HELIOS/DRAGON/NESTLE Codes' Simulation of Void Reactivity in a CANDU Core

Hisham N. Sarsour
Independent Consultant
1114 Nottingham Circle
Cary, NC 27511
HishamSarsour@cs.com

Farzad Rahnema and Scott Mosher
Georgia Institute of Technology
Atlanta, GA 30332
farzad.rahnema@nre.gatech.edu and gt3522a@prism.gatech.edu

Paul J. Turinsky
North Carolina State University
Raleigh, NC 27695-7909
turinsky@eos.ncsu.edu

Dumitru Serghiuta
Canadian Nuclear Safety Commission
280 Slater Street, 7th Floor
Ottawa, Ontario K1P 5S9
serghiutad@cnsc-ccsn.gc.ca

Guy Marleau and Tanguy Courau
Ecole Polytechnique de Montreal
P.O. Box 6079, station Centre-ville
Montreal, Quebec H3C 3A7
guy.marleau@polymtl.ca

Introduction

This paper presents results of simulation of void reactivity in a CANDU core using the NESTLE core simulator [1], cross sections from the HELIOS [2] lattice physics code in conjunction with incremental cross sections from the DRAGON lattice physics code [3]. First, a sub-region of a CANDU6 core is modeled using the NESTLE core simulator and predictions are contrasted with predictions by the MCNP Monte Carlo simulation code [4] utilizing a continuous energy model. In addition, whole core modeling results are presented using the NESTLE finite difference method (FDM), NESTLE nodal method (NM) without assembly discontinuity factors (ADF), and NESTLE NM with ADF. The work presented in this paper has been performed as part of a project sponsored by the Canadian Nuclear Safety Commission (CNSC). The purpose of the project was to gather information and assess the accuracy of best estimate methods using calculational methods and codes developed independently from the CANDU industry.

Simulation Results

A simplified CANDU6 model has been used for this study. Figure 1 shows the full core mesh layout where 2 indicates a fuel node, 1 a reflector node, and 0 a null node. This model has 380 channels with 12 bundles in each channel. The maximum number of channels in the x and y directions is 22. The lattice pitch is 28.575 cm and the bundle length is 49.53 cm. The base spatial mesh is 42x34x22 in (x,y,z) directions. The radial reflector's minimum thickness is 68.525 cm and the notch is not modeled. There is no reflector in the axial direction. The boundary condition is zero flux on all exterior surfaces, with a Cartesian raggedy edge used to represent the cylindrical D_2O radial reflector. The following cases were analyzed by NESTLE for the full core geometry: cooled, fully voided, full core checkerboard voided, half core voided, and half core checkerboard voided. Different light water fractions and presence of adjuster rods were considered.

The sub-region modeled was created from the full core model by extracting the following 12 channels: 13, 14, 15 and 16 on the x-axis, and J, K and L on the y-axis. This sub-region is illustrated in Figure 2. Control device positions and the burnup distribution were taken from the full core model. Axial symmetry was assumed about the core mid-plane; therefore, only half of the sub-region core was modeled axially with reflective boundary condition applied at the core's axial mid-plane. A reflective boundary condition was also applied to the exterior radial boundary, with a zero flux boundary condition applied to the exterior axial boundary. This produces a 4x3x6 spatial nodalization of the sub-region. The following core coolant conditions were simulated to determine core reactivity: cooled, voided, and checkerboard voided. These simulations were completed with both adjuster rods fully inserted and withdrawn. For the cooled case, the coolant density corresponds to the Hot Operating Condition (HOC). For the voided case, the coolant density in every channel is reduced to 0.001 g/cc. For the checkerboard voided case, the coolant density in every other channel is reduced to 0.001 g/cc. As a reference point, Channel J14, along with other channels checkered with respect to this channel, were voided for the checkerboard voided case.

The NM used within NESTLE is based upon the nodal expansion method utilizing a quartic polynomial expansion of the flux and quadratic polynomial expansion to represent the transverse leakage in the 1-D transverse integrated diffusion equation. The NM with ADF is expected to be more accurate relative to FDM and NM without ADF due to the more sophisticated treatments of spatial discretization and cross sections homogenization. For this reason we shall concentrate our comparison of NESTLE predictions with MCNP predictions using NESTLE NM with ADF. Do note the observation that NESTLE NM, with or without ADF, and NESTLE FDM predicted reactivity worths all agree well with the exception of the adjuster worths, which may be due to the fact that adjusters induce in the flux more severe spatial gradients.

As presented in Table I, the differences between HELIOS/DRAGON/NESTLE NM with ADF and MCNP predicted k_{eff} values range from 2.2 mk to 4.9 mk for a wide span of core conditions. Since the standard deviation of MCNP k_{eff} values ranges from 0.12 mk to 0.21 mk over all core conditions examined, this indicates that most of the differences are statistically significant. Given that the two codes utilize different cross sections representations, *e.g*. continuous energy spatially heterogeneous versus two-group spatially homogenized, and neutron transport models, *e.g.* transport theory versus diffusion theory, the ranges of differences noted above are not unexpected.

For the sub-region problem, the two code systems' predictions of void worth differ by less than 1.42 mk (~9%), with NESTLE over-predicting the void worth relative to MCNP except for the checkerboard voided with adjusters case. The differences are again statistically meaningful since they are larger than the standard deviation of 0.17-0.27 mk associated with the MCNP results. Adjuster worths predicted by the two code systems differ by at most 1.0 mk (~3%), which is again a statistically meaningful difference with NESTLE NM and NESTLE FDM over-predicting and under-predicting, respectively, the adjuster worth.

Tables II and III present the prediction results for the full core geometry using NESTLE with different spatial discretization treatments. In all the cases, NESTLE NM with ADF predicts a higher worth for the adjusters compared with NESTLE FDM and NESTLE NM without ADF, with NESTLE FDM predictions agreeing slightly better with NESTLE NM with ADF predictions. Regarding the ZCU predicted worths, NESTLE NM without ADF predictions agree much better than NESTLE FDM predictions with NESTLE NM with ADF predictions. Again, the NESTLE NM with ADF predicted worth in most cases is the highest, but now only slightly larger than the NESTLE NM without ADF predictions. As for the void worth, the predicted values by all three spatial discretization methods are very close, with differences of less than 0.13 mk (~1%) for all cases. This good agreement is to be expected since even for the checkerboard voiding profile, the spatial gradient in the flux is not that severe.

Conclusions

The differences in void and adjuster worths provide some measure of the uncertainties in these worths due to the treatment of cross sections and models used to mathematically describe the core, *e.g.* continuous energy/ heterogeneous regions/neutron transport theory versus two-energy group/homogenous regions/neutron diffusion theory. However, these differences do not address the uncertainties in physical data, which is not possible with this numerical benchmark. For example, errors in microscopic cross sections are masked in our evaluation since both MCNP and HELIOS obtain their cross sections values starting with different versions of ENDF/B-VI. To truly determine the uncertainties of the predicted worths, comparisons of experimental and predicted values at realistic operating core conditions are required, which is not always possible.

References

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Table I. NESTLE versus MCNP reactivity predictions for sub-region simplified CANDU problem
(uncorrected for S(alpha,beta) temperature)

Code	Without Adjusters			With Adjusters		
	Cooled	Checker-board Voided	All voided	Cooled	Checkerboard Voided	All voided
k_{eff} for MCNP	1.03001	1.03817	1.04539	.99568	1.00485	1.01185
	Void Worth (mk)	7.63	14.28	Void Worth (mk)	9.17	16.05
	Adjusters Worth (mk)			34.33	33.32	33.54
k_{eff} for NESTLE FDM NM w/ ADF NM w/o ADF	1.03275 1.03263 1.03254	1.04138 1.04121 1.04112	1.04976 1.04963 1.04955	0.99930 0.99814 0.99819	1.00825 1.00709 1.00713	1.01676 1.01568 1.01572
k_{eff} Difference FDM-MCNP NM w/ ADF- MCNP NM w/o ADF-MCNP (mk)	2.74 2.62 2.53	3.21 3.04 2.95	4.37 4.24 4.16	3.62 2.46 2.51	3.40 2.24 2.28	4.91 3.83 3.87
Void Worth/ Difference (NESTLE-MCNP) (mk)	FDM NM w/ ADF NM w/o ADF	8.02/0.39 7.98/0.35 7.98/0.35	15.69/1.41 15.68/1.40 15.70/1.42	FDM NM w/ ADF NM w/o ADF	8.88/-0.29 8.90/-0.27 8.89/-0.18	17.18/1.13 17.30/1.25 17.29/1.24
Adjusters Worth/ Difference (NESTLE-MCNP) (mk)	FDM NM w/ ADF NM w/o ADF			33.45/-0.88 34.49/0.16 34.40/0.07	33.13/-0.19 34.32/1.00 33.99/0.67	33.00/-0.54 33.95/0.41 33.83/0.29

Table II. NESTLE predicted k_{eff} for full core simplified CANDU-6 problem

Core Condition	Light Water Fraction in all ZCU (With Adjusters)			Light Water Fraction in all ZCU (Without Adjusters)		
	0%	Base Case	100%	0%	Base Case	100%
Full Core Cooled						
FDM	1.00555	1.00249	0.99950	1.02083	1.01824	1.01554
NM with ADF	1.00451	1.00134	0.99819	1.02036	1.01763	1.01472
NM without ADF	1.00587	1.00274	0.99965	1.02106	1.01834	1.01545
Full Core Fully Voided						
FDM	1.02245	1.01943	1.01646	1.03751	1.03493	1.03223
NM with ADF	1.02146	1.01836	1.01524	1.03705	1.03435	1.03145
NM without ADF	1.02274	1.01968	1.01661	1.03773	1.03503	1.03214
Full Core Checkerboard Voided						
FDM	1.01397	1.01095	1.00796	1.02913	1.02655	1.02384
NM with ADF	1.01291	1.00978	1.00664	1.02861	1.02590	1.02299
NM without ADF	1.01423	1.01114	1.00805	1.02930	1.02660	1.02371
Half Core Fully Voided						
FDM	1.01690	1.01391	1.01093	1.03134	1.02876	1.02606
NM with ADF	1.01590	1.01281	1.00968	1.03085	1.02815	1.02525
NM without ADF	1.01727	1.01423	1.01114	1.03159	1.02889	1.02600
Half Core Checkerboard Voided						
FDM	1.01060	1.00757	1.00458	1.02558	1.02300	1.02029
NM with ADF	1.00955	1.00641	1.00326	1.02508	1.02235	1.01944
NM without ADF	1.01090	1.00781	1.00470	1.02579	1.02308	1.02017

Table III. NESTLE predicted reactivity worths for full core simplified CANDU-6 problem

Core Condition		Light Water Fraction in all ZCU (With Adjusters)			Light Water Fraction in all ZCU (Without Adjusters)		
		0%	Base Case	100%	0%	Base Case	100%
Full Core Cooled FDM NM with ADF NM without ADF		Adjusters Worth (mk)			15.28 15.85 15.19	15.75 16.29 15.60	16.04 16.53 15.80
		ZCU Worth (mk)	3.06 3.17 3.13	6.05 6.32 6.22	ZCU Worth (mk)	2.59 2.73 2.72	5.29 5.64 5.61
Full Core Fully Voided FDM NM with ADF NM without ADF		Adjusters Worth (mk)			15.06 15.59 14.99	15.50 15.99 15.35	15.77 16.21 15.53
		ZCU Worth (mk)	3.02 3.10 3.06	5.99 6.22 6.13	ZCU Worth (mk)	2.58 2.70 2.70	5.28 5.60 5.59
Void Worth (mk)	FDM NM with ADF NM without ADF	16.44 16.52 16.40	16.58 16.69 16.57	16.69 16.82 16.69	15.75 15.77 15.73	15.84 15.88 15.83	15.92 15.98 15.92
Full Core Checkerboard Voided FDM NM with ADF NM without ADF		Adjusters Worth (mk)			15.16 15.70 15.07	15.60 16.12 15.46	15.88 16.35 15.66
		ZCU Worth (mk)	3.02 3.13 3.09	6.01 6.27 6.18	ZCU Worth (mk)	2.58 2.71 2.70	5.29 5.60 5.59
Void Worth (mk)	FDM NM with ADF NM without ADF	8.26 8.26 8.19	8.35 8.35 8.28	8.40 8.41 8.34	7.90 7.86 7.84	7.95 7.92 7.90	7.98 7.97 7.95
Half Core Fully Voided FDM NM with ADF NM without ADF		Adjusters Worth (mk)			14.44 14.95 14.32	14.85 15.34 14.66	15.13 15.57 14.86
		ZCU Worth (mk)	2.99 3.09 3.04	5.97 6.22 6.13	ZCU Worth (mk)	2.58 2.70 2.70	5.28 5.60 5.59
Void Worth (mk)	FDM NM with ADF NM without ADF	11.10 11.16 11.14	11.24 11.31 11.30	11.31 11.40 11.37	9.98 9.97 9.99	10.04 10.05 10.07	10.10 10.12 10.13
Half Core Checkerboard Voided FDM NM with ADF NM without ADF		Adjusters Worth (mk)			14.98 15.53 14.89	15.43 15.94 15.27	15.71 16.18 15.47
		ZCU Worth (mk)	3.03 3.14 3.09	6.02 6.29 6.20	ZCU Worth (mk)	2.58 2.73 2.76	5.29 5.64 5.62
Void Worth (mk)	FDM NM with ADF NM without ADF	4.97 4.97 4.95	5.03 5.03 5.02	5.06 5.06 5.03	4.54 4.51 4.52	4.57 4.54 4.55	4.58 4.56 4.56

Figure 1. **Full core mesh layout where 2 indicates a fuel node, 1 a reflector node, and 0 a null node**

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Figure 2. Sub-region modeled indicating the 4x3 channels used in the calculation

J13	J14	J15	J16
K13	K14	K15	K16
L13	L14	L15	L16