EVALUATION OF THE APPLICABLE REACTIVITY RANGE OF A REACTIVITY COMPUTER FOR A CANDU-6 REACTOR

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1. INTRODUCTION

The measurement of a reactivity device’s performance is very important in PHWRs as well as PWRs because the results guarantee the safety features of the reactor. In a PWR, regulations dictate that the worths of control and safety banks be measured during the low power physics test of each cycle. The measurement methods, such as the boron dilution method, the dynamic rod worth measurement method [1], and the rod swap method, had been extensively developed and applied to all PWRs by a reactivity computer system using the inverse point kinetics equation coupled with six delayed neutron precursor groups. KHNP-CRI developed a direct digital reactivity computer system (DDRCS) for 20 PWRs in KOREA in 2006 using the dynamic control rod worth measurement (DCRM) method. The DDRCS for PWR can be applied to a CANDU-6 reactor with appropriate modification. The main problem is the DDRCS’s reactivity estimation capability. According to Section A.3.1.1 of ANS/ANSI-19.6.1 [2], the initial conditions allow “the lead control rod group to be inserted at 2 mk or 20% of the total worth”. Theoretically, a reactivity computer measures the dynamic reactivity not the static reactivity. Therefore, a conversion factor from dynamic to static is needed; however if the difference is small, then the measured reactivity is assumed to be static and compared with the design value to confirm the reactor design values. Section A.3.1.1 states that the maximum measurable reactivity of a reactivity computer in a PWR is 2 mk without correction. To check the performance of the DDRCS in the Low Power Physics Test (LPPT) of a PWR, numerical tests have been conducted. Table 1 shows that the ANS/ANSI-19.6.1 criteria are applicable to all types of PWRs in KOREA. However, the reactor period corresponding to 2.0 mk is about 15 sec, and thus it is very difficult to conduct the physics test under the point of adding heat (POAH). For this reason, the reactivity inserted in the core is restricted up to ~ 0.8 mk during the physics test. Because of ANS/ANSI-19.6.1 and the reactivity variation restricted by the plant test procedure itself, the measured dynamic reactivity is counted as a static worth at every PWR LPPT using a digital reactivity computer. The applicability of the DDRCS for PWR has been approved by the regulatory body. More detailed information regarding Table 1 is described in Chapter III.

In the case of a CANDU-6 reactor, the low power physics test (or Phase B test) is performed one time at the initial (or refurbished) core where only fresh fuel bundles are loaded. [3] As a CANDU reactor has several reactivity devices such as the adjuster, liquid zone controller (LZC. See Fig. 1), shut-off rod (SOR), and mechanical control assembly (MCA), the physics test includes several pro-
cedures to measure the worth of all reactivity devices at low reactor power. Detailed information of the traditional method and the new method using a reactivity computer is provided in Chapters 2 and 3 in Park et al. [3]. However, to apply the DDRCS into the physics test of a refurbished CANDU-6, the maximum allowed measurable reactivity value should be estimated and the regulatory organization should agree on that value in advance. The objective of this paper is to establish if the maximum measurable worth of 2.0 mk of a PWR is sufficient for a CANDU-6 digital reactivity computer system (CDRCS). If not, the maximum worth and correction factors should be derived in advance.

Chapter 2 discusses the basic theory for the CDRCS to calculate the dynamic reactivity, and Chapter 3 shows the detailed process to determine the maximum allowable reactivity and correction factors. Chapter 4 shows the results of the liquid zone controller’s worth measurement conducted at CANDU-6 reactors in KOREA. Chapter 5 presents directions for further study and a conclusion.

### Table 1. Example of the DDRCS Applicability Test for Different PWRs for Given ~ 200 Pcm Reactivity Change

<table>
<thead>
<tr>
<th>WH* (650MWe)</th>
<th>Design Value(A) (pcm)</th>
<th>DDRCS (B) (pcm)</th>
<th>Diff. (A-B)/A *100</th>
<th>OPR1000** (1000MWe)</th>
<th>Design Value(A) (pcm)</th>
<th>DDRCS (B) (pcm)</th>
<th>Diff. (A-B)/A *100</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA***</td>
<td>217.9</td>
<td>217.5</td>
<td>0.18</td>
<td>A3</td>
<td>204.4</td>
<td>203.9</td>
<td>0.24</td>
</tr>
<tr>
<td>CB</td>
<td>204.8</td>
<td>205.5</td>
<td>-0.34</td>
<td>A2</td>
<td>210.0</td>
<td>210.8</td>
<td>-0.38</td>
</tr>
<tr>
<td>CC</td>
<td>207.5</td>
<td>208.8</td>
<td>-0.63</td>
<td>A5</td>
<td>213.3</td>
<td>212.9</td>
<td>0.19</td>
</tr>
<tr>
<td>CD</td>
<td>213.1</td>
<td>213.4</td>
<td>-0.14</td>
<td>R1</td>
<td>212.7</td>
<td>213.6</td>
<td>-0.42</td>
</tr>
<tr>
<td>SA</td>
<td>212.1</td>
<td>213.2</td>
<td>-0.52</td>
<td>R2</td>
<td>202.3</td>
<td>201.9</td>
<td>0.20</td>
</tr>
<tr>
<td>SB</td>
<td>210.8</td>
<td>211.3</td>
<td>-0.24</td>
<td>R3</td>
<td>203.1</td>
<td>203.3</td>
<td>-0.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>R4</td>
<td>203.1</td>
<td>202.9</td>
<td>0.10</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>R5</td>
<td>201.8</td>
<td>202.7</td>
<td>-0.45</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B6</td>
<td>215.4</td>
<td>215.8</td>
<td>-0.19</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B7</td>
<td>214.5</td>
<td>214.9</td>
<td>-0.19</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B9</td>
<td>214.4</td>
<td>214.7</td>
<td>-0.14</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B10</td>
<td>214.2</td>
<td>214.0</td>
<td>0.09</td>
</tr>
</tbody>
</table>

* WH two loop reactor with total 121 Fuel Assemblies
** OPR1000 reactor with total 177 Fuel Assemblies
*** Bank Type: Control Bank A–D, Shutdown Bank A, B or Regulating Bank 1–5, subshutdown bank A2,A3, B7, etc

Fig. 1. LZC Axial and Radial Configuration at CANDU-6 Reactor
2. DIGITAL REACTIVITY COMPUTER FOR CANDU-6 REACTOR

2.1 Theory for Reactivity Calculation

Neutron population variation with time for the given reactivity device can be estimated by a three-dimensional space and time dependent two-group diffusion equation coupled with a multi-group precursor density equation.\(^{(1)}\)\(^{(3)}\) If the introduced reactivity is small and less than ~ 0.8mk, then the spatial neutron variation can be neglected. The huge heterogeneous reactor then assumes a point reactor and the three-dimensional time dependent neutron diffusion equation is reduced to the point kinetics equation\(^{(4)}\) as follows:

\[
\frac{d n(t)}{dt} = \left( \frac{\rho(t) - \beta}{\Lambda(t)} \right) n(t) + \sum_{i=1}^{b} \lambda_i(t) C_i(t) - \frac{\partial C_i(t)}{\partial t} = -\lambda_i(t) C_i(t) + \beta_i(t) \frac{n(t)}{\Lambda(t)},
\]

where

- \(n(t)\) = core averaged neutron number density (#/cm\(^3\)),
- \(\rho(t)\) = reactivity given with time (pcm or mk),
- \(\beta\) = total fraction of delayed neutrons,
- \(\beta_i\) = effective yields of delayed neutrons,
- \(\Lambda(t)\) = average neutron generation time (sec),
- \(\lambda(t)\) = decay constants of each precursor (/sec),
- \(C_i(t)\) = \(i^{\text{th}}\) delayed neutron concentration (#/cm\(^3\)).

There are many methods to solve Eq. (1) and the solution is the neutron number density variation with time. However, in real physics test, the core reactivity not neutron number density with time should be obtained from the variation of measured detector signals \(MS_{n-1}\) and \(MS_n\) at time \(t_{n-1}\) and \(t_n\), respectively. Therefore, the numerical inverse kinetics equation is derived from equation (1) simply as follows\(^{(1)}\)\(^{(3)}\):

\[
\rho(t_{n+1}) = \sum_i \beta_i \left( e^{(\omega_i - \omega_{c,i}) t_{n+1}} B_{n+1,i} + A_{n+1,i} \right) + \Lambda \omega_x,
\]

where

- \(\omega_x = \frac{1}{\Delta t} \ln \left( \frac{MS_{n+1}}{MS_{n-1}} \right)\),
- \(B_{n,i} = e^{(\omega_x - \omega_{c,i}) \Delta t} B_{n-1,i} + A_{n,i},\)
- \(A_{n,i} = \frac{\omega_x}{\lambda_i + \omega_x} \left( 1 - e^{(\omega_x - \omega_{c,i}) \Delta t} \right),\)

and \(t_{n+1} = t_n + \Delta t_n\). The essential concept underlying the application of Eq. (2) is that the variation of measured signals with time should be equal to the change of the core averaged neutron density:

\[
MS_{n}/MS_{n-1} = n(t_n)/n(t_{n-1}).
\]

Because the reactivity of Eq. (2) is dynamic, the previous relationship mandates that the tester regard the measured reactivity as static. If this relationship is not true, a correction factor is required to estimate the static reactivity correctly. For example, the dynamic control rod worth measurement (DCRM) method introduced two correction factors for extracting the static reactivity from the measured signals.\(^{(1)}\)

On the other hand, because of heavy water moderators (D\(_2\)O) there is another delayed neutron source in the CANDU reactor, the photo-neutron. D\(_2\)O interacting with gamma-rays above 2.22MeV can produce neutrons:

\[
H_2^1 + \gamma \rightarrow H_1^1 + n^1.
\]

The characteristics of photo-neutron production are very similar with delayed neutron production from the fission products. Therefore, Eq. (1) should be changed to introduce additional pseudo precursors evoked by moderator-gamma-ray interaction:

\[
\frac{d n(t)}{dt} = \left( \frac{\rho(t) - \beta}{\Lambda(t)} \right) n(t) + \sum_{i=1}^{b} \lambda_i(t) C_i(t) + \sum_{j=1}^{m} \lambda_j(t) Q_j(t),
\]

\[
\frac{\partial C_i(t)}{\partial t} = -\lambda_i(t) C_i(t) + \beta_i(t) \frac{n(t)}{\Lambda(t)},
\]

\[
\frac{\partial Q_j(t)}{\partial t} = -\lambda_j(t) Q_j(t) + \beta_j(t) \frac{n(t)}{\Lambda(t)},
\]

where \(\lambda(t)\) and \(Q(t)\) are the decay constant(/sec) and number density (#/cm\(^3\)), respectively, of the \(j^{\text{th}}\) photo-neutron group. All decay constants and effective yields including the photo-neutron group are provided by the nuclear design code, RFSP\(^{(5)}\). Even though additional delayed neutron groups are considered, Eq. (2) is used to obtain reactivity with time. Fig. 2 shows the algorithm to obtain reactivity from the measured values, and Table 2 shows the detailed kinetic parameter values for all precursor groups in the case of the initial, refueled, and even an equilibrium CANDU reactor.\(^{(3)}\)

2.2 Signal Processing

A CANDU-6 reactor has a total of six ex-core detectors, as shown in Fig. 3. Each detector is a boron coated uncompensated ion chamber that generates electrical current from the \(n(\text{B}^{10})\) reaction at a rate proportional to the neutron population intruding into the chamber. Fig. 3 and Fig. 4 show the radial and axial ex-core detector positions in detail. The CANDU-6 ex-core detector’s electric current proportional to the core power level is converted to voltage signals (0 ~ 10 V) during signal processing such that the DDRCS receives six voltage signals at the output port of the signal processing cabinets. Those analog signals are then converted to digital values through a data acquisition board with 24-bit resolution and a 100KHz sampling rate. The board outputs averaged or median voltages for a user-defined time period such as 0.5 sec or 1 sec. The DDRCS driven by a 2.3GHz dual-core processor calculates the core average neutron population variation by using Eq. (3) based on the digitalized values. The calculated core-wise neutron variation ratio is directly used for estimating the dynamic reactivity by using Eq. (2), and is displayed on a
24 inch monitor in the form of a time history graph. The CDRCS can show the on-line behavior of power level, LZC water level, core inlet temperature, and reactivity. The worth of reactivity devices can be estimated roughly from the reactivity values displayed on the monitor screen, but to obtain the exact worth an additional analysis is performed. As the reactivity estimation is dependent on the measured signal behavior, it should be confirmed whether the output of the CDRCS is treated as the measured static worth. In the case of a PWR, there are enough experience and sufficient data demonstrating that the measured dynamic reactivity can be treated as a static worth if it falls within the criterion of 2.0 mk. In the case of the CANDU-6 reactor, there are no data or information about the CDRCS application.

3. NUMERICAL ESTIMATION

3.1 Introduction

As mentioned above, the relationship between the dynamic and static reactivity for a given perturbation such as the LZC water level change should be clarified and

### Table 2. Kinetic Parameters for a Refurbished and Aged Reactor

<table>
<thead>
<tr>
<th>Group</th>
<th>Yield</th>
<th>Decay Constant (sec⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Refurbished</td>
<td>Aged</td>
</tr>
<tr>
<td>Delayed Neutron Group</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2.57254E-04</td>
<td>1.7558E-4</td>
</tr>
<tr>
<td>2</td>
<td>1.33642E-03</td>
<td>1.0431E-3</td>
</tr>
<tr>
<td>3</td>
<td>1.17220E-03</td>
<td>8.7652E-4</td>
</tr>
<tr>
<td>4</td>
<td>2.55335E-03</td>
<td>1.8873E-3</td>
</tr>
<tr>
<td>5</td>
<td>1.35003E-03</td>
<td>9.9579E-4</td>
</tr>
<tr>
<td>6</td>
<td>6.65333E-04</td>
<td>4.5466E-4</td>
</tr>
<tr>
<td>Photo Neutron Group</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1.44006E-07</td>
<td>1.1560E-7</td>
</tr>
<tr>
<td>8</td>
<td>3.01105E-07</td>
<td>2.4171E-7</td>
</tr>
<tr>
<td>10</td>
<td>6.89921E-06</td>
<td>5.5382E-6</td>
</tr>
<tr>
<td>11</td>
<td>6.10066E-06</td>
<td>4.8972E-6</td>
</tr>
<tr>
<td>12</td>
<td>9.91029E-06</td>
<td>7.9553E-6</td>
</tr>
<tr>
<td>13</td>
<td>2.06323E-05</td>
<td>1.6563E-5</td>
</tr>
<tr>
<td>14</td>
<td>5.86498E-06</td>
<td>4.7080E-6</td>
</tr>
<tr>
<td>15</td>
<td>2.93118E-05</td>
<td>2.3530E-5</td>
</tr>
<tr>
<td>16</td>
<td>2.53976E-05</td>
<td>2.0387E-5</td>
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<tr>
<td>17</td>
<td>2.53976E-05</td>
<td>2.0387E-5</td>
</tr>
</tbody>
</table>
reflect the effect of localized ex-core detector position on the reactivity. As shown in Figs. 3 and 4, localization of the ex-core detector can affect the CDRCS output by reflecting the neutron behavior of peripheral fuel channels only rather than the core average. The problem is how to obtain the above mentioned relationship. Real detector signals cannot give information on the solution because there is no other reference information on the relationship. The only way is to check the theoretical behavior of Eq. (2) and assume that the behavior would be shown in a real situation. ANS/ANSI-19.6.1 only describes the criterion of 2.0 mk for a PWR without references. However, if there are any changes or modifications in the core geometry and devices such as increased reactor size, axial detector position shift, detector size, and type change such as from an uncompensated ion chamber to a fission chamber, or changes to the reactivity computer itself, etc., the effectiveness of the reactivity computer applicability should be checked, even in a PWR. Table 1 presents the results of those activities for PWRs in KOREA when the developed CDRCS is applied to measure the rod worth. The method to check the effectiveness is the same as that described in this paper: from numerical tests reflecting various core conditions, the ex-core detector signals are obtained, the dynamic reactivity is calculated with Eq. (2) and then compared with the static worth, and the relationship between two values is determined. Following the procedure and considering the specific features of the CANDU-6 reactor, one can determine a criterion for CDRCS within which the output can be treated as a static reactivity.

3.2 Estimation of Ex-core Detector Signals

In the case of a PWR, to solve the dynamic-to-static conversion problem, the ex-core detector response factors corresponding to each fuel assembly are obtained from the adjoint calculation of the neutron transport code, DORT/TORT. If the detector response factors (DRF) are known, the relative time dependent variation of each ex-detector signal can be estimated by a simple equation. For example, the relative variation of the bottom detector signal is represented by the following equation:

$$\bar{R} = \frac{\sum_{n=1}^{FA} V_n w_n \sum_{g=1}^{2} k \Sigma_{g, n}^\alpha(t) \psi_{g, n}^\alpha(t)}{\sum_{n=1}^{FA} V_n w_n \sum_{g=1}^{2} k \Sigma_{g, n}^\alpha(0) \psi_{g, n}^\alpha(0)},$$

where \(FA\) is the total number of fuel assemblies connected with the bottom detector, \(V_n\) the volume of node \(n\), and \(w_n\) the DRF of node \(n\) to the bottom detector. Eq. (6) is appropriate and sufficient for the CDRCS because Eq. (2) requires only the relative variation of detector signals not the absolute signal strength. If the CANDU reactor simulation code, RFSP, has similar capability to the PWR design codes, a similar equation should be used. However, unlike the PWR, the RFSP can treat the ex-core detectors explicitly in its modeling so that no transport calculation is required. Fig. 5 shows the core geometry treated by the RFSP code. Radial node numbers of 435, 479, and 752 present the radial detector area (See the red boxes of Fig. 3 and Fig. 5).

To simulate the three dimensional time dependent flux distribution, the CERBERUS module in the RFSP code was used. This module is utilized for the analysis of fast reactor transients, such as those associated with hypothetical large-loss-of-coolant accidents, by means of the improved...
quasi-static method (IQS) with a fixed small time step. During core perturbation, the CERBERUS module calculates the flux variation at all nodes so that the \((n,\bar{B})\) reaction rate \(\sum \phi_n(t)\) variation of the \(j^{th}\) ex-core detector consisting of several neutronic nodes, \(n\), can be extracted as follows:

\[
\tilde{D}(t) = \frac{\sum_{n=1}^{N} \phi_n(t)}{\sum_{n=1}^{N} \phi_n(0)} \approx \frac{\sum_{j=1}^{6} \phi_{j}(t)}{\sum_{j=1}^{6} \phi_{j}(0)}.
\]

and for the sum of all six detector signals,

\[
\tilde{D}(t) = \frac{\sum_{j=1}^{6} \phi_{j}(t)}{\sum_{j=1}^{6} \phi_{j}(0)}.
\]

As the effect of spot installation of ex-core detectors can be weakened in Eq. (8), this equation is preferable to Eq. (7) in the CDRCS. Even though Eq. (7) and (8) are the result of forward calculations while Eq. (6) is a backward computation using the DRF, the resulting pseudo ex-core detector signals from Eq. (7) or (8) can be used for this numerical test because the CANDU reactor’s reactivity device configuration during the Phase B test is fixed except for the LZC water levels. For the obtained ex-core detector signals used to estimate the measured dynamic reactivity (MDR), the CERBERRS module provides the core average power and six detector signals for a 600 sec transient simulation.

3.3 Numerical Test Procedure
To determine the theoretical maximum allowable reactivity of the CDRCS for a CANDU-6 reactor, various numerical simulations have been performed. Table 3 shows the whole domain selected to be simulated. The simulation procedure is as follows:

Stage 1: Calculate the static reference worth for each simulation by calculating the change of the effective neutron multiplication factor \((k_{\text{eff}})\) before and after the water level change (see Fig. 6 showing the power distribution variation for a given initial water level as an example).

![Fig. 5. Face view of a CANDU-6 Nodal Model (Thick Red line for Fuel(Core) Region, and Red Boxes for Excore Detectors)](image)

Table 3. Transient Simulation Cases

<table>
<thead>
<tr>
<th>LZC level change</th>
<th>Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>2030MCA50*, 3040MCA50, 4050MCA50, 5060MCA50, 6070MCA50, 7080MCA50</td>
</tr>
<tr>
<td>15%</td>
<td>2035MCA50, 3045MCA50, 4055MCA50, 5065MCA50, 6075MCA50</td>
</tr>
<tr>
<td>20%</td>
<td>2040MCA50, 3050MCA50, 4060MCA50, 5070MCA50, 6080MCA50</td>
</tr>
<tr>
<td>30%</td>
<td>2050MCA50</td>
</tr>
<tr>
<td>40%</td>
<td>2060MCA50</td>
</tr>
<tr>
<td>50%</td>
<td>2070MCA50</td>
</tr>
<tr>
<td>60%</td>
<td>2080MCA50</td>
</tr>
</tbody>
</table>

* 2030MCA50: LZC water level changes from 20% to 30% with a mechanical control absorber (MCA) 50% inserted
** 2030MCAOUT: LZC water level changes from 20% to 30% in case of a MCA fully out of the core
Stage 2: Start the transient simulation and obtain the ex-core detector signal variation with time by using Eqs. (6), (7), and (8).

Stage 3: Calculate dynamic reactivity from Eq. (2) by using the pseudo detector signals of stage 2 for each simulation case.

Stage 4: Compare the dynamic reactivity of stage 3 with the static worth of stage 1, and determine the ex-core reactivity correction factor (ERCF, see Eq. (9)).

Stage 5: Evaluate the theoretical maximum allowable reactivity in the DDRCS from all simulation results by confining the ERCF such as 0.99 < ERCF < 1.01.

The simulation described in Table 3 uses only the LZC water level to reflect the actual physics test process. Therefore, the water levels of all 14 LZCs are changed to be identical (so called ‘bulk control’ for the control reactor power level) even though the individual water levels can be controlled separately (so called ‘spatial control’ for a flattened power shape). The water level change rate in the LZC was assumed to be 0.1%/sec based on the actual LZC control logic. It takes about 100 sec for 10% water level variation (see Fig. 7 showing the measured LZC level change behavior of Wolsong Unit 2). However, simulation of stage 3 will continue for an additional 500 sec for settling the neutron precursor effects. Because the reactivity curve from Eq. (2) still varies slightly after 100 sec, the measured

![Image of fuel channel power distribution](image-url)

Fig. 6. Fuel Channel Power Distribution Variation with Initial Water Level (See the Thick Red Line in Fig. 5) (A: 2030MCAOUT, B:4050MCAOUT, C:6070MCAOUT)
dynamic reactivity (MDR) is defined as the time averaged reactivity for 100 sec where the reactivity variation has settled (see Fig. 7). The ratio of the static reactivity and MDR is called the excore reactivity correction factor (ERCF) and is defined as follows:

\[
ERCF_{X \rightarrow Y} = \frac{\rho^{\text{static,RFSP}}_{X \rightarrow Y}}{\rho^{\text{INVERSE}}_{X \rightarrow Y}},
\]

where the subscript \( X \rightarrow Y \) represent the water level change from \( X\% \) to \( Y\% \), \( \rho^{\text{static,RFSP}}_{X \rightarrow Y} \) denotes the static reactivity obtained by the RFSP code based on the two reactor conditions of \( X \) and \( Y \), and \( \rho^{\text{INVERSE}}_{X \rightarrow Y} \) is the MDR by Eq. (2) of the CDRCS using the simulated detector signals of Eq. (7) or (8). If Eq. (9) is effective for a real reactor situation, the measured static reactivity (MSW, \( \rho^{\text{static(M)}}_{X \rightarrow Y} \)) can be defined by the following equation:

\[
\rho^{\text{static(M)}}_{X \rightarrow Y} = ERCF_{X \rightarrow Y} \cdot \rho^{\text{INVERSE(M)}}_{X \rightarrow Y},
\]

where \( \rho^{\text{INVERSE(M)}}_{X \rightarrow Y} \) is the MDR obtained from real ex-core detector signals by Eq. (2). Finally, \( \rho^{\text{static(M)}}_{X \rightarrow Y} \) is compared with \( \rho^{\text{static,RFSP}}_{X \rightarrow Y} \) and the relative difference should be less than the criterion\(^{[3]} \), \( \pm 10\% \).

The MCA50 case in Table 3 designates a mechanical control rod (precisely MCA#1 among four MCA rods) at the condition of half insertion. The reason for MCA#1 insertion is to control the reactor status at critical before the water level is changed. The old method using boron ampoules did not consider the criticality of the reactor because the LZC water level is changed automatically to exactly match the reactivity of the boron ampoule. However, as the CDRCS must detect the behavior of the neutron population without any other reactivity perturbation such as boron or Gd concentration variation, there is no way to recover the decreased or increased power to the initial test power level if the MCA #1 is not inserted in the core. A SOR (shutoff rod) is an impossible option because it is not controlled manually. Another option is to use boron or Gd concentration control in the moderator. However, this option takes a long time for recovering the initial power level for the test and produces unwanted liquid and solid wastes. In addition, it is not easy to control the core conditions precisely. Using MCA is the best option considering the above conditions so that MCA#1 only is inserted into the core to minimize the reactor perturbation. This is the reason why the MCA50 option is included in Table 3. Fig. 8 is an example showing how to recover the initial power condition for a physics test using Gd concentration dilution. In the case of a refurbished CANDU-6 reactor MCA#1 option is used. However, the detailed procedure may depend on each plant operating condition.

4. NUMERICAL RESULTS AND DISCUSSION

Table 4 shows the results of stage 5 for several important cases. The static worth of each case reveals the characteristics of LZC function in the CANDU-6 reactor. For example, the worth of the 7080MCA50 case is less than that of the 2030MCA50 case even at the same 10% water level change because the 1st, 3rd, 6th, 8th, 10th, and 13th LZC (see Fig. 1) are installed at the upper side of the reactor so that the neutron absorption capability decreases relatively as the water fills. Therefore, the excore detector signal should contain those neutronic features and the CDRCS must detect and evaluate the differences between the two conditions. The representative reactivity behaviors of the CDRCS for several cases selected from Table 3 are shown from Fig. 9 to Fig. 13. Each figure has the individual reactivity curves of D, E, and F (of SDS1) and H, G, and J (of SDS2) using Eq. (7) as well as the static reactivity.
(SW), the core average dynamic reactivity behavior (SUM) using Eq. (8), and reactor power variation (POW). Fig. 9 corresponds to the 10% water level change while Fig. 13 shows that for 60%. There are large differences between the two graphs. Fig. 9 shows that there is no difference among the individual detector reactivity curves. The SUM
using Eq. (8) is identical to the others. Fig. 11, which shows the case of 15% LZC water level change, looks the same. Even if a detector is revealed as being failed in these cases, the SUM except the bed is sufficient for presenting the MSW because the static and dynamic worth of each detector are nearly identical. Figs. 9, 10, and 11 clearly show that any reactivity value just after the LZC variation is dismissed can be used as a measured value, theoretically.

One can see the same finding in Table 5 where individual ERCFs for eight cases are evaluated and compared with that of the SUM. Detectors D and E installed above the centerline (See Fig. 2) show values of 1.010 and 1.014 of ERCF, respectively, while the SUM shows a value of 1.008 when the water level is changed by about 20% or 1.4 mk. The reason that detectors E and G have the maximum ERCF compared with the other detectors is that they are the farthest detectors from the 6th and 13th LZCs, the source of flux variation with time. Therefore, even though there are different ERCFs among the six detectors, if the SUM of Eq. (8) is used, it is possible to measure the worth of LZC up to a 20% change without ERCF application (ERCF < 1%. See Table 1 for PWR). On the other hand, the reactivity curves of detectors E, J, and G in Fig. 13 have different trends and do not match the SUM. This means that:

- if one has to measure the LZC worth of more than 20% level change or 1.4 mk, the ERCF should be used,
- if any detector fails to provide electrical signals during the Phase B test, the ERCF corresponding to the failure situation should be reevaluated because each detector has a different ERCF.

As for MCA existence in the reactor, Table 4 shows that the ERCF values with and without MCA in the core are nearly the same, although the LZC worth depends on the existence of MCA in the reactor. Therefore, the MCA effect on the MDR or MSW was neglected. From Tables 4 and 5 the criterion for reactivity calculation of the CDRCS using Eq. (8) for the CANDU-6 reactor is determined as 1.4 mk because of ERCF < 1%.
Fig. 12. The Reactivity and Power Behavior of 3050MCA50 Case of 1.362 mk Static Worth

Fig. 13. The Reactivity and Power Behavior of 2080MCA50 case of 3.744 mk Static Worth

Table 5. Comparison of Detector-wise ERCF in Case of Various LZC Water Level Changes

<table>
<thead>
<tr>
<th>Cases</th>
<th>Static Worth (mk)</th>
<th>ERF C using Eq. (7) SDS1</th>
<th></th>
<th></th>
<th></th>
<th>ERF C using Eq. (8)</th>
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<tr>
<td></td>
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<td>D</td>
<td>E</td>
<td>F</td>
<td>H</td>
<td>G</td>
</tr>
<tr>
<td>2030MCA50</td>
<td>0.697</td>
<td>1.003</td>
<td>1.004</td>
<td>1.002</td>
<td>1.000</td>
<td>1.002</td>
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<tr>
<td>4050MCA50</td>
<td>0.668</td>
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<td>1.003</td>
<td>1.001</td>
<td>0.999</td>
<td>1.000</td>
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<tr>
<td>6070MCA50</td>
<td>0.563</td>
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<td>1.000</td>
<td>0.998</td>
<td>0.998</td>
<td>1.000</td>
</tr>
<tr>
<td>2030MCAOUT</td>
<td>0.686</td>
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<td>1.005</td>
<td>1.003</td>
<td>1.003</td>
<td>1.004</td>
</tr>
<tr>
<td>4050MCAOUT</td>
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<td>1.002</td>
<td>1.003</td>
<td>1.002</td>
<td>1.001</td>
<td>1.003</td>
</tr>
<tr>
<td>6070MCAOUT</td>
<td>0.564</td>
<td>1.001</td>
<td>1.002</td>
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<td>1.001</td>
<td>1.002</td>
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<tr>
<td>2035MCA50</td>
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<td>1.009</td>
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<td>1.008</td>
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<tr>
<td>2050MCA50</td>
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<td>1.028</td>
<td>1.019</td>
<td>1.010</td>
<td>1.017</td>
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5. CONCLUSION

The digital reactivity computer system, CDRCS, for CANDU-6 reactors was developed for the Phase B physics test of Wolsong Unit 1, the first refurbished reactor in KOREA. To apply the CDRCS to a CANDU-6, where all fuel bundles are fresh, its applicability should be verified. To do this, the maximum measurable reactivity of the CDRCS for CANDU-6 was investigated from various numerical simulations and determined as 1.4 mk, which indicates that the ERCF does not exceed 1% error. As compared with the value of 2.0 mk of a PWR, the reduction of the maximum measurable worth from 2.0mk to 1.4mk is caused mainly by localization of ex-core detector installation, smaller detectors, and bigger reactor size. The result was approved by the regulatory body and applied to the Phase B test for refurbished Wolsong Unit 1. During the Phase B test, 1.4mk was the criterion used by the operator. The final measured LZC worth was evaluated as a 0.0648 mk /% LZC level change while the design value is 0.06879 mk /%LZL.[3] The process to determine the criterion of 1.4 mk for the CANDU-6 reactor would provide a reference for any CDRCS developed for a CANDU, Enhanced CANDU-6, and Advanced CANDU Reactor.

ACRONYMS

DCRM the dynamic control rod worth measurement
DDRCS the direct digital reactivity computer system
LPPT the low power physics test for PWR
Phase B the low power physics test for CANDU
POAH the point of adding heat
ADJ the adjusters
LZC the liquid zone controller
SOR the shut-off rods
MCA the mechanical control assembly
CDRCS the CANDU-6 digital reactivity computer system
ERCF the excore reactivity correction factor
MDR the measured dynamic reactivity
MSW the measured static reactivity (worth)
SDS1 the shutdown system 1
SDS2 the shutdown system 2
SW the static reactivity
SUM the core averaged dynamic reactivity behavior
POW the reactor power variation
IQS the improved quasi-static method
DRF the detector response factor

REFERENCES