Development of CANDU-PHWR Neutronics Code SCAN

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ABSTRACT

The SCAN code designed as a CANDU-PHWR physics research and development tool in Korea is introduced. In an effort to validate the SCAN code, Wolsong unit 3 phase-B reactor physics measurements are analyzed by 1.5 group and 2 group SCAN model. The results are compared with the corresponding RFSP model calculations.

It is shown that the SCAN code can predict the CANDU-PHWR core neutronics parameters of major importance as accurately as the RFSP with much less CPU time and better convergence characteristics.

1. INTRODUCTION

The SCAN (**S**eoul National University **CAN**DU-PHWR **N**eutronics) code has been developed as a research and development tool for neutronics design and analysis of CANDU-PHWR. It is evolved from the FDM3D[1], a three-dimensional (3-D) finite difference diffusion equation solver, which can solve either the 1.5 group model of the original RFSP[2] (**R**eactor **F**uelling **S**imulation **P**rogram) code or full 2 group model with successive over-relaxation (SOR)/Chebyshev iteration scheme. To facilitate inputing the geometric data for the full 3-D analysis of CANDU reactor, the SCAN is equipped with the automatic 3-D nodalization subroutine which divides the reactor core and reflector regions automatically into the desired number of spatial meshes fit for the intended finite difference calculation of the FDM3D.

Previously, we incorporated the 1.5 group version of FDM3D into the original RFSP and examined the effectiveness of the FDM3D solver in comparison with that of the RFSP using Wolsung units 2 and 3 physics test data. In our continued efforts to examine the computational effectiveness of the FDM3D, e.g., the SCAN code now, we revisit the phase B physics tests of the Wolsung unit 3, analyze 95 test cases using both 1.5 group and 2 group models of SCAN, compare the results with those of the new RFSP, and discuss the validity of the SCAN code.

2. Finite Difference Diffusion Equation Solver, FDM3D

The FDM3D is the 3-D solver for the full two group finite difference diffusion equations given by

$$\sum_{d=0}^{5} \tilde{A}_1^{m,d}(\overline{\phi}_1^m - \overline{\phi}_1^d) + (\Sigma_{a1}^m + \Sigma_{s1\to2}^m)\overline{\phi}_1^m - \Sigma_{s2\to1}^m\overline{\phi}_2^m = \frac{1}{k_{eff}}(\nu\Sigma_{f1}^m\overline{\phi}_1^m + \nu\Sigma_{f2}^m\overline{\phi}_2^m) \tag{1.1}$$

$$\sum_{d=0}^{5} \tilde{A}_2^{m,d}(\overline{\phi}_2^m - \overline{\phi}_2^d) + \Sigma_{a2}^m\overline{\phi}_2^m + \Sigma_{s2\to1}^m\overline{\phi}_2^m - \Sigma_{s1\to2}^m\overline{\phi}_1^m = 0 \tag{1.2}$$

where $\tilde{A}_g^{m,d} = \dfrac{2D_g^m D_g^d}{D_g^m \Delta x^d + D_g^d \Delta x^m} \cdot \dfrac{1}{\Delta x^m}$: the coupling coefficients

Σ_i : i-type group macroscopic cross section (a=absorption, f=fission)

$\Sigma_{sg\to g'}$: group transfer macroscopic cross section from g to g'

m : spatial mesh index with d the six neighbor meshes

For speedy solution to Eq.(1), the FDM3D adopts either successive-over-relaxation (SOR)/two-parameter Chebyshev polynomial method or bi-conjugate gradient stabilization (BICG-STAB)[3]/Wielandt method as the inner/outer iteration scheme.

3. BENCHMARK PROBLEMS AND GEOMETRIC INPUT DATA

The benchmark problems selected for the validation of the SCAN code are 95 cases of the phase B physics tests of the Wolsong unit 3. Table 1 summarizes the 95 test cases.

The test cases require the calculations of the following core properties of Wolsung unit 3 reactor for the phase B[4][5] conditions (less than 0.1% of full power).

a. Boron reactivity worth and the concentration at first criticality
b. Reactivity of control devices; individual rods and banks of adjusters and mechanical control absorbers, and individual shutoff rods
c. Reactivity change following moderator system temperature change

WIMS-AECL[6]/(MULTICELL)/SCAN and WIMS-AECL/(MULTICELL)/RFSP are adopted for all these validation calculations. Figure 1 depicts the simple flowchart for the WIMS-AECL/SCAN code system for these calculations.

For the analysis of the benchmark tests of Wolsung unit 3, the core and reflector region are divided into 42, 34 and 20 meshes in x, y and z directions ($42 \times 34 \times 20$ mesh-model), respectively. This corresponds to the $44 \times 36 \times 22$ mesh-line model used in RFSP composed of 21,696 meshes in total. All kinds of reactivity control devices and related structure materials are explicitly described in terms of incremental cross sections.

4. RESULTS AND DISCUSSIONS

Table 2 shows the average k_{eff} differences between 1.5 and 2 group SCAN and RFSP calculations for the 95 test cases. The k_{eff}(SCAN1.5) and k_{eff}(SCAN2) denote the 1.5 group and 2 group SCAN calculations, while k_{eff}(RFSP1.5) and k_{eff}(RFSP2) the 1.5 and 2 group RFSP calculations. The same group model being adopted, the SCAN and the RFSP calculations predict almost the same k_{eff} with the average difference of 0.008mk. On the other hand, the 1.5 group and 2 group SCAN calculations show large discrepancies, say, about 1.3mk difference in predicted k_{eff} values. The discrepancies of the similar magnitude in k_{eff} values are also observed between the 1.5 group and 2 group RFSP calculations. These discrepancies are ascribed to the differences in 1.5 group and 2 group constants generated by WIMS-AECL code.

For further comparison, the channel power distribution of the Wosung unit 3 core with control devices at normal positions and 45 % liquid zone controller level is calculated by SCAN and RFSP code. Figures 2 and 3 compare SCAN and RFSP calculations for the channel power distribution with 1.5 group and 2 group model, respectively. Again, the results in these figures show that two codes predict practically the same channel power distribution with the same group model. However, they show there are discrepancies between 1.5 group and 2 group predictions by the two codes on the channel power distribution.

The above results indicate that the SCAN code can predict the key design parameters of the CANDU-PHWR as accurately as the RFSP code. But it must be noted that the SCAN code outperforms the RFSP code in terms of computing speed and convergence characteristics. Table 3 shows the total CPU times spent by the SCAN and RFSP codes, respectively, analyzing all of the 95 the test cases. It shows that SCAN calculation requires about 4 times less CPU time than the RFSP calculations by 2 group model. The CPU time reduction by SCAN code is more conspicuous with 1.5 group model.

Table 4 and Table 5 summarize the flux convergence characteristics of SCAN code in comparison with that of RFSP code in terms of the parameter, OCON. OCON is a measure of the average value of flux differences at all meshes of the two consecutive iteration steps when the SCAN or RFSP stops iteration by the given convergence criteria. Thus the smaller OCON is, the more convergent the resulting flux values are. From Table 4 and 5, therefore, it is noted that the SCAN solution for the fluxes is more convergent one than the RFSP solution, especially for the calculation with higher flux convergence criterion.

Table 6 and Table 7 compare the Wolsung unit 3 phase B physics test results with predictions by the SCAN and RFSP code. Table 6 shows the comparison of measurements and calculations for the boron reactivity worth and the critical boron concentration at the first criticality. Both SCAN and RFSP code calculations with the 2 group model underestimate boron reactivity worth than 1.5G calculations. This may stem from the differences between 1.5 group and 2 group constants generated by the AECL-WIMS code. Table 6 shows that both SCAN and RFSP underestimates the critical boron concentration also.

Table 7 summarizes reactivity worth differences of variable devices between measurements and predictions by SCAN or RFSP code. It is shown that prediction accuracy of two codes is indistinguishable. There is one thing worthy to note. We do not know the exact cause but predictions by two codes on the moderator temperature coefficient are far off the measurements.

5. CONCLUSION

The SCAN code is designed as a CANDU-PHWR physics research and development tool in Korea. We demonstrated that the SCAN code can predict the CANDU reactor core neutronics parameters of major importance as accurately as the RFSP code. We also demonstrated that the SCAN code has better convergence characteristics, and requires less CPU time than the current RFSP. These are very encouraging results to merit further works for validating the qualification of the SCAN code as a research tool.

Table 1 DESCRIPTION FOR BENCHMARK TEST CASES

Problem Type	Number of Cases	Meaning of Symbol #	Device Condition	Problem Usage
<B#>	6	Boron Concentration	Normal(ADJ in, SOR out, MCA out)	Boron reactivity worth estimation
<guesscb>	1	-	MCA04 inserted 55% vertically, Other devices Normal	Critical boron concentration search
<ZL#>	11	# [%] of Average Zone Controller Level	Normal	Zone level worth estimation
<ADJ#>	22	ADJ rod Unit Number	ADJ# out, Other devices Normal	ADJ rod worth calculation
<MCA#> <SOR#>	5 29	MCA unit number SOR unit number	MCA# or SOR# out, Other devices Normal	MCA and SOR worth calculation
<MT#>	8	Moderator Temperature	Normal	MTC calculation

* Additional 13 cases for ADJ bank and MCA bank calculations

Table 2 AVERAGE K_{eff} DIFFERENCES (95 Test Cases)

	Average K_{eff} difference [mk]
Average $\lvert K_{eff}$ (SCAN1.5) − K_{eff} (RFSP1.5)$\rvert$	0.008
Average $\lvert K_{eff}$ (SCAN2) − K_{eff} (RFSP2) $\rvert$	0.008
Average $\lvert K_{eff}$ (RFSP2) − K_{eff} (RFSP1.5)$\rvert$	1.281
Average $\lvert K_{eff}$ (SCAN2) − K_{eff} (SCAN1.5)$\rvert$	1.286

Table 3 TOTAL CPU TIME (95 Test Cases)

1.5 Group			2 Group		
SCAN [s]	RFSP [s]	SPEED UP FACTOR	SCAN [s]	RFSP [s]	SPEED UP FACTOR
2381	12627	**5.30**	2378	10098	**4.25**

* SPEED UP FACTOR = CPU Time of RFSP/CPU Time of SCAN
* CPU : HP 9000/120 MHz

Table 4 COMPARISON OF CONVERGENCE CHARACTERISTICS * OF SCAN AND RFSP

	1.5 Group		2 Group	
	SCAN	RFSP	SCAN	RFSP
Average OCON(a)	3.000E-06	4.241E-06	2.991E-06	4.768E-06

(a) $$OCON = \frac{1}{M}\sum_{m=1}^{M}\left|\frac{\sum_{g=1}^{2}(\Phi^{m,\ t+1}_{g} - \Phi^{m,\ t}_{g})}{\sum_{g=1}^{2}\Phi^{m,\ t}_{g}}\right|$$

* Maximum relative flux error of 1.0e-5 used as convergence criterion.

Table 5 FLUX CONVERGENCE CHARACTERISTICS

Flux Convergence Criterion	Total CPU Time(a)		Total Number of Outer Iterations(b)		OCON	
	RFSP	SCAN	RFSP	SCAN	RFSP	SCAN
1.00E-05	839	146	1822	435	3.75590E-06	3.33525E-06
5.00E-06	934	178	2382	505	1.87475E-06	1.58293E-06
3.00E-06	1266	184	4298	567	8.55955E-07	9.11438E-07
1.00E-06	3396	222	15984	685	2.17654E-06	2.70275E-07
1.00E-15	-	1495	-	6309	-	1.40953E-16

* 8 cases of <ADJBNK_REF>, <ADJBNK01>, … ,<ADJBNK07> problems are tested.

(a) Total CPU time for the 8 cases.

(b) Total number of outer iterations for the 8 cases.

Table 6 BORON REACTIVITY WORTH AND CRITICAL BORON CONCENTRATION FOR PHASE-B CONDITON OF WOLSONG UNIT 3

	WIMS-AECL/ RFSP1.5	WIMS-AECL/ SCAN1.5	WIMS-AECL/ RFSP2	WIMS-AECL/ SCAN2
Boron reactivity worth [mk/ppm]	8.1724	8.1700	7.7274	7.7267
C.B. [a] **concentration measurement[ppm]**	8.9300			
Calculated C.B. concentration[ppm]	8.3031	8.3030	8.1298	8.1294
C.B. concentration diff[%] [b]	-7.02	-7.02	-8.96	-8.97

(a) Critical boron

(b) (Calculation – Measurement)/Measurement × 100 [%]

Table 7 TOTAL REACTIVITY WORTH DIFFERENCE FOR PHASE-B CONDITON OF WOLSONG UNIT 3

	WIMS-AECL/ RFSP1.5	WIMS-AECL/ SCAN1.5	WIMS-AECL/ RFSP2	WIMS-AECL/ SCAN2
ADJ rods	-6.34	-5.94	-5.83	-5.43
ADJ banks	-5.93	-6.04	-5.64	-5.73
MCA rods	4.85	4.53	4.16	3.83
MCA banks	13.64	13.33	11.75	11.66
SOR	6.75	5.89	6.29	5.64
MT 35~69℃	-45.46	-48.35	-47.45	-49.59

* Value = (Calculation – Measurement)/Measurement × 100 [%]

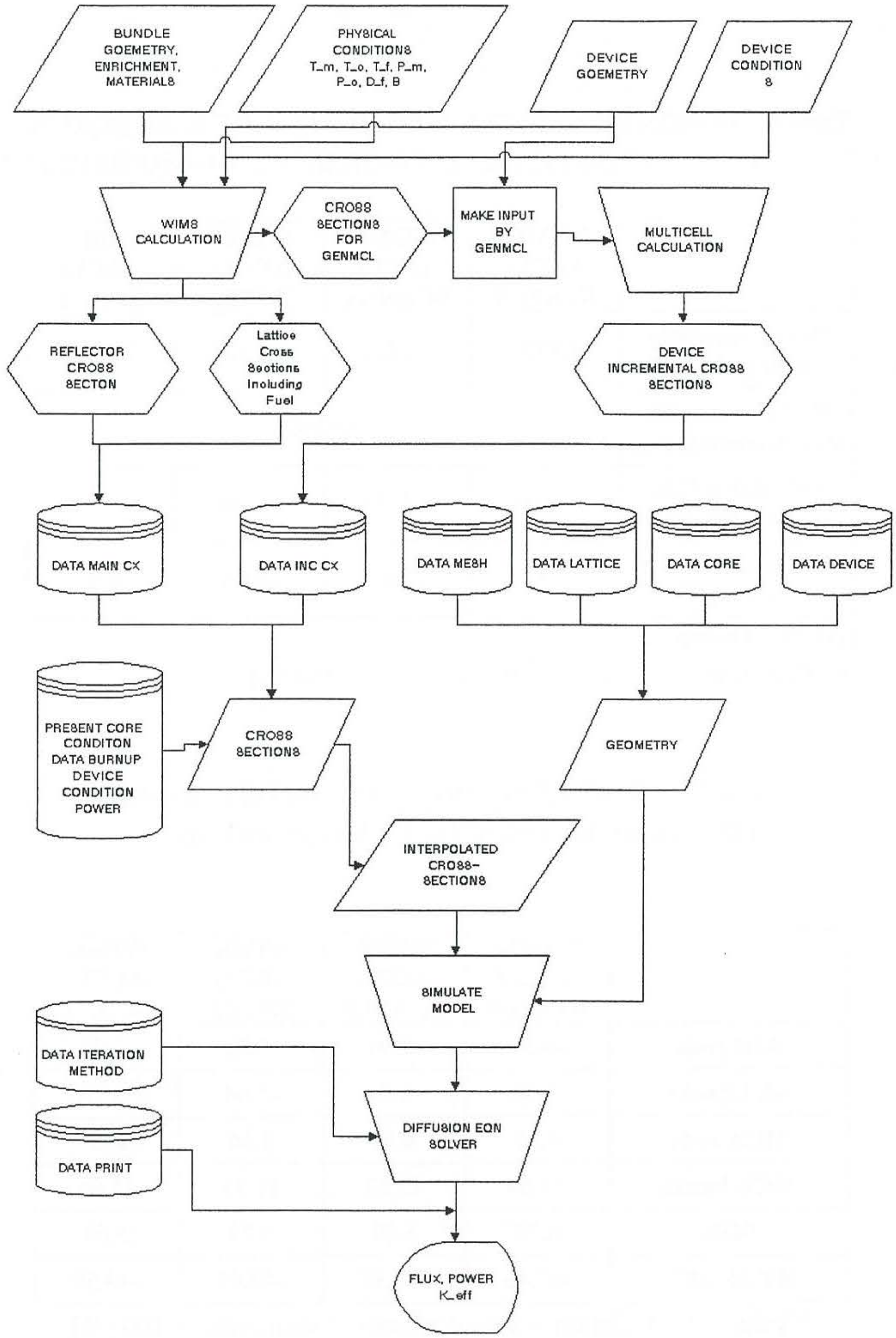

Figure 1 WIMS-AECL/SCAN CALCULATION FLOWCHART

SCAN RFSP Diff(%)								0.5897 0.5928 -0.53	0.6265 0.6297 -0.50	0.6470 0.6502 -0.49
					0.5347 0.5379 -0.59	0.6560 0.6590 -0.45	0.7642 0.7670 -0.37	0.8335 0.8364 -0.34	0.8770 0.8799 -0.33	0.8905 0.8933 -0.32
				0.6063 0.6091 -0.46	0.7528 0.7556 -0.37	0.8880 0.8906 -0.30	0.9898 0.9925 -0.27	1.0554 1.0579 -0.24	1.0859 1.0884 -0.23	1.0841 1.0865 -0.22
			0.6246 0.6273 -0.42	0.7935 0.7960 -0.32	0.9506 0.9530 -0.25	1.0771 1.0793 -0.21	1.1634 1.1656 -0.19	1.2108 1.2128 -0.17	1.2228 1.2248 -0.17	1.2013 1.2032 -0.15
		0.5857 0.5880 -0.39	0.7821 0.7842 -0.27	0.9502 0.9523 -0.22	1.0898 1.0919 -0.19	1.1920 1.1938 -0.15	1.2521 1.2537 -0.13	1.2721 1.2734 -0.10	1.2661 1.2673 -0.10	1.2373 1.2386 -0.10
		0.7320 0.7340 -0.27	0.9261 0.9280 -0.20	1.0707 1.0723 -0.15	1.1832 1.1848 -0.13	1.2507 1.2519 -0.10	1.2792 1.2801 -0.07	1.2598 1.2607 -0.07	1.2370 1.2377 -0.05	1.2150 1.2154 -0.04
	0.6345 0.6365 -0.32	0.8530 0.8548 -0.21	1.0338 1.0353 -0.15	1.1351 1.1363 -0.10	1.2167 1.2176 -0.07	1.2628 1.2633 -0.04	1.2641 1.2642 -0.01	1.2217 1.2218 -0.01	1.1458 1.1457 0.01	1.1344 1.1341 0.03
	0.7456 0.7473 -0.23	0.9609 0.9624 -0.16	1.1183 1.1195 -0.10	1.1815 1.1824 -0.07	1.2299 1.2303 -0.03	1.2478 1.2478 -0.00	1.1785 1.1781 0.03	1.1312 1.1307 0.04	1.1008 1.1000 0.07	1.0940 1.0930 0.09
0.5766 0.5786 -0.34	0.8248 0.8264 -0.20	1.0384 1.0397 -0.13	1.1753 1.1761 -0.07	1.2062 1.2067 -0.04	1.2236 1.2235 0.01	1.2102 1.2098 0.03	1.1315 1.1306 0.08	1.0898 1.0889 0.09	1.0613 1.0600 0.12	1.0513 1.0498 0.15
0.6323 0.6345 -0.35	0.8902 0.8917 -0.17	1.0965 1.0976 -0.10	1.2173 1.2178 -0.04	1.2154 1.2154 -0.00	1.2073 1.2069 0.04	1.1403 1.1396 0.07	1.0978 1.0965 0.12	1.0577 1.0561 0.15	1.0266 1.0249 0.17	1.0113 1.0095 0.18
0.6621 0.6642 -0.31	0.9217 0.9232 -0.16	1.1268 1.1276 -0.07	1.2459 1.2461 -0.01	1.2484 1.2482 0.01	1.2283 1.2273 0.08	1.1365 1.1354 0.10	1.0850 1.0834 0.15	1.0400 1.0382 0.17	1.0035 1.0013 0.22	0.9757 0.9735 0.23

Figure 2 NORMALIZED CHANNEL POWER DIFF. <B6-1.5G-45%ZL>

SCAN RFSP Diff(%)								0.5604 0.5628 -0.44	0.6018 0.6041 -0.38	0.6226 0.6249 -0.36
					0.5109 0.5134 -0.50	0.6340 0.6362 -0.34	0.7411 0.7431 -0.27	0.8129 0.8148 -0.24	0.8580 0.8599 -0.22	0.8722 0.8740 -0.21
				0.5830 0.5851 -0.36	0.7344 0.7364 -0.27	0.8709 0.8727 -0.20	0.9735 0.9752 -0.18	1.0403 1.0419 -0.15	1.0724 1.0738 -0.13	1.0711 1.0725 -0.13
			0.6016 0.6035 -0.31	0.7762 0.7779 -0.22	0.9362 0.9377 -0.16	1.0648 1.0662 -0.14	1.1527 1.1540 -0.11	1.2018 1.2028 -0.08	1.2154 1.2165 -0.09	1.1945 1.1954 -0.07
		0.5629 0.5648 -0.34	0.7649 0.7665 -0.21	0.9371 0.9385 -0.15	1.0800 1.0812 -0.11	1.1851 1.1860 -0.08	1.2475 1.2482 -0.06	1.2696 1.2701 -0.04	1.2653 1.2657 -0.03	1.2369 1.2373 -0.03
		0.7117 0.7132 -0.21	0.9124 0.9136 -0.14	1.0618 1.0627 -0.08	1.1784 1.1792 -0.07	1.2499 1.2504 -0.04	1.2811 1.2813 -0.02	1.2647 1.2648 -0.01	1.2434 1.2434 0.00	1.2211 1.2209 0.01
	0.6118 0.6133 -0.24	0.8375 0.8387 -0.14	1.0235 1.0244 -0.09	1.1298 1.1304 -0.05	1.2160 1.2163 -0.02	1.2667 1.2666 0.01	1.2706 1.2703 0.02	1.2308 1.2305 0.02	1.1572 1.1565 0.06	1.1458 1.1451 0.06
	0.7260 0.7274 -0.19	0.9480 0.9492 -0.12	1.1111 1.1118 -0.07	1.1796 1.1800 -0.04	1.2327 1.2327 -0.00	1.2550 1.2546 0.03	1.1892 1.1884 0.06	1.1439 1.1431 0.07	1.1146 1.1136 0.09	1.1080 1.1068 0.11
0.5556 0.5574 -0.32	0.8102 0.8115 -0.16	1.0285 1.0294 -0.09	1.1709 1.1715 -0.05	1.2073 1.2072 0.01	1.2294 1.2290 0.03	1.2205 1.2200 0.04	1.1449 1.1438 0.09	1.1046 1.1035 0.10	1.0771 1.0758 0.12	1.0675 1.0660 0.14
0.6158 0.6177 -0.31	0.8784 0.8797 -0.15	1.0892 1.0900 -0.07	1.2156 1.2159 -0.02	1.2197 1.2196 0.01	1.2161 1.2155 0.05	1.1537 1.1529 0.07	1.1129 1.1116 0.12	1.0742 1.0729 0.12	1.0441 1.0424 0.16	1.0290 1.0273 0.17
0.6465 0.6483 -0.28	0.9113 0.9125 -0.13	1.1212 1.1219 -0.07	1.2461 1.2461 -0.00	1.2555 1.2552 0.02	1.2396 1.2388 0.07	1.1512 1.1501 0.10	1.1015 1.1000 0.13	1.0578 1.0563 0.14	1.0222 1.0203 0.18	0.9941 0.9923 0.18

Figure 3 NORMALIZED CHANNEL POWER DIFF. <B6- 2G-45%ZL>

ACKNOWLEDGEMENT

This work has been carried out under the Nuclear Research and Development Program of Korea Ministry of Science and Technology.

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