Validation of WIMS-AECL With ENDF/B-V Against Phase-B Reactor Physics Tests at Wolsong Units 2 and 3

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ABSTRACT

The validation calculations of the WIMS-AECL code as a lattice physics design code of CANDU-PHWR were performed with the Phase-B reactor physics test results of Wolsong units 2 and 3. The physics simulation results for the two new Wolsong units by WIMS/RFSP code system show considerable improvement in prediction of boron reactivity worth when they are compared with those for the Wolsong unit 1 and Point Lepreau with the same code system. But there are differences between the calculated and the measured values in liquid zone level worth and large errors in the heat transport system and moderator temperature coefficient calculations. To elaborate the causes for these differences and errors, further studies need to be made.

1. INTRODUCTION

The POWDERPUFS-V (PPV) code [1] has long been used for the lattice physics design of CANDU reactors. In the cores with advanced CANDU bundle structure like CANFLEX which contains SEU (slightly enriched uranium) or RU (recovered uranium), however, the neutron spectra become harder than that of NU (natural uranium) fuel and, thereby, the POWDERPUFS-V (PPV) code does not satisfactorily predict lattice physics parameters. It is suggested that the WIMS-AECL [2], a supplementary lattice physics code, is to be utilized instead of PPV code not only for improved prediction accuracy of a certain safety parameters but also for the lattice physics design of advanced CANDU fuels such as CANFLEX and DUPIC. Motivated by this, we herein examine the validation of the WIMS-AECL code as a lattice physics design code of CANDU-PHWR using the phase-B reactor physics test results of the Wolsong units 2 and 3 which started commercial operations in the middle of 1997 and 1998, respectively.

2. WIMS/RFSP CODE SYSTEM

For the computation of physics parameters, the WIMS-AECL lattice code [2] is combined with the core design code RFSP [1] for CANDU reactor. The group constants input to the RFSP code are prepared by the WIMS-AECL code. Also, the major incremental cross sections for reactivity devices are obtained with the help of MULTICELL code [3]. The cross section library for the WIMS-AECL is derived from the ENDF-B/V.

Figure 1 shows the calculational flow chart of WIMS-AECL/RFSP, which has been widely tested for the physics simulations of the CANDU reactors such as Point Lepreau and Wolsong unit 1 before.

3. SIMULATIONS OF PHASE-B PHYSICS TESTS AT WOLSONG UNITS 2 AND 3

The CANDU specific terminology, 'Phase-B', is defined as follows; " This phase includes the first approach to criticality and the low power tests necessary to verify the physics design and to evaluate the performance of control and protective systems. Most tests are performed at less than 0.1 % of full power" [4]. The simulations of the Phase-B physics tests of Wolsong units 2 and 3 for the validation of the WIMS-AECL code include following tests,

a. Boron reactivity worth
b. Approach to first criticality
c. Calibration of liquid zone control system
d. Reactivity of control devices; individual rods and banks of adjusters and mechanical control absorbers, and individual shutoff rods
e. Heat transport temperature reactivity coefficient
f. Moderator temperature coefficient
g. Flux distribution measurement

The input values and procedures of above tests were referenced from the Phase-B measured data and PPV/RFSP inputs used during the physics tests carried out previously.

During the simulation, we have made some corrections on WIMS-AECL Material and Mixture cards input values. The input values for boron 7 ppm before and after corrections are given below as an example.

Before Corrections

Material boron 1.08579 303.16 Moder b10=198.255 b11=889.899
Mixture moder water1 1 boron **7.0000e-06** 303.16 moder

After Corrections

Material boron 2.3 303.16 Moder b10=18.430943 b11=81.569057
Mixture moder water1 1 boron **3.35694e-06** 303.16 moder

The value of 7.0000e-06 used before correction is the wrong form of weight fraction of boron 7 ppm. After correction, this value has changed to the value of 3.35694e-06, the volume fraction of same amount of boron. Also, the values used in the Material card before corrections were modified into new values, i.e. 2.3 for boron density, 18.430943 and 81.569057 for the weight fractions of B10 and B11, respectively, which were calculated from atomic weight fractions of those isotopes. This correction is important because boron reactivity worth is strongly affected by these values.

To transform the experimental liquid zone level change into the corresponding amount of reactivity change, we have introduced a third-order polynomial fitting function given by

$$\rho(z) = Az^3 + Bz^2 + Cz + D,$$

where z is liquid zone level, ρ reactivity at a given liquid zone level, and A, B, C, D the fitting coefficients. Thus the reactivity difference between the liquid zone level of z_1 and z_2, can be determined by

$$\Delta\rho = A(z_2^3 - z_1^3) + B(z_2^2 - z_1^2) + C(z_2 - z_1) \quad (1)$$

FIGURE 3 shows the third order fitting polynomials and numerical values of the expansion coefficients of those polynomials for Wolsong units 2 and 3, respectively.

4. RESULTS AND DISCUSSIONS

Boron reactivity worth is obtained purely from the WIMS/RFSP computation instead of experiment. It is the most important value because it determines other kind of reactivity worth such as average liquid zone level worth and worths of various control devices.

TABLE 1 shows the boron reactivity worth and the critical boron concentration when the reactor reached its first criticality. The predicted boron reactivity worth of 8.225 (Wolsong 2) and 8.172 (Wolsong 3) are very similar to those predicted by PPV/RFSP code, e.g., 8.310 mk/ppm and 8.290 mk/ppm [5]. In contrast to these results, it is interesting to note that previous calculations with the WIMS/RFSP code for Wolsong 1 and Point Lepreau showed 7.851 and 7.915 mk/ppm [3], respectively. Because we have not changed environmental conditions, the seemingly improved prediction on boron reactivity worth is ascribed to the previously mentioned corrective changes made in input values to the WIMS-AECL code. WIMS/RFSP results for critical boron concentrations are lower than those of PPV/RFSP. According to the previous study, the WIMS code showed a tendency to underestimate the criticality of the ZED-II critical experiments also. The underestimation of the WIMS/RFSP code for the initial critical soluble boron concentration by 0.50 ppm at Wolsong unit 2, 0.6 ppm at Wolsong unit 3 appears to be consistent with the previous finding.

FIGURE 2 shows that the reactivity changes linearly with the boron concentration change.

TABLE 2 summarizes the results for the calibration of liquid zone control system. In calibration of liquid zone control system, it is the most important to have the precise measurements on the purity of every boron batches. The errors in predictions of AVAL worth by WIMS/RFSP come partly from the purity measurements of the batches and partly from the measurement errors of liquid zone levels.

TABLEs 3.1 to 3.5 show the reactivity worth of various control devices. The predictions are mostly good. But, the reactivity worth calculations of MCA and MCA bank show relatively large errors.

TABLEs 4 and 5 show reactivity changes of core by the temperature change of heat transport system and moderator, respectively, each for the calculation of heat transport system temperature coefficient and moderator temperature coefficient (MTC). Prediction on the MTC by WIMS/ RFSP shows large discrepancies, say, about 50%, from the measurements. The exact cause for such large discrepancies is not known at present. More studies need to be made in terms of performance of the WIMS-AECL code itself and the heavy water cross sections in ENDF-B/V cross section library.

FIGURE 4 are the results of horizontal and vertical fluxscans at Wolsong unit 3. There are no such results for Wolsong unit 2. The cases of fluxscans included in FIGURE 4 are

Case 1 : Nominal core condition. (ADJs in, MCAs out)
Case 2 : MCA BNK#1 50% insertion with all adjusters in
Case 3 : All MCAs in with all ADJs in
Case 4 : All MCAs out with ADJ BNK#1~#4 out
Case 5 : All ADJs and MCAs out

The WIMS/RFSP calculations agree well with fluxscans. Such agreements have been observed in the PPV/RFSP system. Besides fluxscans, the 102 in-core vanadium detector readings were also checked for the cases listed above. We found that WIMS/RFSP predictions on in-core detector reading are fairly good with maximum RMS (root mean square) error of 14.07 % for the Case 2 and less than 6.57 % errors for other cases. Again, these results are similar to those of the PPV/RFSP system.

5. CONCLUSIONS

The validation of WIMS-AECL lattice code were examined in combination with RFSP code and with the help of MULTICELL code for the incremental cross sections of devices using phase-B reactor physics tests results of Wolsong units 2 and 3.

The examination shows much improved results when it is compared with older results of Wolsong unit 1 and Point Lepreau especially in boron reactivity worth calculation with the help

of some corrections on WIMS-AECL input. We observed that the WIMS/RFSP code predicted 8.225 mk/ppm for boron reactivity coefficient at Wolsong unit 2 and 8.172 mk/ppm at Wolsong unit 3, which are very similar to the prediction by PPV/RFSP code 8.310 mk/ppm and 8.290 mk/ppm. It shows fairly good predictions on reactivity worth of various control devices and fluxscan.

In spite of the improvement in boron reactivity worth calculations, we need more studies and tests of the WIMS/RFSP system for the large errors observed in liquid zone level worth tests and moderator temperature coefficient calculations.

ACKNOWLEDGEMENT

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2. J. Griffiths, "WIMS-AECL Users Manual", RC-1176, AECL (1994)

3. "Validation of WIMS-AECL Reactivity Device Calculations for CANDU Reactor", KAERI/TR-876, 1997.

4. "Phase-B Physics Tests Reports", KAERI ,1995.

5. Sung Min Kim, "Physics Post Simulation of Wolsong unit 2", Wolsong NPP, 1997.

TABLE 1. Boron reactivity worth and critical boron concentration

	Wolsong 2		Wolsong 3	
	WIMS/RFSP	PPV/RFSP	WIMS/RFSP	PPV/RFSP
Boron reactivity worth (mk/ppm)	8.225	8.310	8.172	8.290
Critical boron concentration (ppm)	8.504	9.000	8.303	8.930
Critical boron concentration Error (%)	-5.51		-7.02	

Error = (WIMS/RFSP – PPV/RFSP)/(PPV/RFSP) x 100%

***TABLE 2.* Comparison of WIMS/RFSP predictions and Experiments on AVZL Worth**

AVZL (Average Zone Level)	Wolsong 2			Wolsong 3		
	WIMS/RFSP (mk/%)	Experiment (mk/%)	Error(%)	WIMS/RFSP (mk/%)	Experiment (mk/%)	Error(%)
20 ~ 60 %	0.07872	0.07139	10.27	0.07764	0.07282	6.62
20 ~ 80 %	0.07252	0.06702	8.21	0.07323	0.06894	6.22

TABLE 3.1 Reactivity worth of individual adjuster rods

Adjuster rod	Wolsong 2			Wolsong 3		
	WIMS/RFSP (mk)	Experiment (mk)	Error(%)	WIMS/RFSP (mk)	Experiment (mk)	Error(%)
ADJ#1	0.232	0.220	5.65	0.226	0.233	-3.15
ADJ#2	0.584	0.562	3.96	0.556	0.606	-8.33
ADJ#3	0.738	0.708	4.20	0.690	0.739	-6.61
ADJ#4	0.379	0.389	-2.52	0.353	0.388	-9.10
ADJ#5	0.741	0.715	3.57	0.684	0.748	-8.52
ADJ#6	0.581	0.564	3.04	0.552	0.585	-5.63
ADJ#7	0.232	0.220	5.65	0.222	0.227	-2.34
ADJ#8	0.270	0.253	6.86	0.261	0.299	-12.68
ADJ#9	0.733	0.686	6.89	0.708	0.680	4.11
ADJ#10	0.957	0.916	4.48	0.906	0.943	-3.95
ADJ#11	0.530	0.528	0.43	0.493	0.550	-10.41
ADJ#12	0.949	0.923	2.77	0.906	0.979	-7.50
ADJ#13	0.731	0.735	-0.51	0.702	0.736	-4.64
ADJ#14	0.270	0.290	-7.06	0.261	0.283	-7.79
ADJ#15	0.231	0.221	4.67	0.223	0.228	-2.21
ADJ#16	0.586	0.530	10.65	0.557	0.548	1.71
ADJ#17	0.744	0.711	4.57	0.686	0.738	-6.99
ADJ#18	0.384	0.378	1.65	0.354	0.399	-11.36
ADJ#19	0.738	0.721	2.32	0.683	0.781	-12.59
ADJ#20	0.577	0.583	-1.01	0.551	0.584	-5.63
ADJ#21	0.231	0.224	3.29	0.221	0.249	-11.39
Total	11.418	11.075	3.09	10.795	11.525	-6.34

Error = (WIMS/RFSP - Experiment)/Experiment x 100 %

TABLE 3.2 Reactivity worth of each adjuster banks

Adjuster bank	Wolsong 2			Wolsong 3		
	WIMS/RFSP (mk)	Experiment (mk)	Error(%)	WIMS/RFSP (mk)	Experiment (mk)	Error(%)
Adj_b#1	1.396	1.348	3.52	1.334	1.410	-5.41
Adj_b#2	1.548	1.517	2.04	1.475	1.449	1.79
Adj_b#3	1.539	1.497	2.79	1.449	1.404	3.17
Adj_b#4	2.307	2.310	-0.14	2.212	1.962	12.75
Adj_b#5	1.738	1.755	-0.97	1.600	1.909	-16.17
Adj_b#6	1.762	1.775	-0.72	1.636	1.842	-11.19
Adj_b#7	3.145	3.341	-5.88	2.942	3.469	-15.20
Total	13.435	13.544	-0.81	12.648	13.446	-5.93

TABLE 3.3 Reactivity worth of each mechanical control absorbers

MCA	Wolsong 2			Wolsong 3		
	WIMS/RFSP (mk)	Experiment (mk)	Error(%)	WIMS/RFSP (mk)	Experiment (mk)	Error(%)
MCA#1	2.094	1.865	12.30	2.109	1.993	5.84
MCA#2	2.086	1.926	8.33	2.105	2.077	1.37
MCA#3	2.096	1.854	13.03	2.109	1.880	12.21
MCA#4	2.082	1.990	4.61	2.096	2.081	0.73
Total	8.358	7.635	9.47	8.419	8.029	4.85

TABLE 3.4 Reactivity worth of each mechanical control absorber banks

MCA bank	Wolsong 2			Wolsong 3		
	WIMS/RFSP (mk)	Experiment (mk)	Error(%)	WIMS/RFSP (mk)	Experiment (mk)	Error(%)
MCA#1,#4	5.614	4.809	16.74	4.001	3.588	11.51
MCA#2,#3	5.613	4.690	19.68	5.703	4.951	15.18
Total	11.227	9.499	18.19	9.704	8.539	13.64

Error = (WIMS/RFSP - Experiment)/Experiment x 100 %

TABLE 3.5 Reactivity worth of each shutoff rods

SOR	Wolsong 2			Wolsong 3		
	WIMS/RFSP (mk)	Experiment (mk)	Error(%)	WIMS/RFSP (mk)	Experiment (mk)	Error(%)
SOR#1	1.291	1.258	2.62	1.293	1.243	4.05
SOR#2	1.632	1.572	3.84	1.607	1.627	-1.20
SOR#3	1.629	1.569	3.82	1.605	1.636	-1.87
SOR#4	1.288	1.276	0.93	1.287	1.354	-4.93
SOR#5	0.998	0.876	13.94	1.018	0.901	13.04
SOR#6	2.217	1.869	18.65	2.184	1.909	14.43
SOR#7	2.209	1.935	14.16	2.181	1.983	10.00
SOR#8	0.991	0.942	5.180	1.007	0.968	4.01
SOR#9	1.550	1.278	21.32	1.576	1.300	21.19
SOR#10	2.526	2.250	12.25	2.512	2.284	10.00
SOR#11	2.612	2.382	9.66	2.573	2.432	5.79
SOR#12	2.519	2.307	9.21	2.507	2.392	4.80
SOR#13	1.53	1.361	12.44	1.556	1.428	8.96
SOR#14	1.514	1.280	18.25	1.550	1.316	17.78
SOR#15	1.507	1.389	8.47	1.530	1.489	2.74
SOR#16	1.541	1.503	2.53	1.574	1.289	22.13
SOR#17	2.532	2.195	15.34	2.512	2.258	11.23
SOR#18	2.612	2.349	11.19	2.571	2.432	5.72
SOR#19	2.520	2.320	8.64	2.501	2.388	4.74
SOR#20	1.537	1.349	13.96	1.556	1.421	9.48
SOR#21	0.997	0.870	14.63	1.012	0.897	12.80
SOR#22	2.219	1.823	21.75	2.183	1.938	12.64
SOR#23	2.211	1.925	14.85	2.176	2.000	8.81
SOR#24	0.988	0.971	1.70	1.003	0.977	2.61
SOR#25	1.287	1.229	4.68	1.297	1.228	5.60
SOR#26	1.626	1.563	4.05	1.602	1.648	-2.79
SOR#27	1.623	1.602	1.28	1.600	1.655	-3.34
SOR#28	1.280	1.317	-2.84	1.281	1.370	-6.53
Total	48.986	44.560	9.93	48.854	45.763	6.75

Error = (WIMS/RFSP - Experiment)/Experiment x 100 %

TABLE 4. Reactivity change by heat transport temperature change (Heat transport temperature coefficient calculations)

Wolsong 2				Wolsong 3			
HT. Temp (℃)	WIMS/RFSP (mk)	Experiment (mk)	Error (%)	HT. Temp (℃)	WIMS/RFSP (mk)	Experiment (mk)	Error (%)
35.25	-	-	-	38.70	-	-	-
50.06	-0.826	-0.882	-6.39	50.10	-0.641	-0.745	-14.02
64.87	-0.772	-0.732	5.50	65.10	-0.782	-0.824	-5.15
79.92	-0.725	-0.727	-0.24	80.00	-0.759	-0.860	-11.73
96.85	-0.851	-0.770	10.48	96.60	-0.801	-0.628	27.57
110.84	-0.382	-0.680	-43.79	110.00	-0.671	-0.586	14.44
125.53	-0.857	-0.719	19.21	125.00	-0.631	-0.717	-12.01
140.82	-0.594	-0.592	0.37	140.00	-0.600	-0.574	4.55
155.26	-0.561	-0.533	5.34	155.10	-0.566	-0.545	3.80
174.14	-0.553	-0.555	-0.31	170.10	-0.498	-0.532	-6.35
187.21	-0.629	-0.534	17.79	185.00	-0.648	-0.510	27.18
199.78	-0.359	-0.450	-20.31	199.90	-0.443	-0.469	-5.53
215.04	-0.405	-0.424	-4.49	215.00	-0.401	-0.550	-27.13
230.07	-0.320	-0.271	17.96	229.90	-0.342	-0.297	15.11
245.09	-0.263	-0.239	9.97	245.10	-0.244	-0.286	-14.66
259.84	-0.184	-0.164	12.06	260.10	-0.190	-0.217	-12.27

Moderator temperature : 35℃ ± 1℃

TABLE 5. Reactivity change by moderator temperature change (Moderator temperature coefficient calculations)

Wolsong 2				Wolsong 3			
Mod.Temp (℃)	WIMS/RFSP (mk)	Experiment (mk)	Error (%)	Mod.Temp (℃)	WIMS/RFSP (mk)	Experiment (mk)	Error (%)
69.00	-	-	-	36.65	-	-	-
65.00	-0.057	-0.103	-44.47	40.07	0.092	0.126	-26.96
60.06	-0.075	-0.172	-56.34	44.96	0.109	0.172	-36.72
54.45	-0.102	-0.189	-46.12	49.93	0.111	0.200	-44.62
50.25	-0.087	-0.160	-45.59	55.08	0.080	0.166	-51.69
45.52	-0.111	-0.193	-42.45	60.01	0.073	0.151	-51.58
40.42	-0.138	-0.230	-40.06	64.91	0.058	0.099	-41.51
34.99	-0.146	-0.279	-47.75	68.52	0.039	0.116	-66.43

Heat transport system temperature : 260℃ ± 3℃

Error = (WIMS/RFSP - Experiment)/Experiment x 100 %

FIGURE 1. Flow Chart of WIMS-AECL/(MULTICELL)/RFSP system

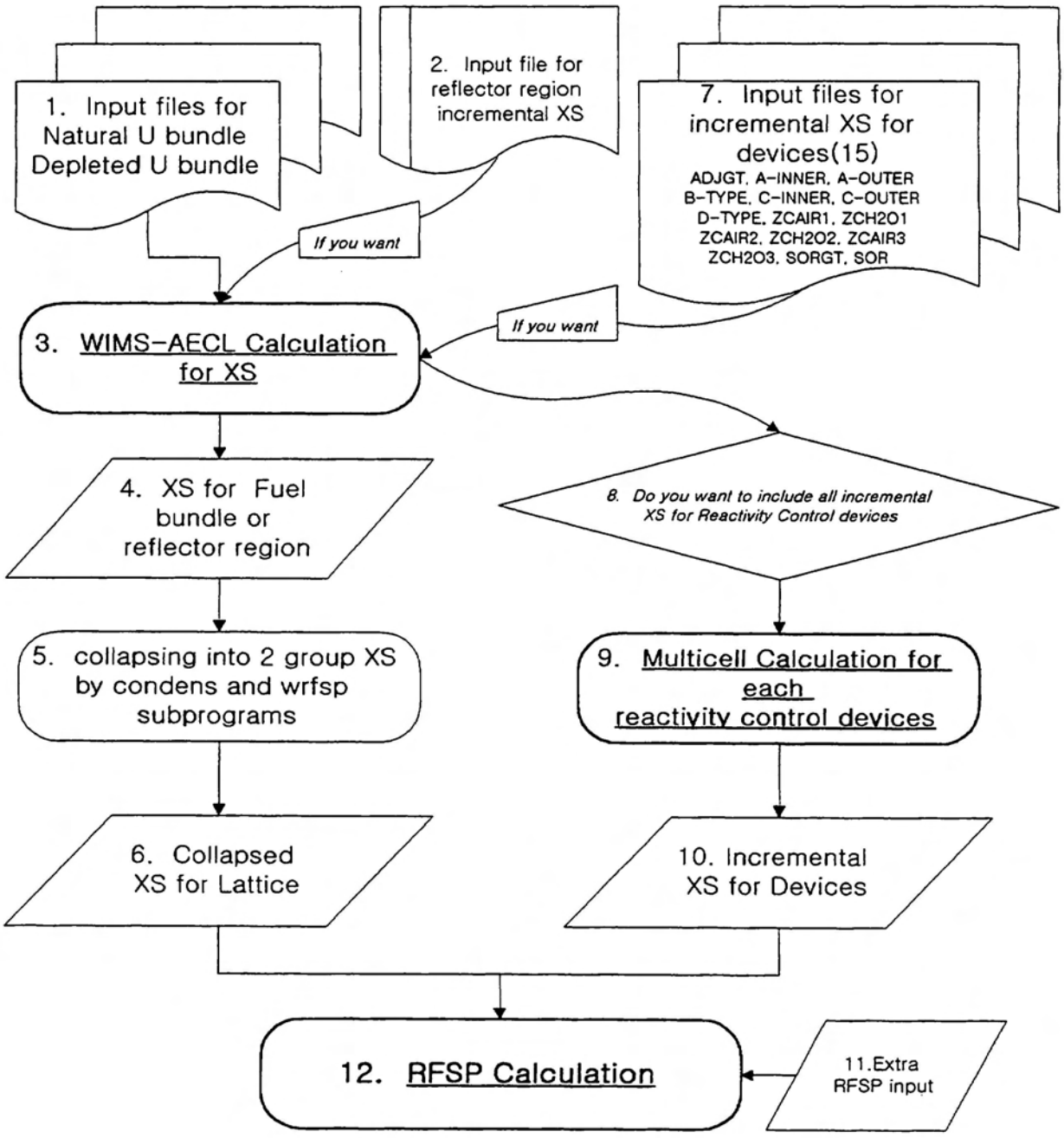


FIGURE 2. Boron reactivity worth graph

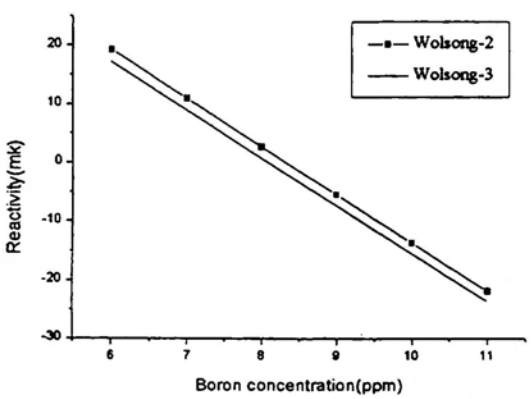
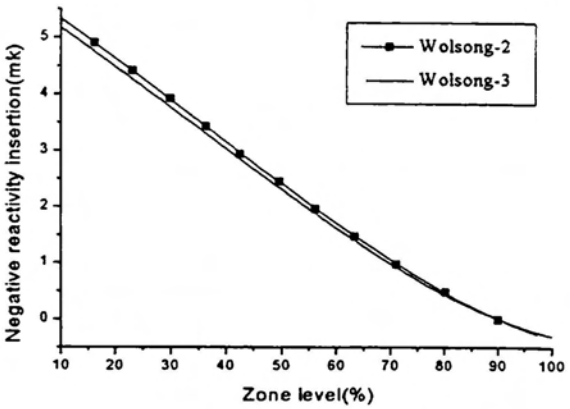
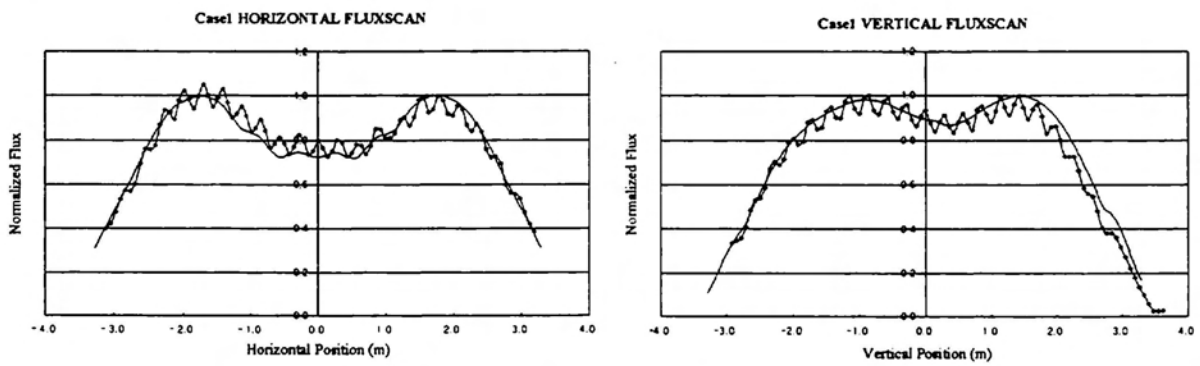


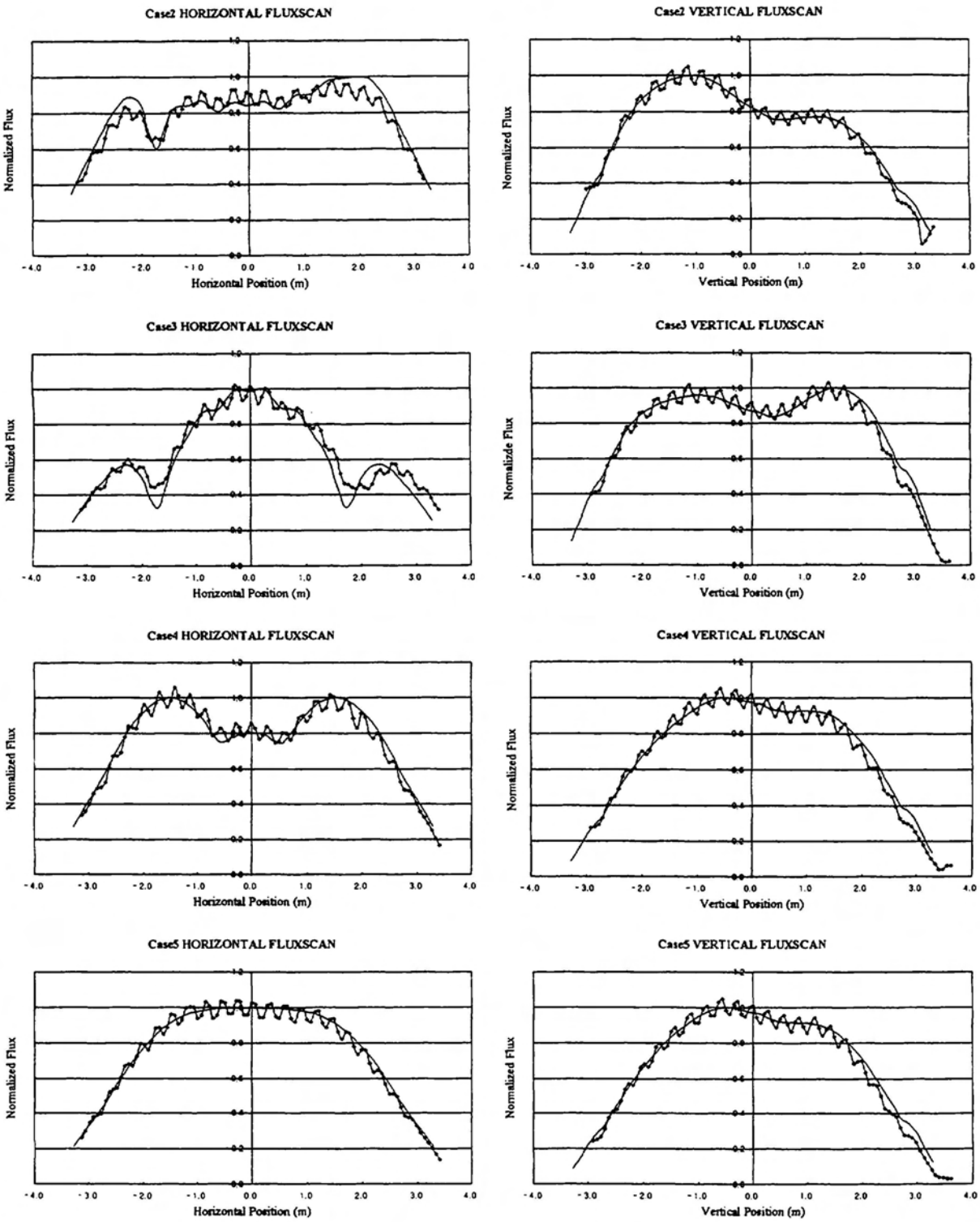
FIGURE 3. Polynonial fitting functions ($f(z)=\rho(z)$)



Coefficients	Wolsong 2	Wolsong 3
A	4.12620E-06	3.88605E-06
B	-4.43992E-04	-4.20476E-04
C	-5.76700E-02	-5.98900E-02
D	5.78889E+00	5.97377E+00

FIGURE 4. Horizontal and vertical FLUXSCAN results(Case1 ~ Case5) (Wolsong 3)




Case2 HORIZONTAL FLUXSCAN
Normalized Flux
Horizontal Position (m)
Case2 VERTICAL FLUXSCAN
Normalized Flux
Vertical Position (m)
Case3 HORIZONTAL FLUXSCAN
Normalized Flux
Horizontal Position (m)
Case3 VERTICAL FLUXSCAN
Normalizde Flux
Vertical Position (m)
Case4 HORIZONTAL FLUXSCAN
Normalized Flux
Horizontal Position (m)
Case4 VERTICAL FLUXSCAN
Normalized Flux
Vertical Position (m)
Case5 HORIZONTAL FLUXSCAN
Normalized Flux
Horizontal Position (m)
Case5 VERTICAL FLUXSCAN
Normalized Flux
Vertical Position (m)
Computed values
Experimented values