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BENCHMARK CALCULATION OF WIMS-AECL AGAINST WOLSONG 3 & 4 PHASE-B MEASUREMENT DATA

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ABSTRACT

For the validation of WIMS/RFSP code system, benchmark calculations were performed using the physics measurement data of Wolsong 3 & 4 reactors. Lattice parameters of the fuel channel were generated by WIMS-AECL code, and incremental cross sections of reactivity devices and structural material were generated by SHETAN code. The benchmark calculations were performed for the criticality, boron worth, reactivity device worth, reactivity coefficient, and flux scan. The results have shown that the criticality is under-predicted by 3 6 mk and boron worths are underestimated by 7%. The reactivity device worths are generally consistent with the measured data except for the strong absorbers such as shutoff rod and mechanical absorber. The heat transport system temperature coefficient and flux distributions are in good agreements with the measured data. But the moderator temperature coefficient has a relatively large discrepancy.

I. INTRODUCTION

For the CANDU core design and analysis, a lattice code POWDERPUFS-V(PPV)[Ref. 1] has long been used in conjunction with a supercell code MULTICELL[Ref. 2] and a core analysis code RFSP[Ref. 3]. However the application of PPV is limited to natural uranium fuel because of empirical correlations implemented. Therefore a multigroup transport code WIMS-AECL[Ref. 4] has been widely used for the advanced CANDU fuel development programs owing to the capability of modelling two-dimensional geometry and diverse isotopic compositions. Also the incremental cross-sections can be generated by a 3-dimensional transport code SHETAN[Ref. 5], which solves for the cylindrical and rectangular geometry together by the collision probability method, using the material cross-sections supplied by WIMS-AECL. In this study, the benchmark calculations of the CANDU core analysis code system composed of WIMS-AECL, SHETAN and RFSP have been performed against the physics measurement data of Wolsong Nuclear Power Plants 3 & 4.[6]

II. CROSS-SECTION GENERATION TOOLS AND METHOD

II.1 Fuel Lattice

Several options are available in WIMS-AECL to solve the cluster-type fuel bundle geometry. For the solution method, the two-dimensional collision probability method is used to solve the main transport equations in 89 energy groups. For the leakage calculation, B1 method with Benoist diffusion coefficient has been suggested. Once the multi-group burnup-dependent cell-average cross sections are generated, they are collapsed into two-group lattice parameters by WIMCORE[Ref. 8] program to be used for the core analysis.

II.2 Reactivity Device

In the CANDU reactor, the fuel channels are horizontally aligned, and most of the reactivity devices are located vertically between two fuel channels, which necessitates three-dimensional modelling to generate the cross-sections of the devices. In the core simulation, the presence of the device is represented by the difference in the macroscopic cross-section of the unit lattice bundle with and without the device, which is defined as the incremental cross-section. Considering the symmetry, one-eighth of one lattice bundle ($14.2875\times14.2875\times24.765$) is modelled by SHETAN, as shown in Fig. 1.[9]

II.3 Core Analysis Model

In the RFSP code, the finite-difference model is used to describe the reactor core, including reflector region. The basic mesh structure is 1LP (Lattice Pitch) by 1LP in XY plane and 1BL (Bundle Length) in axial direction, respectively. At present, the number of meshes used for the core simulation has already been optimized to 44x36x22 through various numerical tests.[10] In X direction, one lattice pitch is typically divided into two numerical meshes in the core center region. In Y- and Z-direction, the meshes have been set to describe the reactivity devices and the fuel bundle correctly.

IV. PHASE-B TESTS SIMULATION OF WOLSONG NUCLEAR POWER PLANTS 3 & 4

The Phase-B test includes the first approach to the 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 0.1% of full power. The critical boron concentrations are 8.93 and 9.34 ppm for Wolsong 3 and 4, respectively.

IV.1 Criticality Measurement

The effective multiplication factors of the core were 0.997 and 0.994 for Wolsong 3 & 4, respectively. Therefore the criticality is underestimated by 3 and 6 mk, which corresponds 0.4 and 0.8 ppm in terms of critical boron concentration for Wolsong 3 and 4, respectively.

IV.2 Reactivity Device Worth

The reactivity worth of liquid zone controller unit (ZCU) was calculated at the initial condition. Since the ZCUs are calibrated by the boron concentration change in the moderator, the boron reactivity coefficient was calculated at first. The boron reactivity coefficients are 7.66 and 7.70 mk per ppm boron for Wolsong 3 and 4, respectively. The calibration of the ZCU was performed by dissolving a boron batch in the moderator. After a batch was added, the average ZCU water level was fitted in order to maintain the criticality. The average ZCU level worth is given in Table 1 and compared with the measurement result for typical operating ranges. The variation of average ZCU level is also plotted in Fig. 2 and compared with the measurement result. It can be seen that the maximum error is 8% for Wolsong 4 unit.

The reactivity worth of individual adjuster (ADJ) rod was calculated by RFSP code for the calibration. Independent eigenvalue calculation was performed to estimate the reactivity worth of individual ADJ. As given in Table 2, the largest difference of the reactivity worth between the calculation and measurement is 20%, while the difference of total ADJ worth is 2%. The reactivity worths of ADJ banks were also calculated and the results are given in Table 3.

The reactivity worth of individual shutoff rod (SOR) was calculated as shown in Table 4 where the maximum error is 20%. The individual and bank worths of the mechanical control absorber (MCA) were also calculated as given in Table 5 and 6, respectively. Unlike the case of ADJ, the reactivity worths of SOR and MCA are over-predicted by WIMS/RFSP, which seems to be due to the poor estimation of thermal flux in the absorber region.

IV.3 Reactivity Coefficients

For the heat transport system temperature coefficient measurement, the moderator temperature was fixed at 35℃ and the boron concentration in the moderator was 8.5 ppm. The coolant and fuel temperatures were the same, and varied from 35 to 260℃. The corresponding coolant densities were calculated for D_2O at saturated and non-boiling condition with 99.24 and 99.27 wt% purity for the Wolsong 3 and 4, respectively. The variation of heat transport system temperature coefficient is shown in Fig. 3. The heat transport system temperature coefficient is generally consistent with the measured data.

For the moderator temperature coefficient, the coolant and fuel temperatures were fixed to 260℃ and the boron concentration in the moderator was set to 8.5 ppm. The moderator temperature coefficient was calculated by decreasingly the temperature from 69℃ to 35℃. The moderator density was calculated for D_2O at the saturated and non-boiling condition with 99.81 and 99.84 wt% purity for the Wolsong 3 and 4, respectively. The variation of reactivity with temperature is shown in Fig. 4. Compared with the measured data, the simulation error is very large (50%). It is thought that the error is largely dependent on the low boron reactivity worth in WIMS/RFSP simulation and probably on the inconsistent measurement procedure.

IV.4 Flux Distribution

During Phase-B test, thermal flux scans have been performed several times for various reactor configurations. The flux measurement confirms the physics design method and, in particular, the effects of various reactivity devices and depleted fuel on the neutron flux distributions.

The flux scans along a chord of the reactor core are made with a fission chamber mapping detectors. The vertical fission chamber scans are performed along 26 vertical flux detector (VFD) assemblies. A horizontal fission chamber scan is carried out along the horizontal flux detector (HFD) tube. The flux scan calculations have been performed for the following cases:

1 : Nominal case (with all adjusters),

2 : MCA bank # 1 inserted by 50% with adjusters,

3 : MCA all inserted with adjusters,

4 : Without adjuster bank # 1, 2, 3, and 4,

5 : Without all adjusters.

The ZCU water level was fixed at 40% and the moderator boron concentration was 8.5 ppm. The flux calculations were performed using the INTREP module of RFSP code. The flux scan calculations were performed for VFD #19 and HFD #1 for the vertical and horizontal fluxes, respectively. In order to obtain the flux at the detector position, a shape function was generated by MCNP, which is shown in Fig. 5. The horizontal and vertical thermal fluxes corrected by the shape function are shown in Fig. 6. The root-mean-square errors of flux calculations are summarized in Table 7, in which the largest error is 10% for case 3.

V. SUMMARY AND RECOMMENDATION

Benchmark calculations of WIMS/RFSP have been performed using Wolsong Units 3 & 4 Phase-B measurement data. The estimation of the reactivity device worth and flux scan were generally consistent with the measured results. But the boron worth and moderator temperature coefficient have shown a relatively large error, which could be caused by the incremental cross-section generation methodology for the reactivity device. It should be noted that the incremental cross section generation by WIMS/SHETAN does not introduce any adjustment during the super homogenization process. However, considering a strong heterogeneity effect in the reactivity device, it would be appropriate to adjust the local parameters to conserve the total absorption rate in the device region. In the future, the super homogenization method will be investigated to improve the performance of reactivity device modelling in the CANDU core analysis.

Acknowledgement

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Table 1. Comparison of Average Zone Level Worth

AVZL(%)	Wolsong 3			Wolsong 4		
	WIMS (mk/%AVZL)	Measured (mk/%AVZL)	Diff.(%)	WIMS (mk/%AVZL)	Measured (mk/%AVZL)	Diff.(%)
20 60 (*20 70)	0.07630	0.07423	2.791	*0.07333	*0.06807	7.729
20 80	0.07230	0.07050	2.549	0.07028	0.06523	7.739

Table 2. Reactivity Worth of Individual Adjuster Rod

	Wolsong 3			Wolsong 4		
Number	WIMS (mk)	Measured (mk)	Diff (%)	WIMS (mk)	Measured (mk)	Diff (%)
1	0.182	0.218	-16.40	0.178	0.205	-13.22
2	0.59	0.567	3.99	0.583	0.533	9.34
3	0.672	0.692	-2.93	0.671	0.700	-4.14
4	0.348	0.363	-4.03	0.342	0.383	-10.76
5	0.67	0.701	-4.38	0.666	0.711	-6.28
6	0.592	0.547	8.22	0.589	0.574	2.65
7	0.181	0.212	-14.66	0.18	0.229	-21.53
8	0.215	0.279	-22.93	0.209	0.242	-13.48
9	0.744	0.637	16.80	0.743	0.649	14.50
10	0.885	0.888	-0.29	0.882	0.868	1.60
11	0.481	0.515	-6.57	0.475	0.533	-10.95
12	0.886	0.922	-3.93	0.879	0.907	-3.13
13	0.745	0.691	7.89	0.741	0.712	4.12
14	0.214	0.264	-19.02	0.208	0.262	-20.65
15	0.187	0.213	-12.12	0.18	0.207	-12.88
16	0.593	0.512	15.73	0.582	0.511	13.98
17	0.677	0.692	-2.11	0.667	0.686	-2.79
18	0.348	0.373	-6.73	0.341	0.372	-8.42
19	0.676	0.733	-7.81	0.667	0.703	-5.15
20	0.591	0.546	8.17	0.587	0.585	0.42
21	0.183	0.233	-21.37	0.179	0.232	-23.00
Total	10.66	10.880	-2.03	10.549	10.804	-2.36

Table 3. Reactivity Worth of Adjuster Bank

Number	Wolsong 3			Wolsong 4		
	WIMS (mk)	Measured (mk)	Diff (%)	WIMS (mk)	Measured (mk)	Diff (%)
1	1.175	1.35	-12.96	1.468	1.361	7.89
2	1.509	1.39	8.56	1.751	1.420	23.28
3	1.496	1.34	11.64	1.743	1.431	21.82
4	2.164	1.93	12.12	2.192	1.911	14.70
5	1.571	1.87	-15.99	1.6	1.350	18.52
6	1.596	1.8	-11.33	1.602	1.370	16.96
7	2.846	3.31	-14.02	2.082	1.844	12.89
Total	12.357	12.99	-4.87	12.438	10.687	16.39

Table 4. Reactivity Worth of Individual Shutoff Rod

	Wolsong 3			Wolsong 4		
	WIMS (mk)	Measured (mk)	Diff.(%)	WIMS (mk)	Measured (mk)	Diff.(%)
1	1.37	1.218	12.48	1.364	1.239	10.096
2	1.712	1.592	7.53	1.705	1.586	7.487
3	1.718	1.585	8.38	1.716	1.585	8.253
4	1.362	1.338	1.82	1.352	1.297	4.280
5	1.021	0.890	14.71	1.021	0.918	11.232
6	2.137	1.858	15.01	2.131	1.892	12.655
7	2.136	1.908	11.98	2.132	1.901	12.160
8	1.02	0.973	4.83	1.013	0.969	4.531
9	1.493	1.286	16.14	1.486	1.230	20.810
10	2.663	2.207	20.68	2.654	2.169	22.366
11	2.786	2.329	19.61	2.774	2.303	20.455
12	2.651	2.304	15.04	2.65	2.293	15.570
13	1.497	1.393	7.44	1.487	1.405	5.841
14	1.554	1.297	19.84	1.554	1.282	21.257
15	1.557	1.455	7.04	1.549	1.444	7.268
16	1.488	1.280	16.29	1.488	1.230	20.938
17	2.661	2.173	22.45	2.643	2.145	23.232
18	2.79	2.338	19.35	2.775	2.302	20.573
19	2.66	2.295	15.92	2.651	2.276	16.481
20	1.487	1.392	6.83	1.494	1.388	7.647
21	1.025	0.896	14.36	1.017	0.880	15.540
22	2.143	1.873	14.45	2.139	1.793	19.311
23	2.134	1.934	10.32	2.129	1.880	13.273
24	1.012	0.969	4.42	1.009	0.959	5.199
25	1.372	1.213	13.10	1.372	1.227	11.800
26	1.707	1.601	6.60	1.712	1.536	11.476
27	1.712	1.619	5.76	1.703	1.583	7.554
28	1.361	1.343	1.37	1.362	1.309	4.081
Total	50.229	45.378	10.69	50.082	45.378	10.365

Table 5. Reactivity Worth of Individual Mechanical Control Absorber

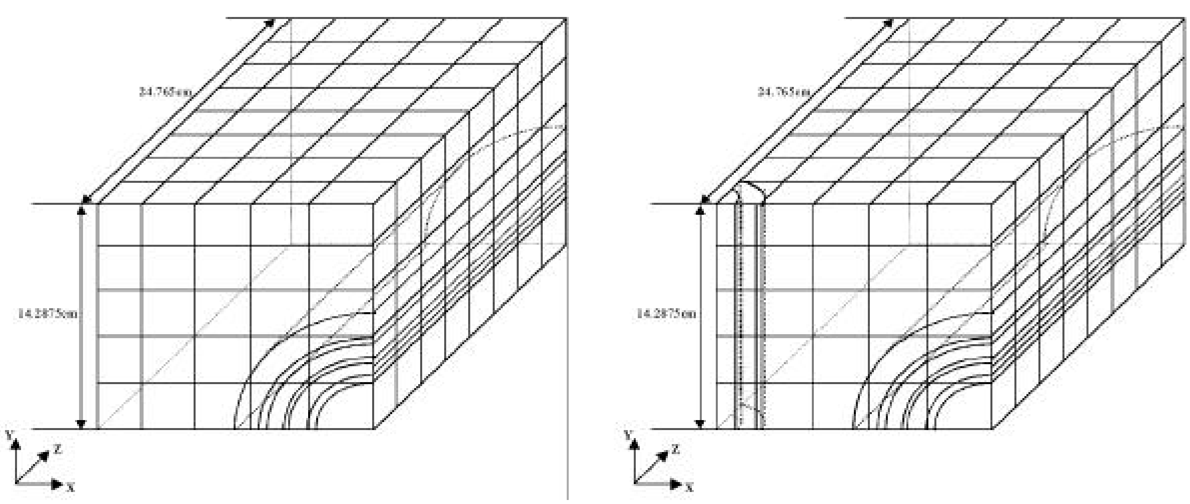
	Wolsong 3			Wolsong 4		
	WIMS (mk)	Measured (mk)	Diff.(%)	WIMS (mk)	Measured (mk)	Diff.(%)
1	2.14	1.920	11.47	2.138	1.762	21.33
2	2.15	1.999	7.58	2.137	1.902	12.38
3	2.177	1.814	19.99	2.166	1.771	22.29
4	2.17	2.001	8.43	2.156	1.901	13.41
	8.637	7.734	11.68	50.082	45.378	10.365

Table 6. Reactivity Worth of Mechanical Control Absorber Bank

	Wolsong 3			Wolsong 4		
	WIMS (mk)	Measured (mk)	Diff.(%)	WIMS (mk)	Measured (mk)	Diff.(%)
1	5.843	3.4545	69.14	5.801	4.686	23.79
2	5.843	5.0421	15.89	5.802	4.595	26.27
Total	11.686	9.58	21.98	11.603	9.58	21.12

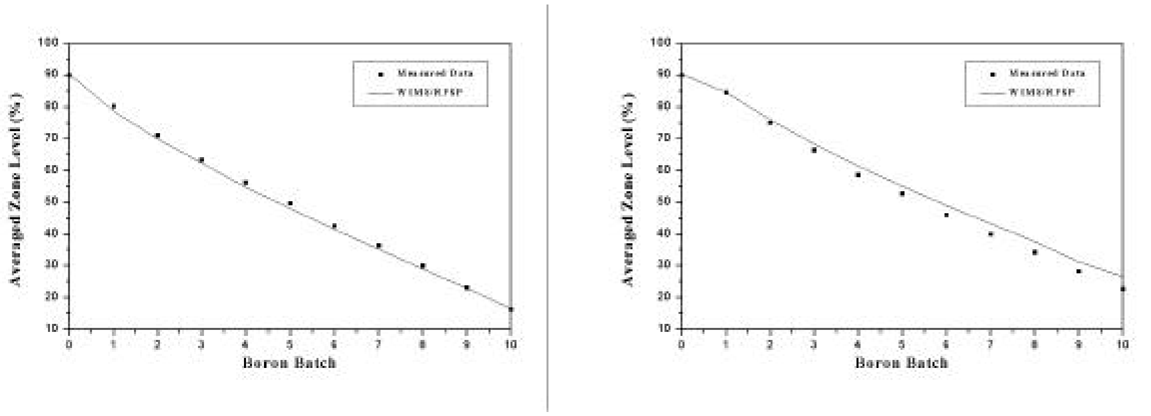
Table 7. Root Mean Square Error of Flux Distribution

RMS Error(%)		CASE1	CASE2	CASE3	CASE4	CASE5
Wolsong 3	Vertical	7.39	1.55	1.02	4.78	4.08
	Horizontal	7.21	6.35	9.87	4.42	6.98
Wolsong 4	Vertical	3.32	7.68	11.2	6.45	6.26
	Horizontal	4.98	4.68	6.27	5.54	2.78



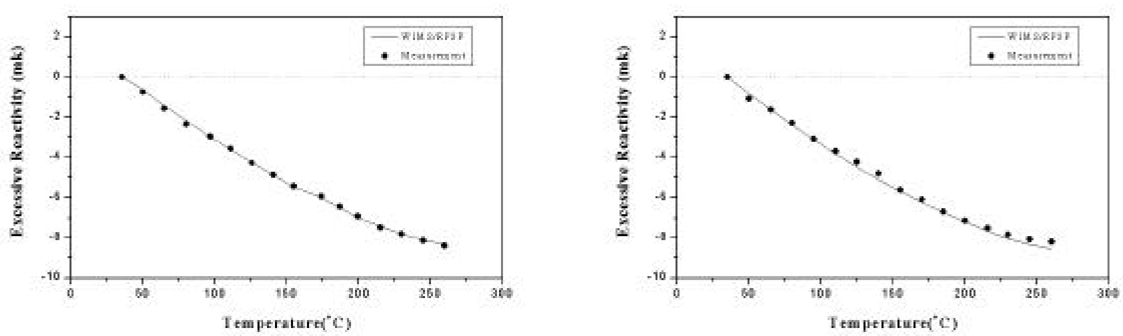
(a) (b)

Fig. 1. Supercell Model without(a) and with(b) Reactivity Devices.



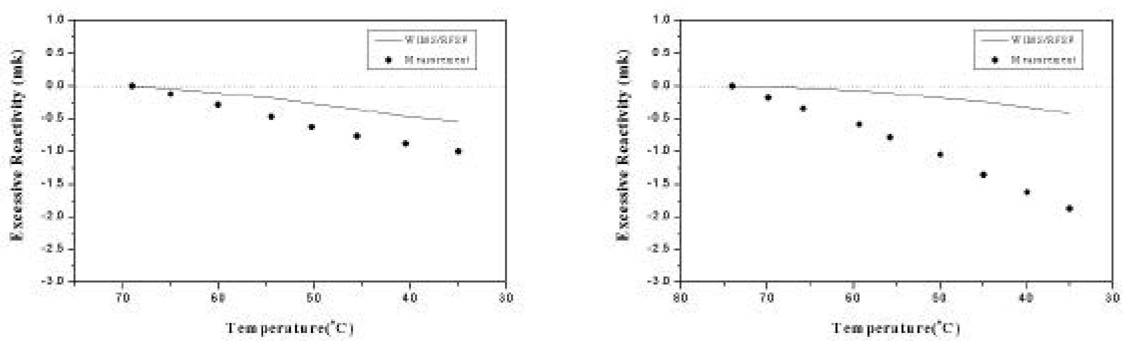
(a) Wolsong 3 (b) Wolsong 4

Fig. 2. Calibration of Zone Controller



(a) Wolsong 3 (b) Wolsong 4

Fig. 3. Heat Transport System Temperature Effect



(a) Wolsong 3 (b) Wolsong 4

Fig. 4. Moderator Temperature Effect

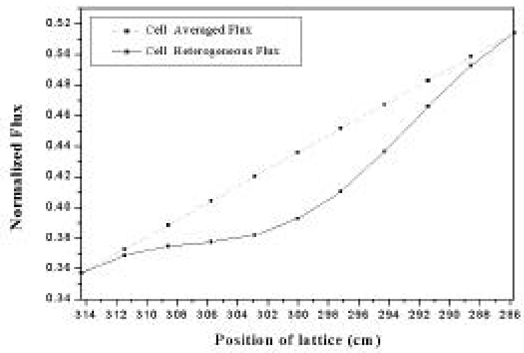
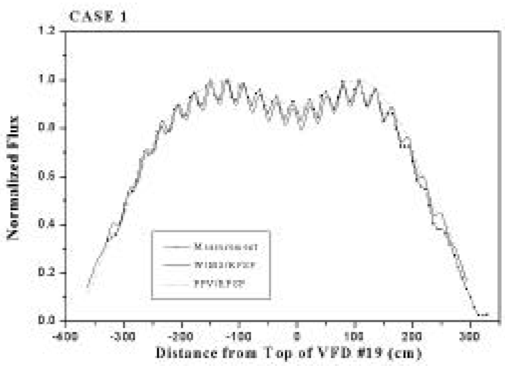
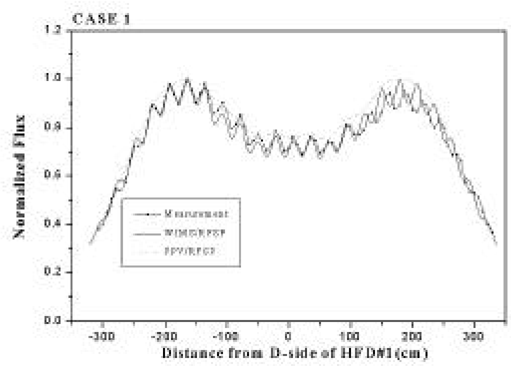


Fig. 5. Heterogeneity of Lattice Flux

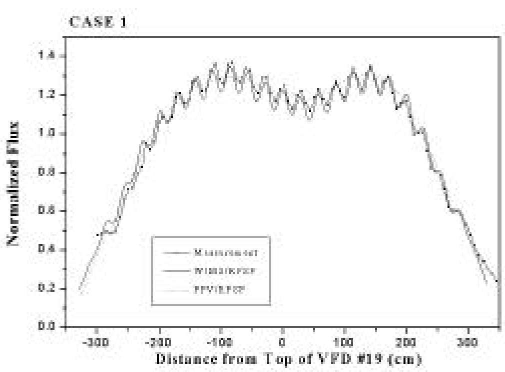


Vertical Flux

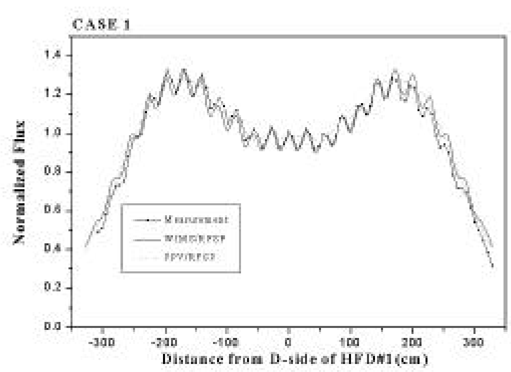


Horizontal Flux

(a) Wolsong 3



Vertical Flux



Horizontal Flux

(b) Wolsong 4

Fig. 6. Flux Scan of Wolsong 3 & 4