Measurement and Analysis for Determination of Power Coefficient of Reactivity of an Operating CANDU6

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Abstract

The power coefficient of reactivity (PCR) needs to be negative to achieve the inherent safety of a reactor, but the PCR of CANDU-6 has been evaluated to be positive in recent studies. In this circumstances, an experiment was performed at a CANDU-6 reactor in Korea to measure the PCR of CANDU-6. Based on the measurement data, the PCR was evaluated by a newly proposed methodology which requires several estimations of reactivity variation due to liquid zone controllers, xenon, etc. Consequently, the PCR of CANDU-6 was evaluated to be about 0.5 pcm/%Power which is slightly smaller than the latest official value, 1.7 pcm/%Power.

1. Introduction

The uniqueness of CANDU (CANada Deuterium Uranium) reactor comes from the natural Uranium fuel. To utilize natural uranium (NU) as the fuel, heavy water (D_2O) is used as both the coolant and the moderator for the minimization of the neutron absorption in the core. In a standard CANDU-6 lattice, the fuel and coolant channels are surrounded by a bulky and separated D_2O moderator which induces the highly thermalized neutron spectrum of the CANDU reactor. Due to such innate characteristics, it is well known that CANDU reactor has a positive coolant void reactivity (CVR), a positive coolant temperature coefficient (CTC), and a small fuel temperature coefficient (FTC). Consequentially, the power coefficient of reactivity of CANDU-6 has been estimated to be close to zero at full power condition while the PCR is the combined effect of the CTC and the FTC as in the Eq. (1), where α_P is the PCR, α_{T_f} and α_{T_c} are the FTC and the CTC respectively.

$$\alpha_P = \frac{\partial \rho}{\partial P} = \sum (\frac{\partial \rho}{\partial T})(\frac{\partial T}{\partial P}) \cong \frac{\partial \rho}{\partial T_f}\frac{\partial T_f}{\partial P} + \frac{\partial \rho}{\partial T_c}\frac{\partial T_c}{\partial P} = \alpha_{T_f}\frac{\partial T_f}{\partial P} + \alpha_{T_c}\frac{\partial T_c}{\partial P} \quad (1)$$

It is obvious that the PCR of a reactor needs to be sufficiently negative to achieve the inherent stability and safety. For this reason, there have been many efforts to evaluate or improve the safety parameters of CANDU reactors [1-11]. By RFSP-IST [12], based on the cross sections generated by WIMS-IST [13] where they are the Industry Standard Tools (IST), the official value of PCR was evaluated to be positive in a wide range of power level, ~1.7 pcm/%Power at full power. Also in recent studies, a high-fidelity estimation by the Monte Carlo method in a CANDU-6 standard lattice model and in a CANDU whole-core model have given a slightly positive PCR, ~0.5 pcm/%Power [7,11]. It has been widely accepted that the CANDU reactors have a slightly positive PCR, and it is now a potential safety issue of greater concern regarding the inherent safety of CANDU reactors.

In this circumstances, there was an experimental approach on the PCR of a CANDU reactor in 2012 [14]. In the assessment, the PCR of a CANDU reactor was measured with the measurement data of Wolseong Unit-2 reactor which has been in operation since 1997 in Korea. Some information of the core was measured in several power transient experiments near full power condition. Based on the measurement data, the PCR was indirectly estimated by RFSP-IST. The PCR was measured to be ~2 pcm/%Power at 99% power which is quite consistent with the Monte Carlo estimation in a CANDU whole-core model. However, some unique behaviors of the measurement data have lately been observed which can highly affect the PCR measurement result.

In this study, the PCR of the Wolseong Unit-2 reactor is re-evaluated by using improved methods based on the same raw measurement data. Above all, a basic analysis regarding the raw measurement data was performed and the optimized method to process the raw data was determined properly. Then the post-processed data was utilized for the reactivity estimation by several computer codes, RFSP-IST, Serpent2 [15], and an in-house code, for the PCR measurement. Finally, the PCR was estimated by combining the results from such computer codes. The methodologies to measure the PCR of a reactor used in this study will be explained in detailed at the following sections of this paper.

2. Methodologies and Models for the PCR Determination

2.1 Measurement Principles

Since the PCR is the change in reactivity per unit power change, basically, a power transient is needed to measure the PCR. The PCR cannot be directly measured in a power transient because there are several accompanying factors which affect the reactivity of the core as well as the change in the temperature. However, it indicates that the PCR can be estimated if the other contributing factors can properly be counted out. This is the basic idea of the PCR measurement in this study. Figure 1 describes a power transient model in which the PCR measurement can be performed.

Once the power changes from a steady state to a perturbed quasi-steady state with a different power level, first of all, the change in the temperature of coolant and fuel causes the reactivity variation, which is represented by the PCR. At the same time, the change in the number density of fission products and the continuous depletion of the fuel during the transient also affects the reactivity of the core. Lastly, the worth of the reactivity control devices should be taken into account because they keep the reactor critical during the quasi-steady state. In case of CANDU, they are the 14 Liquid Zone Controllers (LZC) which control the reactivity by adjusting the light water level of the compartments in each 14 zone. All of these factors can be expressed as Eq. (2) where α_p is the PCR and ΔP is the power change. The summation of all contributing factors is zero because the reactor is critical in both states.

$$\Delta\rho = \alpha_p \Delta P + \Delta\rho_{Xe} + \Delta\rho_{otherFP} + \Delta\rho_{LZC} + \Delta\rho_{Dep} = 0 \quad (2)$$

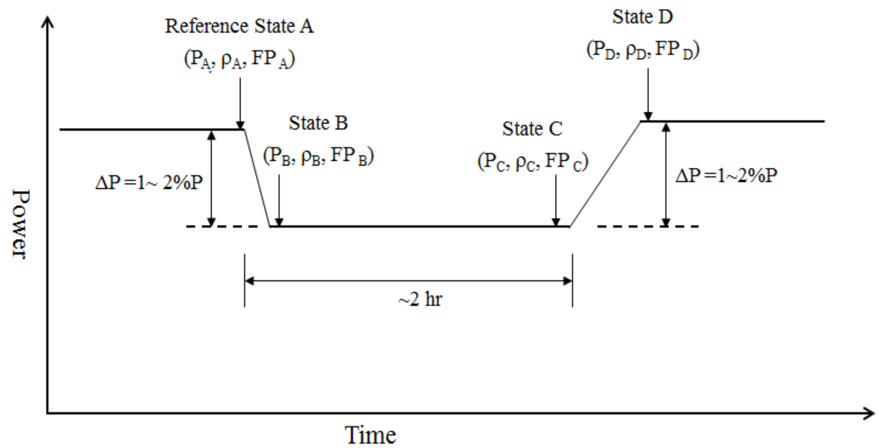


Figure 1 Power transient diagram.

Since the contributions of the other minor fission product poisons are negligible in such a short transient, Eq. (2) can be simplified and transformed as Eq. (3). Based on it, the PCR was measured by comparing the initial steady state and several specific points in time during the transient.

$$\alpha_p = \frac{1}{\Delta P}(-\Delta\rho_{Xe} - \Delta\rho_{LZC} - \Delta\rho_{Dep}) \quad (3)$$

In the method described above, selection of the measurement time can actually be influential. Since the condition of a reactor changes minute by minute in a transient, the measurement time needs to be carefully determined so that the potential error can be minimized. Taking into account some merits and demerits regarding the measurement time, the PCR was measured at several points in time after power change: 5.5 min, 9 min, 15 min, and 115 min after the perturbation at 3:00 pm while the reference initial state was set to be 15 seconds before the perturbation.

2.2 Analysis Models for Reactivity Estimation

Prior to the introduction of the analysis models, it needs to be indicated that some minor factors that affect the reactivity were simply estimated as follows. First, the reactivity change due to fuel depletion was estimated with an instantaneous core reactivity decay rate, -43.6108 pcm/FPD, which was estimated by the RFSP-IST using a core-tracking model. In addition, though not expressed in Eq. (3), the reactivity can be affected by the coolant inlet temperature variation since the change in the coolant inlet temperature indicates the overall shifting of the coolant temperature in the core. The reactivity change due to the coolant inlet temperature variation was separately estimated and corrected with the typical CTC of CANDU reactors at near full power, 4 pcm/K.

The factors which were significantly treated in this study are the Xe and LZC. To estimate the reactivity variation due to these factors, several codes were used in company with RFSP-IST. For the transient Xe estimation, an in-house code using the finite difference method in a 3-D CANDU core model was developed and a detailed CANDU-6 time-average whole-core model [11] was used in Serpent2 for the LZC reactivity estimation. Meanwhile, the CANDU-6 core model in RFSP-IST is a core-tracking model which considers all the day-to-day variations. The direct-access file used in RFSP-IST was from the actual management record of Wolseong Unit-2 reactor.

ENDF/B-VII.0 is used in all of the Serpent2 analysis of this paper while the two-group cross section data used in RFSP-IST analysis is generated using ENDF/B-VI by WIMS-IST.

2.2.1 Time-average core model

In this study, a simplified time-average core model was adopted in both Serpent2 and the in-house codes for the reactivity estimation of LZC and Xe. A time-average model is a generalized equilibrium core model which approximates the impact of everyday fuel reloading with the time-average cell properties. The time-average model was constructed by RFSP-IST based on the actual management history of the Wolseong Unit-2 reactor, and it was then simplified by zone-average manner for the analysis by Serpent2 and the in-house code. Table 1 shows the zone-averaged fuel burnup in the approximate time-average CANDU-6 model.

On the other hand, a deterministic two-group 3-D in-house code is used for the transient Xe reactivity estimation. The CANDU-6 whole core was modeled with fine meshes. To obtain the two-group properties with the consideration of fuel burnup and nearby structures, various kinds of CANDU-6 lattices are analyzed by Serpent2. The fuel compositions corresponding to zone-wise burnup were obtained from a standard CANDU-6 lattice burnup calculation by Serpent2. Various reactivity devices vertically located between fuel channels were geometrically considered in the lattice homogenization calculations by Serpent2.

Table 1 Zone-averaged burnup by RFSP-IST

Zone #	**Average burnup (MWd/kgU)**
1	3.9
2	3.8
3	3.8
4	4.3
5	3.9
6	3.6
7	3.9
8	3.8
9	3.9
10	3.8
11	4.3
12	3.8
13	3.7
14	3.8

2.2.2 Xenon transient modeling

The transient Xe reactivity was evaluated by RFSP-IST and also by a two-group in-house 3-D FDM code which was verified by a nodal code MASTER [16]. In both codes, the two-group diffusion equations are solved by the finite-difference method and the Xe-I kinetics is governed by following differential equations where γ is fission yield, σ_a is microscopic absorption cross section, and I , X is the number density of I-135 and Xe-135 in Eq. (5) and (6).

$$\frac{dI}{dt} = \sum_{g=1}^{2} \gamma_I \Sigma_{f,g} \phi_g - \lambda_I I \tag{5}$$

$$\frac{dX}{dt} = \sum_{g=1}^{2} \gamma_X \Sigma_{f,g} \phi_g + \lambda_I I - \lambda_X X - \sum_{g=1}^{2} \sigma_X^a X \phi_g \tag{6}$$

In RFSP-IST, the Xe transient was simulated by using *SIMULATE module so that the xenon concentration is quasi-statically tracked. Likewise, the Xe transient simulation was also performed in a quasi-static manner in the in-house code. The required lattice parameters and the two-group capture cross section of Xe of the in-house code were separately obtained by two Monte Carlo codes Serpent2 and McCARD [17] code.

3. Measurement Data and Analysis

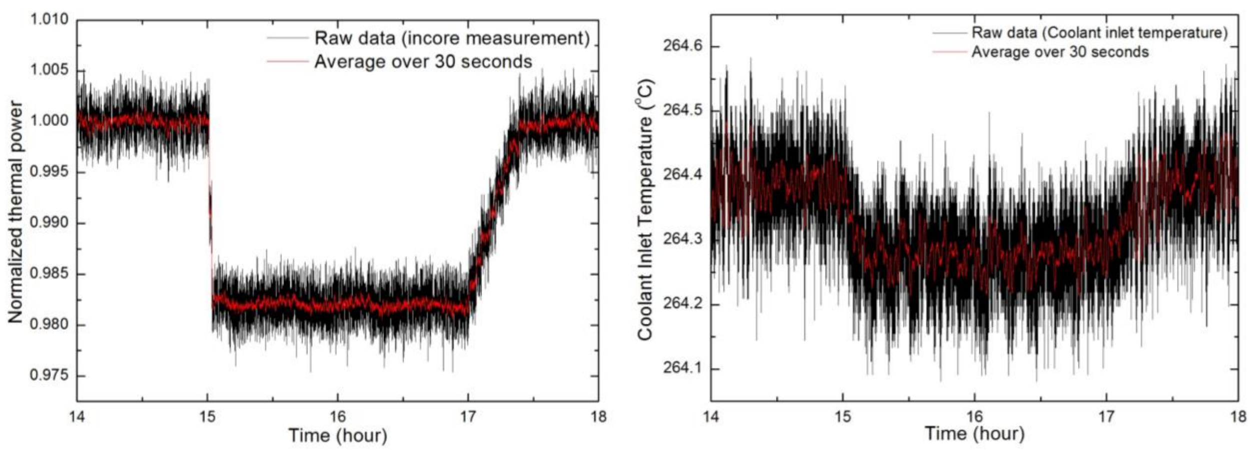
For the purpose of the PCR measurement, the actual measurement was performed in the Wolseong Unit-2 CANDU reactor on May 25th, 2011. A power transient from full power to ~98.2 %Power was carried out over 2 minutes and was remained for about 2 hours from 3:00 pm to 5:00 pm. During the transient, the power level, the coolant inlet and outlet temperatures, the water level of 14 LZCs, and the moderator temperature were recorded every 0.5 second. Since the data contains non-negligible white noises, the data is needed to be appropriately post-processed to determine the representative values at several points in time.

3.1 Post-processing of Measurement Data

The measurement data can be classified into two groups according to its behavior during the transient; that remains unchanged during the transient, or not so that the data can be post-processed according to its characteristics. The reactor power and the coolant inlet temperature are quite unchanged during the transient. In this study, to determine representative values of them for the two near steady-power period, the original data were simply averaged over a 30 second time window centered at a specific time of interest. The original data and the averaged data of thermal power and coolant inlet temperature are plotted together in Figure 2 (a) and (b), respectively.

Since the coolant inlet temperature is not kept to be constant in CANDU-6, it usually tends to increase from the design value (~263^{o}C) over the operation period due to the deposition of corrosion materials in the steam generator tubes. Actually, the observed initial coolant inlet temperature is ~264.4^{o}C, which is already ~1.4^{o}C higher than the design value. Such elevation of coolant inlet temperature can significantly affect the CTC because the coolant outlet temperature of CANDU-6 reactors is quite close to the boiling point. Thus, it needs to be noted that the measured PCR of this thesis will be of an operational condition.

Unlike the thermal power level, the LZC levels are continuously being adjusted during the transient to cancel out the Xe absorption while some LZCs for the zone power control. Thus, the process by averaging over a specific period is not desirable for the LZC levels. In Figure 3, the light water level data of 14 LZCs are plotted as a function of time. Figure 3 shows that the water level in LZCs gradually decreases.



(a) Normalized thermal power (b) Coolant inlet temperature

Figure 2 Measurement data during the transient

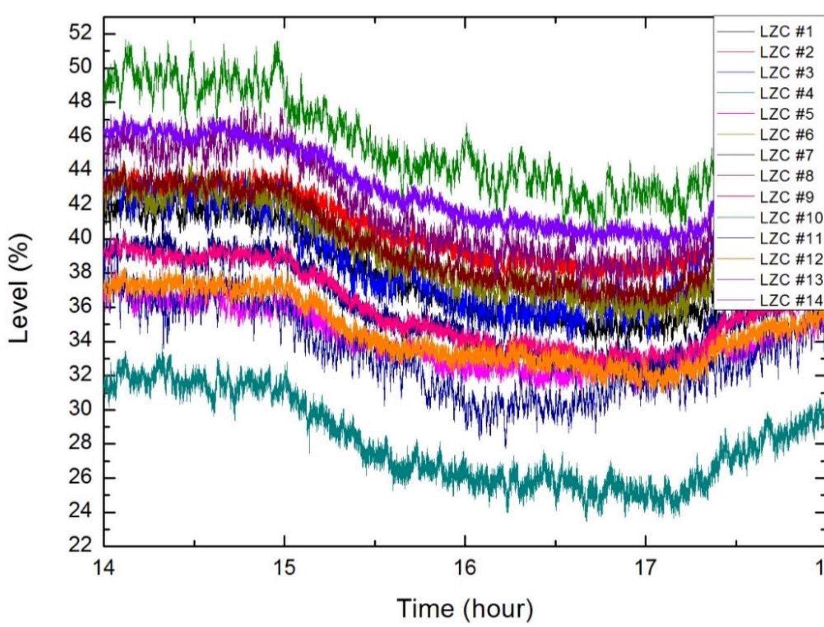


Figure 3 14 LZC level data during the transient

In the measurement data, periodic and synchronized fluctuations of LZC levels on a ~10 sec period were observed while some of them moves independently. In consideration of the regulating mechanism of the LZC, it can be easily understood that the synchronized oscillations are resulted from the regulation for the whole-core reactivity and the individual behaviors of some LZCs are for controlling the target local power of certain zones. When the average LZC level is plotted together with the thermal power data, the correlation between them is clearly observed as in Figure 4 so that such fluctuations are believed to be actual control actions.

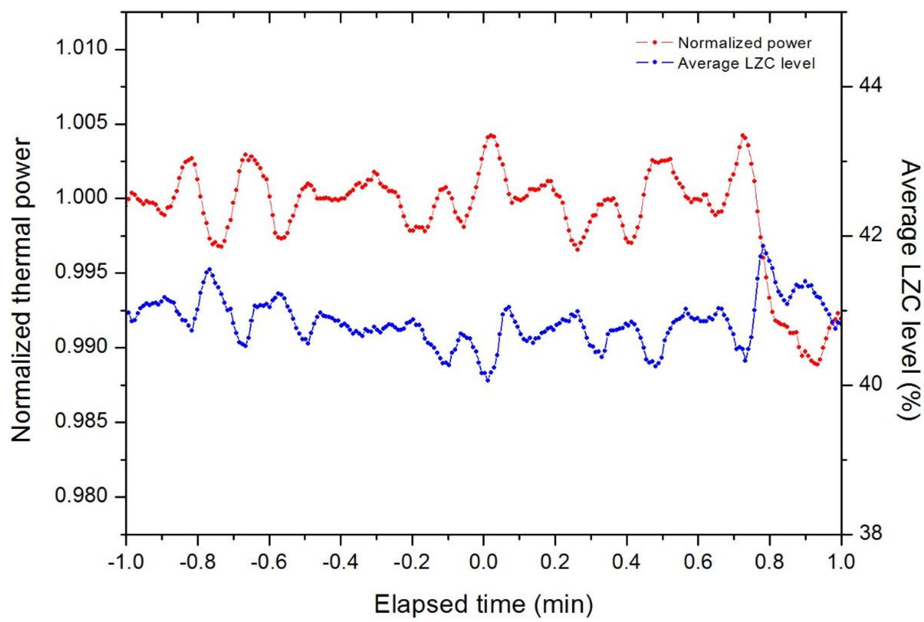


Figure 4 Correlation between reactor thermal power and the average LZC water level

At this point, it can be appropriate to model the measured LZC level data as a polynomial function within a time window centered at the measurement time. In this work, a second-order polynomial regression is used to fit the measured data within a time window. Through this low-order polynomial fitting, the high frequency noises can be effectively removed. 2 different ranges of time were adopted to determine the LZC level: 10 sec and 60 sec.

3.2 Reactivity Variation Estimation

The reactivity variations due to several factors during the transient were estimated based on the post-processed data and some constants. First, the reactivity variation due to fuel depletion and coolant inlet temperature change were estimated with a core reactivity decay rate and the typical CTC value, respectively, as in Table 2.

The reactivity variation due to LZC was analyzed by RFSP-IST and Serpent2 whole-core model, and the results are shown in Table 3. In Table 3, a reversed tendency is observed between the estimated LZC reactivity of 5.5 min and 9 min case with 10-second time window, which is supposed to be due to the oscillatory behavior. However, since the LZCs are canceling out the raising negative reactivity due to Xe build-up during the transient, the positive reactivity of LZC also needs to be increased over time. In this sense, such inversed results is unphysical, and it indicates that the 10-second time window is inappropriate for the LZC level determination using polynomial fitting.

The Xe reactivity variation evaluated by both RFSP-IST and the in-house code. Figure 5 compares the transient Xe reactivity variation estimation by RFSP-IST and the in-house codes as a function of elapsed time and the exact results at the 5 measurement points are given in Table 4. It is clear that the two codes provide very similar Xe reactivity change during the transient while some strange fluctuations are observed only in the results by RFSP-IST which seems to be unphysical.

Based on above results regarding the reactivity variation during the transient, the PCR was evaluated according to Eq. (3).

Table 2 Reactivity variation due to fuel depletion and coolant inlet temperature change

Elapsed time (min)	**Reactivity variation (pcm)**	
	Fuel depletion, $\Delta\rho_{Dep}$	**Coolant inlet temperature, $\Delta\rho_{T_i}$**
0	-	-
5.5	-0.16	-0.24
9	-0.27	-0.24
15	-0.45	-0.24
115	-3.42	-0.32

Table 3 LZC reactivity variation

Elapsed time (min)	**LZC reactivity variation (pcm)**			
	RFSP-IST		**Serpent 2**	
	10-seccond time window	60-second time window	10-seccond time window	60-second time window
5.5	7.0	5.9	5.86 ($\pm$1.56)	4.77 ($\pm$1.50)
9	6.6	6.9	4.27 ($\pm$1.56)	6.86 ($\pm$1.53)
15	12.9	13.6	10.34 ($\pm$1.56)	11.03 ($\pm$1.50)
115	41.1	38.3	38.37 ($\pm$1.53)	39.96 ($\pm$1.50)

Table 4 Transient Xe reactivity variation

Elapsed time (min)	**Xe reactivity variation, $\Delta\rho_{Xe}$ (pcm)**	
	RFSP-IST	**In-house code**
0	-	-
5.5	-3.5	-3.49
9	-5.6	-5.75
15	-9.7	-9.25
115	-31.5	-31.04

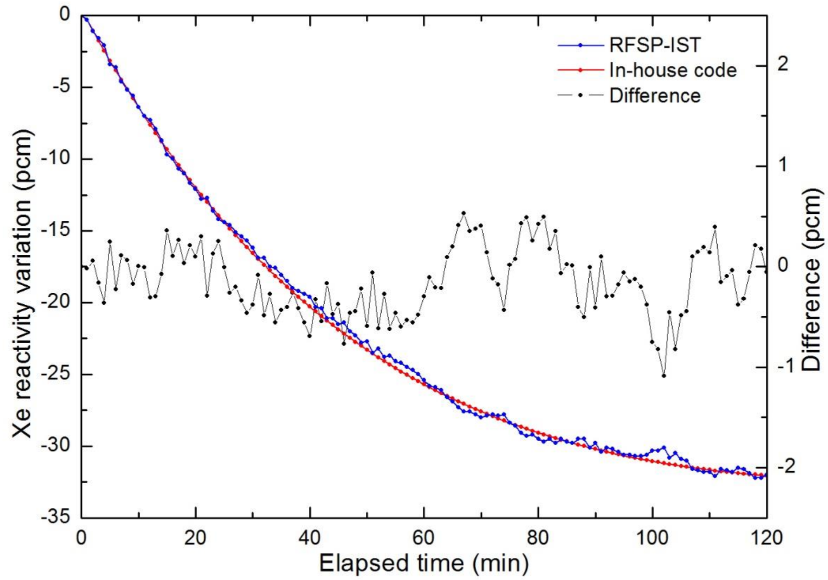


Figure 5 Xe reactivity variation

4. PCR Evaluation

The PCR of CANDU-6 was determined through the combinations of the measured data and the several reactivity factors estimated by several computer codes. It should be mentioned that the PCR results of this study is an approximate value for ~99 %power of the CANDU-6 reactor in an operating condition. Table 5 shows the results of PCR determination with either RFSP-IST only or a combination of the in-house code and RSFP-IST. First of all, results are very similar since both RFSP-IST and the in-house code provide a very similar transient Xe reactivity. In the cases, the PCR was evaluated to be clearly positive in the majority of the cases and it ranges 1~2 pcm/%Power. It is observed that the PCRs are rather sensitive to the time window to determine the LZC reactivity and the values are not consistent with the measurement and analysis conditions.

Table 5 PCR measurement using RFSP-IST for LZC estimation

Elapsed time (min)	**PCR (pcm/%Power)**			
	RFSP-IST ($\Delta\rho_{Xe}, \Delta\rho_{LZC}$)		**In-house code ($\Delta\rho_{Xe}$) / RFSP-IST ($\Delta\rho_{LZC}$)**	
	10-second time window	**60-second time window**	**10-second time window**	**60-second time window**
5.5	1.75	1.13	1.76	1.14
9	0.27	0.44	0.17	0.34
15	1.37	1.75	1.56	1.94
115	3.13	1.62	2.92	1.41
Average*	1.13	1.10	1.17	1.14

*115 min case excluded

Table 6 contains the PCR values with the LZC reactivity estimated by Serpent2. By using the Serpent2 results, the PCR became much less positive and even negative PCR was obtained in the case of the 10-second time window. As already discussed, the inconsistency among the results with 10-second time window demonstrates the inappropriateness of it. Meanwhile, a 60-second window provides rather consistent. In this regard, the 60-second time window is more appropriate for the PCR determination of the CANDU-6 reactor.

Table 6 PCR measurement using Serpent2 for LZC estimation

Elapsed time (min)	**PCR (pcm/%Power)**			
	RFSP-IST($\Delta\rho_{Xe}$) / Serpent2($\Delta\rho_{LZC}$)		**In-house code($\Delta\rho_{Xe}$) / Serpent2($\Delta\rho_{LZC}$)**	
	10-second time window	**60-second time window**	**10-second time window**	**60-second time window**
5.5	1.11 (±0.86)	0.49(±0.83)	1.12 (±0.86)	0.50 (±0.83)
9	-1.02 (±0.86)	0.41 (±0.85)	-1.11 (±0.86)	0.32 (±0.85)
15	-0.03 (±0.86)	0.35 (±0.83)	0.17 (±0.86)	0.54 (±0.83)
115	1.65 (±0.85)	2.51 (±0.83)	1.45 (±0.85)	2.31 (±0.83)
Average*	0.02 (±0.86)	0.42 (±0.83)	0.06 (±0.86)	0.45 (±0.83)

*115 min case excluded

It is important to note that PCR at 115 min is exceptionally higher than in other cases, which is due to the large theoretical correction. Thus, the average PCR value is determined without the 115 min case. Table 6 indicate that the PCR of CANDU-6 can be about 0.5 pcm/%Power when the reactor power is ~99% and the coolant inlet temperature is about 264.4^{o}C. The calculational uncertainty of the PCR values in Table 6 is quite big, actually bigger than the average PCR. Although the reactivity change due to the coolant inlet temperature change and fuel depletion is rather small, their corrections are not negligible in this CANDU-6 PCR measurement since the PCR value is also quite close to zero.

5. Conclusions

Based on measured data at Wolseong Unit-2 CANDU-6, the PCR was re-determined for a near full-power condition by using improved methods. For the Xe reactivity estimation, an in-house 3-D FDM code was developed and applied to a time-average CANDU-6 model. For a more accurate PCR measurement, the measured data were carefully reanalyzed and characterized to minimize the possible influence of noise signals. In addition, a detailed 3-D time-average CANDU-6 model was constructed and analyzed by the Monte Carlo method to obtain accurate reactivity change associated the LZC water levels.

For a reliable measurement of the CANDU-6 PCR, the reactivity associated with the LZC water level should be accurately estimated. The LZC water level can be carefully determined by taking into account the periodic natures of the measured signals. It is recommended that an instantaneous LZC signal should not be used in the PCR measurement. The current study clearly shows that the

PCR measurement should be performed within about 10 minutes after the power perturbation to minimize the potential uncertainties.

The results of this work consistently reveal that the PCR of CANDU-6 at full power is very likely to be slightly positive. The PCR was evaluated to be ~+0.45 pcm/%Power at 99% power, which is much smaller than the official CANDU-6 PCR of ~1.7 pcm/%Power at 100% power.

6. Acknowledgement

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