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〈Technical Note〉

PHASE-B PRE-SIMULATION USING BORON AND GADOLINIUM AS POISON IN THE MODERATOR SYSTEM FOR WOLSONG-1

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The Wolsong-1 (W-1) Phase-B pre-simulations were carried out in preparation for tests to be conducted for the restart of the reactor after a major refurbishment project that included replacement of the pressure tube. These pre-simulations for Wolsong-1 Phase-B differ from those in the past that were performed for the Wolsong-1,2,3,4 tests in that these tests use the WIMS/DRAGON/RFSP-IST code suite for verification of the tests and gadolinium instead of the traditional PPV/MULTICELL/RFSP code system and boron as poison in the moderator system. The use of gadolinium is deemed not to have domestically accumulated experience gained from the previous Phase-B tests. Thus, it is appropriate to conduct a study in order to gain a correct understanding and interpretation of potential differences in test results stemming from using gadolinium rather than boron. Although the calibration of the reactivity device will not be noticeably different using boron and gadolinium at a constant moderator temperature, the temperature dependency of the neutronic behavior due to the presence of gadolinium in the moderator system might be pronounced. The results of the pre-simulations using gadolinium revealed that the moderator temperature reactivity coefficients indeed showed significant differences in comparison with those with boron. In order to secure the validity of the analysis results, the newly acquired WIMS/DRAGON/RFSP-IST code suite was verified against the W-2,3,4 Phase-B test results. The results of the new code suite verifications revealed some overall improvements in accuracy; justification of the use of the code can be claimed for the validation of the W-1 Phase-B test results

KEYWORDS : CANDU, WIMS/DRAGON/RFSP-IST, Initial Fresh Core, Phase-B Tests and Pre-simulations, Gadolinium, Moderator Temperature Reactivity Coefficients

1. INTRODUCTION

It has been nearly thirteen years since the Phase-B tests of the W-2,3,4 (W-2,3,4) and CANDU 6 reactors were undertaken. The W-1 reactor, which is currently undergoing a major refurbishment project, including replacement of the pressure tube after nearly 26 years of service, is scheduled for Phase-B tests in April 2011 in preparation for licensing submission to restart the reactor after the refurbishment.

The objective of the Phase-B tests is to verify the physics design. To this end, various tests have been designed to collect extensive measurement data, which are checked against pre-simulations. These pre-simulations were done well before the actual tests, with the same methods and models used in the physics design process.

For the preparation of licensing applications, the W-1 safety analysis and reactor operational support code system was changed from PPV/MULTICELL/RFSP (Refs. 1~6) to the Canadian Industry Standard Toolset (IST) based WIMS/DRAGON/RFSP-IST (Refs. 7~12) in an attempt to resolve the Generic Action Items (GAI) issued by the Canadian Nuclear Safety Commission (CNSC). In accordance with this, all the W-1 Phase-B pre-simulations were performed using the newly acquired WIMS/DRAGON/RFSP-IST code suite.

For the W-1 Phase-B pre-simulations and also for the

upcoming post-simulations, a change from the view point of neutronic characteristics was introduced on top of the code system change, namely, the use of gadolinium as poison in the moderator system instead of the traditional boron. This resulted in two pre-simulations using boron and gadolinium, respectively (Ref. 13). The pre-simulation results of the current W-1 Phase-B with boron as poison were compared to the Phase-B pre-simulations and test results of W-2,3,4 so that the overall functioning and capability of the WIMS/DRAGON/RFSP-IST code suite could be verified in detail and also so that a realistic assessment of the new code system could be solidly established. The comparison results confirmed the qualification of the new code system for the verification of Phase-B test results and in addition, some improvements in overall accuracy were confirmed (Ref. 13).

2. WIMS/DRAGON/RFSP-IST

Since the inception of CANDU reactors, fuelled by natural-uranium and cooled and moderated by heavy water, the lattice physics code POWDERPUFS-V (PPV) has been serving for design and safety analyses as well as for operational support including fuel management. The code is characterized by its simplicity: it was trimmed by some experimental data and specifically tailored for CANDU lattice physics calculations. The fuel-coolant clustered region was lumped into a single rod where the neutron transport phenomena was treated by the so-called Westcott convention one and a half energy group formalism. The overall reaction rates in the lattice cell were then determined by solving a one-dimensional diffusion equation in the moderator region, which was coupled with the clustered fuel-coolant region through interfacial neutron current.

The strength of and preference for PPV were rooted in the era of mainframe computer dominance, which was marked by expensive costs for cheap computing expenses. In that era, the numbers produced using PPV served well to cope with the practical problems of CANDU reactor physics. However, with the growing experience of CANDU reactor operations, the weaknesses of PPV compared to WIMS-AECL, which is based on more rigorous mathematics and physics models, have become concerns, e.g., the underestimation of coolant void reactivity from the safety analysis viewpoint and also the under-prediction of ^{239}Pu number densities with burnup from the operational support aspect. Thus, a compelling argument favoring the introduction of WIMS-AECL as the production code to replace PPV has been continuously rising in the CANDU reactor physics community.

Beside the lattice physics calculations, the majority of members of the CANDU reactor physics community have used RFSP to carry out global core physics simulations. For the core physics simulations of a CANDU reactor, the presence of neutron absorbing reactivity device materials in the core affects local reaction rates and power distribution. The representation of reactivity device materials is modeled by adding the so-called incremental cross sections to the homogeneous macroscopic cross sections of a lattice cell that are produced by a lattice cell code.

In the past, the incremental cross sections for the W-1 reactor were calculated using the traditional PPV/MULTICELL code system. However, with the acquisition of the new code system, the DRAGON-IST code now calculates incremental cross sections based on the supercell method using the WIMS-IST lattice cell calculation results, the so-called side-step method. The DRAGON supercell method represents the neutron transport phenomena by collision probabilities whereas the PPV/MULTICELL generates incremental cross sections using reaction rate averaging approximations. Thus, the WIMS/DRAGON-IST codes are expected to yield more accurate solutions compared to PPV/MULTICELL for reactivity device materials of stronger absorption.

RFSP-IST is a further evolution of the RFSP program, which now features comprehensive application of the full two-group formalism of neutron diffusion equations in conjunction with WIMS-IST based fuel tables and contains the developmental pieces tailored for the individual utilities in a consolidated format. In general, the use of WIMS/DRAGON/RFSP-IST is anticipated to yield some overall improvements in accuracy and to add reliability to the interrelated consistency between design, safety and operation support; it is also expected to improve the test result analysis related to CANDU reactor physics calculations.

3. PHASE-B PRE-SIMULATIONS

The commissioning tests of a CANDU type NPP are divided into four parts, namely, Phases-A, B, C and D. The Phase-B tests are conducted at a low reactor power level, in most tests about 10^{-4}~10^{-3} Full Power (FP) level, and in a cold state. The Wolsong CANDU 6 reactor initial core, loaded with fresh fuel, is under guaranteed shutdown mode through the suppression of excessive system reactivity of about -340 mk by dissolving a sufficient concentration of boron or gadolinium as poison in the moderator system.

Traditionally, the Phase-B tests consist of the following ten tests:

1) Approach to first criticality
2) Calibration of Liquid Zone Control System
3) Calibration of Adjuster rods
4) Calibration of Mechanical Control Absorbers
5) Calibration of Shutoff rods
6) Flux shape measurements
7) Heat Transport System temperature reactivity coefficient test

8) Moderator temperature reactivity coefficient test
9) Shutdown System 1 power rundown test
10) Shutdown System 2 power rundown test

In the past it was confirmed that the PPV/MULTICELL/RFSP Phase-B pre-simulations in general over-predicted compared to the test results (Refs. 14~16) due to the fact that the lattice code PPV was experimentally adjusted to yield better agreement for the normal operating range of power reactors. Thus, the differences between the predictive calculations and the actual measurements become larger for the low power range, like Phase-B tests at a cold state.

In order to establish reliability and confidence in the WIMS/DRAGON/RFSP-IST code system, which is designed based on theoretically more rigorous modeling practices, a thorough and detailed verification of the newly adopted code system was first attempted with an elaborate effort in view of the domestic inexperience of using it by comparing the simulation results to the past W-2,3,4 Phase-B test results. The details of this validation work for the W-1 Phase-B pre-simulations using boron and gadolinium as poison in the moderator system can be found in Reference 13 and presented in this paper in a comprehensive format; the results of this validation work are also selectively summarized elsewhere for quick review (Ref. 17).

3.1 Model

The RFSP-IST full core model for the W-1 reactor consists of 44x36x24 mesh spacing's in the x,y,z-directions for steady-state simulations and transient simulations. The steady-state calculations were performed using the SIMULATE module of RFSP-IST for all simulations; the Shutdown System 1 and 2 (SDS1/2) power rundown dynamic simulations were carried out using the CERBERUS module.

The initial fresh core was loaded with 160 depleted uranium (^{235}U 0.52 at.%) fuel bundles in the central 80 channels at bundle positions #8 and #9 and 4,400 natural uranium fuel bundles at the rest of the bundle positions in the core. The depleted fuel bundles were used to achieve power flattening in the central region of the core until the burnup distribution in the core reached the equilibrium state. The 37 element depleted and natural uranium fuel bundles were identical in geometrical dimensions.

The fresh fuels in the initial core at cold state and low power level were fission-product free. The relevant parameter values used as input to WIMS-IST for the Phase-B cold state are given in Table 1 below.

The state described in Table 1 is defined as the reference cold state; the nominal core configuration corresponds to the state with all adjuster rods in, all mechanical control absorbers and shutoff rods out and a uniform level of liquid zone controllers at 15% fill.

During the life time of the W-1 reactor operation, the adjuster rods stayed inserted in the core and the depletion effect of the stainless steel composition of the rods was appropriately accounted for in the modeling for the calculation of the incremental cross sections using DRAGON-IST. The depletion effect of the adjuster rods after nearly 26 years of service resulted in an increase of RFSP-IST calculated system excess reactivity (1-1/keff) by about 0.7 milli-k compared to the loading of fresh adjuster rods.

the Simple Cell Method (SCM), fuel tables to be used for the RFSP-IST core simulations were generated using the WIMS Utilities programs (Ref. 18). All pre-simulations for Phase-B were carried out using SCM fuel tables but the calculation of the moderator temperature reactivity coefficients were performed using detailed SCM fuel tables.

Furthermore, the incremental cross sections were calculated for the reference cold state condition with 8.5 ppm boron in the moderator system, which would be approximately equivalent to the boron concentration required for the criticality. The incremental cross section set so obtained was used throughout all the simulations presented in this Section for the verification purposes against the past W-2,3,4 Phase-B tests. In other words, even for the coolant temperature reactivity change simulations, the incremental cross section set generated for 30 °C of coolant and fuel temperature was used throughout the entire range of coolant and fuel temperatures, as those values increased up to 260 °C. This practice could safely be used because the temperature change in the clustered fuel region, including the coolant, would not significantly affect the neutron energy spectrum and population in the thermal range at the lattice cell boundary for a given constant moderator temperature, so

Table 1. W-1 Phase-B WIMS-IST Input Parameters

Parameter	Condition
Reactor power [FP]	10^{-4}
W/g of Initial heavy element	33.4902×10^{-4}
Coolant temperature [°C]	30
Moderator temperature [°C]	35
Fuel temperature [°C]	30
Coolant density [g/cm^3]	1.10320
Moderator density [g/cm^3]	1.10167
Natural Uranium fuel density [g/cm^3]	10.4919
Avg. Uranium weight [kgU/BND]	19.13525
Coolant purity [atom%]	99.000
Moderator purity [atom%]	99.833

that the reaction rates associated with the device materials in the vicinity of the lattice cell boundaries would not be subject to susceptible changes.

3.2 Approach to Criticality

The past W-2,3,4 Phase-B tests started with the approach to criticality by gradually removing boron from the moderator system, which initially contained a boron concentration of about 44 ppm to sustain the guaranteed shutdown state. Criticality was reached in roughly 33 hours, with a moderator D_2O purification mass of 10 kg/s, by means of ion exchange resin with 260 tons of heavy water filled in the moderator system.

For example, the approach to the first criticality of W-2 was monitored by installing three BF3 counters in View Port #2, connected to Channels D, E and F at the Startup Instrumentation. One BF3 counter was installed in the ion chamber housing positioned exterior to the core and connected to the spare at Startup Instrumentation. The reason for this connection was to minimize the detector irradiations inside the core by rotating the detectors to the outside of the core one by one while the fluxes were monitored. The first criticality of W-2 was observed at $6.5x10^{-11}$ FP and the detector installed outside the core started to measure the fluxes at about 10^{-8} FP. The upcoming W-1 Phase-B tests with gadolinium in the moderator system would be expected to reach the criticality in a way similar to that of W-2 except for the detector change with Fission Chambers.

The RFSP-IST simulations with the loading of aged (depleted) adjuster rods predicted W-1 criticality boron and gadolinium concentrations at the reference cold state with a uniform level of liquid zone controller 15% fills of about 8.95 and 2.527 ppm, respectively, as described in Table 2, for the nominal core configurations. With the 55% insertion of mechanical control absorber (MCA) #4 into the core, the criticality poison concentrations were about 8.82 and 2.49 ppm for boron and gadolinium, respectively. It is usual practice to prefer using MCA to achieve fine increments of core system reactivity by pulling the MCA rod in fine movements step by step instead of removing the poison in very small concentrations from the moderator system to compensate for the required increase of the core system reactivity during the approach to criticality.

The comparison of the current W-1 pre-simulations using boron with the previous W-2,3,4 Phase-B test results confirmed that the differences were within "satisfactory" bounds of ± 0.5 ppm. For the upcoming W-1 Phase-B test with gadolinium in the moderator system, the criticality concentration was expected to be about 2.49 ppm ± 0.14 ppm based on the pre-simulation results.

In the past the W-1,2,3,4 guaranteed shutdown state (GSS) during the Phase-B tests was maintained with boron as poison in the moderator system. According to past experience one ion exchange resin would be useful for removal of about 5-6 ppm boron until the saturation point was reached. This limitation resulted in a prolongation of the test schedule with five ion exchange resins in total. In order to avoid this limitation, it is planned for the upcoming W-1 Phase-B tests to use gadolinium as poison. Therefore, shortening of the test schedule is anticipated.

Furthermore, it is generally thought that the reliability

Table 2. Criticality Conditions – Measurements and Pre-simulations with Boron in the Moderator

	W-2			W-3			W-4			W-1	
	Measure	Pre	Cal	Measure	Pre	Cal	Measure	Pre	Cal	Pre Boron	Pre Cal
LZC AVZL(%)	16.94	15.00	-0.14	15.44	15.00	-0.03	15.75	15.00	-0.05	15.00	15.00
MCA #4 position(%)	55.00	55.00	0.00	55.00	55.00	0.00	55.00	45.00	-0.70	55.00	55.00
Coolant purity(atom%)	99.60	99.00	0.58	99.16	99.00	0.15	99.19	99.00	0.18	99.00	99.00
Moderator purity(atom%)	99.82	99.83	-0.37	99.79	99.83	-1.46	99.81	99.83	-0.78	99.83	99.83
Coolant temp(ºC)	35.00	25.00	-0.61	32.15	30.00	-0.13	34.36	30.00	-0.27	30.00	30.00
Moderator temp(ºC)	29.50	35.00	-0.32	37.74	35.00	0.16	34.03	35.00	-0.06	35.00	35.00
Excess Reactivity(mk)		0.00			0.00			0.00		-0.191	-0.445
R'ty difference(mk)			-0.86			-1.31			-1.67		
Critical ppm	9.00	9.12	9.23	8.93	9.10	9.27	9.24	9.13	9.32	8.82	2.49
Total reactivity(mk)	69.34	70.27	71.12	68.80	70.08	71.39	71.17	70.33	71.78	67.79	67.59
Difference %*			-2.51			-3.62			-0.85		

(Measure-Cal)/Cal*100, Cal: Calibration, Measure: Measurement

of the precise measurement of poison concentrations is better for gadolinium than for boron. In other words, the use of gadolinium as poison is justified based on the above-mentioned considerations.

3.3 Reactivity Calibrations

The reactivity worth of the liquid zone controller system (LZCS), adjuster rods (ADJs), mechanical control absorbers (MCAs) and shutoff rods (SORs) were calibrated at the reference cold state with a reactor power level of about 10^{-4} FP and uniform level of liquid zone controller 15% fills. The calibration of LZCS reactivity worth is summarized in Table 3 by comparing the past W-2,3,4 Phase-B tests to the W-1 pre-simulations. The differences between the measurements and pre-simulations show that the current W-1 pre-simulations under-predict by about 4.06% for the LZC uniform fill range of 20~60%. Note that this fill range of water level in the LZC compartment was overwhelmed by the linearity of reactivity change with %Fill. For the other fill range of 20~80%, the under-prediction was about 5.49%.

The differences between measurements and pre-simulations shown here are within the "satisfactory" bounds of ± 10%.

The calibration of reactivity worth of ADJs, MCAs and SORs are given in Table 4. The current W-1 pre-simulation results were compared to the average values of the previous W-2,3,4 Phase-B test results. For ADJ and MCA, the reactivity worth was calibrated both for individual rods and banks. The pre-simulation results revealed that the reactivity worth of devices was slightly different for the cases in which either boron or gadolinium was used as poison. The new IST codes were in better agreement with the past Phase-B results and under predicted compared to the PPV/MULTICELL/RFSP Phase-B pre-simulations. The difference between measurements and pre-simulations of the ADJs, MCAs and SORs shown here were within the "satisfactory" bounds of ± 15%

3.4 Flux Shape Measurements

Five reactor configurations were considered for the flux shape measurements, consisting of the following combinations of ADJ and MCA bank positions:

Case 1: Nominal configuration
Case 2: MCA bank #1 50% in and all ADJs in
Case 3: All MCAs in and all ADJs in
Case 4: All MCAs and ADJ banks #1,2,3,4 out
Case 5: All MCAs and all ADJ banks 1~7 out

The fluxes were scanned and measured at the sites of

Table 3. Liquid Zone Control Systems Reactivity Worth – Measurements and Pre-simulations

LZC Level	W-2 Measure mk/%	W-3 Measure mk/%	W-4 Measure mk/%	W-2,3,4 Average mk/%	W-1 Pre(Gd) mk/%	W-1 Pre(B) mk/%	Diff(%)
20~60%	0.072	0.074	0.068	0.071	0.069	0.069	-4.06
20~80%	0.068	0.071	0.064	0.068	0.064	0.064	-5.49

Diff(%) = (Measurement of W-2,3,4 average – Pre-simulation of W-1) / Pre-simulation of W-1 x 100

Table 4. Reactivity Device Worth – Measurements and Pre-simulations

R'ty device	W-2 Meas Rho (mk)	W-3 Meas Rho (mk)	W-4 Meas Rho (mk)	W-2,3,4 Aver Rho(mk), R	W-2 Old Pre Rho(mk), S	W-1 New Pre Rho (mk), P, Gd	W-1 New Pre Rho (mk), B, Boron	W-1		
								Measure /Old Pre (R-S)/S	Measure /New Pre (R-B)/B	New Pre /Old Pre (B-S)/
Boron ppm					8.31		7.70			-7.29
LZC 20~60%	0.072	0.074	0.068	0.071	0.072	0.069	0.069			-4.06
Adjuster rods total	10.88	10.80	10.80	10.83	11.26	*	9.92	-3.87	9.12	-11.91
Adjuster banks total	13.65	12.99	10.69	12.44	13.12	*	11.58	-5.15	7.51	-11.78
MCA rods total	-7.71	-7.73	-7.34	-7.59	-8.29	-7.88	-7.90	-8.33	-3.84	-4.67
MCA banks total	-9.58	-8.50	-9.28	-9.12	-10.87	-10.59	-10.62	-16.13	-14.13	-2.33
SOR rods total	-45.37	-44.56	-42.42	-44.12	-48.14	-46.57	-46.65	-8.36	-5.43	-3.10

* No calculation
Meas: Measurement, Aver: Average, Pre: Pre-simulation

102 vanadium detectors, vertical and horizontal flux detectors (fission chambers) at 47 different locations, 34 SDS1 vertical ROP detectors and 24 SDS2 horizontal ROP detectors, respectively, in the cold state with a reactor power level of about 10^{-3} FP, uniform level of liquid zone controller 15% fills and gadolinium was used as poison in the moderator system.

The predicted fluxes at the various detector sites to be compared to the measurements were obtained by interpolating the RFSP-IST calculated mesh cell-averaged fluxes using the INTREP module. The comparisons between the current W-1 pre-simulations and the past W-2,3,4 Phase-B tests were comprehensively conducted and the comparison results for all the cases showed that the Root Mean Square (RMS) average differences were within the "satisfactory" bounds of ± 15%. The comparison results between the past W-3 Phase-B tests and current W-1 pre-simulations are given in Table 5 and Figure 1.

Table 5. Comparisons between W-3 Flux Shape Measurements and W-3 and W-1 Pre-simulations for 102 Vanadium Detectors

	W-3Pre-Simulations RMS Avg diff (%)	W-1Pre-Simulations RMS Avg diff (%)
Case #1	5.9206	6.0240
Case #2	5.8653	6.9413
Case #3	14.7152	11.6246
Case #4	8.9980	4.9199
Case #5	3.2244	4.7920

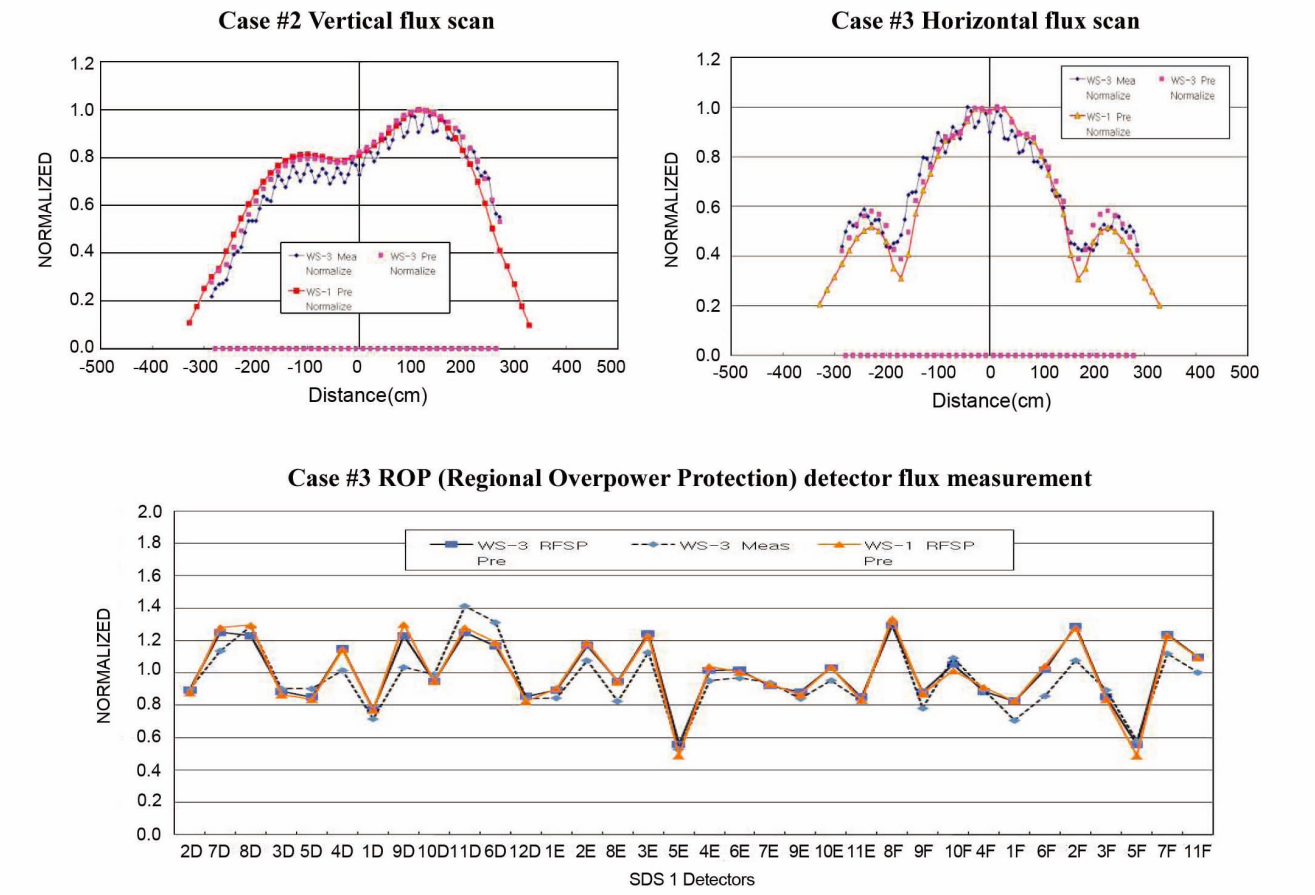

Fig. 1. Comparisons between W-3 Flux Shape Measurements and W-1 Pre-simulations

3.5 Coolant Temperature Coefficient

The reactivity change with the coolant temperature was observed here between 35~260 ºC with 45 ºC increment at the reactor power level of 10^{-3} FP with 15% uniform fill of liquid zone controllers. The fuel temperature was set to be equal to the coolant temperature during the measurements while the moderator temperature was kept unchanged at 35 ºC. The considered temperature range covered the interval between the cold state for Phase-B tests and the normal operating conditions.

The coolant reactivity change was negative and the net decrease was greater than 8 mk based on the past measurements of the W-2,3,4 Phase-B. Thus, the reactivity change exceeded the reactivity worth of the liquid zone controller system. The comparisons between the past W-2,3,4 Phase-B tests and the present W-1 pre-simulations for the coolant temperature reactivity change are given in Table 6. The difference between the measurements and the pre-simulation results showed the largest positive value of 9.35% at the last step of 260 ºC; the differences had a tendency of gradual decrease in magnitude with a negative sign, and finally turned positive at 215 ºC, with a tendency of gradual increase. The average difference was 2.39% with the measured values of W-2,3,4 Phase-B tests and W-1 pre-simulations. This result is a very good agreement, as before, of -9.8%.

The behavior of the relative differences between the measurements and current W-1 pre-simulations exposed a statistically well settled pattern. The value of relative

Table 6. Comparisons between W-2,3,4 Coolant Temperature Reactivity Change Measurements and W-1 Pre-Simulations

HT. Temp (ºC)	W-2 Measure		W-3 Measure		W-4 Measure		W-2,3,4 Average		W-2 Pre		W-1 Pre Gd		W-1 Pre B		Difference (%)		
	(mk)	Total (mk)	(mk)	Total (mk)	(mk)	Total (mk)	(mk)	Total (mk)R	(mk)	Total (mk)S	(mk)	Total (mk)P	(mk)	Total (mk)G	Old M/ Old Pre	Old M/ New Pre(B)	
																Gd	B
															(R-S)/S	(R-P)/P	(R-G)/G
35	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000	0.00	0.00	0.00
80	-2.38	-2.377	-2.36	-2.356	-2.28	-2.283	-2.34	-2.339	-2.56	-2.564	-2.42	-2.420	-2.43	-2.429	-8.78	-3.35	-3.71
125	-2.17	-4.552	-1.93	-4.287	-1.96	-4.244	-2.02	-4.361	-2.26	-4.822	-2.00	-4.420	-2.02	-4.444	-9.56	-1.34	-1.87
170	-1.81	-6.366	-1.65	-5.936	-1.83	-6.075	-1.76	-6.125	-1.99	-6.811	-1.70	-6.122	-1.72	-6.160	-10.07	0.06	-0.56
215	-1.16	-7.526	-1.55	-7.490	-1.45	-7.522	-1.39	-7.513	-1.46	-8.270	-0.73	-6.848	-0.75	-6.910	-9.16	9.70	8.72
260	-0.74	-8.266	-0.89	-8.383	-0.69	-8.207	-0.77	-8.285	-1.10	-9.368	-0.45	-7.294	-0.67	-7.577	-11.56	13.59	9.35
Aver															-9.82	3.73	2.39

M,Measure: Measurement, Pre: Pre-simulation, MOD: Moderator system, Gd: Gadolinium, Aver: Average
B: Boron

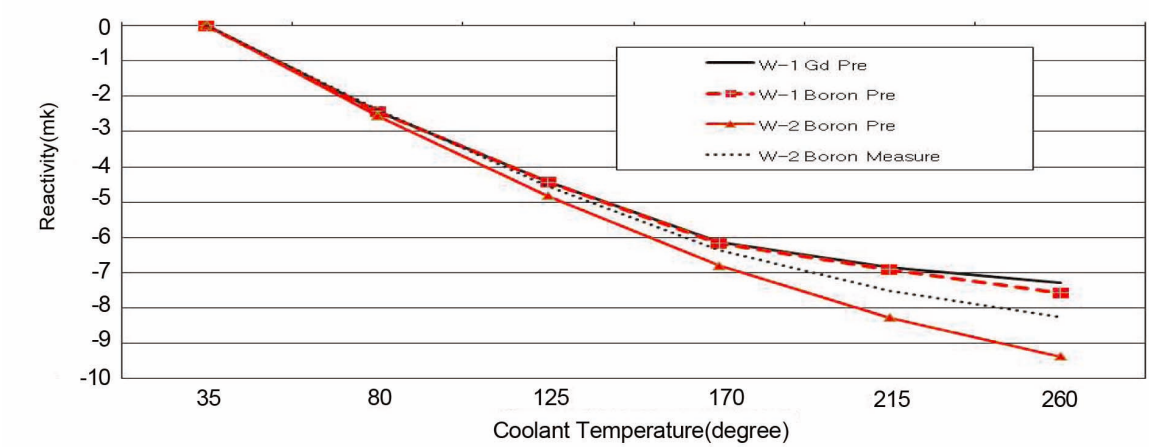

Fig. 2. Comparisons between W-2,3,4 Coolant Temperature Reactivity Change Measurements and W-1 Pre-simulations

Table 7. Moderator Temperature Reactivity Change using Gadolinium and Boron as Poison

MOD Temp (°C)	W-2 Measure		W-3 Measure		W-4 Measure		W-2,3,4 Average		W-2 Pre		W-1 Pre Gd		W-1 Pre B		Difference (%)	
	(mk)	Total (mk)	(mk)	Total (mk)	(mk)	Total (mk)	(mk)	Total (mk)R	(mk)	Total (mk)S	(mk)	Total (mk)P	(mk)	Total (mk)G	Old M/ Old Pre	Old M/ New Pre(B)
															(R-S)/S	(R-G)/G
70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.612	0.00	0.750	0.00	0.00	0.00
65	-0.09	-0.09	-0.11	-0.11	-0.17	-0.17	-0.10	-0.10	-0.12	-0.12	2.267	-0.35	0.642	-0.11	-16.77	-5.98
60	-0.15	-0.25	-0.12	-0.23	-0.25	-0.41	-0.14	-0.24	-0.16	-0.29	1.905	-0.71	0.521	-0.23	-16.53	3.88
55	-0.19	-0.44	-0.14	-0.37	-0.19	-0.61	-0.16	-0.40	-0.18	-0.47	1.525	-1.09	0.387	-0.36	-13.92	10.74
50	-0.16	-0.60	-0.15	-0.52	-0.27	-0.87	-0.16	-0.56	-0.20	-0.66	1.130	-1.48	0.236	-0.51	-15.51	8.82
45	-0.19	-0.79	-0.19	-0.71	-0.31	-1.18	-0.19	-0.75	-0.20	-0.86	0.715	-1.90	0.075	-0.68	-13.15	11.03
40	-0.22	-1.01	-0.16	-0.87	-0.26	-1.45	-0.19	-0.94	-0.21	-1.08	0.283	-2.33	0.100	-0.85	-12.53	10.63
35	-0.25	-1.26	-0.12	-0.99	-0.25	-1.69	-0.18	-1.13	-0.22	-1.30	0.166	-2.78	0.287	-1.04	-13.38	8.50
Aver															-14.54	6.80

M,Measure: Measurement, Pre: Pre-simulation, MOD: Moderator system, Gd: Gadolinium, Aver: Average
B: Boron

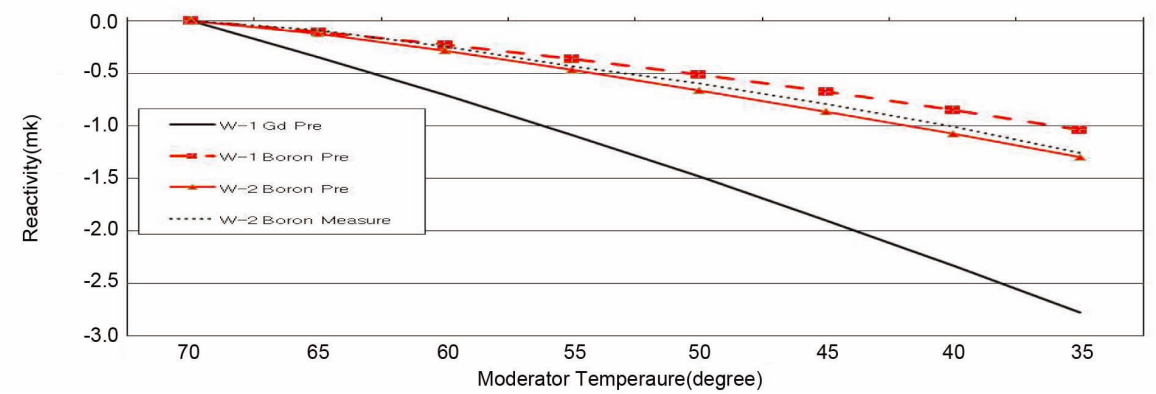

Fig. 3. Comparisons between W-2,3,4 Moderator Temperature Reactivity Change Measurements and W-1 Pre-simulations using Boron and Gadolinium as Poison

differences changed from negative to positive between 210~215 °C; the reason for this should be attributed to the temperature dependency of the microscopic cross sections of the coolant and fuel isotopic compositions as contained in the nuclear data library of the WIMS-IST code.

The pre-simulation results revealed that the reactivity worth of devices was slightly different according to which poison was used, boron or gadolinium. The new IST codes were in better agreement with the past Phase-B test results and under predicted compared to the PPV/MULTICELL/RFSP Phase-B pre-simulations.

3.6 Moderator Temperature Coefficient

As mentioned earlier, the W-1,2,3,4 guaranteed shutdown state (GSS) during the Phase-B tests in the past was maintained using boron as the poison in the moderator system. However, for the upcoming W-1 Phase-B tests, gadolinium will be used as the poison. Thus, a clear understanding of the neutronic behavior in the moderator with changing physical conditions, such as temperature and poison concentration, is a prerequisite for a correct understanding of the test results as well as for fair validation of the simulation results against the measurements.

For the sake of understanding the moderator temperature susceptibility to the reactivity change, the Phase-B test results of W-2,3,4 were compared with the pre-simulations. The results of these comparisons are given in Table 7 and are also graphically displayed in Figure 3.

It is generally known that the moderator temperature reactivity coefficient measurements of a CANDU power reactor are very difficult to perform and, in addition to that, the reactivity change is calibrated by observing the change in water levels of the liquid zone controllers based on a small change in reactivity, say, slightly greater than 1 mk, between the temperatures 35~70 °C with boron as poison in the moderator. The comparison of the current W-1 pre-simulations using boron with the past W-2,3,4 Phase-B test results confirms that the accuracies are increased as before pre-simulations. For the upcoming W-1 Phase-B test with gadolinium in the moderator system, the reactivity change for this case was +2.78 mk, which is 2.67 times larger than the value with boron at the same temperature.

It is well known that boron is a 1/v absorber, in contrast to gadolinium, whose microscopic cross sections represent in the thermal range non-1/v and in the epi-thermal range resonance behavior of absorptions. Thus, the presence of gadolinium in the moderator system will affect neutronic characteristics differently with respect to the energy and space dependency of fluxes compared to the case of boron. These phenomena will obviously be pronounced for a CANDU type lattice cell, in which ~95% of thermal neutron populations reside in the moderator region.

3.7 SDS1 and SDS2 Power Rundown Tests

SDS1 and SDS2 power rundown tests were performed using the CERBERUS module of RFSP-IST. The module solves the space-time dependent 3-D two energy group neutron diffusion equations based on the Improved Quasi-Static (IQS) method. The initial reactor power was set to 10^{-3} FP with 15% uniform fill of the liquid zone controllers. Six delayed-neutron-precursor groups were use to simulate the transient with the additional inclusion of eleven photo-neutron groups.

The SOR drop curve was consistent with the one that was used for the W-1 safety analysis, namely, LLOCA. Two of the most effective SORs, namely, #4 and #8, were assumed to be missing, and the SOR incremental cross sections used for the reference cold conditions were calculated using DRAGON-IST. For the SDS2 test, one of the most effective injection nozzles of #2 was assumed to be missing, and the gadolinium injection incremental cross sections were used, "poison.dat" file (Ref. 19). The relative fluxes of the W-1 CERBERUS pre-simulations were calculated at different time points during the transient using the INTREP module with several detectors at different positions; the results are graphically compared in Figure 4 along with the W-3 Phase-B tests.

The comparisons show that the W-1 predicted flux run-down curve is positioned to the right compared to the W-3 measured flux run-down curve. This phenomenon confirmed the conservatism claimed in the context of the W-1 safety analysis.

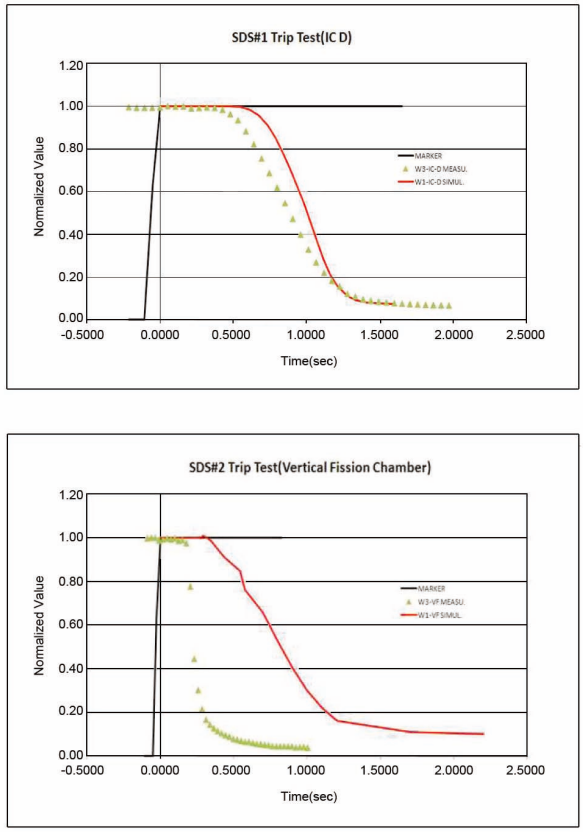

Fig. 4. Comparisons between W-3 Power Rundown Measurements and W-1 Pre-simulations

3.8 Discussions

In the past the W-1,2,3,4 guaranteed shutdown state (GSS) during the Phase-B tests was maintained with boron as poison in the moderator system. According to past experience, one ion exchange resin was useful for the removal of about 5~6 ppm boron until the saturation point was reached. This limitation translates into a prolongation of the test schedule with five ion exchange resins in total. In order to avoid this limitation, it is planned for the upcoming W-1 Phase-B tests to use gadolinium as poison and, therefore, shortening of the test schedule is consequently anticipated.

Furthermore, it is generally thought that the reliability of precise measurement of poison concentrations is better with gadolinium than with boron. In other words, the use of gadolinium as poison is justified based on the above-mentioned considerations.

The comprehensive W-1 Phase-B pre-simulation package proved that the WIMS/DRAGON/RFSP-IST code suite generates fairly comparable pre-simulations in agreement with the previous PPV/MULTICELL/RFSP pre-simulations, and the W-2,3,4 Phase-B test results with a slight improvement in overall accuracy accompanied by an increase in consistency. Furthermore, the simulations conducted using either boron or gadolinium as poison show

small differences for the test items discussed in Sections 3.3~3.5 except for the moderator temperature reactivity coefficient test.

The Phase-B tests at Wolsong NPP belong to the critical path and it is therefore necessary to produce a "satisfactory" conclusion for one test step before the test schedule is allowed to move on to the next test step. Thus, in order to cope with the overall comprehensive, time-consuming and tedious tasks of completing Phase-B tests, reliable and efficient analysis of the test results and comparison to the pre-simulations with a quick determination of whether or not a test step has passed "satisfactorily" are very important. With respect to these considerations, the automation of the WIMS-IST Uniform and SCM fuel table as well as the DRAGON incremental cross section generations are strongly desired, along with the computerized interpretation and display of test results with total removal of human error.

It can be concluded that based on the verification results presented here the justification for the use of the WIMS/DRAGON/RFSP-IST code suite and gadolinium as poison in the moderator system instead of the traditionally used boron can be safely claimed for the verification of the upcoming W-1 Phase-B test results. In view of this prospect, the systematic approach to gaining in-depth knowledge of the newly acquired code system, as well as to accumulating experience to use it, are thought to be desirable.

4. CONCLUSIONS

In order to secure the validity of the analysis results, the newly acquired WIMS/DRAGON/RFSP-IST code suite has been verified against the past W-2,3,4 Phase-B test results. The results of the new code suite verifications revealed some overall improvements in accuracy; justification of the use of the code suite can be claimed for the validation of the W-1 Phase-B test results.

The use of gadolinium instead of boron as poison in the moderator system is anticipated to yield a significant shortening of the test schedule for the W-1 Phase-B tests. The pre-simulation results revealed that the reactivity worth of devices is slightly different for the cases of either boron or gadolinium used as poison except for the moderator temperature reactivity coefficient test which revealed a significant difference.

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