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《**Original**》

Some Studies on Physics Parameters of Wolsung Unit No. 1

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Abstract

Nuclear physics parameters of the Wolsung CANDU-PHW reactor are computed by use of the PHWCELL computer code that is an improved version of LATREP. The PHWCELL code mainly computes cell parameters of heavy water moderated reactors, and modeling scheme of heavy water reactor cell calculations has been developed with the PHWCELL computer code. The reactor operating conditions considered in the study are cold zero power (CZP) and hot full power (HFP) with equilibrium poison. The cell parameters are also computed as a function of fuel burnup and the numerical results are compared with the results in PSR of the Wolsung unit and in the previous study.

요 약

LATREP의 새로운 version인 PHWCELL을 사용하여 월성 CANDU 원자로의 핵물리상수를 계산하였다. 이 코드는 주로 중수원자로에 대한 격자상수를 계산하며, 이 코드를 사용하여 중수원자로의 격자계산의 model방안을 개발하였다. 본 연구에서 고려된 원자로 운전조건은 Cold Zero Power (CZP)와 Hot Full Power (HFP)로서 독작용이 평형인 상태에서 고려한 것이다. 격자상수는 핵연료의 연소에 대한 것도 고려하였으며, 계산된 결과들은 월성 원자로의 예비안전보고서에 주어진 값과 이전의 연구결과와 비교하였다.

I. Introduction

The economic and safe operation of a nuclear power reactor requires accurate core analysis which in turn provides optimum fuel management for power generation. This is essentially supported by the precise estimates of various cell parameters for specific fuel and lattice configurations along fuel burnup with use of computer codes.

Embarking on the introduction of the CANDU-PHWR, Wolsung Unit No. 1, into Korea, it is strongly felt that an investigation of the reactor design parameters be necessarily carried out to confirm the design data and to establish independent calculation capability as well.

In view of reactor physics, the lattice parameter calculations in heavy water moderated reactors are somewhat different from those in light water moderated systems because of large thermal diffusion area and small neutron absorption in heavy water. Those involve, for instance, four factor calculation of infinite neutron multiplication

and special treatment of thermal neutron cross sections with the Westcott convention[1]. Neutron collisions with elements in a fuelled cell are handled in such a way that a cell with fuel bundle is divided into concentric annuli and number of neutron collisions are calculated by the single collision probability[2] in the annuli.

The objective of this study is to make cell parameter calculations for fuel bundles of the Wolsung reactor by use of the PHWCELL computer code. This code is a lattice parameter calculation program that utilizes the differential equations for fuel burnup calculations, and the code can handle uranium oxide fuel as well as uranium metal fuel. Since the Preliminary Safety Report of the Wolsung reactor does not include any cell parameter variations along fuel burnups, the study is conducted not only to compute the cell parameters for the operating conditions, CZP and HFP with equilibrium poison, but also to produce cell parameters with fuel burnups. Then the cell parameters computed by the PHWCELL code are compared with those of the previous study[3] and with the design values of the Wolsung PSR[4] as well.

Following the introduction, Section Ⅱ describes the lattice configuration to be investigated, and numerical calculations of various reactor physics parameters are presented in Section Ⅲ and the last section discusses the results and draws a conclusion from this study.

Ⅱ. Lattice Configurations

The fuel channels of the Wolsung CANDU-PHW reactor are arranged on a

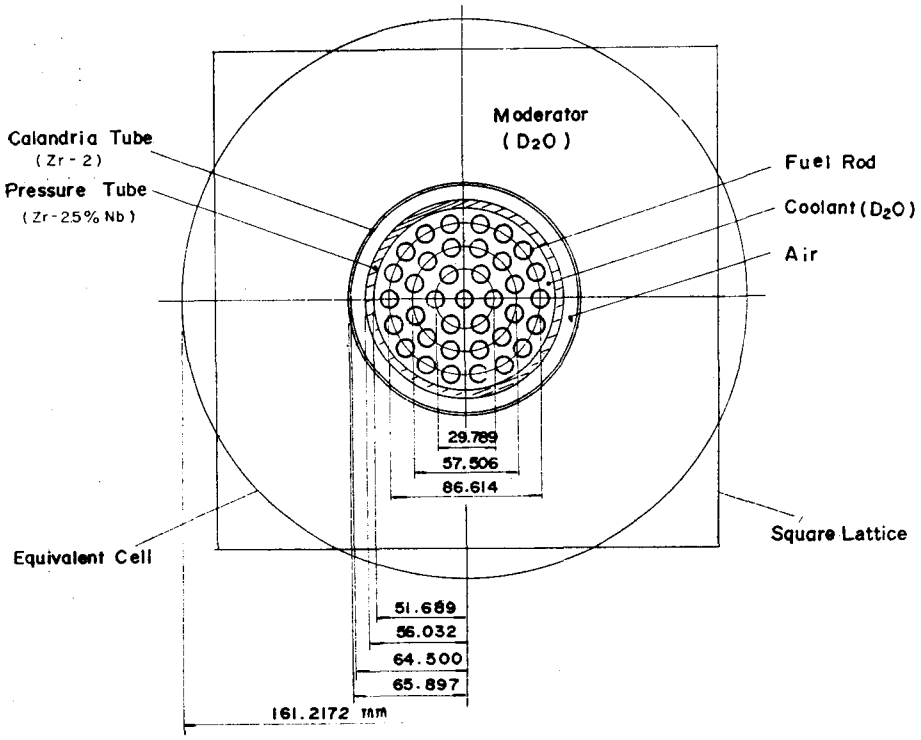

Fig 1. Fule Channle & Equivalent Cell

right square lattice with a center-to-center spacing of 28.575 cm. A lattice is then composed of Zr-2.5% Nb pressure tube which contains fuel bundle cooled by heavy water, and Zr-2 calandria tube which is surrounded by heavy water moderator. There is also air gap between a Zr-2.5% Nb pressure tube and a Zr-2 calandria tube. In a pressure tube, there are twelve fuel bundles, each of which comprises 37 uranium dioxide fuel elements clad with Zr-4. The air gap serves to insulate the hot heavy water coolant inside the pressure tube from the relatively cold heavy water in the reactor vessel.

Fig. 1 illustrates the geometrical details of a lattice of the Wolsung CANDU-PHW reactor to be investigated. Also presented in Table 1 are dimensions of the cell constituents required for the cell parameter calculations.

Table 1. Lattice Cell Data

Fuel	37 elements UO_2
Element Outside Diameter	13.081mm
Air Gap Thickness	0.0455mm
Average Clad Wall Thickness	0.419mm
Pellet Outside Diameter	12.154mm
Stack Length(Bundle Length)	480.31mm
UO_2 Density	10.6g/cm^3
UO_2 Area	42.926cm^2
Coolant Area	34.211cm^2
UO_2 Weight per Bundle	20.987kg
Zircaloy Weight per Bundle	2.2799kg
Pressure Tube(Zr-2.5% Nb) Inside Diameter	103.378mm
Average Pressure Tube Wall Thickness	4.343mm
Calandria Tube (Zr-2) Inside Diameter	129.0mm
Average Calandria Tube Wall Thickness	1.297mm
Lattice Pitch	285.75mm
Equivalent Channel Diameter	322.4344mm

Ⅱ. Numerical Calculations

A. PHWCELL Code

PHWCELL is a lattice parameter computing code which is only applicable to heavy water moderated cell calculations and many simplifying approximations are adapted in the treatment of complex neutron physics processes in order to reduce computing time with high degree of accuracy. The geometry that can be handled in the code is cylindrical, and each cell consists of three regions for fuel, annuli containing coolant and tube materials, and moderator. The first region is confined with a homogenize fuel that has the radius of a circle having an area equal to the cross-sectional area enclosed by a rubber band. The second region which can be divided into 1 to 5 annuli of various materials contains coolant, pressure tube, air, and calandria tube. The third one is just moderator taken from outside of calandria tube to the equivalent radius of the lattice area. Equations to compute the numerical values will be detailed in the following section.

In computing physics parameters, the code employs the conventional four factor formula and takes the assumption of a two group leakage. The Westcott convention[5] is used for calculating the microscopic cross sections of the heavy elements. Thus the effective cross section, σ, of a given nuclide in the program must have the property that the reaction rate of the nuclide is given by Nv_0 in which v_0 is the neutron speed of 2200m/sec. The effective cross section can, therefore, be written in the form of

$$\sigma=\sigma_0(g+rs)$$

where σ_0 is the cross section measured at the neutron energy of 0.0253 eV. The value of g is a measure of non-1/v absorber in a Maxwellian specturm and r is the fraction of the neutrons in the epithermal parts of

the specturm. Thus the value of r is a measure of the 'hardness' of the spectrum and typically the numerical value of r is approximated to be 0.05 for a CANDU lattice fueled with natural UO_2. It should be noted here that g=1.0 and s=0 for a pure 1/v-absorber.

Fast fission is only accounted for in U-238 and the resonance capture in U-238 is assumed to take place in a resonance trap at a single effective energy.

The fission products are divided into two groups. One group constitutes three saturating fission products of Xe, Sm, and Rh, whose absorption cross sections are characterized to be very high. The other group involves three non-saturating fission products each with a constant effective cross section.

In the program, fuel burnup is also taken into account. Burnup equations are a set of coupled differential equations incorporated with the atom densities of the heavy element isotopes and non-saturating fission products by the way of the appropriate cross sections. Solution of the coupled equation set yields atom densities as a function of burnup, from which macroscopic cross sections are computed.

B. Input Descriptions

As mentioned in the previous section, the homogenized fuel radius obtaining from the rubber band concept is the most important input data to run the PHWCELL computer code. The homogenized fuel is encircled with a radius having an area equal to the cross-sectional area enclosed by a rubber band, taking the sheath of each outermost element wrapped around the bundle at its midplane. Fig. 2 explains the rubber band and the perimeters to be computed.

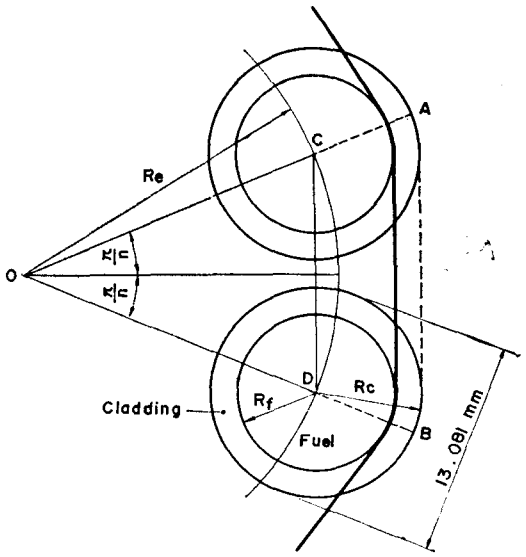

Fig. 2. Fuel Rod & Rubber Band

The rubber band perimeter is equal to the length of a rubber band wrapped around the fuel bundle acrossing the actual fuel elements or fuel pellets on the outermost circle. That is, clad thickness of the respective fuel rods is not independently taken account of computing the cell parameters. Detail calculations of the perimeters are as following: In a fuel bundle it is assumed that fuel elements are equally spaced on concentric circles as shown in Fig. 2, and then

$$\text{OAB area}=nR_e^2\sin\left(\frac{\pi}{n}\right)\cos\left(\frac{\pi}{n}\right)+2nR_cR_e\sin\left(\frac{\pi}{n}\right)+\pi R_c^2$$

where

R_e=the radius of a circle acrossing the centers of the outermost fuel elements

R_c=Outside radius of the clad of the fuel elements

n =the number of elements on the outermost circle of a fuel bundle.

And the length of the rubber band wrapping the outermost fuel elements is obtained to be:

$$\text{The band length}=2nR_e \sin\left(\frac{\pi}{n}\right)+2\pi R_f$$

in which R_f is the fuel pellet radius.

In addition, the total fuel perimeter is also computed and given by

$$\text{fuel perimeter}=2\pi R_f \sum_i n_i$$

in which n_i is the number of fuel elements on the i-th circle of a fuel bundle. Defined is the coolant thickness d that is a ratio of the volume per unit bundle length of the coolant contained within the surface formed by straight line CD in Fig. 2 to the fuel surface area per unit bundle length within the same boundary. Thus the value of d can be computed by

$$d=2\frac{V}{S}$$

in which

$$V=nR_e^2 \sin\left(\frac{\pi}{n}\right)\cos\left(\frac{\pi}{n}\right)-\frac{n-2}{2}\pi R_c^2-\pi\sum_i n_i R_{ci}^2$$

$$S=(n-2)\pi R_f+2\pi\sum_i n_i R_{fi}$$

The summations in the above equations are taken over all fuel elements except those outermost circle.

Upon the values in Table 1, the parameters for the Wolsung fuel bundles are as follows:

Homogenized fuel radius=4.94353cm
Rubber band perimeter=30.88967cm
Total fuel perimeter=141.24679cm
Coolant thickness=0.4159343cm

Ⅳ. Results and Discussions

Prior to computing the Wolsung CANDU-PHW reactor physics parameters, operating conditions of the reactor should be set in terms of respective component temperature that is summarized in Table 2. The abbreviations in the table are CZP (Cold Zero Power), HZP (Hot Zero Power), and HFP (Hot Full Power). As is shown in Table 2, the fuel temperatures are the same for the two computer codes except the fuel temperature of HFP. When the lattice parameters were computed by the LATREP code in the previous study[3], the fuel temperature for HFP was simply taken as the value given in the Wolsung PSR. As shown in the previous study, the computed results were found to be somewhat different from the PSR values, which was not well understood at that time. Thus, the fuel temperature of the HFP condition for this study is taken to be 924°C instead of 936°C as given in the reference[6].

Table 2. Reactor Operating Conditions

Section	CZP	HZP	HFP	
			LAT REP	PHW CELL
Fuel Temp.(°C)	25	290	936	924
Clad Temp.(°C)	25	290	339	339
Coolant Temp.(°C)	25	290	290	290
Mod. Temp.(°C)	25	73	73	73

In examining the efficiency of the PHW-CELL code, four factors of neutron multiplication are computed for the three reactor operating conditions and the results are illustrated in Table 3 with the LATREP results. The numerical values are simply for fresh fuel which is just natural uranium oxide with no irradiation, i.e., the reactor is clean without any poison. The differences between two calculations are detected to be −0.11% and 0.50% for CZP and HFP, respectively. Aside from the four factor calculations without poison, the neutron multiplication of the HFP operating condition with equilibrium poison are computed and the numerical results are presented in Table 4 with the LATREP results and the Wol-

Table 3. Four Factors of Fresh Fuel

Factor	Code	CZP	HZP	HFP
ϵ	LATREP	1.02971	1.03153	1.03155
	PHWCELL	1.02593	1.02593	1.02593
p	LATREP	0.90309	0.90208	0.89634
	PHWCELL	0.91627	0.91201	0.90617
η	LATREP	1.31951	1.30979	1.30671
	PHWCELL	1.30957	1.29959	1.29669
f	LATREP	0.93263	0.93454	0.93399
	PHWCELL	0.93066	0.93186	0.93135
k_∞	LATREP	1.14437	1.13901	1.12845
	PHWCELL	1.14567	1.13312	1.12274

sung PSR values. Table 4 shows that among three values, the PHWCELL results are closer to the PSR values, and the LATREP code tends to over estimate the k_∞-value by 0.34%. This is attributed not only to the different fuel temperature but also to the PHWCEELL code efficency.

The four factors of fresh fuel are also

Table 4. HFP with Equilibrium Poison

Factors	LATREP	PHWCELL	PSR
ϵ	1.03153	1.02593	1.026
p	0.89634	0.90617	0.9047
η	1.24991	1.24118	1.241
f	0.93589	0.93335	0.9358
k_∞	1.08158	1.07698	1.078

computed by the PHWCELL code as fuel is irradiated in the reactor. Although these are not presented in the Wolsung PSR[4,7], it is necessary to investigate the variations of neutron multiplication with fuel burnups, and the results are plotted vs burnup in Fig. 3.

As show in Fig. 3, the values of ϵ, p, and f are not the very strongly varying function of neutron irradiation. The variation of η is, however, significant with fuel irradiation. This is owing mainly to the drastic change of U-325 concentration. That is, the production rate of Pu-239 cannot be greater than the consumption rate of U-235 although the

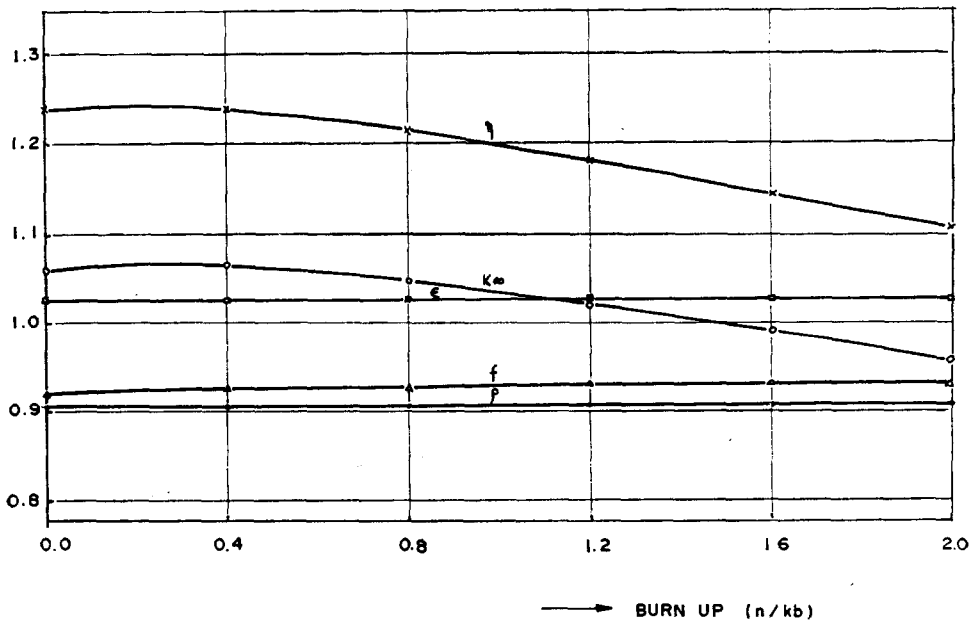

Fig. 3. Four Factors of Fresh Fuel with Burnups

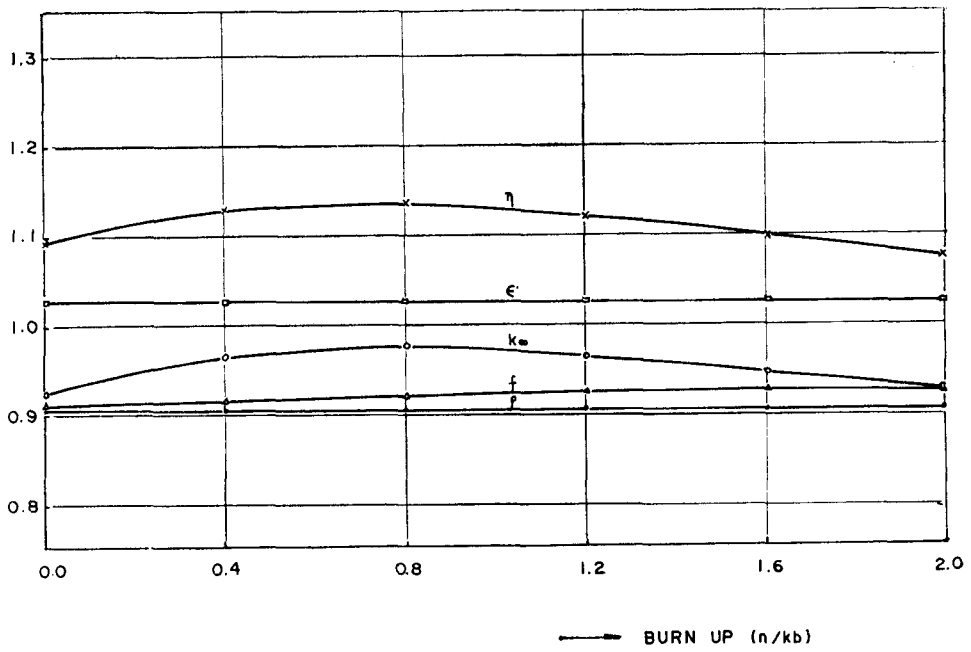

Fig. 4. Four Factors of Depleted Fuel

value of ν for Pu-239 produced from the neutron absorption is high. And hence the value of η is considerably decreasing with fuel irradiations.

In a CANDU type reactor, the fuel loading is composed of two types, that is, natural uranium oxide and so called "depleted fuel" containing 0.52% U-235 without retaining any fission products. To make the depleted fuel, natural uranium oxide is usually mixed with depleted uranium that contains 0.25% U-235 tails of enrichment process. And the depleted fuel bundles serve to make axial neutron distribution flat in the inner channel of a CANDU type reactor. Also computed in the study are the four factor variations along with neutron irradiations of depleted fuel and the results are illustrated in Fig. 4. It is noted from Fig. 4 that the values of p, ϵ, and f are not the strong functions of U-235 concentrations for fresh and depleted fuel.

Group constants of fresh fuel and depleted fuel are computed with 1.59 ppm boron concentration in heavy water moderator, and the results are presented in Table 5. The subscripts 1 and 2 in the group constants refer to fast and thermal neutron, respectively, and Σ_r is the removal cross section in cm^{-1}. Comparing the results of PHWCELL to those of PSR[4], the differences in two values are found to be negligible. It should be noted in Table 5 that the reflector is heavy water surrounding the outermost coolant channels with the D_2O thickness of about 65cm in the Wolsung reactor.

When a normal operation is started, maintaining the criticality of a reactor is of prime importance with fuel burnup. Typically in a CANDU type reactor, excess reactivity is not large even for a fresh core and hence the changes of fuel and heavy element concentrations are carefully investigated in view of group constants with fuel

Table 5. Group Constants with Boron in Moderator

Group Constant	PHWCELL			PSR		
	Fresh fuel	Depleted	Reflector	Fresh fuel	Depleted	Reflector
D_1	1.273918	1.273966	1.317107	1.273959	1.273959	1.317065
D_2	0.941061	0.939841	0.878719	0.941049	0.639816	0.878703
$\Sigma_{a1}\times10^3$	0.76604	0.76746	0.	0.765259	0.766679	0.
$\Sigma_{a2}\times10^2$	0.37312	0.33621	0.014299	0.373261	0.336359	0.0142985
$\nu\Sigma_{f2}\times10^2$	0.43716	0.34312	0.	0.437372	0.343315	0.
$\Sigma_r\times10^2$	0.73895	0.73881	1.0124	0.739032	0.73889	1.01241

irradiations. Thus computed are the group constants of fresh fuel with no boron, and the results are summarized with the PSR values in Table 6. The group constants here are averaged over the fuel life and the discrepancies in two group constants are in the range of $\pm0.1\%$ so as to be negligible. It should also be noted that the diffusion coefficient for fast neutron has been computed to be 1.27cm which is equal to the PSR value throughout the fuel burnup considered.

Table 6. Group Constants with no Boron in Moderator

Burnup (n/kb)	D_2	$\Sigma_{a1}\times10^3$	$\Sigma_{a2}\times10^2$	$\nu\Sigma_{f2}\times10^2$	$\Sigma_{r1}\times10^2$
0.0	0.94106	0.76604	0.36832	0.43771	0.73895
	0.94106	0.76526	0.36846	0.43792	0.73903
0.2	0.94121	0.76550	0.37832	0.45035	0.73901
	0.94116	0.76486	0.37553	0.44650	0.73907
0.4	0.94137	0.7649(	0.38942	0.46405	0.73906
	0.94134	0.76431	0.38721	0.46203	0.73913
0.6	0.94143	0.76441	0.39655	0.46932	0.73912
	0.94142	0.76377	0.39544	0.46888	0.73918
0.8	0.94142	0.76386	0.40219	0.46980	0.73917
	0.94143	0.76322	0.40117	0.47035	0.73923
1.0	0.94139	0.76331	0.40583	0.46735	0.73923
	0.94140	0.76267	0.40515	0.46849	0.73929
1.2	0.94133	0.76267	0.49837	0.46310	0.73928
	0.94134	0.76212	0.40789	0.46458	0.73935
1.4	0.94126	0.76221	0.41014	0.45780	0.73934
	0.94127	0.76157	0.40982	0.45949	0.73940
1.6	0.94123	0.76166	0.41143	0.45203	0.73939
	0.94120	0.76102	0.41120	0.45378	0.73945
1.8	0.94111	0.76111	0.41240	0.44610	0.73945
	0.94112	0.76047	0.41222	0.44785	0.73951

Note: PSR / PHWCELL

Group constant variations with boron are of interest and are not presented anywhere in the Wolsung PSR. According to the safety report[4], 1.59 ppm of boron is, however, required for the reactor startup, there is no description on changes of boron in the heavy water moderator. Regarding boron changes in moderator of the Wolsung reactor, the variations of cell parameters with 1.59 ppm boron are computed for fresh fuel and the numerical results are presented in Table 7. Comparing these values to the results without boron, changes can be detected in the cell parameter for thermal neutrons. This is due mainly to thermal neutron absorption effect of boron.

For the cell parameter calculations with boron, the boron concentrations in the moderator are fixed to be 1.59 ppm throughout the fuel burnup. It remains to study more carefully the nature of burning out boron in the moderator as well as the sen-

Taqle 7. Group Constants with Boron in Moderator

Burnup	D_2	$\Sigma_{a1}\times10^3$	$\Sigma_{a2}\times10^2$	$\nu\Sigma_{f2}\times10^2$	$\Sigma_{r1}\times10^2$
0.0	0.94105	0.76526	0.37326	0.43737	0.73903
0.2	0.94115	0.76486	0.38032	0.44595	0.73907
0.4	0.94133	0.76431	0.39200	0.46145	0.73913
0.6	0.94141	0.76377	0.40023	0.46830	0.73918
0.8	0.94142	0.76322	0.40595	0.46976	0.73924
1.0	0.94139	0.76267	0.40992	0.46790	0.73929
1.2	0.94133	0.76212	0.41268	0.46400	0.73935
1.4	0.94127	0.76157	0.41460	0.45891	0.73940
1.6	0.94119	0.76102	0.41598	0.45321	0.73946
1.8	0.94111	0.76047	0.41700	0.44729	0.73951
2.0	0.94104	0.75993	0.41780	0.44141	0.73957

Note: D =1.27395cm for the burnups considered with boron.

sitivity of the high-resolution cell parameters for the early stage of the operation. The PHWCELL computer code does give, however, an adequate information for the quantitative cell parameter calculations of the Wolsung reactor.

V. Conclusions

The lattice parameters for the Wolsung CANDU-PHW reactor are investigated by use of the PHWCELL computer code, and as shown in the previous section the numerical results computed are in excellent agreement with the valuer of the Wolsung PSR. With regard to the fuel temperature reduction, 936°C to 924°C in the calculations, four factors of fresh fuel at the HFP operating condition with equilibrium poison and cell parameters of fresh and depleted fuel are computed, and the results are summarized in Table 8 and Table 9, respectively. It can be clearly seen from the tables that the PSR values for the Wolsung reactor are based on the fuel temperature of 936°C at HFP with equilibrium poison as described in the Wolsung PSR. And in Table 8 and Table 9 the fuel temperature reduction by 12°C does not give rise to any significant changes in the four factors and the cell parameters. Therefore, the temperature reduction is simply considered to be a safety concern at the full power operation of the Wolsung reactor.

Table 8. Four Factors at HFP with Equilibrium Poison

factor	T_f=924°C	T_f=936°C	difference(%)
η	1.24118	1.24113	0.005
ϵ	1.02593	1.02593	0.0
p	0.90617	0.90607	0.01
f	0.93335	0.93334	0.001
kw	1.07698	1.07682	0.006
keff	1.0440	1.04383	0.017

Finally, it can be concluded from the study that PHWCELL is useful to compute lattice parameters of heavy water moderated reactors and the rubber band concept is helpful to modelize the reactor cells in computing the cell parameters.

Table 9. Lattice Parameters at HFP with Equilibrium Poison

Lattice Parameter	Fresh Fuel			Depleted Poison		
	T_f=924	T_f=936	PSR	T_f=924	T_f=936	PRS
D_1	1.27396	1.27396	1.2739	1.27396	1.27396	1.27396
D_2	0.94105	0.94105	0.94106	0.93982	0.93983	0.93984
$\Sigma_{a1}\times10$	0.76526	0.76602	0.76604	0.76668	0.76744	0.76746
$\Sigma_{a2}\times10^2$	0.37326	0.37311	0.37312	0.33636	0.33620	0.33621
$\Sigma_{r1}\times10_2$	0.73903	0.73896	0.73895	0.73889	0.73881	0.73881
$\upsilon\Sigma_{f2}\times10^2$	0.43737	0.43717	0.43716	0.34332	0.34313	0.34312

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