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Comparisons of Power Distribution in a Research Reactor with Modified Steady State and Transient Monte Carlo Calculation during Rod Drop Test

Han Jong Yoo*, Kyung-O Kim, Beom Woo Park,
111, Daedeok-Daero 989Beon-Gil, Yuseong-Gu, Daejeon, Korea
**Corresponding author: hjyoo@karei.re.kr*

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1. Introduction

During the low-power physics test (LPPT) of the Jordan Research and Training Reactor (JRTR), the drop time of each control absorber rod (CAR) was measured. Along with this test, detector signals are collected to analyze rod worth.

As CAR drops, neutron flux distribution changes from initial state. After rod drop, flux distribution quickly settle down to its new fundamental mode. Due to the difference between flux distribution before and after rod drop, the correlation between detector flux and core neutron density loses its consistency.

It is well known that spatial correction factors of dynamic rod worth measurement method recover consistency between the local detector signal to core average neutron density. Reactivity worth calculated from inverse point kinetics equation with a consistent detector signal would be reliable.

These spatial correction factors are called flux redistribution factor [1], static spatial factor (SSF) [2], or density-to-detector response conversion factor (DRCF) [3] depending on literature. Spatial correction factor is usually defined as a ratio between detector signals at specific rod position to rod-out position. Detector signal is calculated from power distribution or fast neutron flux distribution via integration with adjoint neutron flux.

In previous work [4], the power distribution after rod-drop was obtained by steady-state calculation with modified delayed neutron source strength. Although the result corresponded well with measured signals and rod worth derived from it, verification of new method was postponed due to the absence of reference data.

In this paper, thanks to time-dependent Monte Carlo code, McCARD[5], reference power distribution after rod-drop has been studied and compared with steady-state calculation results.

2. Rod Drop Test of JRTR

2.1 Reactor Model and Detector Position

JRTR is consists of 18 MTR type fuel assemblies (FAs). Four square-shaped, Hf material CARs are located in four position. Inner reflectors are Be blocks and outer reflector is D_2O tank. For the simulation of rod drop test, FAs are divided in 10 axial zones.

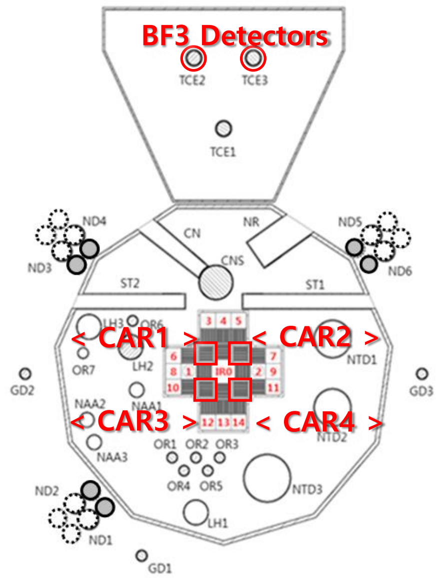

Fig. 1. JRTR Core Schematic Diagram and Positions of Detector and CARs

2.2 Rod-Drop Test Scenario

During rod drop test, two BF_3 detectors were located in thermal column. For the rod drop test, one CAR to be dropped is withdrawn first and critical state is achieved by adjusting three other CARs. Few minutes are given for the saturation of delayed neutron precursors. When the detector signal is settled CAR is dropped by operator. Drop time for the simulation is assumed to be 1.0 sec. In this paper, only CAR1 is of interest. Reactivity worth of CAR1 for rod drop test situation is around 10$ with normal steady state Monte Carlo calculation (MCNP, McCARD).

3. Methods and Theory

3.1 Spatial Correction Factor

Reactor core is monitored indirectly through ex-core detector. When reactor core status is changed significantly, detector signal lose its representativeness to the reactor core. If flux distribution or ratio between core average neutron density and detector flux remain unchanged, it can be assumed that detector signal represent reactor core status. However, locally inserted large reactivity significantly distorts flux shape of the system. Rod drop test is one of the case. By applying correction factor to detector signal, core average neutron density can be represented by detector signal. DRCF is one of the static correction factor and can be calculated by,

$$\mathrm{DRCF}_{T,B}(\mathrm{t}) = \frac{\sum_{n=1}^{N} \Delta V_n \omega_n^{T,B} \sum_{g=1}^{G} \kappa\Sigma_{fg}^{n} \phi_g^n(t)}{\sum_{n=1}^{N} \Delta V_n \omega_n^{T,B} \sum_{g=1}^{G} \kappa\Sigma_{fg,ARO}^{n} \phi_g^n(t_{ARO})}, \quad (1)$$

where, *T/B* represents detector position, *n* for cell number, *g* for *E* group, ARO for rod-out position.

V means volume of cell, *ω* represents contribution of fission neutron to detector (adjoint flux). $\kappa\Sigma_{fg}^{n}\phi_g^n$ means released energy from fission induced by neutron of energy group g in cell *n*.

3.2 Strength of Delayed Neutron Source

As can be seen in Eq. (1), detector signal is proportional to the summation of the product of power and its corresponding adjoint flux. Since the adjoint flux quickly decreases away from detector, only fuel assembly in vicinity of detector contributes to detector signal. In transient situation, such as dynamic rod worth measurement, power distribution must be provided by transient core simulation since delayed neutron source plays a significant role and simple k-eigenvalue steady state calculation cannot reproduce power distribution of transient case. In the previous work [4], it is assumed that after rod drop and few seconds later, power distribution will be settled down to its new fundamental mode and this power distribution can be obtained from steady state calculation with proper delayed neutron source distribution.

To find out the ratio of prompt and delayed fission neutron for each node, point kinetics equation (PKE) is solved for given condition. The procedure is as followed.

(1) For given reactivity and rod insertion time (1sec), calculate neutron and delayed neutron precursor density for every time step (from PKE)
(2) From given neutron generation time and neutron density, calculate prompt fission neutron source strength ($(1-\beta)n/\Lambda$)
(3) Given precursor density and decay constants, calculate delayed neutron source strength ($\sum_i \lambda_i C_i$)
(4) Calculate fission source ratio (delayed/prompt) for each time step and find out converged value.

3.3 Power Distribution Calculation from Steady-State Calculation

Given new ratio between prompt and delayed fission neutron source, neutron cross section library for MCNP (in ACE format) can be prepared. Both delayed neutron and total neutron yield data are modified. Since the power distribution is calculated for 180 nodes (18 FAs and 10 axial segments), 180 new nuclear data file is prepared. Only U-235 data is modified as the most of the fission reaction is occurred with U-235.

After neutron cross section data is prepared, whole calculation is done as in the following procedure:

(a) Calculate reactivity and power distribution for initial state (before rod drop)
(b) Calculate reactivity and power distribution for final state (after rod drop)
(c) Calculate reactivity worth and solve point kinetics equation (procedure (1~4))
(d) Modify delayed neutron yield data and prepare new cross section file
(e) Go to (b) and calculate with new delayed neutron strength data. Repeat (b~d) until convergence.

Fig. 2. shows the convergence of power distribution for 18 FAs for after CAR1 dropped case.

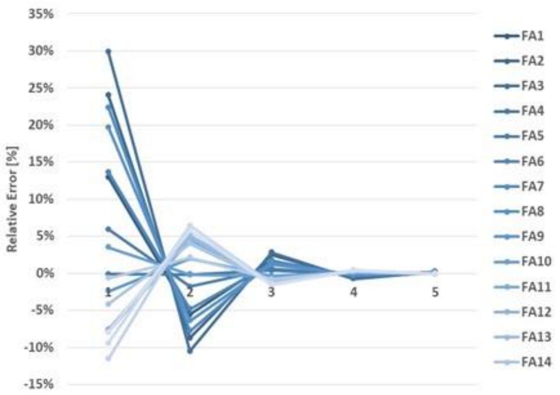

Fig. 2. Convergence of Power Distribution for CAR1 drop test

After five iterations, assembly power was converged within 1% relative to adjacent iteration step. Calculations are done with ENDF/B-VIII.0 cross section data and MCNP6.1 code.

3.4 Time-Dependent Monte Carlo Calculation Simulation

Reference solution for rod drop test is prepared with McCARD[5]. Since the neutronics design of JRTR was performed with McCARD, it was easy to prepare input file for McCARD time-dependent simulation. Some structures were deleted (beam tube, CNS hole, etc.) due to incompatible functions but it did not affect power distribution. Simulations were done with 0.002 sec time step and 10,000 neutrons and 10,000 delayed neutron precursor populations for each time step. CAR1 position is linearly changed after rod drop in 1sec and whole simulation is done up to 10sec. Power distribution is tallied with 'TimeReaction' tally flag and fission reaction option 'FIS' for every 0.1sec time width.

4. Results and Discussions

Table I. shows comparisons between TDMC and steady-state calculation results. The 'Original' column means normal steady state calculation results with original cross section data and 'New-DN' means calculation results with new delayed neutron source strength. Relative difference with TDMC is given in % error. Relative standard deviation of FA power results are normally below 0.1% (except few cases) and given in parenthesis.

Table I. Normalized FA Power Distribution after CAR1 Drop by Steady-State Calculations and Comparisons with TDMC Results

FA	Original(rsd,%)	Diff [%]	New-DN(rsd,%)	Diff [%]
1	3.94E-02(0.07)	-27.0%	4.62E-02(0.07)	-14.4%
2	5.78E-02(0.07)	-20.4%	6.59E-02(0.07)	-9.3%
3	6.08E-02(0.08)	-14.9%	6.48E-02(0.08)	-9.2%
4	3.25E-02(0.06)	-22.6%	3.63E-02(0.06)	-13.5%
5	1.90E-02(0.07)	-19.3%	2.14E-02(0.07)	-8.9%
6	3.53E-02(0.11)	-7.5%	3.81E-02(0.08)	-0.2%
7	5.13E-02(0.09)	-1.5%	5.30E-02(0.11)	1.6%
8	6.14E-02(0.06)	-1.8%	6.05E-02(0.09)	-3.1%
9	3.72E-02(0.06)	-0.3%	3.78E-02(0.06)	1.3%
10	5.77E-02(0.08)	9.9%	5.65E-02(0.08)	7.5%
11	5.44E-02(0.06)	-1.7%	5.42E-02(0.06)	-2.2%
12	5.43E-02(0.06)	7.6%	5.29E-02(0.06)	4.8%
13	5.72E-02(0.06)	14.8%	5.39E-02(0.06)	8.3%
14	6.34E-02(0.07)	16.0%	6.01E-02(0.07)	10.0%
15	6.96E-02(0.07)	10.0%	6.56E-02(0.07)	3.7%
16	7.63E-02(0.06)	10.1%	7.24E-02(0.06)	4.5%
17	9.00E-02(0.06)	14.1%	8.45E-02(0.06)	7.2%
18	8.26E-02(0.06)	14.3%	7.58E-02(0.06)	4.9%

As shown in Table I, power distribution of original steady state calculation is largely differ from TDMC (reference) result. Although calculation results with modified delayed neutron source distribution improved noticeably, there remains huge error. It is worth noting that power of FAs near CAR1 increased while power of other FAs (far from CAR1) decreased. PKE solution seems correctly predicts tendency of delayed neutron source distribution for transient case but accuracy is in question.

4. Conclusions

Attempts to predict power distribution after rod drop with steady state calculation is described and compared with reference solution. Reference power distribution is given with TDMC code McCARD. To simulate transient situation by steady state calculation, delayed neutron source strength is calculated from PKE solution and neutron cross section data is modified properly. Although new method showed noticeable improvement and more study is required to fill the huge gap.

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REFERENCES

[1] Trkov, A., et al, "Application of the rod-insertion method for control rod worth measurements in research reactors", Kerntechnik Vol 60, p. 255–261, 1995

[2] Y. A. Chao et al., "Dynamic Rod Worth Measurement", *Nuclear Technology*, Vol. 132, p. 403, 2000

[3] E. K. Lee et al., "New Dynamic Method to Measure Rod Worths in Zero Power Physics Test at PWR Startup", Annals of Nuclear Energy, Vol. 32, p.1457-1475, 2005

[4] H.J. Yoo et al, "Analysis of the Rod-Drop Experiments in JRTR Commissioning Stage", European Research Reactor Conference, Budapest, 6-10 June, 2022.

[5] N. Shaukut et al, "for the Organization for Economic Co-operation and Development Nuclear Energy Agency (OECD/NEA) C5G7-TD benchmark", *Nuclear Engineering and Technology*, Vol 49, p.920-927, 2017.