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《Original》

Two Dimensional Analysis for Equilibrium Core of CANDU-PHWR

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CANDU형 원자로의 평형로심에 대한 이차원적 해석

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Abstract

The WBURN (2-D, 2-group, coarse mesh) code is developed to analyze the equilibrium core characteristics of CANDU-PHWR. The equilibrium characteristics of Wolsung reactor computed by using WBURN are compared with the values given in the Wolsung FSR. The changes of equilibrium core characteristics caused by the variation of design parameters for operating conditions are also investigated. The numerical results indicate that the average discharge irradiation in the Wolsung reactor can be increased up to about 5%.

요 약

본 연구에서는 평형로심 특성을 계산하기 위하여 로심 해석용 코드인 WBURN (2-D, 2-group, coarse mesh)을 개발하여 월성 원자로의 평형 로심 특성을 해석하고 최종 안전성 보고서에 주어진 결과와 비교하였다. 그리고 최근에 입수된 설계상수들의 변화에 기인된 평형로심 특성변화를 조사하였으며, 월성 원자로의 가동 조건이 변화되어 핵연료의 연소도를 약 5% 높일 수 있음이 나타났다.

I. Introduction

CANDU-PHWRs moderated and cooled by heavey water are fueled with natural uranium in pressure tubes. The core thus inherently retains small excess reactivity due to use of natural uranium. In view of fuel management, the operating life of a CANDU reactor is separatd in three periods as such initial, transient and equilibrium period.[1]

Owing to loading fresh fuel in the initial core, the excess reactivity is relatively large compared to the reactivity in the burned core. The excess neutron may be absorbed by a poison material dissolved in heavy water moderator and the excess reactivity in the core gradually decreases as fuel burns up.

After operating CANDU reactor for a certain period of time, the poison concentration will be approached to nearly zero and the reactor cannot maintain critical state with the moderator. Consequently fuel bundles must be started to be refuelled by means of inserting excess reactivity. The initial period is then defined as the time interval from the initial loading to the start of refuelling. The initial period is about 100 FPD (full power day) operation.

The transient period followed by the initial period spans from 100 FPD to 400 FPD. This is very sensitive period of operation from a fuel management point of view. During the transient period, each channel of the core will be refuelled more than once. Then the core of reactor would be consisted of the fuel bundles with different irradiation varying from fresh to high burnups.

Approaching the end of transient period, the average discharge irradiation of spent fuel bundles and refuelling rate are almost constant. This core can be considered to be equilibrium, and the equilibrium period covers about 95% of reactor life.

The study on refuelling and fuel management is based on core characteristics that include average discharge irradiation, refuelling rate, the dwelling time of fuel bundles and power distribution in equilibrium state. The core characteristics for equilibrium state are depending on the irradiation histories of fuel bundles, namely burnup and fuel bundle positions. Therefore it requires long computer execution time to obtain the irradiation histories by simulating individual burnup states and fuel site changes throughout the dwelling time of fuel bundles. Thus approximation is essential to analyze the core characteristics at equilibrium.

In order to calculate flux distributions, two approximate methods are introduced: homogenous equilibrium core calculation and time averaged equilibrium core calculation. Homogenous calculation takes the assumptions of continuous refuelling at constant ramp rate. This method is characterized by use of constant cross sections in the axial direction and in the given regions of the core, respectively. Therefore this calculation cannot determine the followings: the variation in axial power and flux distribution expected because of the different numbers of bundles refuelled; the variations in channel power anticipated due to different irradiation histories of individual channels.

On the other hand, time average calculation employes the time averaged flux concept that the flux and power distribution is calculated from cross sections averaged over the dwelling time of the fuel bundles, and hence time average calculation is considered to be more practical to analyze CANDU core.

Used to analyze equilibrium core in Canada is generally FMDP[2] (Fuelling Model Design Program) which is three dimensional fine mesh and two group diffusion code. Since the FMDP code, which is not available in Korea, needs large computer memory and long execution time, WBURN code based on STOKE[3,4,5] is developed to analyze CANDU-PHWR core characteristics.

Equations are followed in Section II to delineate time averaged cross section and average discharge irradiation. Core modeling and group constant generating method are presented in Section III, Section IV summarizes the results and discussions, and Section V draws conclusions from the study.

II. Time Averaged Cross Section and Average Discharge Irradiation.

In order to calculate time averaged flux, the group constants of neutron diffusion equations at each mesh point are obtained from averaging over the dwelling time of the fuel bundles which are defined as the refuelling period of each channels.

$$\bar{\Sigma}=\frac{1}{\Delta\omega}\int_{\omega i}^{\omega_f}\Sigma(\omega)\,d\omega, \qquad (1)$$

where ω_i and ω_f are initial and final irradiation of the fuel bundles after being irradiated, respectively and $\Delta\omega(\omega_f-\omega_i)$ is the increment of irradiation. The irradiation in fuel bundles are related to the thermal neutron flux averaged over homogenized cell. The fuel irradiation ω can be written by

$$d\omega=\xi\phi dt, \qquad (2)$$

where ξ is flux depression factor (average thermal flux in the fuel region/average thermal flux in the whole cell), ϕ is thermal neutron flux, and t is irradiation time.

Since changes with the flux at each position, $\bar{\Sigma}$ also varies with axial position in a channel. To obtain the initial and final irradiation at each axial position in a channel, a known or assumed axial flux distribution will be used for the first trial. Then the increments of irradiation, $\Delta\omega$, is computed by integrating Eq. (2),

$$\Delta\omega=\int_0^T\xi\phi dt=\bar{\xi}\bar{\phi}\,T \qquad (3)$$

Where T is the dwelling time at each position which is generally unknown.

In CANDU-PHWR core, eight bundle shift refuelling scheme is generally adopted for normal operation, and Fig. 1 shows the eight bundle-shift refuelling per a channel. That is, eight fresh fuel bundles are inserted along the coolant flow direction in a pressurized coolant channel, and the parts of irradiated fuel bundles and

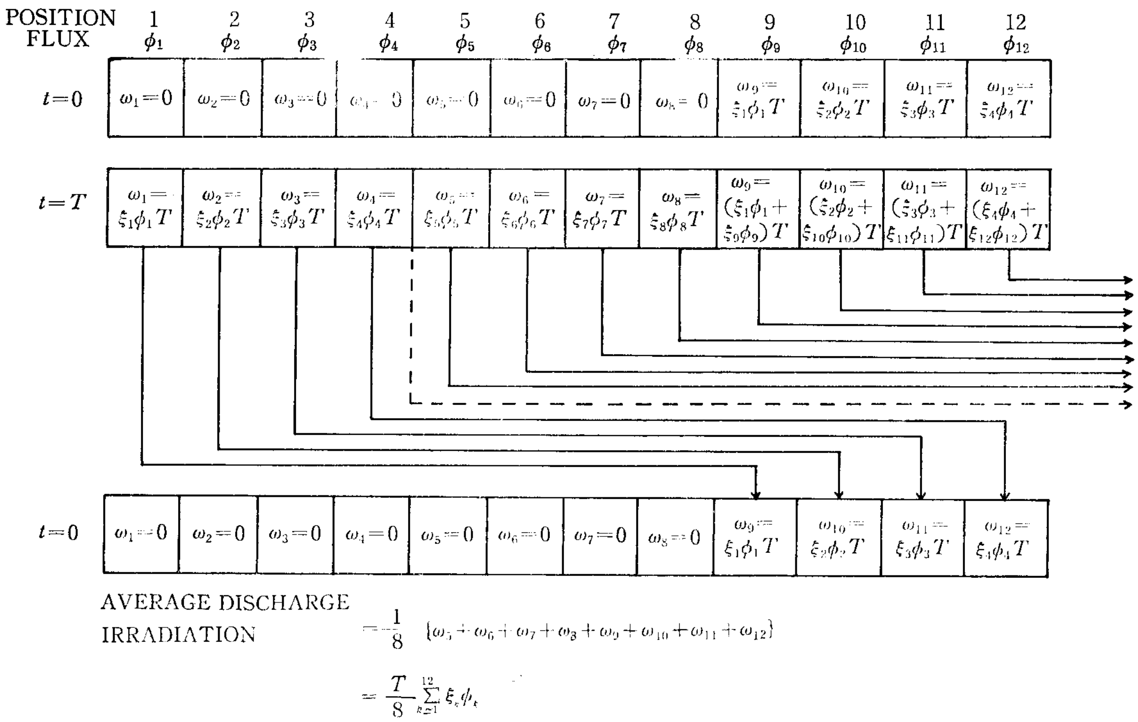


Fig. 1. Eight Bundle Shift Refuelling Scheme and Average Discharg Irradiation.

fresh fuel bundles will be arranged as shown in Fig. 1. Fuel bundles irradiated in the channel will be eventually discharged at the other end of the channel. When a fuel string is pushed to a new position, the irradiation at the start of the new cycle (ω_i) is equal to the end of cycle irradiation (ω_f) at the previous position. Thus starting from the fresh fuel bundles and knowing the refuelling scheme, the average discharge irradiation of spent fuel budles (ω_{out}) can be specified in the following form:

$$\begin{aligned}\omega_{out} &= \frac{1}{8}[\omega_5+\omega_6+\omega_7+\omega_8+\omega_9+\omega_{10} \\ &\quad +\omega_{11}+\omega_{12}], \\ &= \frac{T}{8}\{\xi_5\bar{\phi}_5+\xi_6\bar{\phi}_6+\xi_7\bar{\phi}_7+\xi_8\bar{\phi}_8+(\xi_9\bar{\phi}_9 \\ &\quad +\xi_1\bar{\phi}_1)+(\xi_{10}\bar{\phi}_{10}+\xi_2\bar{\phi}_2)(\xi_{10}\bar{\phi}_{10}+\xi_3\bar{\phi}_3) \\ &\quad +(\xi_{11}\bar{\phi}_{11}+\xi_4\bar{\phi}_4)\} \\ &= \frac{T}{8}\sum_{k=1}^{12}\xi_k\bar{\phi}_k \end{aligned} \tag{4}$$

From Eq. (4) the dwelling time of the fuel bundles can be specified in the following form:

$$T = \frac{\omega_{out}}{\frac{1}{8}\sum_{k=1}^{12}\xi_k\bar{\phi}_k}. \tag{5}$$

Inserting Eq. (5) into Eq. (3) yields

$$\Delta\omega = \frac{8\omega_{out}}{\sum_k \xi_k\bar{\phi}_k}\cdot\xi\bar{\phi} \tag{6}$$

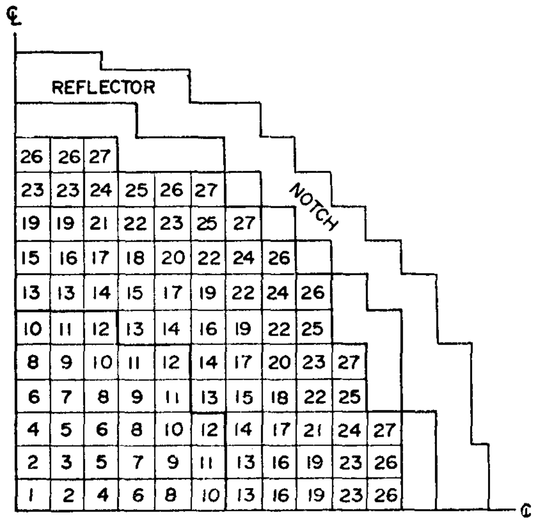
It should be noted here that the fluxes used in Eq. (6) are time averaged neutron flux which should be calculated in time averaged calculation.

III. Numerical Analysis

III. 1. Core Modeling

The CANDU-600 reactor consists of 380 coolant channels in the core and is accommodated with the reflector region in radial direction. Each channel has 12 fuel bundles in axial direction.

WBURN is two dimensional (R-Z) code and treats all channels and bundles with coarse mesh



Ring No. 1-12 Inner Region (124 Channel)
Ring No. 13-27 Outer Regino (256 Channel)
Fig. 2. The Method of Grouping Channel into Ring

point in a cylindrical reactor with notch at the both ends. Modeling a CANDU core in WBURN, the core region is radially divided into several rings that include several channels and their associated moderator. When channels are grouped into rings, the channels located in approximate same circle should be grouped into the same ring, and the volume of each ring should be equal to the summation of individual channel volumes and their associated moderator region. Fig. 2 shows the method each channel of core region is divided into rings for core simulation in WBURN.

For numerical calculations, one mesh point is assigned to the center of each bundle in the axial direction. A homogenized cell in WBURN, therefore, forms a ring with full length of a fuel bundle, and reflector is consisted by fictitious cells simply containing moderator.

CANDU-PHWR has a large number of reactivity devices: adjuster rods, zone controller units, mechanical control absorbers and shut off rods. Of these reactivity devices, mechanical control absorbers and shutoff rods are fully

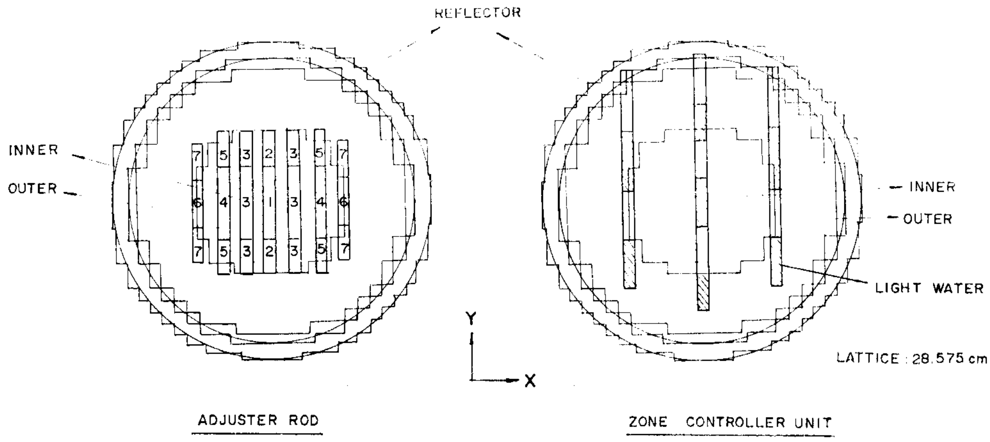


Fig. 3. Face View Showing Adjuster Rods and Zone Controllers

withdrawn when reactor is normally operating at full power. Consequently these reactivity devices need not be considered in equilibrium core analysis.

All adjuster rods are, however, fully inserted in the reactor core durning the full power operation, and provide xenon over-ride when reactor restarts up within one half hour. The liquid zone controller units are to provide the continuous fine control of the reactivity and regional power of the reactor. Figs. 3 and 4 show the locations of adjuster rods and zone controller units.

In modeling the core, structure materials and guide tubes of the reactivity control devices are not simulated for equilibrium core analysis in

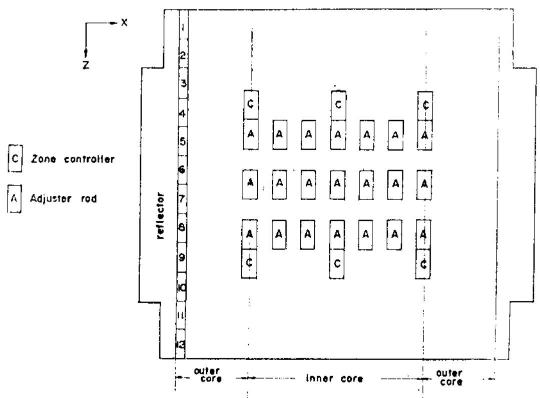


Fig. 4. Top View Showing Adjuster Rods and Zone Controllers

WBURN. The effect from the structure materials are, however, taken into account their reactivity worth, i.e., assumed as poison uniformly distributed in the core.

Adjuster rods and zone controller units which are not included in the lattice cell calculation, are then treated by adding cross section increments to the cell containing these materials. These increments of cross sections are called incremental cross sections. Due to intrinsic positioning of reactivity control device, calculations of incremental cross sections involve complex geometrical treatment and neutron flux tracsk as well. Based on the appropriate treatment of hyper fine supercell of reactivity devices, SUPERCELL[2] code has been developed in Canada to compute incremental cross sections and the result sre provided in the final safety report of Wolsung reactor. Therefore the incremental cross sections of adjuster rods and zone controller units are simply taken from FSR, and Table 1 shows their incremental cross sections.

The incremental cross sections given in FSR of Wolsung reactor cannot be, however, directly adapted because of employing two dimensional coarse ring mesh in WBURN code. Therefore these incremental cross sections are taken to be

Table 1. Incremental Cross Sections of Reactivity Devices

Reactivity Devices		$\Delta\Sigma_{a1}$ ($\times 10^{-4}$cm^{-1})	$\Delta\Sigma_{a2}$ ($\times 10^{-3}$cm^{-1})	$\Delta\Sigma_{tr1}$ (cm^{-1})	$\Delta\Sigma_{tr2}$ ($\times 10^{-3}$cm^{-1})	$\Delta\nu\Sigma_{f2}$ ($\times 10^{-3}$cm^{-1})	Σ_{r1} ($\times 10^{-3}$cm^{-1})
Adjuster rod	type 1	.2792	.5964	0.	−.2205	.08607	0.
	type 2	.2792	.4900	0.	−.2205	.0750	0.
	type 3	.2792	.9044	0.	−.2947	.11549	0.
	type 4	.2792	.7950	0.	−.2183	.1055	0.
	type 5	.2792	.3553	0.	−.1523	.05934	0.
	type 6	.2792	.4349	0.	−.1785	.06948	0.
	type 7	.2792	.0760	0.	−.0823	.03202	0.
Zone controller unit		.5720	1.1115	−0.01716	139.3	−.0132	1.753

note: i) These incremental cross sections are value at 1.8n/kb
ii) (−) sign repressents that cross section decreases when reactivity devices are located

smeared into the respective coarse meshes. It requires that the reaction rates averaged over the mesh volumes must be equal to those computed by using can now be written by

$$\Delta\Sigma_{in}{}^{c}=\frac{\int_v \Delta\Sigma_{in}{}^{f}\phi dv}{\int_v \phi dv} \tag{7}$$

where $\Delta\Sigma_{in}{}^{c}$ is collapsing incremental cross section and $\Delta\Sigma_{in}{}^{f}$ is incremetal cross section for a fine mesh. Integrated is Eq. (7) over the volume of the ring mesh where reactviity devices are located. The flux distribution is calculated over two dimensional $(X-Y)$ fine mesh point by using WBURNIN which is a simple computer code for two dimensional two group diffusion code. In axial direction, the collapsing incremental cross seetions are added to group constants of the plane located the adjuster rods and zone controller units.

III. 2. Time Averaged Core Calculation

CANDU-PHWR requires that refuelling rate should be minimized (or averaged discharge irradiation should be maximized) while constaints on maximum power and on excess reactivity are met. In the current practice, this is achived by defining two radial burnup regions (inner region and outer region) in which the respective average discharge irradiations are almost constant.

Refuelling rate and average discharge irradiation of individual regions are adjusted so that power flattening and criticality can be maintained. In the usual application of time averaged calculation, as shown in Fig. 5, the average

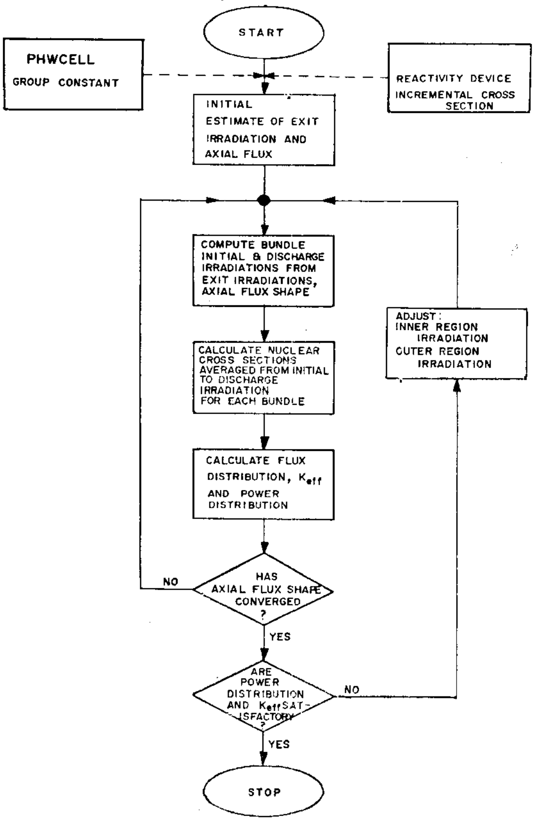


Fig. 5. Flow Diagam of Time Averaged Calculation

discharge irradiation in the two regions are varied in order to obtain a desired excess reactivity and radial form factor (defined as average channel power/maximum chandel power).[6,7,8]

In WBURN simulation, the form factor is practically converged to 0.8415 and the excess reactivity to 3.1mk. This form factor is calculated from the reference channel power distribution averaged over ring mesh, and the excess reactivity is the reactivity worth of structure material which is not included in WBURN model. The form factor from WBURN is higher than the nominal value of 0.832 in CANDU-600. It is due mainly to the fact that mesh points of WBURN are coarse and hence the code has a trend of generating smoother flux distribution and lower power peak than those of the fine mesh calculations.

Table 2. Design Data and Operating characteritics

	Parameter	Value
Operation condition	Fuel temperature (°C)	936(687)*
	Moderator temperature (°C)	73 (68)*
	Coolant temperature (°C)	290
Lattice data	Fuel	37 element
	Element outside diameter	13.081mm
	Air gap thickness	0.0455mm
	Average clad wall thickness	0.419mm
	Pellet outside diameter	12.154mm
	Stack length	480.31mm
	UO_2 area	34.211mm
	UO_2 weight per bundle	20.98kg
	Zircaloy weight per bundle	2.2799kg
	Pressure tube(Zr-2.5% Nb) inside diameter	103.378mm
	Average pressure tube wall thickness	4.343mm
	Callandria tube (Zr-2) inside diameter	129.0mm
	Average calandria tube wall thickness	1.297mm
	Lattice pitch	285.75mm
	Equivalent channel diameter	322.434mm

* ( ) Value is update design pa rameter.

Two group diffusion constants, flux depression factor and energy generation ratio are obtained by using PHWCELL.[9] This code generates group constants as function of fuel irradiation for various fuel geometries and pressure tube and calandria tube characteristics, and also for various values of lattice pitch and operating conditions. These constants are put into WBURN as tabular form and calculated by simple interpolation at fine irradiation.

Table 2 shows lattice cell data and operating conditions of Wolsung reactor taken from the final safety report[10]. These data are used for calculation of cell group constant over lattice cell which is defined with one coolant channel and its associated moderator. Lattice cell calculation is done over two situations, CANDU calculation and WOLSUNG calculation. CANDU calculation uses the old data given in FSR and WOLSUNG calculation the new data for operating conditions provided recently.

IV. Results and Discussions

In order to veryfy the WBURN code, equilibrium core analysis on CANDU-600 is attempted, i.e., the old design cell parameters given in Wolsung FSR^are used for the cell calculations. The results computed by use of the WBURN are compared to the eeference values provided in the Wolsung FSR.

The reactivity worth of adjuster rods and zone controller units in equilibrium core are

Table 3. Reactivity Worth of Reactivity Devices (mk)

Reactivity device	Reference value	WBURN Calculation	
		CANDU Simulation	WOLSUNG Simulation
Adjuster rod*	17.2	17.378	17.263
Z.C.U.**	3.96	3.964	3.930

* All adjuster rod fully inserted.

** Average water level 49.6%

computed and the results are summarized in Table 3 with the reference values of Wolsung FSR. Taking into account collapsed incremental cross sections, the reactivity worth are calculated for the adjuster rods and zone control units, and the discrepancies are detected to be 1% and 0.1%, respectively, compared to the values of Wolsung FSR.

Table 4 shows some results of the equilibrium core characteristics estimated from the CANDU simulation with the reference value given in Wolsung FSR. The average discharge irradiations of individual regions (inner region and outer region) and whole core are higher than those of the reference values by about 3.5%. That is, the average discharge irradiations of inner and outer region are 1.7407n/kb and 1.541n/kb, respectively, which result in the average discharge irradiation of 1.621n/kb for the whole core. The regional power fractions are 0.3837 and 0.6163 in the inner region and outer region, respectively and they are in a good agreement with the reference values. Refuelling rate and dwelling time of fuel bundles in the individual regions are also estimated, and the results are illustrated in Table 4. As would be expected, dwelling time of fuel bundles increases as the discharge irradiation increases, but re-

Table 4. Equilibrium Core Characteristics of CANDU Simulation

Contents		Region	Reference* value	WBURN Calculation**	
				Present result	Difference(%)
Average discharge irradiation (n/kb)		inner	1.681	1.7407	3.55
		outer	1.490	1.541	3.42
		average	1.558	1.612	3.47
Fractional power		inner	0.384	0.3837	−0.07
		outer	0.616	0.6163	0.04
Refuelling rate (channels/FPD)		inner	0.811	0.7825	−3.5
		outer	1.465	1.4186	−3.2
		total	2.275	2.2010	−3.3
Feed rate (kg.U/FPD)		inner	—	115.08	—
		outer	—	209.95	—
		total	—	325.75	—
Dwelling time (FPD)	Maximum	inner	159.5	165.9	—
		outer	297.3	271.6	—
	Minimum	inner	149.7	156.8	—
		outer	133.1	140.8	—
	Average	inner	153.1	158.5	3.6
		outer	184.4	189.6	2.9
Max. channel power (kw)			6523	6445	−1.2
Radial form factor			0.832	0.8419	—
Max. bundle power (kw)			885	792	−10.5
Overal from factor			0.511	0.571	—

* Numerical values are estimated by use FMDP (3-D)
** Numerical values are estimated by use WBURN (2-D)

fuelling rate decreases. The refuelling rate over the whole core is found to be 2.201 channels/FPD which is lower than the reference value of 2.275 channels/FPD by 3.3%. The average dwelling times of the fuel bundles are estimated to be 158.5 FPD and 189.6 FPD in the inner region and outer region, respectively, which are overestimated by 3.6% nd 2.9% in the respective region. The maximum channel and bundle powers are, however, underestimated by the WBURN code, and the discrepancies are 1.2% and 10.5% for the maximum channel and bundle power, respectively. The large deviation of the maximum bundle power is mainly attributed to treatment of the core region in the coarse meshes. The channel powers in the Wolsung FSR are avereged over the rings corresponding to the meshes in the core simulation, and the channel power distributions are plotted in Fig. 6. with the results obtained from the WBURN code. The difference between two distributions are in the range of 1.2% at most.

It can be drawn a conclusion from the CANDU simulation that the coarse mesh two

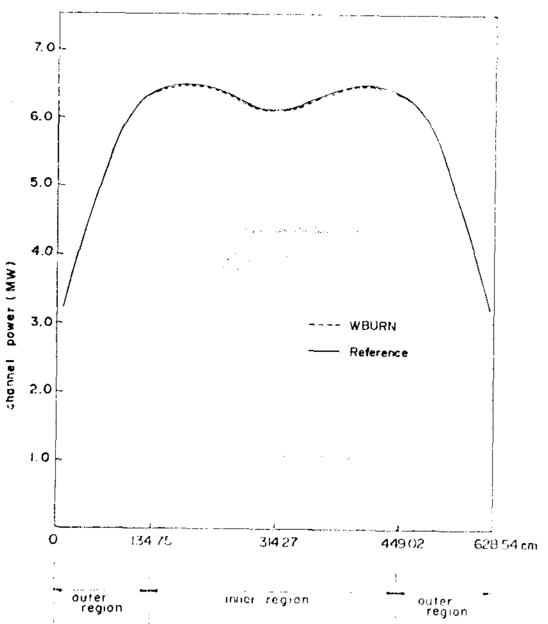


Fig. 6. Channel Power Distribution

dimensional code WBURN predicts practical results for equilibrium core characteristics of CANDU type reactors.

With the verification of the WBURN code by the CANDU simulation, the equilibrium core characteristics of the Wolsung reactor are analyzed by use of up-dated operation conditions, ie., fuel and moderator temperature changes. Assessed with the new cell parameters and cross sections are:

1) reactivity worth of the adjuster rods and zone controller units. (Table 3)
2) equilibrium core characteristics including average discharge irradiation, refuelling rate, dwelling time and maximum channel and bundle power (Table 5).

Of the results, maximum channel and bundle powers are again appeared to be underestimated by 1.1% and 10.3%, respectively. Compared to the discharge irradiation computed over the whole core increases by 8.1%. Taking into consideration of the intrinsic deviation in the WBURN code, the change of operating conditions gives rise to increase of the average discharge irradiation by 4.6%. Consequently the average dwelling time of fuel bundles in the inner and outer region increases by 7.0 and 10.1 FPD, respectively.

Based on the fuel temperature change only,

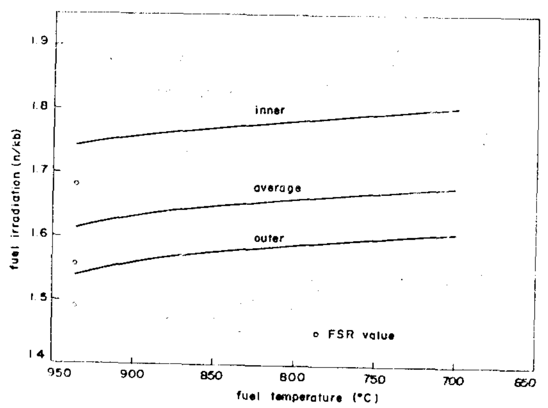


Fig. 7. Average Discharge Irradiation v.s. Fuel Temperature

Table 5. Equilibrium Core Characteristics of WOLSUNG Simulation

Contents		Region	Reference value	WBURN Calculation	
				Present Results	Difference(%)
Average discharge irradiation (n/kb)		inner	1.681	1.8108	7.7
		outer	1.490	1.613	8.3
		average	1.558	1.6837	8.1
Fractional power		inner	0.384	0.3839	—
		outer	0.616	0.6161	—
Refuelling rate (channels/FPD)		inner	0.811	0.7492	−7.6
		outer	1.465	1.3475	−8.0
		total	2.275	2.0967	−7.8
Feed rate (kg. U/FPD)		inner	—	110.88	—
		outer	—	199.43	—
		total	—	303.31	—
Dwelling time (FPD)	Maximum	inner	159.5	178.2	—
		outer	297.3	286.3	—
	Mimimum	inner	149.7	163.8	—
		outer	133.1	147.9	—
	Average	inner	153.1	165.5	8.1
		outer	184.4	199.7	8.3
Max. channel power (kw)			6523	6449	−1.1
Radial form factor			0.832	0.8414	—
Max. bundle power (kw)			885	793.5	−10.3
Overal form factor			0.511	0.570	—

discharge irradiations are illustrated in Fig. 7 which shows the average discharge irradiations of individual regions increase as fuel temperature decreases. This is believed to be due to the fact that the fuel temperature coefficient is nearly constant over the operating period of interest.

V. Conclusions

Equilibrium core characteristics of the Wolsung reactor are assessed by use of the independently developed code WBURN. Since the code is programmed in two dimensional coarse meshes, it requires relatively small computer memory and short execution time. For instance, WBURN requires 150 seconds of the CDC-73 system to analyze one case of equilibrium core while FMDP approximately takes about 8000~10000 seconds with the same system.

With the two dimensional coarse mesh method, the code overestimates the average discharge irradiation by about 3.5% compared to the reference value given in the final safety report of the Wolsung reactor. Among other numerical analyses, WBURN provides relatively accurate results for equilibrium core of CANDU-PHWR. It can be, therefore, concluded that WBURN is found to be very useful to assess the tendencies of core responses and/or power tilts from various perturbations in a short cut.

Taking into account the inherent numerical errors in WBURN, change of the operating conditions gives rise to 4.6% of increase in average discharge irradiation of spent fuel bundles. This increment implies that the average refuelling rate could be decreased by 4.9% without changing the radial form factor.

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