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WIMS-AECL/MULTICELL Calculations with SPH for Wolsong-1 Reactivity Devices

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Abstract

Simulations of Wolsong-1 Phase-B commissioning measurements have been performed, as part of the program to validate WIMS-AECL lattice cell calculations for application to CANDU reactor simulations in RFSP. A required component of these simulations is the calculation of incremental cross sections representing reactivity control devices in the reactor. The incremental cross section properties of the Wolsong-1 adjusters, Mechanical Control Absorbers (MCA) and liquid Zone Control Units (ZCU) are based on the WIMS-AECL/MULTICELL modelling methods and the results are compared with those of WIMS-AECL/DRAGON-2 modelling methods.

1. Introduction

The modelling of reactivity control devices in CANDU reactor is an important component of the reactor physics analysis techniques. The analysis of movable reactivity devices in CANDU reactors is a three-dimensional problem, because the geometry in CANDU reactors has the horizontal fuel channels and vertical reactivity devices.

A calculation method [1] of the three-dimensional neutron flux distribution for CANDU reactivity control devices has been developed. WIMS-AECL [2] is used for all neutron transport calculations in one or two dimensions. The SPH method [3] produces homogenized-region cross section data such that the diffusion-theory calculation in MULTICELL [4] will preserve the results of the WIMS-AECL transport calculation for the geometry in the original model. The neutron flux in models representing reactivity devices in a lattice of fuel channels is solved using conventional two-energy-group, finite-difference, three-dimensional diffusion theory. Representation of reactivity devices in the reactor core is calculated by using incremental cross sections in the RFSP code [5]. DRAGON-2 [6], a three-dimensional transport code, was used with cross section calculated from WIMS-AECL results, for numerical benchmark comparisons with MULTICELL.

The results for the analysis of Wolsong-1 CANDU reactivity devices are calculated using the new methodology, and compared with Wolsong-1 Phase-B measured data in this paper.

2. Method

2.1 WIMS-AECL Calculations

A WIMS-AECL Version 2-4x calculation with the 89-energy group ENDF/B-V nuclear data library is performed for the lattice cell calculations. The geometric models represents the configuration

of fuel, cladding, D_2O coolant, pressure and calandria tubes, and D_2O moderator in two dimensions. The models of reactivity devices in WIMS-AECL are designed to simulate those devices accurately in one- or two-dimensional geometry with representative environments of the devices.

2.2 CONDENS Calculations and Homogenization

The cross-section data in 33 energy groups calculated by WIMS-AECL is condensed by the CONDENS code into two neutron energy groups for all following calculations. The two neutron energy groups are: group 1 "fast" for neutron energies greater than 0.625 eV, and group 2 "thermal" for neutron energies less than 0.625 eV.

The homogenized properties of selected regions of the WIMS-AECL solution are calculated to form properties of the "cell-of-interest" for use in the MULTICELL calculations. All of the reactor core calculations were performed with the RFSP code (version 2-09hp).

2.3 SPH Homogenization

The neutron flux distribution near strong sources may not be accurately solved using homogenized-region diffusion theory. The diffusion-theory solution may deviate from the original transport solution when conventional homogenized cross sections are applied. These deviations are generally significant within a CANDU unit cell, especially when reactivity devices are present.

In the SPH method, the solution to a homogenized-region flux calculation of the desired form is compared to the existing heterogeneous solution and iteratively improved according to the procedure developed by the SPH developers [3], until the two solutions are consistent.

The SPH method has been implemented in the REGAV code, and calculates an SPH factor $\mu_{i,m}$ for each energy group "i" and homogenized zone "m". The cross sections are modified:

$$\Sigma_{i,a,m} = \mu_{i,m}\Sigma_{i,a,m} \tag{1}$$

$$\Sigma_{s,m,i\to j} = \mu_{i,m}\Sigma_{s,m,i\to j} \tag{2}$$

$$\nu\Sigma_{i,f,m} = \mu_{i,m}\nu\Sigma_{i,f,m} \tag{3}$$

$$\Sigma_{i,tr,m} = \Sigma_{i,tr,m}/\mu_{i,m} \tag{4}$$

The $\mu_{i,m}$ are calculated iteratively according to the procedure specified in Reference 3.

To apply the SPH factors calculated in REGAV for one-dimensional radial geometry to the three dimensional Cartesian geometry used in MULTICELL, it is necessary to preserve the effective mesh spacings in two calculations. The overall scale of mesh spacings in each region can be controlled in the input to REGAV. So long as the mesh sizes in REGAV and MULTICELL are reasonably small compared to the mean-free-paths in the homogenized materals, the SPH factors will be relatively mesh-independent.

2.4 MULTICELL Models

Three types of WIMS-AECL models are prepared for each zone of the MULTICELL model. These are "fuel region", "moderator" and "device" models. To simplify preparation of the MULTICELL input while varying cross sections, mesh distributions and material distributions, a utility code,

GENMCL, was written. The GENMCL code looks after all of the detailed generation of MULTICELL input from a relatively simple specification of the problem by the user. The unit cell size used in the models in this study was 14.2875 by 14.2875 by 24.765 cm, with the device at one edge and the fuel in middle of the cell, oriented perpendicularly to the adjuster, similar to that shown in Figure 1.

2.5 DRAGON-2 Models

The computer code DRAGON-2 results from an effort at École Polytechnique de Montréal to rationalize and unify a number of different models and algorithms used to solve the neutron transport equation and to facilitate the development of new calculation techniques. The models used in DRAGON-2 were constructed to be equivalent to the MULTICELL models, although the geometric capabilaties in DRAGON-2 required coarser spatial discretization and allowed the cylindrical structures to be represented explicitly. Homogenized-region cross sections to be used in DRAGON-2 were derived from the same WIMS-AECL models as for the MULTICELL calculations. It should be noted that these DRAGON-2 calculations used only cross sections calculated from WIMS-AECL results, rather than cross sections calculated internally within DRAGON-2.

The unit cell size used in the models in this study was 14.2875 by 14.2875 by 24.765 cm, including one quarter of a fuel bundle and an adjuster rod. Geometry and homogenized region for incremental cross sections in RFSP are shown in Figure 1 and Figure 2, respectively.

3. Results

3.1 Wolsong-1 Phase-B Measurements

Measurements of the reactivity worth of the ZCU, ADJ and MCA in the Wolsong-1 CANDU-6 reactor during Phase-B Commissioning(fresh fuel configuration) are analyzed in this paper. Figure 3 presents the measured and calculated ZCU reactivity worth. The reactivity worth of boron was calculated to be 7.851 mk per ppm B (8.644 mk per ppm B in PPV [7]). The calculated ZCU reactivity worth (6.89 mk) agrees to within 1 percent of the measured value (6.82 mk).

Adjuster reactivities were measured by withdrawing single rods. Table 1 presents the measured and calculated adjuster rods reactivity worths. The results in Table 1 indicate the calculated adjuster rods reactivity worths agree on average to within 8 percent of the measured values. This error is slightly higher than PPV results [7].

Measurements of the reactivity worth of the MCA's relative to dissolved boron in the moderator and the ZCU's are presented in Table 2. Table 2 shows the measured and calculated MCA reactivity worths. The results in Table 2 indicate that the calculated MCA reactivity worths agree on average to within 1 percent of the measured values.

3.2 Comparison of WIMS/MULTICELL and WIMS/DRAGON-2

The results in Table 3 show that the incremental cross sections calculated for stainless steel adjuster rods are in very good agreement between MULTICELL and DRAGON-2 (0.1% agreement in $\Delta\Sigma_{a,2}$). For ZCU , the agreement is not quite as good as in the adjuster rod case (-1.4% agreement in $\Delta\Sigma_{a,2}$), but is still considered quite acceptable. For the MCA's, there is an appreciable discrepancy between the MULTICELL and DRAGON-2 results (-13.8% discrepancy in $\Delta\Sigma_{a,2}$). The worsening trend in agreement between MULTICELL and DRAGON-2 is consistent with greater challenge to the SPH treatment and diffusion theory in MULTICELL with the strong absortions and three-dimensional flux gradients associated with the MCA's. A number of the approximations involved in the WIMS-AECL/MULTICELL models of the MCA's were investigated, but none were found to change the fundamental discrepancy significantly.

4. Conclusion

A new method [1] is used for the analysis of Wolsong-1 CANDU reactivity devices, based on WIMS-AECL transport calculations, SPH homogenization and MULTICELL diffusion calculations. DRAGON-2 transport calculations are used for comparison with MULTICELL diffusion calculations. In validation comparisons with measurements in Wolsong-1 CANDU reactors, calculated reactivity worths of Mechanical Control Absorbers and Zone Control Units are in good agreement with measured values, but those of adjuster rods are slightly lower than PPV results [7].

We still have an effort to make a good agreement between measured value and calculated value for CANDU reactivity devices. Further works will be needed that the cross sections calculated internally within DRAGON-2.

5. References

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Table 1. Measured and Calculated Adjuster Rods Reactivity Worths in Wolsong-1

Adjuster Rod	Initial Zone Fill (%)	Final Zone Fill (%)	Measured Worth (mk)	Calculated Worth (mk)	Agreement (%)
1	36.66	39.76	0.24	0.225	-6.3
2	36.58	44.62	0.58	0.541	-6.7
3	36.51	46.21	0.69	0.658	-4.6
4	36.42	42.34	0.44	0.341	-22.5
5	36.52	46.46	0.697	0.650	-6.7
6	36.40	44.84	0.61	0.533	-12.6
7	36.61	39.85	0.25	0.222	-11.2
8	36.63	40.12	0.27	0.259	-4.1
9	36.55	47.00	0.72	0.689	-4.3
10	36.50	50.05	0.88	0.883	+0.3
11	36.47	45.07	0.59	0.482	-18.3
12	36.19	49.39	0.86	0.874	+1.6
13	35.68	47.51	0.78	0.689	-11.7
14	36.38	40.10	0.28	0.261	-6.8
15	36.72	39.42	0.21	0.226	+7.6
16	36.63	44.56	0.57	0.539	-5.4
17	36.40	46.61	0.71	0.660	-7.0
18	36.68	42.68	0.45	0.346	-23.1
19	36.43	47.00	0.73	0.655	-10.3
20	36.47	44.56	0.60	0.533	-11.2
21	36.49	39.69	0.20	0.219	+9.5
Total			11.357	10.485	-7.7

Table 2. Measured an Calculated MCA Reactivity Worths in Wolsong-1

MCA Rod	Initial Zone Fill (%)	Final Zone Fill (%)	Measured Worth (mk)	Calculated Worth (mk)	Agreement (%)
1	57.68	30.07	2.045	2.09	+2.2
2	58.61	28.93	2.196	2.08	-5.3
3	58.00	30.26	2.050	2.09	+2.0
4	57.24	28.92	2.112	2.07	-2.0
Average			2.101	2.08	-1.0

Table 3. MULTICELL and DRAGON-2 Incremental Cross Sections for Wolsong-1 Reactivity Devices (10^{-3} CM^{-1})

Method of Calculation	$\Delta\Sigma_{tr,1}$	$\Delta\Sigma_{tr,2}$	$\Delta\Sigma_{a,1}$	$\Delta\Sigma_{a,2}$	$\Delta\Sigma_{m}$	$\Delta\nu\Sigma_{f}$
MULTICELL A-INNER	1.076	1.787	0.021	0.628	0.127	-0.026
DRAGON-2 A-INNER	1.005	1.879	0.028	0.627	0.095	0.004
MULTICELL ZCU-1F	17.261	134.3	0.180	1.223	0.067	2.701
DRAGON-2 ZCU-1F	20.608	148.7	0.202	1.240	0.053	-0.033
MUTICELL MCA	1.239	4.000	0.167	4.544	0.886	-0.061
DRAGON-2 MCA	0.825	7.337	0.216	5.272	0.714	0.016

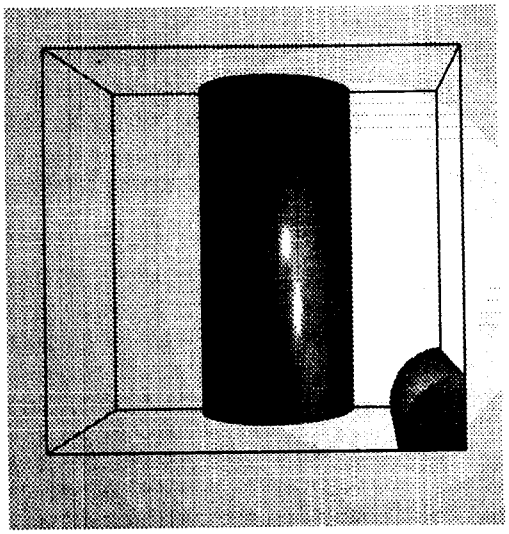

Figure 1. Geometry Used in MULTICELL and DRAGON-2 Reactivity Device Models

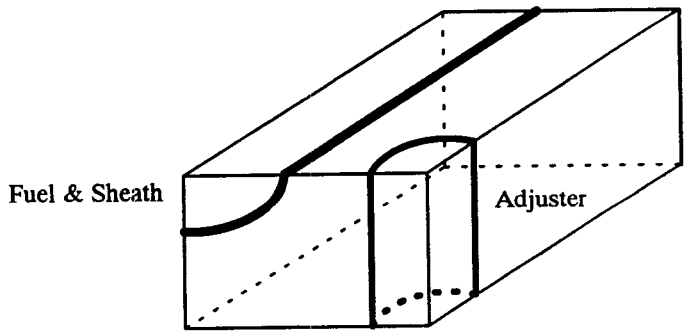

Figure 2. Homogenized Region Geometry for RFSP Incrementals

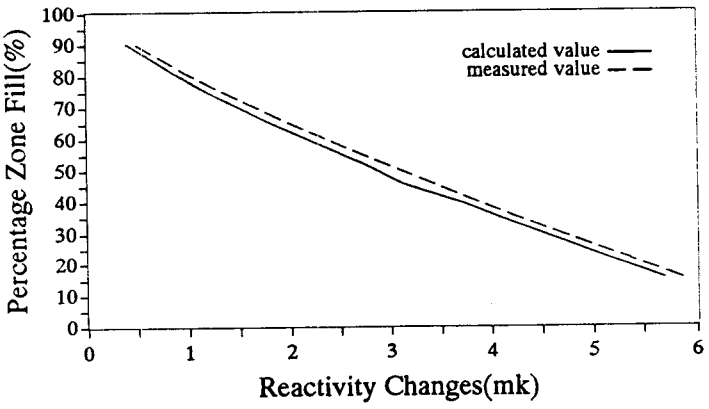

Figure 3. Measured and Calculated Wolsong-1 ZCU Reactivity Worth