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A Calculation on Core Transient during On-Power Loading of Irradiation Targets on a Research Reactor

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1. Introduction

Research reactors are applicable to a very wide range of utilization of neutron. Among them is to get radioisotopes by irradiating targets [1].

Some research reactors have the capability to load and unload irradiation targets during power operation. Irrespective of total reactivity inserted per single irradiation target and rate of reactivity insertion, a reactor should be kept in a safe condition.

Thus international standards [2,3] as well as Korean laws have assigned the parameters related to reactivity and reactivity control as one of the Limiting Conditions for safe Operation (LCO) specified in the technical specification for a research reactor so that a reactor may not be vulnerable to an On-Power Loading (OPL) of irradiation targets, i.e., insertion of positive reactivity to a reactor core. LCOs, a part of Operational Limits and Conditions (OLC) that includes safety limits, safety system settings, requirements for inspection, periodic testing, and maintenance and administrative requirements [3], should be established in a comprehensive manner.

For supporting the establishment of a set of LCOs, a calculation of the transients of a research reactor is presented based on a set of design features such as control rod worth, performance of the drive mechanism, and controller in the reactor power regulating system which are essential for controlling the reactor during the OPL of the irradiation targets.

2. Theoretical Model

The dynamic model for a core transient simulation includes neutron point kinetics, Iodine-Xenon behavior, reactor/thermal power from a core and reflector, reactivity feedback, and controller. Individual component models of the reactor such as control rod drive mechanism, control rod worth are also incorporated into a simulation program of the RRSSIM, Reactor Regulating System SIMulator [4,5]. The program was originally developed in FORTRAN, but was modernized in MATLAB/SIMULINK [6] for enhancing its flexibility to construct a virtual reactor with all of the components.

2.1 Neutron Point Kinetics

To have the capability to represent reactor containing material(s) of high photo-neutron yield, such as Be and heavy water, a model slightly modified from the conventional point kinetics is selected to cover retarded photo-neutrons created by gamma rays in Be and heavy water. Balance equations of neutron concentration, delayed neutron precursors, and photo-neutron precursors are expressed as follows [7].

$$\frac{dN(t)}{dt} = \frac{\rho(t)-\beta_C-\beta_D}{\Lambda}\mathrm{N(t)} - \sum_{i=1}^{I}\lambda_{C_j}C_j(t) + \sum_{j=1}^{J}\lambda_{D_j}D_j(t) + S,$$

$$\frac{dC_i(t)}{dt} = \frac{\beta_{C_i}}{\Lambda}\mathrm{N(t)} - \lambda_{C_i}C_i(t), i = 1, \ldots, I,$$

$$\frac{dD_j(t)}{dt} = \frac{\beta_{D_j}}{\Lambda}\mathrm{N(t)} - \lambda_{D_j}D_j(t), j = 1, \ldots, J.$$

2.2 Thermal Power and Primary Cooling System

Thermal power from neutron and gamma radiation in a core and reflector is considered as follows. The fuel element temperature is modeled by a simple energy conservation law as

$$M_{FE}C_{FE}\frac{dT_{FE}}{dt} = \eta_F Q_C - H_F(T_F - T_C),$$

The coolant temperature passing through a core, Tc, is modeled as

$$\mathrm{M}_C C_C\frac{dT_C}{dt} = (1-\eta_F)Q_C + H_F(T_F - T_C) - W_C C_C(T_{CO} - T_{CI}).$$

2.3 Reactivity Feedback

Reactivity feedback is considered to be due to variations of 1) temperature in fuel, coolant, and reflector and 2) xenon load. In addition, an external reactivity insertion is modeled in the form of an arbitrary shape such as a step or ramp insertion.

2.4 Controller

The response of a reactor system to an external disturbance such as reactivity insertion is managed by a controller. Controllers are very specific case by case, but only a conventional PID controller is assumed.

2.5 Initial Conditions

In addition to the models described previously, initial conditions are essential to simulate transients of the system. The initial control rod position besides initial power and initial temperature may be crucial to instantaneous response of the system because the typical rod worth in a differential form is as shown in Figure 1[8]: with respect to the initial position of a rod, the rod worth for controlling reactivity of the reactor is outstandingly different from position to position. From

Beginning of Cycle (BOC) to End of Cycle (EOC), the criticality position moves upward.

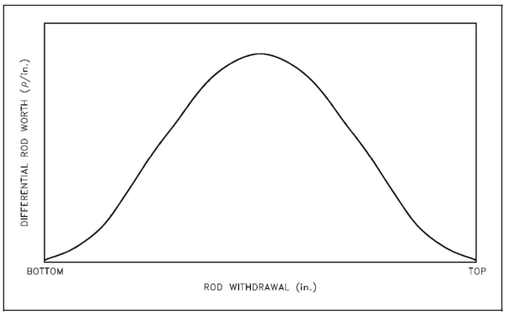

Fig. 1. Conceptual differential control rod worth

3. A set of LCO for operating Irradiation Targets

An example of LCOs for irradiation rig includes reactivity of each irradiation rig (fixed or movable during On-Power), total irradiation rig reactivity, rate of change of reactivity, and total reactivity change: only a part of those are as follows [9]:

1) Maximum allowed reactivity per single target for OPL
2) Insertion rate
   - No limit on the reactivity insertion rate for small reactivity perturbations
     - Any rate for reactivity smaller than $\rho_{ext,Min}$
   - The reactivity rate in the range
     - $d\rho_{ext}/dt$ for $\rho_{ext,Min}<\rho_{ext}< \rho_{ext,Max.}$

The first, maximum allowed reactivity per single target for OPL is determined from the safety analysis. Thus only issues about insertion rate are dealt with from operational point of view in this paper.

4. Results and Discussion

4.1 Reactivity Limit free of insertion rate

For predicting the limit of small perturbation free of insertion rate, the free fall of an irradiation target in a reactor core is assumed.

The reactivity inserted into a core in dollars is about 0.3, 0.05, and 0.02, respectively, as shown in Figure 2.

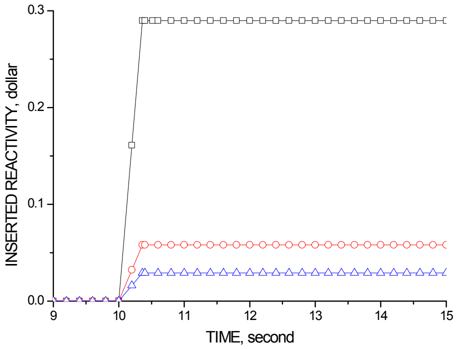

Fig. 2. Stepwise inserted reactivity

The excess reactivity as a representative parameter to show the system response including delay is shown in Figure 3. Excess reactivity was predicted to become smaller to the extent that inserted reactivity decreases: the peak of excess reactivity looks proportional to the inserted reactivity

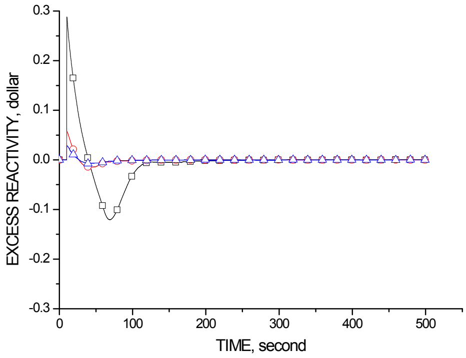

Fig. 3. Calculated Excess reactivity when small reactivity inserted

The power transient when a stepwise reactivity is inserted is presented in Figure 4. The same trend as in the excess reactivity is found in the power transient: the bigger disturbance, the greater the overshoot. However, for the power transient, a much larger power excursion was expected when the inserted reactivity was about 0.3 in dollars.

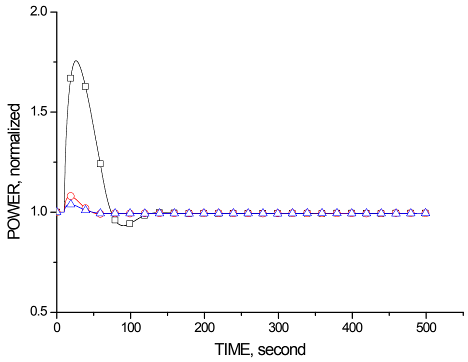

Fig. 4. Power transient when small reactivity inserted

4.2 Limit of Insertion Rate

The inserted reactivity, excess reactivity, and power transient with respect to time are shown in Figures 5, 6, and 7, respectively.

Reactivity of about 0.3$ is assumed to be inserted into the core for 20, 30, 60, 120 seconds, respectively.

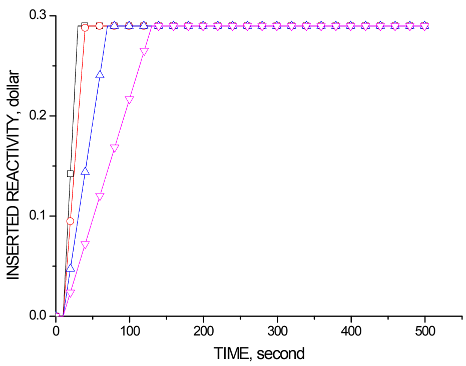

Fig. 5. Inserted reactivity with respect to time

It is shown that the overshoot of excess reactivity and overshoot becomes smaller as the reactivity is slowly inserted.

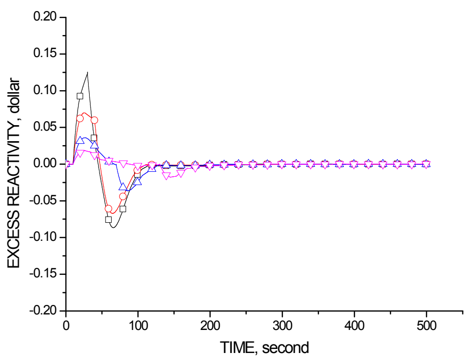

Fig. 6. Calculated excess reactivity with respect to time

The same appears to hold for the simulation of the test of the rate as in the test of the small perturbation above. In addition, a non-proportional decrease in overshoot is also predicted.

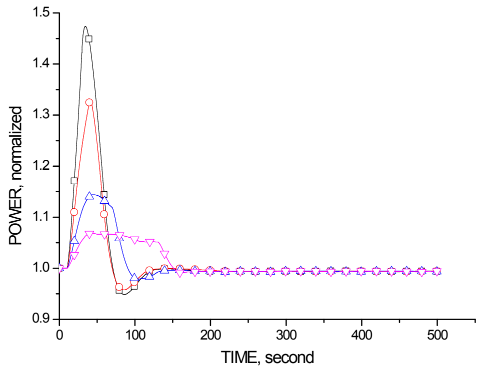

Fig. 7. Power transient with respect to time

4.3 Rule of Thumb for System Response

Excess reactivity can be depicted in a conceptually simplified but quite a realistic manner, as in Figure 8. When reactivity as disturbance is inserted into a reactor core, control rod will compensate the perturbation as quickly as possible but with some delay due to both response and delay time in measurement in fact. If the reactivity cannot be covered, then excess reactivity is accumulated in the core. But if the insertion is small enough to catch up fast, then overshoot probably can be much smaller than before. This relationship has been already shown in the results.

Here the characteristics of transient of power itself can be figured out by using an unsophisticated relation for neutron flux assuming point kinetics due to small reactivity:

$$\phi = e^{t/T}$$

where,

$$T = \frac{1}{\rho}\sum_i \frac{\beta_i}{\lambda_i}$$

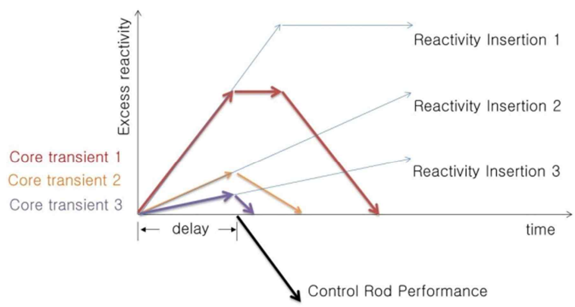

Fig. 8. Conceptual system transients depending on the reactivity insertions

The neutron flux is an exponential function of the reciprocal of the reactor period, and the reactor period is proportional to the reciprocal of the inserted reactivity. That is, the flux is an exponential function of the inserted reactivity. One of the reasons for a non-proportional decrease or increase in an overshoot may be this exponential relationship.

5. Conclusions

From the calculation, it was shown that the RRSSIM provided quite a reasonable prediction of the reactor transient when positive reactivity is inserted into a reactor core. In addition, the RRSSIM can be useful to determine and improve the operational performance of a research reactor

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