Estimation of the Excore Reactivity Correction Factor for a Liquid Zone Controller's Worth Measurement in a CANDU Reactor

Eun Ki Lee
KHNP-Central Research Institute, 70 1312 Beon-gil, Yusung-daero, Yusung, Daejeon, KOREA, 305-343

1. Introduction

Recently, KHNP-CRI developed a reactivity computer (RC) to measure the reactivity of the unit liquid zone level, which is required to confirm the nuclear design values related to reactivity devices in a refurbished or an initial CANDU-6 design. While the old method for a liquid zone controller (LZC) worth measurement takes about 24 hrs and requires predetermined 50 mg boron ampoules, the new reactivity computer for the CANDU-6 reactor estimates these values within 3 hrs without any additional devices. However, the reactivity computer has a critical drawback caused by its reactivity calculation solver pertaining to the inverse point kinetics equation. According to the ANS/ANS-19.6.1-2005[1] specification for a PWR, the maximum measureable reactivity by the RC is about 200 pcm. However, there is no guide for a CANDU design, in which the photo-neutron effect is important. This paper studies the limitation of the RC for a CANDU reactor by estimating the reactivity correction factors for various reactivity changes.

2. Methods and Results

2.1 Reactivity Estimation Method

The reactivity in a CANDU reactor can be estimated by an inverse point kinetics equation including the photo-neutron variation with excore detector signals, as follows:

$$\begin{aligned}\frac{dn(t)}{dt} &= \frac{(\rho(t)-\beta)}{\Lambda(t)}n(t)+\sum_{i=1}^{6}\lambda_i(t)C_i(t)+\sum_{p=1}^{11}\lambda_p(t)P_p(t),\\ \frac{\partial C_i(t)}{\partial t} &= -\lambda_i(t)C_i(t)+\beta_i(t)\frac{n(t)}{\Lambda(t)},\\ \frac{\partial P_p(t)}{\partial t} &= -\lambda_p(t)P_p(t)+\beta_p(t)\frac{n(t)}{\Lambda(t)}.\end{aligned} \tag{1}$$

Here the notations are identical to the nominal definitions, except that $P_p(t)$ denotes the photo neutron density. Photo-neutrons caused by neutron-deuterium interaction have characteristics similar to those of delayed neutrons and can be neglected in Eq. (1) in the case of a PWR. However, they should be considered in the CANDU case where a considerable amount of deuterium oxide solution is used as a moderator.

If the excore detector signals are proportioned to the core-averaged neutron density (or population) $n(t)$, the measured reactivity due to LZL changes can be calculated by the following equation[2]:

$$\rho(t_n)=\sum_k\beta_k\left(e^{-(\lambda_k+\omega_n)\Delta t_n}B_{n-1,k}+A_{n,k}\right)+\Lambda\omega_n, \tag{2}$$

where

$$\begin{aligned}B_{n,k} &= e^{-(\lambda_k+\omega_n)\Delta t_n}B_{n-1,k}+A_{n,k},\\ A_{n,k} &= \frac{\omega_n}{\lambda_k+\omega_n}\left(1-e^{-(\lambda_k+\omega_n)\Delta t_n}\right),\ \omega_n=\frac{1}{\Delta t}\ln\left(\frac{n(t_n)}{n(t_{n-1})}\right).\end{aligned} \tag{3}$$

2.2 Overall Process

Although we assumed that the excore detector signals are proportioned to $n(t)$, this is not an accurate assumption in an actual reactor because the solver is based on a point reactor and not on a three-dimensional time-dependent reactor. We have to confirm that the measured reactivity is identical to the true static reactivity. Because the reactivity is not a variable that can be measured directly, it must be estimated with measurable data such as excore detector signals. Therefore, a computational approach was adopted to estimate the limit of the inverse point kinetics solver. First, the excore detector signal variations with time and the true static reactivity are simulated by the nuclear design tool known as the RFSP-IST code[3] with various LZL changes, typically from 20% to 30%, 20% to 40%, or 30% to 60% for instance. The next step is to estimate the case-wise reactivity based on the simulated detector signals and to compare them to those of the true reactivity from the RFSP code. The final step is to consider the difference and draw the limitation within which RC results can be guaranteed.

2.3 LZL Simulation

In this case, six excore detectors in total were installed in the CANDU reactor. These were three detectors (D, E, and F) for Shutdown System (SDS) 1 located at the upper right side and three for SDS2 at the lower left side. Figure [1] shows a core map in which the excore detector and fuel channels are modeled. The RFSP code can calculate the flux level with the time at the detector positions.

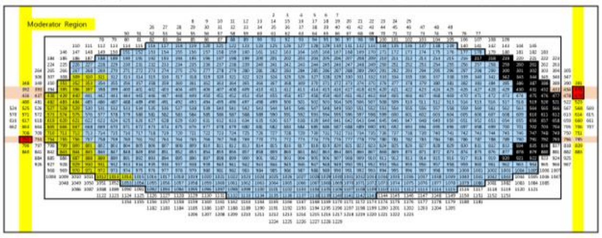

Fig. 1. Excore detector positions (red cells) in the geometry model of the RFSP code

Simulations of LZL changes are classified into two types: Mechanical Control Assembly (MCA) Half IN or Full OUT. For each condition, the LZL changes from

10% to 30% from its starting level of 20% to 60%. As an example, Figure [2] shows the trends of the core averaged neutron density (①) over time and the static reactivity (②,$\rho^{static.design}$) when the LZL changes slowly from 70% to 80% during a time of 100 sec.

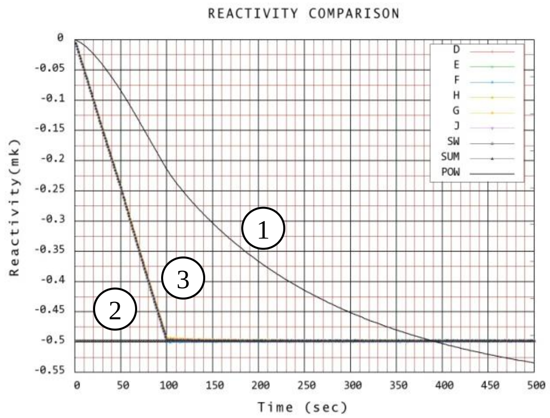

Fig. 2. Estimated reactivity behavior during a LZL change from 70% to 80%

The reactivity values (③,$\rho^{avg.stable.IKE.design}$) with time are calculated by the inverse point kinetics solver using simulated detector signals. Seven reactivity values in total for each detector are always reflected: D, E, F, G, H, J and SUM. In a real situation, to increase the signal-to-noise ratio, all individual detector signals with time are added and supplied to the solver to evaluate the core average reactivity. In this specific case, all seven curves show the same behavior – decreasing from critical status (0 pcm) to -50 pcm and staying at that point past 100 sec with the flux dropping down continuously. This indicates that there is no need to consider the limitation of the point kinetic solver because the introduced reactivity from the changes in the LZL is small, having no impact on the local flux variation. If the worth increases to 200 pcm, SUM can vary with time after 100 sec due to the limitation of the point kinetics equation. Therefore, the final measured reactivity is defined as the averaged value for 300 sec after the LZL variation vanishes. The ERCF (Excore Reactivity Correction Factor) is determined using the following equation:

$$ERCF_{X\rightarrow Y} = \frac{\rho_{X\rightarrow Y}^{static.design}}{\rho_{X\rightarrow Y}^{avg.stable.IKE.design}} \qquad (4)$$

2.4 Results

Table I shows the ERCFs upon changes of 15%, 20%, 30% and 60% from various starting levels. One can also apply ERCF for each excore detectors not SUM. Table II shows individual ERCFs in case of 15% and 30% variation of LZL.

For the various conditions including MCA half IN, 27 ERCFs overall were obtained and reviewed. If an ERCF of 1% signifies that it is possible to neglect the computational error caused by the point kinetics equation, the maximum available reactivity from the LZL changes is about 100 pcm. If selecting an ERCF of 2%, the limitation of RC applicability in the CANDU design increases to about 200 pcm. (See Table I for the 20% - 50% case)

Table I: Estimated ERCF Comparisons for Various LZL Changes including MCA 50% IN

LZL		Static	Inverse	ERCF
Initial	End	(pcm)	(pcm)	(%)
20%	35%	104.3	103.5	0.7878
30%	45%	104.0	103.4	0.5686
60%	75%	0.808	0,808	0.0080
20%	40%	139.1	137.9	0.8420
40%	60%	1.291	1.285	0.4441
20%	50%	206.2	202.5	1.8177
20%	70%	324.9	316.6	2.6282

Table II: Estimated individual ERCF Comparison for various LZL changes

Detector	ERCF (%)	
	LZL change (20% - 35%)	LZL change (20% - 50%)
D	0.90	2.11
E	1.19	2.82
F	0.82	1.94
H	0.47	0.98
G	0.73	1.72
J	0.43	0.87

3. Conclusions

From sensitivity studies of various liquid zone level changes using the RFSP code and the INVERSE-CANDU program, excore reactivity correction factors (ERCF) are estimated. The results led to the following conclusions:

1) If the LZL worth is less 114pcm, there is no need to use ERCFs because the ERCFs are very close to 1.0s.
2) If the worths are greater than 100pcm, then the ERCFs shown in Table I should be used to reflect the correct three-dimensional reactivity behavior in the point kinetics approach.

REFERENCES

[1] ANSI/ANS-19.6.1-2011, "Reload Startup Physics Tests for Pressurized Water Reactors," American Nuclear Society, 2011.
[2] E.K. Lee, H.C. Shin, S.M. Bae, and Y.K. Lee, "New Dynamic Method to Measure Rod Worths in a Zero Power Physics Test at PWR Startup," Annals of Nuclear Energy, 32, pp1457-1475, 2005
[3] P. Schwanke, "RFSP-IST Version REL_3-04: User's Manual", 153-117360 -UM-002, 2006 December.