1. CONTROL ROD CALIBRATION

1.1 INTRODUCTION

Control rods are installed in a reactor to control nuclear fission chain reactions. Primarily, they are used to adjust criticality, change reactor power level, and shut down the reactor, among others. Materials with a large neutron absorption cross-section such as boron (B), cadmium (Cd), and hafnium (Hf) are used for control rods. When a control rod is pulled out from a reactor, the amount of fission reactions increases; conversely, inserting the control rod into the core causes a decrease of fission reactions. This means that control rods can change the effective multiplication factor (k_{eff}) of the core.

1.2 PURPOSE

For safe operation of a reactor, it is required to know the total reactivity of each control rod, which means the amount of reactivity measured by moving a control rod from its lower limit to the upper limit. Also, the reactivity insertion rate as a function of the position of the control rod, which is designated the control rod calibration curve, is also an important parameter of the control rod. Measurement of the total reactivity value, or calibration curve, is known as the control rod calibration experiment. When a new reactor core is constructed, the control rod calibration experiment is conducted just after the criticality approach experiment for safety reasons.

2. SAFETY MEASURES

Control rod calibration is important not only for safe operation, but also for other reactivity measurement experiments. For example, the amount of sample reactivity caused by introducing a material into the core can be determined by the difference of the position of a calibrated control rod before and after the introduction.

3. INSTRUMENTS AND MATERIALS

KUCA core has 6 identical control rods, however, 3 rods out of 6 (C1 to C3) are used for adjustment of criticality, and the remaining 3 rods (S4 to S6) are used as safety rods that are always pulled out from the core during operation as a backup system for emergency shutdown. Note that all control rods were composed of aluminum tube covered by cadmium thin plate.

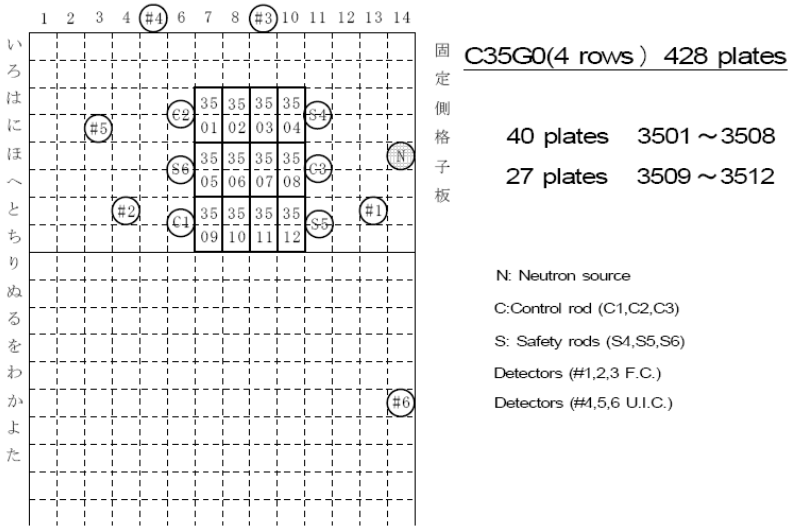


Fig. 2-3 Core Configuration of the KUCA core (horizontal view).

4. EXPERIMENTAL PROCEDURES

The experimental procedure for the positive period method is as follows:

(1) Adjust criticality
(2) Extract a designated control rod to a specified distance
(3) Wait a specified time period for the disappearance of higher order terms
(4) Measure the doubling time t_d (time to double the power level) with a stop watch
(5) Obtain period t by $t=t_d/\ln 2$ relationship
(6) Obtain ρ through the inhour equation
(7) Insert another control rod to a specified length to reestablish criticality
(8) Repeat procedures (1) to (7) until the first rod is in the upper limit position, namely, fully extracted from the core.

The experimental procedure for the rod drop method is as follows:

(1) Adjust criticality
(2) Measure the n_0 count several times to confirm criticality
(3) Start the multi-channel scalar (MCS)
(4) Kill the electric current of a control rod that is in the upper limit position and start measuring the integral count
(5) Stop the above counting when the neutron flux level becomes very small

5. MAIN PARAMETER(S) MEASURED

The following quantities should be measured:

(1) Control rod value (reactivity) of C1, C2, C3 rods
(2) Integrated and differential calibration curves of measured rods
(3) Excess reactivity of the core
(4) Mass reactivity of each fuel plate
(5) Shutdown margin of the core

6. TYPICAL REAL DATA COLLECTED

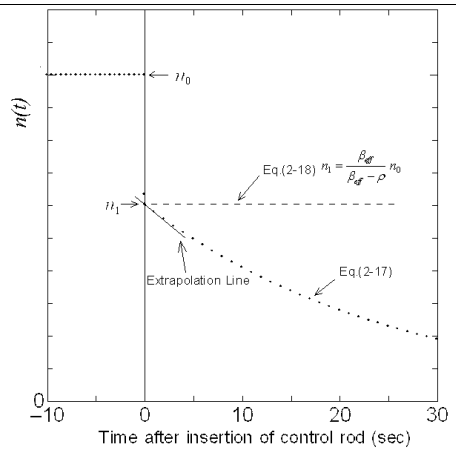


Fig. 2. Reactor power change after insertion of a control rod

7. DATA ANALYSIS, ASSUMPTIONS AND EQUATIONS

The reactor kinetic equations per one-point reactor approximation, which are the basis for reactivity measurement, are written as follows;

$$\frac{dn}{dt} = \frac{\rho - \beta_{eff}}{\Lambda} n + \sum_{i}^{6} \lambda_i C_i$$

$$\frac{dC_i}{dt} = \frac{\beta_{i,eff}}{\Lambda} n - \lambda_i C_i$$

where n(t) is neutron density, C_i is the i^{th} group delayed neutron precursor density, λ_i is the decay constant of the i^{th} group delayed neutron precursor, Λ is the neutron generation time which is the neutron life time ℓ is divided by k_{eff}, β_{eff} is the effective delayed neutron fraction, and $\beta_{i,eff}$ is the i^{th} group delayed neutron fraction.

Based on the above reactor kinetic equations, reactivity ρ can be obtained by the following in-hour equation,

$$\rho = \frac{\ell}{T + \ell} + \frac{T}{T + \ell} \sum_{i=1}^{6} \frac{\beta_{i,eff}}{1 + \lambda_i T}$$

where T is measured positive period.

In the control rod drop method, total reactivity worth ρ of the control rod can be obtained by the following equation,

$$-\frac{\rho}{\beta_{eff}} = \frac{n_0 \sum_i \frac{a_i}{\lambda_i}}{\int_0^\infty n(t)dt} = \frac{13.04 \times n_0}{\int_0^\infty n(t)dt}$$

where n_0 is the count rate before the control rod drop, $\int_0^\infty n(t)dt$ is the total count after the control rod drop is measured.

8. PRE-KNOWLEDGE REQUIRED FROM STUDENTS

Defining reactivity as,

$$\rho = \frac{k_{eff} - 1}{k_{eff}} \ .$$

where ρ is the reactivity and k_{eff} is the effective multiplication factor. Reactivity ρ is a non-dimensional quantity, however, its unit is usually represented as $\Delta k/k$ ($10^{-2}\,\Delta k/k$ is 1% $\Delta k/k$、and $10^{-5}\,\Delta k/k$ is equal to 1 pcm). Reactivity ρ divided by β_{eff} (effective delayed neutron fraction) is known as reactivity in dollar units, namely, the reactivity of 1 dollar means the prompt critical state.

9. RESULTS

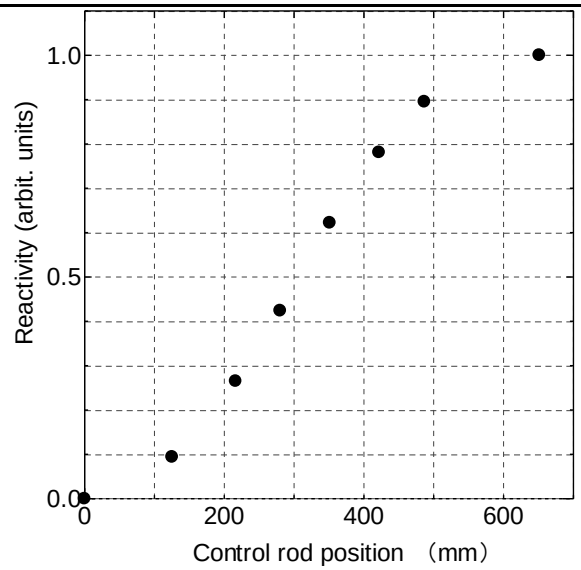


Fig. 3. Integral reactivity worth calibration curve of a control rod measured by positive period method

10. CONCLUSIONS

The following quantities were measured through the experiments

(1) Control rod reactivity of C1, C2, C3 rods by rod drop method
(2) Integrated and differential calibration curves of C2 rod by the positive period method
(3) Excess reactivity of the core
(4) Mass reactivity of each fuel plate
(5) Shutdown margin of the core