Assessment of the WIMS-D5 Applicability to CANDU Reactors

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SUMMARY

The purpose of this study is to develop a WIMS/CANDU code for a lattice calculation on the basis of WIMS-D5 code for the safety analysis of CANDU reactors. To assess the WIMS-D5 applicability to a CANDU reactor, a lattice model was developed for CANDU-6 reactors at the Wolsong site. As for the benchmark of the code validation, the code-to-code comparison was performed between the WIMS-D5 code with both the 69- and 172-energy groups of ENDF/B-VI nuclear data library and the WIMS-AECL code with the 89-energy group. The comparison studies of the reactor physics parameters such as void reactivity, coolant/fuel/moderator temperature coefficients were conducted with the change of the internal isotopic composition due to the fuel burning-up using both WIMS-AECL and POWDERPUFS-V (PPV) codes. The results show that the present results between the WIMS-D5 code and WIMS-AECL code agreed well with those of the PPV at the beginning of the fuel burn-up phase. As burning-up progresses, the results of WIMS-D5 show a large deviation from those of PPV for CANDU 6 reactors.

1. INTRODUCTION

In CANDU reactors, there is an increase of core power (so called "power pulse") inherently due to the positive void reactivity feedback during the postulated event of a large loss-of-coolant accidents (LLOCA). To enhance the safety margin for the power pulse for a CANDU reactor, it is important to improve the performance of the safety system. For enhancing safety, it is, therefore, necessary to assess the reliability of both the lattice code and nuclear data library with the aim of ensuring an adequate allowance for the void reactivity of the safety system.

Recently, the development of a new lattice code has been performed to enhance the assessment reliability for the void reactivity of the irradiated fuels at AECL in Canada. As a replacement of the POWDERPUFS-V code [1], the WIMS-AECL code was developed to conduct the lattice calculation for the irradiated fuels of CANDU reactors [2]. The validation of the WIMS-AECL

code was carried out with the experimental data at the ZED-II facility [3].

In order to validate the WIMS-D5 for CANDU 6 reactors, a code-to-code comparison was performed using lattice codes such as WIMS-D5 [4], WIMS-AECL and POWDERPUFS-V with the modeling the CANDU lattice for the Wolsong Unit 2. The nuclear data libraries in the WIMS-D5 are adopted with the 69- and 172-energy groups of the ENDF/B-VI, while for the WIMS-AECL with the 89-energy group.

The results of both the WIMS-D5 and WIMS-AECL agreed well with those of POWDERPUFS-V at the beginning of the fuel burning-up phase. However, the deviation is increased as the burn-up progresses. In terms of the code-to-code comparison, the results of the WIMS-D5 with the 172-energy group of the ENDF/B-VI library are in better agreement with those of the WIMS-AECL rather than the WIMS-D5 with the 69-energy group.

2. CODE-TO-CODE COMPARISON STUDY

The code-to-code comparison was performed with the modeling of a uniform lattice containing fresh natural uranium with 37-elements CANDU fuel for the Wolsong Unit 2 as shown in Figure 1. The lattice pitch is 28.575 cm and the fuel is of cluster-type contained in a pressure tube together with a coolant and is separated from the moderator by a calandria tube. The lattice codes used in this study are the WIMS-D5 with the 69- and 172-energy group library ENDF/B-VI, and the WIMS-AECL with 89-energy group library ENDF/B-VI, and POWDERPUFS-V.

Since the core physics codes such as the WIMS-D5 and WIMS-AECL are deterministic codes, they solve a mathematical form of the multi-group neutron transport equations in a two-dimension using the collision probability and other methods. They approximate by averaging the neutron cross sections over discrete energy ranges in the nuclear data libraries. Moreover, geometrical simplification can modify a real 3-D model into 2-D model so as to permit a numerical computation of the neutron flux variation over a region divided by spatial mesh intervals. Therefore, WIMS-D5 and WIMS-AECL can provide methods to solve the equations for a neutron flux and the values of k-infinity or k-effective in a discrete energy and spatial mesh.

For a WIMS calculation, the fuel assembly was modeled as an infinite lattice including a fuel pellet, clad, coolant, pressure tube, air gap, calandria tube and a moderator. The transport calculation was performed by the collision probability (PIJ) option using the 69- and 172-energy group library ENDF/B-VI for WIMS- D-5 and the 89-energy group library ENDF/B-VI for WIMS-AECL. The B1 method was not used to calculate the effective cell flux using the WIMS-AECL because the present WIMS-D5 does not consider the end-region effect with the B1 method

simultaneously. However, the Benoist diffusion constant model was used to generate the cell average diffusion coefficients.

POWDERPUFS-V is a lattice code designed especially for CANDU reactors and is validated within the range of experimental results. In this study, the simulation is performed for the regions by dividing them into three parts; (i) a homogenized fuel zone containing the fuel bundle and some coolant, (ii) annulus region containing the coolant, pressure tube, air gap and calandria tube, and (iii) a third region containing moderator. The POWDERPUFS-V code was validated with the experimental measurements of void reactivity for the standard CANDU lattice in the ZED-II. These measurements were carried out for fresh natural uranium fuel as well as fresh plutonium bearing fuel.

The comparisons were made for k-infinity, coolant temperature coefficient, void reactivity, fuel temperature coefficient, and a moderator temperature coefficient. As the temperature coefficient due to the change of core reactivity in the coolant/moderator/fuel were perturbed from the reference lattice, the void reactivity is able to measure the change of reactivity in such a way by removing the coolant from the fuel channel as follows;

$$\Delta\rho / \Delta t = (\rho_{perturbed} - \rho_{reference}) / \Delta t = (1/k_{perturbed} - 1/k_{reference}) / \Delta t, \qquad \Delta t : \text{change of temperature}$$

3. RESULTS AND DISCUSSIONS

To assess the WIMS-D5 applicability for the safety analysis of CANDU-6, a lattice calculation was performed using lattice cell codes such as WIMS-D5 with the 69- and 172-energy group nuclear data library ENDF/B-VI, and the WIMS-AECL with 89-energy group nuclear data library ENDF/B-VI, and POWDERPUFS-V. The reactor physics parameters like the infinite multiplication factor, coolant temperature coefficient, void reactivity, fuel temperature coefficient, and moderator temperature coefficient were investigated.

(1) Multiplication Factor

The variation of the infinite multiplication factor, $k_{infinity}$, with fuel burn-up is shown in Figure 2. The calculated results of WIMS-D5 with the 69- and 172-energy group library ENDF/B-VI are in agreement with those of the WIMS-AECL as a function of fuel burn-up. However, the results of the POWDERPUFS-V are not in agreement with the others. Since POWDERPUFS-V was validated for the fresh fuel at the ZED-II reactors, the calculated results of both WIMS-AECL and WIMS-D5 show an under-prediction in terms of infinite multiplication factor. In comparison of the WIMS-D5 and WIMS-AECL, WIMS-D5 with 172-energy group nuclear data library agreed well with WIMS-AECL, but there is a little difference as the fuel burn-up increases. The

differences between WIMS-D5 and WIMS-AECL are 4mk at mid burn-up and 0mk at end burn-up respectively and the relative difference is less than 0.5%. This implies that the WIMS-D5 agreed well with the WIMS-AECL.

(2) Coolant Temperature Coefficients

The coolant temperature coefficients were calculated by POWDERPUFS-V, WIMS-D5 (69- and 172-energy group library) and WIMS-AECL by varying the coolant temperature of 561.0K±10K and coolant density of 0.807859×0.972470(g/cm^3), 0.807859×0.025608(g/cm^3), respectively. In the Figure 3, it is shown that the POWDERPUFS-V under-predicts the coolant temperature coefficient compared to WIMS-codes such as WIMS-AECL and WIMS-D5; (i) lower by 0.010mk/°C to 0.015mk/°C than the WIMS-AECL and (ii) lower by 0.009mk to 0.015mk/°C than the WIMS-D5 with the 172-energy group library. Comparing the WIMS-D5 and WIMS-AECL, the WIMS-D5 is slightly higher by 0.004mk/°C for the 69-energy group and 0.001mk/°C for the 172-energy group respectively.

(3) Void Reactivity

For CANDU reactors using natural uranium fuels, the void reactivity is positive due to a long prompt neutron lifetime. In the design basis accidents such as a large loss-of-coolant accident (LLOCA), the void reactivity is an important parameter affecting the integrity of the fuels and fuel channels. Since the void reactivity leads to overpower, the magnitude and duration of a transient has an effect on the safety of fuel and the reactor. Therefore, it is required to treat an accurate void reactivity and assess the accuracy of this coefficient. Regarding this, the experiment in the ZED-II facility has conducted for fresh fuel at cold conditions so as to provide a set of data aimed at validating the theoretical models and computer codes. However, the uncertainties associated with void reactivity are not well defined due to a lack of experimental data at in-reactor operation conditions. Therefore, the void reactivity worth of a CANDU lattice of the Wolsong Unit 2 was calculated by the lattice codes and was compared with those of the ZED-II experiment.

As for the void reactivity calculated on the assumption of 100% full void in the coolant, it is shown that the POWDERPUFS-V under-predicts the void reactivity compared with the WIMS-D5 and WIMS-AECL at the beginning phase of the burn-up; (i) lower by about 2.0mk for WIMS-D5 with 172-energy group library and about 2.9mk for WIMS-D5 with the 69-energy group library, and (ii) lower by about 0.6mk for the WIMS-AECL.

As the fuel burns up, the difference between the POWDERPUFS-V and WIMS-code (WIMS-D5, WIMS-AECL) increases as shown in Figure 4; (i) POWDERPUFS-V predicts it lower by about 4.6mk(172-energy group) and 5.5mk(69-energy group), compared to the WIMS-D5, and (ii)

4.1mk, compared to the WIMS-AECL at the mid burn-up (4000MWD/T). However, since the POWDERPUFS-V was validated only for the fresh clean fuel, there is an uncertainty of void reactivity prediction using POWDERPUFS-V for an in-reactor operating condition. Therefore, it is required to define well the uncertainties and error allowance associated with void reactivity.

(4) Fuel Temperature Coefficient

While the fuel temperature coefficient is one of the critical safety parameters in light water moderated reactors, it isn't in heavy water moderated CANDU reactors due to the relatively long diffusion time of the thermal neutrons. Although the fuel temperature coefficient hasn't large effect on the reactor safety, it is a parameter for determining the physical characteristic of a reactor core. Taking a fuel temperature as 960.0K±50K, the fuel temperature coefficient was calculated by both the POWDERPUFS-V and WIMS-codes (WIMS-D5 and WIMS-AECL). Figure 5 shows that the fuel temperature coefficient is negative at the beginning of fuel burn-up phase and at the mid burn-up. At the end burn-up, it becomes positive too small to affect the safety of the reactor. The result shows that the POWDERPUFS-V prediction has no difference from those of the WIMS-code at the beginning of the fuel burn-up phase. As the fuel burn-up increases, the POWDERPUFS-V under-predicts the fuel temperature coefficient compared to those of the WIMS-codes (WIMS-D5 and WIMS-AECL); (i) lower by 0.005mk/°C at the mid burn-up and (ii) lower by 0.009mk/°C compared with WIMS-D5 and 0.008mk/°C at th eexit burn-up (8000MWD/T) compared with the WIMS-AECL. The difference between the WIMS-code and POWDERPUFS-V becomes larger with fuel burning-up and WIMS-D5 with 172-energy group library shows a smaller difference from the WIMS-D5 with the 69-energy group.

(5) Moderator Temperature Coefficient

Varying the moderator density 1.085089×0.993998(g/cm^3), 1.085089×1.005365(g/cm^3) and moderator temperature by 341.0K±10.0K, the moderator temperature coefficient was calculated by WIMS-D5, WIMS-AECL and POWDERPUFS-V. Figure 6 shows that while th ePOWDERPUFS-V under-predicts the moderator temperature coefficient at the beginning of fuel burn-up phase, it over-predicts it compared with those of the WIMS-codes from the mid burn-up (about 4000MWD/T); (i) lower by 0.042mk/°C for the WIMS-D5 and by 0.058mk/°C for the WIMS-AECL at the beginning phase respectively and (ii) higher by 0.004mk/°C for the WIMS-D5 and 0.002mk/°C for the WIMS-AECL at the mid burn-up phase respectively. As the difference is varied with fuel burning-up, the prediction of the POWDERPUFS-V shows a lower prediction at the beginning phase and a higher prediction at the end burn-up rather than those of the WIMS-codes. In a comparison of the different physics parameters, the results of the WIMS-D5 with 172-energy group library are in good agreement with those of the WIMS-AECL.

4. CONCLUSIONS

The multiplication factor, $k_{infinity}$, coolant temperature coefficient, void reactivity, fuel temperature coefficient and moderator temperature coefficient, calculated by the WIMS-D5 with the 69- and 172-energy group nuclear data library, and the WIMS-AECL with the 89-energy group nuclear data library and POWDERPUFS-V (PPV), were compared for the uniform lattice of a natural uranium fuel modeled on the CANDU-6 reactor at Wolsong. The conclusions are as follows:

1. POWDERPUFS-V over-predicted the multiplication constant compared to WIMS-D5 and WIMS-AECL. The results for the coolant/fuel temperature coefficient and void reactivity show that the POWDERPUFS-V under-predicts them when compared with the WIMS-D5 and WIMS-AECL and the difference becomes larger with fuel burn-up. It implies that the uncertainty is increasing with fuel burn-up since the POWDERPUFS-V was validated for the fresh clean fuel.
2. WIMS-D5 results with the ENDF/B-VI library of 172-energy group shows a smaller difference from the WIMS-AECL results, when compared to the WIMS-D5 results with the 69- energy group library. This means that it is necessary to assess the cross section for each energy level of a neutron, from the fact that the WIMS-AECL uses an 89-energy group nuclear data library.
3. The WIMS-D5 with the 172-energy group library ENDF/B-VI under-predicts the $k_{infinity}$, fuel temperature coefficient and moderator temperature coefficient in the range of about 5mk, 2microk/°C and 7microk/°C, respectively. And it over-predicts coolant temperature coefficient and void reactivity in the range of about 1microk/°C and 0.55mk respectively, compared to the prediction of the WIMS-AECL with the 89-energy group library.

ACKNOWLEDGEMENT

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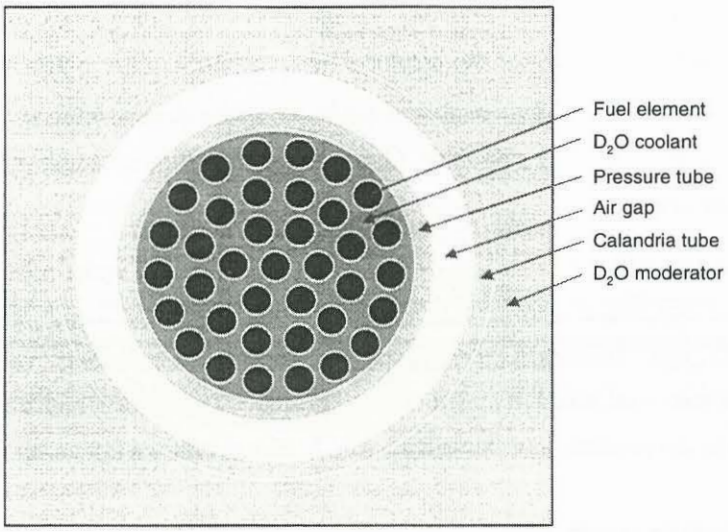

Figure 1 CANDU CELL

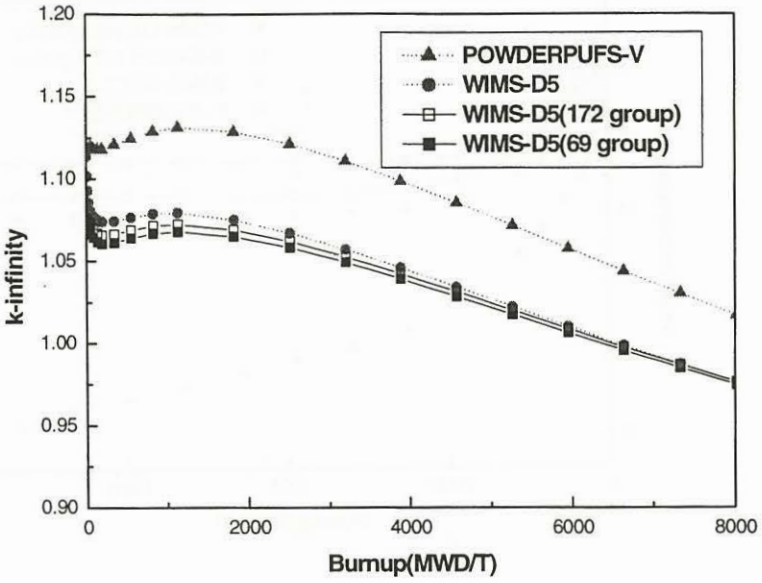

Figure 2 Multiplication constant

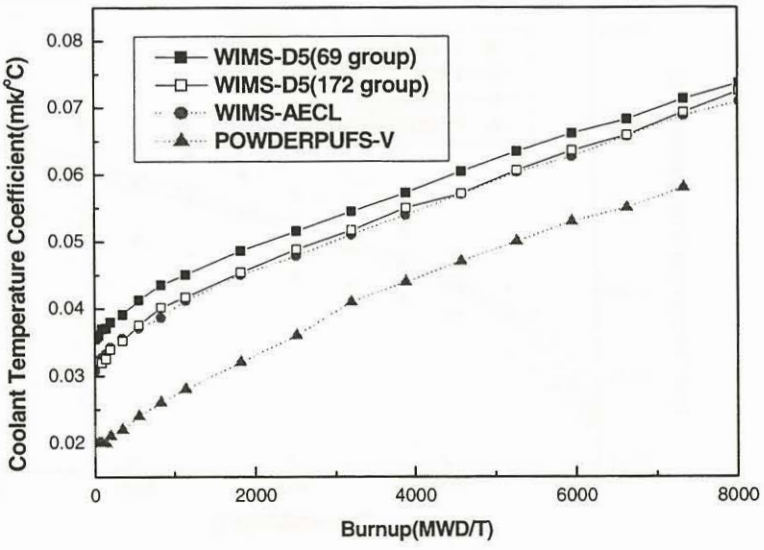

Figure 3 Coolant temperature coefficient

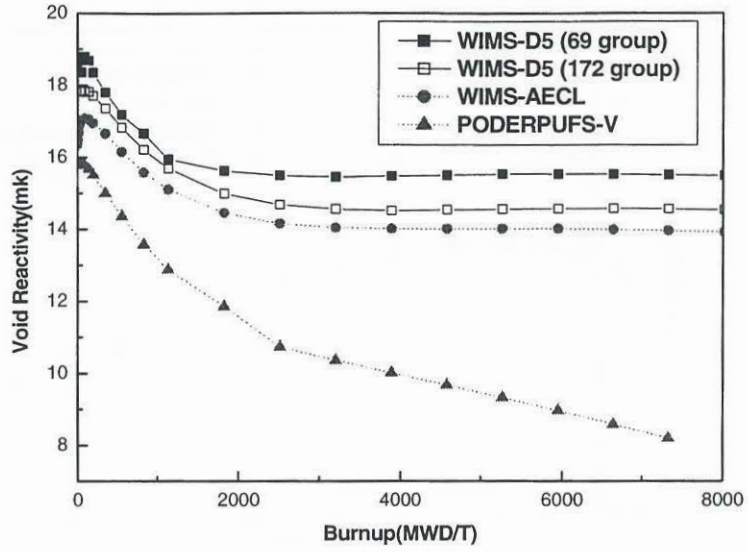

Figure 4 Void reactivity

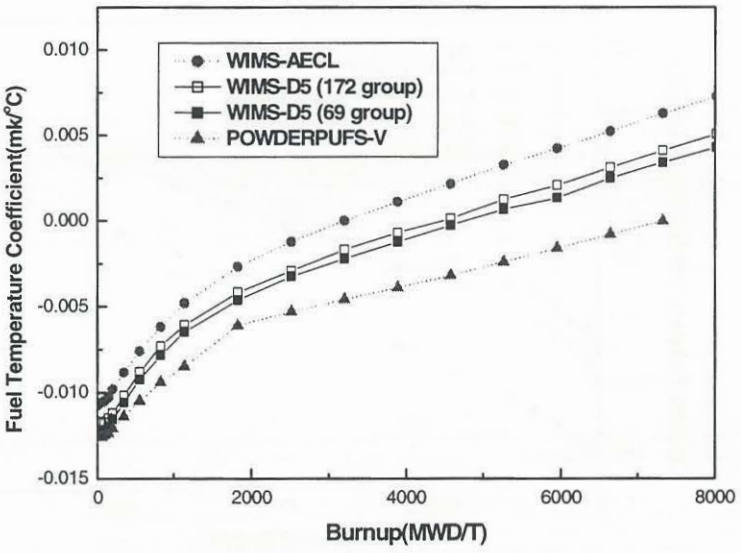

Figure 5 Fuel temperature coefficient

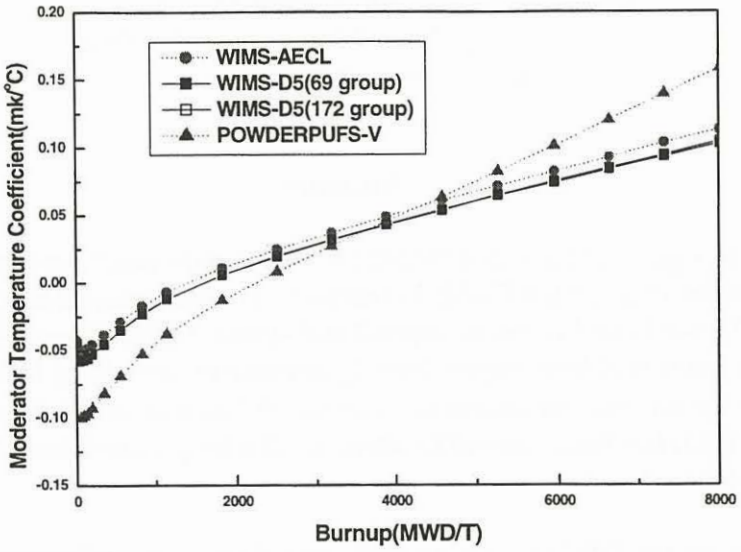

Figure 6 Moderator temperature coefficient