the differences in the critical rod positions. Since the core cannot be exactly critical, so the temperature reactivity can be obtained as Eq (1).

$$\Delta\rho_{T_i \rightarrow T_j} = \left(\rho_{P_j}^{T_j} - \rho_{P_i}^{T_i} \right) + \Delta\rho_{CR} \quad (1)$$

where P_i and P_j are the control rod positions at temperature T_i and T_j respectively; $\Delta\rho_{CR}$ is inserted rod worth; $\rho_{P_i}^{T_i}$ and $\rho_{P_j}^{T_j}$ are reactivity of the core at temperature T_i and T_j with control rod positions P_i and P_j respectively.

$\rho_{P_i}^{T_i}$ in Eq. (1) can be expressed as:

$$\rho_{P_i}^{T_i} = 1 - \frac{1}{k_{P_i}^{T_i}} \quad (2)$$

where $k_{P_i}^{T_i}$ is the criticality of the core at temperature T_i with control rod position P_i .

In the 3-Step method, the inserted rod worth $\Delta\rho^{CR}$ can be estimated as:

$$\Delta\rho_{CR} \approx \rho_{P_i}^{T_i} - \rho_{P_j}^{T_j} = \frac{1}{k_{P_i}^{T_i}} - \frac{1}{k_{P_j}^{T_j}}. \quad (3)$$

After substituting Eq. (2) and (3) into Eq (1), we get Eq. (4) as:

$$\begin{aligned} \Delta\rho_{T_i \rightarrow T_j} &= \left(\frac{1}{k_{P_i}^{T_i}} - \frac{1}{k_{P_j}^{T_j}} \right) + \left(\frac{1}{k_{P_j}^{T_j}} - \frac{1}{k_{P_i}^{T_i}} \right) \\ &= \frac{1}{k_{P_j}^{T_j}} - \frac{1}{k_{P_i}^{T_i}}. \end{aligned} \quad (4)$$

Note that the reactivity in Eq (4) does not include the calculation results at temperature T_i with control rod position P_i .

The temperature coefficient is normally estimated with reactivity at multiple temperature steps. So, the reactivity at the i -th step would be:

$$\Delta\rho_i \equiv \Delta\rho_{T_i \rightarrow T_{i+1}} = \frac{1}{k_{P_{i+1}}^{T_{i+1}}} - \frac{1}{k_{P_i}^{T_i}}. \quad (5)$$

Therefore, the reactivity from T_1 to T_3 can be obtained from summation of $\Delta\rho_1$ and $\Delta\rho_2$. In this manner, the reactivity at temperature T_N can be estimated as follows:

$$\sum_{i=1}^{N-1} \Delta\rho_i = \frac{1}{k_{P_2}^{T_2}} - \frac{1}{k_{P_N}^{T_N}} - \sum_{i=2}^{N-1} \left(\frac{1}{k_{P_i}^{T_i}} - \frac{1}{k_{P_{i+1}}^{T_{i+1}}} \right) \quad (6)$$

On the other hand, by the definition of 3-step method in Eq. (4), the temperature reactivity at T_n can be determined as:

$$\Delta\rho_{T_1 \rightarrow T_N} = \frac{1}{k_{P_N}^{T_N}} - \frac{1}{k_{P_1}^{T_1}}. \quad (7)$$

The reactivity in Eq. (6) is not the same as $\Delta\rho_{T_1 \rightarrow T_N}$ in Eq. (7), and this implies that the typical approach for estimating temperature coefficient will not properly work with the 3-Step method; Eq.(7) must be used for 3-step method. By substituting Eq. (7) from Eq. (6), we can define the error of Eq. (6) as:

$$\begin{aligned} \varepsilon_{T_1 \rightarrow T_N} &= \sum_{i=1}^{N-1} \Delta \rho_i - \Delta \rho_{T_1 \rightarrow T_N} \\ &= \left(\frac{1}{k_{P_2}^{T_1}} - \frac{1}{k_{P_N}^{T_1}} \right) - \sum_{i=2}^{N-1} \left(\frac{1}{k_{P_i}^{T_i}} - \frac{1}{k_{P_{i+1}}^{T_i}} \right) \quad (8) \\ &= \sum_{i=2}^{N-1} \left\{ \left(\frac{1}{k_{P_i}^{T_1}} - \frac{1}{k_{P_{i+1}}^{T_1}} \right) - \left(\frac{1}{k_{P_i}^{T_i}} - \frac{1}{k_{P_{i+1}}^{T_i}} \right) \right\}. \end{aligned}$$

The first and second parentheses in Eq. (8) means the inserted rod worth difference between P_i and P_{i+1} , for two different temperatures, T_1 and $T_{i,i>1}$. Those two terms might be similar in the measurement, but not the same. Therefore, the error is accumulated at each step, and never canceled out.

3. Numerical Results

We compared the temperature reactivity based on two different formula, Eq. (6) and (7), and we call them as 3-Step method A (incorrect approach) and B (correct approach) for convenience. A Monte Carlo simulation code McCARD [2] with ENDF/B-VII.0 library was employed for criticality calculation, and the standard deviation of each Monte Carlo simulation was measured about 4 pcm.

In CEFR, five different control rods were used for reactivity control: two regulating rods (RE1 and RE2) and three shim rods (SH1, SH2, and SH3). The temperature and control rod positions are given in Table I, II, and III for experimental method, 3-Step method A, 3-Step method B respectively. The first four temperature steps are the measurements for the increasing phase, while the other four, steps from 5 through 8, are temperature steps for the decreasing phase.

Note that the step-wise temperature increment can be found at Table II, while base temperature (250 for increasing phase, and 300 for decreasing phase) are fixed in Table III. The control rod positions are the same in Table II and Table III because the next temperature's positions are used in the 3-step method.

Table I Temperature and control rod positions in the experimental method

Step	Temp.	CR positions [cm]				
	[°C]	RE1	RE2	SH1	SH2	SH3
-	250	207.2	207.7	247.9	247.7	248
1	275	212.3	212.9	253.6	253.1	253.8
2	283	239.7	239.3	253.4	253.1	254
3	293	282.8	283.4	253.4	253	253.7
4	302	307.5	307	254.7	254.6	255.9
-	300	407.7	408.5	501.5	162.3	162.2
5	290	283.4	283.8	254	253.7	254.4
6	281	285.2	284.6	502	162.2	162.2
7	270	232.4	232.2	501.9	162.2	162.2
8	250	118.5	118.9	501.8	162.2	163

Table II Temperature and control rod positions in the 3-step method A

Step	Temp.	CR positions [cm]				
	[°C]	RE1	RE2	SH1	SH2	SH3
1	250	212.3	212.9	253.6	253.1	253.8
	275	212.3	212.9	253.6	253.1	253.8
2	275	239.7	239.3	253.4	253.1	254
	283	239.7	239.3	253.4	253.1	254
3	283	282.8	283.4	253.4	253	253.7
	293	282.8	283.4	253.4	253	253.7
4	293	307.5	307	254.7	254.6	255.9
	302	307.5	307	254.7	254.6	255.9
5	300	283.4	283.8	254	253.7	254.4
	290	283.4	283.8	254	253.7	254.4
6	290	285.2	284.6	502	162.2	162.2
	281	285.2	284.6	502	162.2	162.2
7	281	232.4	232.2	501.9	162.2	162.2
	270	232.4	232.2	501.9	162.2	162.2
8	270	118.5	118.9	501.8	162.2	163
	250	118.5	118.9	501.8	162.2	163

Table III Temperature and control rod positions of the 3-step method B

Step	Temp.	CR positions [cm]				
	[°C]	RE1	RE2	SH1	SH2	SH3
1	250	212.3	212.9	253.6	253.1	253.8
	275	212.3	212.9	253.6	253.1	253.8
2	250	239.7	239.3	253.4	253.1	254
	283	239.7	239.3	253.4	253.1	254
3	250	282.8	283.4	253.4	253	253.7
	293	282.8	283.4	253.4	253	253.7
4	250	307.5	307	254.7	254.6	255.9
	302	307.5	307	254.7	254.6	255.9
5	300	283.4	283.8	254	253.7	254.4
	290	283.4	283.8	254	253.7	254.4
6	300	285.2	284.6	502	162.2	162.2
	281	285.2	284.6	502	162.2	162.2
7	300	232.4	232.2	501.9	162.2	162.2
	270	232.4	232.2	501.9	162.2	162.2
8	300	118.5	118.9	501.8	162.2	163
	250	118.5	118.9	501.8	162.2	163

The estimated temperature reactivity can be found in Table IV for three methods. Note that the rod worth in the experimental method was evaluated by linear interpolation of S-Curve, which was also estimated by McCARD Monte Carlo calculation as plotted in Fig. 1 and Fig. 2. The temperature reactivities in Table IV are similar among 3 different approaches, but 3-Step Method-A shows slightly greater reactivity in the increasing phase, but smaller reactivity in the decreasing

phase. Note that the difference becomes greater as the step index increase.

The estimated temperature coefficients are given Fig. 3 through Fig. 5, and the 3-step method A results showed slightly different slope in the increasing phase (blue dotted line) compared to others. As shown in Eq. (8), the error cannot be canceled out, so the temperature coefficient would have large compared to other methods. Note that the experimental method in the decreasing phase also have large error because of the large uncertainty at temperature 290°C and 281°C, it is difficult to judge which results is more reliable in the decreasing phase. However, the 3-Step method B provides consistent temperature coefficient both increasing and decreasing phases.

Table IV Estimated Temperature Reactivity

Step	Temp. [°C]	Exp. Method	3-Step Method A	3-Step Method B
-	250	0	0	0
1	275	-96.4±6.0	-106.5±5.7	-106.5±5.7
2	283	-141.5±7.4	-152.6±5.7	-143.9±5.7
3	293	-173.8±7.7	-191.0±5.7	-176.8±5.7
4	302	-213.3±6.4	-231.1±5.7	-212.9±5.7
-	300	0	0	0
5	290	91.5±12.3	40.1±5.7	40.1±5.7
6	281	73.7±10.5	64.0±5.7	71.7±5.7
7	270	130.0±7.7	115.0±5.7	121.4±5.7
8	250	208.9±8.2	192.3±5.7	201.7±5.7

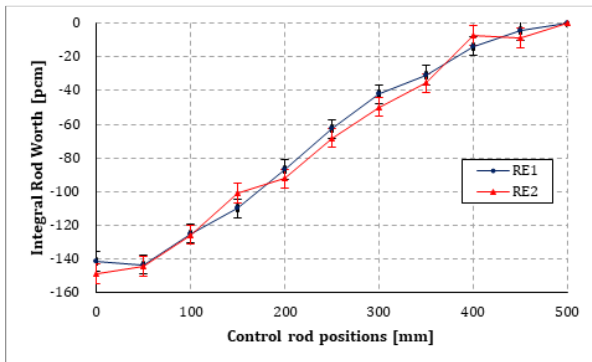


Fig. 1 S-Curve for regulating rods

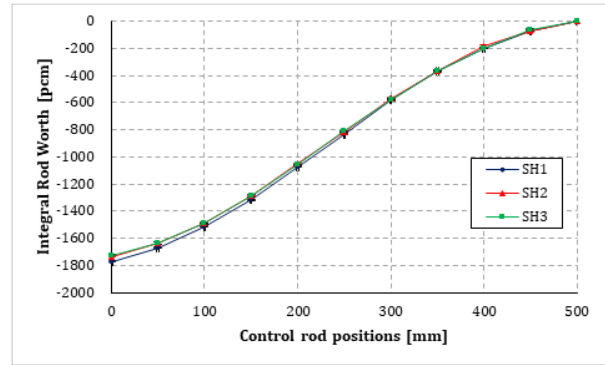


Fig. 2 S-Curves for shim rods

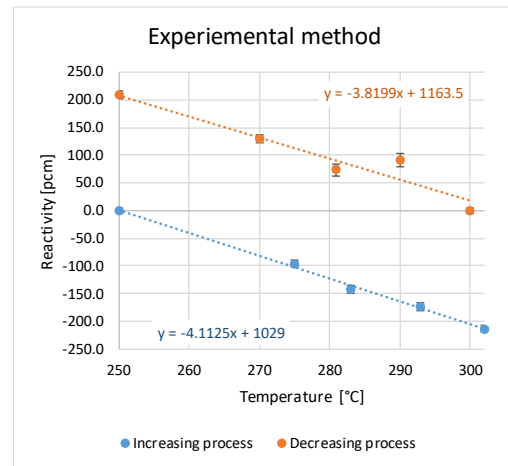


Fig. 3 Temperature Coefficient from Experimental Method

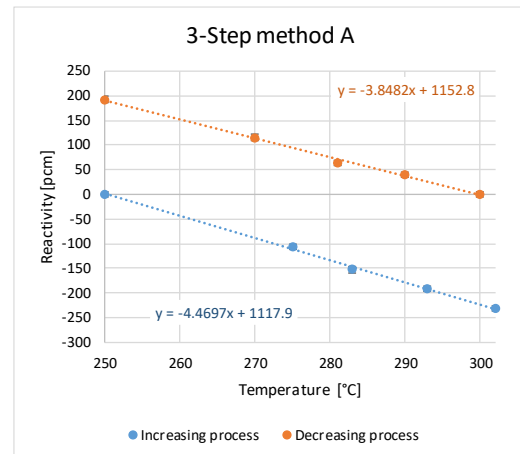


Fig. 4 Temperature Coefficient from 3-Step Method A

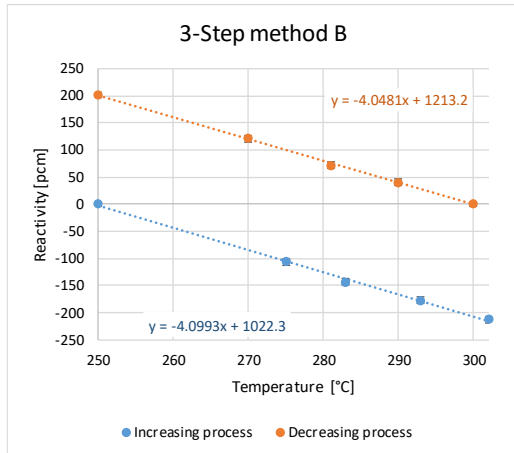


Fig. 5 Temperature Coefficient from 3-Step Method B

4. Conclusions

In this work, an appropriate application of 3-step method was proposed for temperature reactivity measurements in the CEFR start-up test. The error of conventional 3-step method was analytically analyzed, and quantified in the numerical analysis.

Experimental methods as well as two different 3-step approaches are compared by McCARD Monte Carlo simulations. Incorrect approach of 3-step method gives relatively greater reactivity worth in the increasing temperature phase, while smaller reactivity worth in the decreasing temperature phase. Therefore, the estimated temperature coefficient becomes greater for the increasing temperature phase, and the opposite for the decreasing phase. On the other hand, the experimental method and correct approach of 3-step method give consistent temperature coefficient, which is about 4 for both increasing and decreasing temperature phases.

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