VALIDATION OF 3-DIMENSIONAL NEUTRON TRANSPORT CALCULATIONS OF CANDU REACTIVITY DEVICES

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ABSTRACT

The reactor physics analysis techniques used to represent the reactivity control devices of CANDU® reactors are an important component of the analysis methodology. The particular configuration of CANDU reactors, horizontal fuel channels separated by heavy-water moderator and interstitial reactivity control devices, results in a true 3-dimensional (3-D) problem, and the neutronic characteristics of this problem require that the neutron-flux solution be performed in 3-D calculations. The application of 3-D neutron-transport calculations in the DRAGON code to this problem has been successfully validated for three types of CANDU reactivity-control devices: light-water liquid zone-control rods, adjuster rods, and shutoff rods/mechanical-control absorbers.

1. INTRODUCTION

The reactor physics analysis techniques used to represent the reactivity control devices of CANDU reactors are an important component of the analysis methodology. The particular configuration of CANDU reactors, horizontal fuel channels separated by heavy-water moderator and interstitial reactivity control devices, results in a true 3-dimensional (3-D) problem, and the neutronic characteristics of this problem require that the neutron-flux solution be performed in 3-D calculations.

The configuration of the reactivity control devices in a CANDU reactor requires complex neutronic analyses outside of conventional lattice-cell calculations. The "basic" lattice of a typical CANDU reactor consists of horizontal fuel channels of a radius about 7 cm, consisting of fuel, cladding, coolant, and pressure and calandria tubes, on a square pitch of about 29 cm. Between the fuel channels is heavy-water moderator, in which reactivity devices are positioned in interstitial configurations, and mainly vertical orientations. CANDU reactors have three main types of reactivity devices: light-water-filled liquid zone compartments (LZCs), stainless-steel adjuster rods, and cadmium mechanical-control absorbers (MCAs) and shutoff rods (SORs). Their radii are typically in the range of 4.5 to 6.6 cm.

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The method that has recently been adopted for performing 3-D neutron-transport calculations for CANDU reactivity devices is based on application of the DRAGON [1] code. The DRAGON computer code was developed at the Institut de Génie Nucléaire, École Polytechnique de Montréal. It allows a selection of models that can simulate the neutron-flux distribution inside a unit cell or fuel assembly within a nuclear reactor, including all the functions that characterize a lattice-cell code. A particular strength of the DRAGON code is its ability to perform neutron-transport calculations in a range of 1-, 2-, and 3-dimensional geometries (such as mixed Cartesian and $R-\theta-Z$ geometries) in a collision-probability formalism, allowing practical CANDU analyses to be performed with the required spatial discretization and precision. The DRAGON code is able to use nuclear data from libraries in a variety of formats, including that of the 89-energy-group library, derived from ENDF/B-V for use with WIMS–AECL [2,3] in standard CANDU lattice-cell calculations.

The method used to represent reactivity-control devices in CANDU reactor-core models is to add incremental cross sections representing the neutronic characteristics of these devices to the unperturbed lattice cross sections. The region over which the incremental cross sections are applied is chosen to approximate the spatial extent over which the local perturbation caused by the reactivity device is significant; the dimensions of this region are typically the device length by one lattice pitch by one bundle length. The required incremental cross sections are calculated from the results of 3-D calculations in 89 energy-groups, with a typical spatial extent of between one and a few lattice cells, by computing the difference in homogenized-region cross sections in the appropriate region, with and without the device present.

To qualify the application of DRAGON to CANDU reactivity-device analyses, the results of those calculations must be validated against measurements. An important component of this validation is comparison of calculated device reactivity worths against measurements made during reactor commissioning. In this document, comparisons are made between calculated reactivity-device properties and data from the commissioning of two CANDU reactors, Pickering-A Unit 4 and Darlington-NGSA Unit 4. The reactivity measurements were made by reactivity balances against dissolved neutron poisons in the moderator, and by inter-device reactivity balances.

2. CANDU REACTIVITY DEVICE MEASUREMENTS

The reactivity-device measurements analyzed in this document were all performed in CANDU reactors during low-power commissioning with fresh natural-uranium fuel, referred to as “Phase B” measurements. Measurements in two different CANDU reactors were analyzed, LZCs and adjuster rods in Pickering-A Unit 4, and SOR and MCA rods in Darlington NGS-A Unit 4. The method used to measure the reactivity worth of the devices was by reactivity balance against added poisons or intercalibration between different devices. The methods used for the three reactivity-device types discussed in this document were as follows:

- Liquid zone-control compartments: these (14 in the Pickering-A Unit 4 reactor) are cylindrical devices containing light water and helium gas, the level of light-water being varied under automatic control of the reactor-regulating system to implement bulk and spatial control. These devices were calibrated by adding pre-weighed batches of neutron poisons (boron) to the moderator, and measuring the average LZC levels at criticality.
- Stainless-steel adjuster rods: these devices (6 in the Pickering-A Unit 4 reactor) are cylindrical tubes which may be moved in or out of the reactor core under automatic control of the reactor regulating system, but are normally positioned in the core. These devices were calibrated against the LZC system by sequentially or individually withdrawing or inserting adjuster rods and measuring the average LZC

levels at criticality.

- Shutoff rods: these devices (32 in the Darlington NGS-A Unit 4 reactor) are cylindrical tubes of stainless-steel sandwiched cadmium, normally residing out of the core which are inserted into the reactor to rapidly reduce core reactivity. The 4 MCAs are physically identical to the SORs, and were also measured. These devices were calibrated against the LZC system by individually inserting rods and measuring the average LZC levels at criticality.

3. METHOD OF CALCULATION

All of the lattice-cell calculations for the reference lattices without reactivity-control devices present were performed using the WIMS–AECL code with an 89-energy-group ENDF/B-V nuclear data library. All of the reactor-core calculations were performed in two-energy-group diffusion-theory simulations using the RFSP [4] code. The WIMS–AECL lattice-cell calculations and RFSP core calculations are the standard methodology for the analysis of CANDU reactors.

All of the 3-D neutron-transport calculations used to generate the reactivity-device properties were performed using the DRAGON code. In this study, DRAGON has been used primarily as a "supercell" code to calculate the incremental properties representing CANDU reactivity devices. The overall calculational strategy can be summarized as follows:

1. Two-dimensional (2-D) cluster cell calculations in 89 energy groups;
2. 89-group macroscopic cross-section (Σ) computations using the 2-D results;
3. Homogenization of fuel-cladding-coolant region without energy condensation;
4. Cylinderization of the reactivity device, if necessary;
5. Two-bundle-model 3-D supercell calculation with and without the reactivity device; and
6. Incremental cross sections ($\Delta\Sigma$) calculation using the difference between the previous 3-D results.

After the k_{eff} calculations in Step 5, all cross sections were homogenized and condensed into 2-energy-group properties. The $\Delta\Sigma$ results from Step 6, as produced by DRAGON for the reactivity devices, are subsequently used as standard input to the RFSP code to perform 3-D core diffusion calculations in 2-energy-groups.

All of the DRAGON calculations were performed with geometric models based on the standard 28.575 cm-square unit cells, and with material properties representing natural-uranium fuel and conditions of the Phase B measurements for each of the reactors under study. The supercell geometry used in the 3-D DRAGON models is illustrated in Figure 1. The models were all of dimensions 2 lattice pitches $\times$ 1 lattice pitch $\times$ 1 bundle length (57.150 cm $\times$ 28.575 cm $\times$ 49.520 cm), which is the normal supercell size given the device arrangement and symmetries in the reactor cores.

The incremental properties representing the effect of each reactivity device in the reactor core are formed by homogenizing over the inner sub-region of the model presented in Figure 1. The homogenization region is defined to be centered on the reactivity device and to extend from the centre of one fuel bundle to the centre of the next fuel bundle along the x axis as shown in Figure 2. The homogenization region used was selected

from the results of a sensitivity analysis considering theoretical rigor, and model preparation and processing effort.

4. RESULTS

The reactivity worth of the LZCs in the Pickering-A Unit 4 reactor was measured by recording the average LZC light-water fills required to balance the addition of pre-measured amounts of boron dissolved in the moderator. The results of analyses of LZC reactivity-worth measurements with the adjuster rods positioned in-core are presented in Table I, and of LZC measurements with the adjuster rods out-of-core are presented in Table II. The "simulation error" was computed from the difference between the reactivity changes calculated from changes in moderator boron and the reactivity changes calculated from the changes in LZC fills:

$$\text{Simulation Error}(\%) = \frac{100 \times (\rho_{\text{LZC}} - \rho_{\text{B}})}{\rho_{\text{B}}} \tag{1}$$

The calculated results are in good agreement with measurement: an average error of $-4.2 \pm 5.9\%$ in the configuration with all adjusters inserted and $-6.3 \pm 2.6\%$ with the adjusters withdrawn. These two agreements are not different statistically, and combine to give an average of $-5.3 \pm 2.4\%$.

The reactivity worths of the adjusters in the Pickering-A Unit 4 reactor were measured by recording the changes in average LZC fills required to balance changes in adjuster-rod configurations. The results of analyses of adjuster-rod-worth measurements during insertion of individual rods while all other rods are kept withdrawn from the core are presented in Table III. The analysis results of sequential withdrawal of individual rods beginning from the configuration with all rods inserted are presented in Table IV. The "simulation error" was computed from the difference between the reactivity changes calculated from changes in adjuster-rod configuration and the reactivity changes calculated from the changes in LZC fills:

$$\text{Simulation Error}(\%) = \frac{100 \times (\rho_{\text{ADJ}} - \rho_{\text{LZC}})}{\rho_{\text{LZC}}} \tag{2}$$

The adjuster-rod reactivity-worth calculations were in agreement with the measurements in the individual-rod insertions to $-4.5 \pm 1.0\%$, and with the sequential-withdrawal measurements were in agreement to $-6.8 \pm 3.2\%$. These two agreements are not different statistically, and combine to give and average of $-5.7 \pm 1.0\%$.

The reactivity worths of the SORs and MCAs in the Darlington-NGSA Unit 4 reactor were measured by recording the changes in average LZC fills required to balance changes in rod configurations. The results of analyses of sequential insertion of MCAs is presented in Table V, of sequential withdrawal of individual rods beginning from the configuration of all rods inserted are presented in Table VI, and of individual rod insertions with all adjusters out-of-core are presented in Table VII. The results of analyses of SOR worth measurements during insertion of individual rods while all other rods are kept withdrawn from the core are presented in Table VIII. During the sequential MCA insertion and withdrawal measurements, initial average LZC fills were adjusted by changing moderator boron concentrations. The simulation errors in these analyses were calculated in the same way as for adjuster rods, using Equation 2.

The agreement in the Darlington analyses between calculated and measured reactivity balance between the

light-water-filled liquid zone compartments and the MCAs was $-1.7 \pm 2.4\%$ during sequential insertion, $-5.0 \pm 6.5\%$ during sequential MCA withdrawal, and $-8.4 \pm 4.9\%$ during individual MCA insertions. One of the sequential withdrawal measurements (MCA 1) appears to be in error, resulting in an apparently large simulation error ($> 5\sigma$ of the other sequential withdrawal and insertion measurements) but was not dropped from the averages. In the analysis of the reactivity worths of SORs during individual rod insertions, the calculations agreed with the measurements to about $-6.6 \pm 4.2\%$. The agreements between individual SOR and MCA insertions are consistent, and combine to give an average of $-7.5 \pm 3.2\%$. The agreements between sequential MCA insertions and withdrawals is consistent, and combine to give an average of $-3.4 \pm 2.3\%$.

5. CONCLUSIONS

The application of 3-D neutron-transport calculations of CANDU reactivity-device properties with the DRAGON code has been validated against measurements made in the Pickering-A Unit 4 and Darlington-NGSA Unit 4 reactors. The calculation accuracy obtained for each of the measured devices can be described as follows:

- The reactivity worth of the liquid zone control devices was calculated to be on average $5.3 \pm 2.4\%$ less than the calculated worth of measured changes in moderator boron concentration.
- The reactivity worth of adjuster rods was calculated to be on average $5.7 \pm 1.0\%$ less than the calculated worth of measured changes in the liquid zone control devices.
- The reactivity worth of individual shutoff and mechanical-control rods was calculated to be on average $6.6 \pm 4.2\%$ less than the calculated worth of measured changes in the liquid zone control devices. The corresponding agreement during sequential insertion and withdrawal of the mechanical-control rods was $-3.4 \pm 2.3\%$.

In all cases, the calculated device reactivity worths were slightly less than the calculated worths of measured changes in moderator boron. These levels of agreement are considered to be within an acceptable range for commissioning measurements.

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REFERENCES

1. G. Marleau, A. Hébert, and R. Roy, "A User Guide for Dragon Version DRAGON_980911 Release 3.03", Technical Report IGE-174 Revision 4, École Polytechnique de Montréal, 1998 September.
2. J. R. Askew, F. J. Fayers, and P. B. Kemshell, "A General Description of the Lattice Code WIMS", *Journal of the British Nuclear Engineering Society*, 5:564–585, 1966.

3. J.V. Donnelly, "WIMS–CRNL: A User's Manual for the Chalk River Version of WIMS", Atomic Energy of Canada Limited Report, AECL-8955, 1986 January.

4. B. Rouben, "Overview of Current RFSP-Code Capabilities for CANDU Core Analysis", Atomic Energy of Canada Limited Report, AECL-11407, 1996.

Table I: LZC Reactivity Worth with Adjusters In-Core

Boron Concentration (ppm)	Calculated Boron Reactivity Change (mk)	LZC Fill (%)	Calculated LZC Reactivity Change (mk)	Simulation Error (%)
9.850	0.00	88.4	0.000	—
9.906	0.39	74.3	0.42	$+7.7$
9.963	0.79	65.0	0.73	-7.6
10.019	1.18	56.1	1.05	-12.4
10.076	1.58	45.0	1.51	-4.4
10.132	1.97	38.5	1.82	-7.6
10.189	2.36	29.3	2.28	-4.2
10.245	2.75	21.0	2.73	-0.7
Average				-4.2 ± 5.9 %

Table II: LZC Reactivity Worth with Adjusters Out-of-Core

Boron Concentration (ppm)	Calculated Boron Reactivity Change (mk)	LZC Fill (%)	Calculated LZC Reactivity Change (mk)	Simulation Error (%)
11.261	0.00	91.4	0.000	—
11.317	0.39	79.4	0.36	-7.7
11.374	0.79	68.4	0.71	-10.1
11.430	1.18	56.8	1.12	-5.1
11.487	1.57	48.4	1.44	-8.3
11.543	1.97	38.5	1.85	-6.1
11.599	2.36	30.0	2.24	-5.1
11.656	2.75	19.9	2.71	-1.5
Average				-6.3 ± 2.6 %

Table III: Individual Adjuster Reactivity Worth Starting with Adjusters Out-of-Core

Adjuster Rod	Average Zone Level		Calculated LZC Reactivity Worth (mk)	Calculated ADJ Reactivity Worth (mk)	Simulation Error (%)
	ADJ out Initial (%)	ADJ in Final (%)			
AA-7	73.5	35.5	1.43	−1.39	−2.8
AA-12	73.7	34.5	1.48	−1.40	−5.4
AA-9	73.5	34.6	1.47	−1.40	−4.8
AA-10	73.5	35.1	1.45	−1.39	−4.1
AA-8	73.6	20.2	2.26	−2.13	−5.8
AA-11	73.3	20.1	2.22	−2.13	−4.1
Average					-4.5 ± 1.0 %

Table IV: Adjuster Reactivity Worths During Sequential Withdrawal Starting with Adjusters In-Core

Adjuster Rod	Average Zone Level		Calculated LZC Reactivity Worth (mk)	Calculated ADJ Reactivity Worth (mk)	Simulation Error (%)
	ADJ out Initial (%)	ADJ in Final (%)			
AA-7	21.0	46.8	−1.30	1.12	−13.8
AA-12	31.3	54.9	−1.09	1.02	−6.4
AA-9	29.6	60.3	−1.41	1.35	−4.3
AA-10	30.5	58.1	−1.28	1.20	−6.3
AA-8	29.3	71.9	−1.78	1.68	−5.6
AA-11	20.9	73.0	−2.10	2.01	−4.3
Average					-6.8 ± 3.2 %

Table V: Sequential MCA Insertion Reactivity Worths

MCA Rod	Average Zone Level		Calculated LZC Reactivity Worth (mk)	Calculated MCA Reactivity Worth (mk)	Simulation Error (%)
	MCA Out Initial (%)	MCA In Final (%)			
1	69.8	43.0	1.77	−1.72	−2.8
4	70.8	34.0	2.39	−2.37	−0.8
3	71.3	41.3	1.92	−1.95	+1.6
2	73.0	19.0	3.24	−3.08	−4.9
Average					-1.7 ± 2.4 %

Table VI: Sequential MCA Withdrawal Reactivity Worths

MCA Rod	Average Zone Level		Calculated LZC Reactivity Worth (mk)	Calculated MCA Reactivity Worth (mk)	Simulation Error (%)
	MCA Out Initial (%)	MCA In Final (%)			
2	19.0	70.5	-3.31	3.24	-2.1
3	32.5	60.4	-1.94	1.93	-0.5
4	25.5	60.4	-2.49	2.46	-1.2
1	23.7	51.7	-2.09	1.75	-16.2
Average					-5.0 ± 6.5 %

Table VII: Individual MCA Insertion Reactivity Worths

MCA Rod	Average Zone Level		Calculated LZC Reactivity Worth (mk)	Calculated MCA Reactivity Worth (mk)	Simulation Error (%)
	MCA Out Initial (%)	MCA In Final (%)			
1	64.8	31.2	2.05	-1.89	-7.8
2	64.9	27.9	2.01	-2.02	-0.5
3	65.1	27.8	2.32	-2.04	-12.1
4	64.1	29.2	2.16	-1.88	-13.0
Average					-8.4 ± 4.9 %

Table VIII: Individual SOR Reactivity Worths

SOR Rod	Average Zone Level		Calculated LZC Reactivity Worth (mk)	Calculated SOR Reactivity Worth (mk)	Simulation Error (%)
	SOR Out Initial (%)	SOR In Final (%)			
1	63.7	54.5	0.63	−0.59	−6.3
2	63.7	44.2	1.36	−1.31	−3.7
3	63.7	43.2	1.42	−1.34	−5.6
4	63.7	53.5	0.68	−0.60	−11.8
5	63.7	46.5	1.17	−1.07	−8.5
6	63.7	38.0	1.73	−1.61	−6.9
7	63.7	45.2	1.26	−1.10	−12.7
8	63.7	48.6	1.04	−0.94	−9.6
9	63.7	48.0	1.08	−0.95	−12.0
10	63.7	45.6	1.30	−1.22	−6.2
11	63.7	40.2	1.71	−1.61	−5.8
12	63.7	37.0	1.96	−1.93	−1.5
13	63.7	34.0	2.13	−2.16	+1.4
14	63.7	36.0	2.02	−1.95	−3.5
15	63.7	39.1	1.77	−1.60	−9.6
16	63.7	44.3	1.39	−1.21	−12.9
17	63.4	44.8	1.35	−1.23	−8.9
18	63.0	39.8	1.69	−1.63	−3.6
19	63.0	36.0	1.99	−1.98	−0.5
20	62.8	33.7	2.11	−2.17	+2.8
21	62.8	36.2	1.94	−1.91	−1.5
22	63.2	39.4	1.72	−1.58	−8.1
23	63.0	44.1	1.36	−1.20	−11.7
24	63.2	47.2	1.11	−0.97	−12.6
25	62.8	47.8	1.04	−0.93	−10.6
26	62.8	45.4	1.21	−1.12	−7.4
27	62.7	37.5	1.69	−1.63	−3.6
28	63.0	45.4	1.20	−1.06	−11.7
29	63.2	53.6	0.66	−0.62	−6.1
30	63.0	43.0	1.40	−1.35	−3.6
31	63.0	43.5	1.36	−1.31	−3.7
32	63.0	53.8	0.62	−0.58	−6.5
Average					-6.6 ± 4.2 %

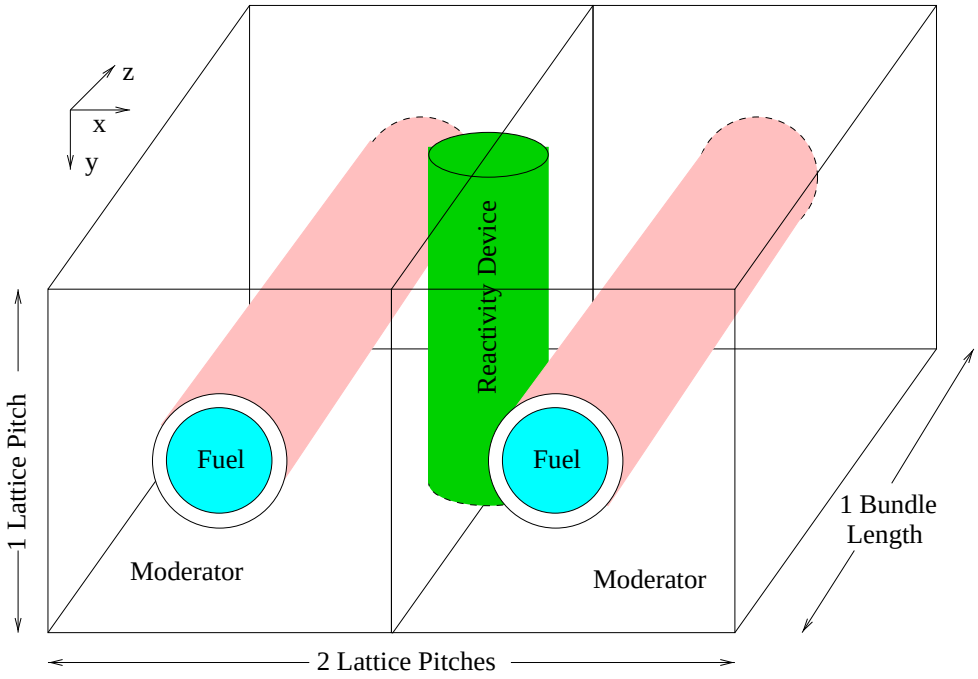

Figure 1: Typical Supercell Model Used in DRAGON

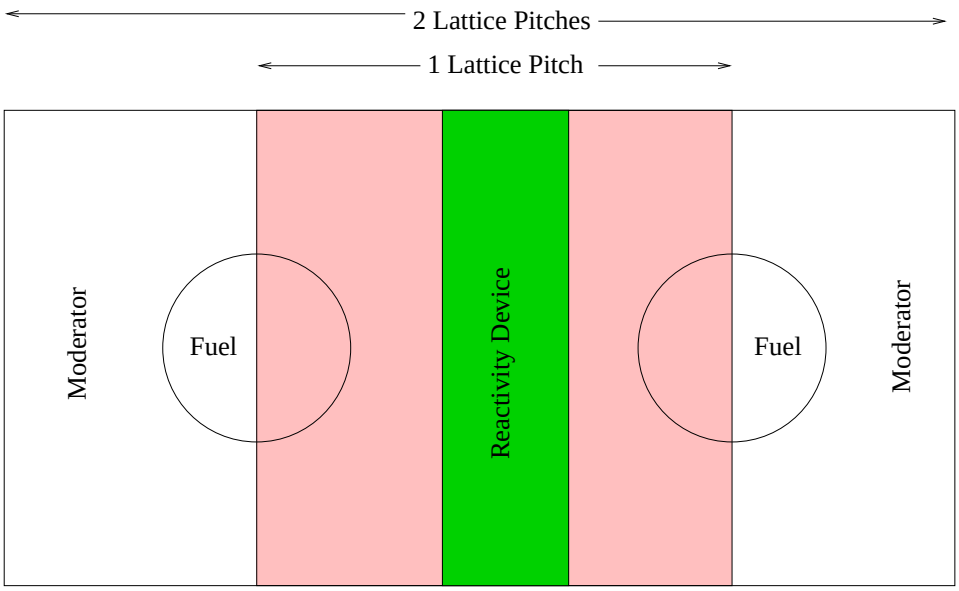

Figure 2: Homogenization Region Used in DRAGON Models