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VALIDATING MODELS FOR COOLANT VOID REACTIVITY EVALUATION IN CANDU GENERATION III+

Alexi V. Popov, Monchai Assawaroongruengchot*, Guy Marleau, Alain Hébert
Institut de Génie Nucléaire,
École Polytechnique de Montréal
C.P. 6079, succ. Centre-ville, Montréal, Québec, CANADA H3C 3A7
alexi.popov@polymtl.ca; monchai.assawar@polymtl.ca;
guy.marleau@polymtl.ca; alain.hebert@polymtl.ca

Ramamoorthy Karthikeyan
Reactor Physics Design Division
Bhabha Atomic Research Center
Trombay, Mumbai 400085, INDIA
rkarthi@barc.gov.in

ABSTRACT

Studying large-break loss-of-coolant accidents in CANDU for Generation III+ strongly benefits from cross-sections generated in checkerboard-voided *colorsets*. This claim is validated against Monte-Carlo simulations in the present study. The result is a long-sought, precise methodology with slight conservative bias for checkerboard-voiding reactivity in Generation III+ of CANDU.

Key Words: CANDU Generation III+, coolant void reactivity, DRAGON, DONJON, TRIVAC

1. INTRODUCTION

In simulations of large-break loss-of-coolant accidents (LBLOCA) for CANDU reactors, it is very important to evaluate well coolant-void reactivity (CVR). This parameter indicates the reactor neutronic response to the thermalhydraulic transient. For CANDU-NG, also known as *early* ACR-700 of Generation III+ [1], CVR varies significantly with voiding patterns. In checkerboard voiding (when every voided channel neighbors a cooled one to its left, right, top and bottom), cross-sections produced in 2×2 *colorsets* [2] of CANDU lattices are required for proper evaluation, as it was recently claimed [3]. The present attempts to validate this statement against Monte-Carlo studies.

2. IMPORTANCE OF CHECKERBOARD VOIDING IN CANDU

In the most probable case of LBLOCA in CANDU, checkerboard voiding occurs in half the core. Otherwise said, cooled and voided channels form a checkerboard pattern over the channel map at the beginning of the transient. Moreover, LBLOCA is the most serious accident in CANDU of Generation II because of positive CVR [4]. It was found that uniform voiding of all channels achieves negative CVR for ACR-700 of Generation III+ in an equilibrium core. CVR for

*Presently at Idaho National Laboratory (INL), Idaho Falls, ID 83415 USA

checkerboard voiding is still positive however [3], when properly evaluated with *colorset* cross sections (of course, reactivity may be varied by modifying fuel enrichment and poison concentration).

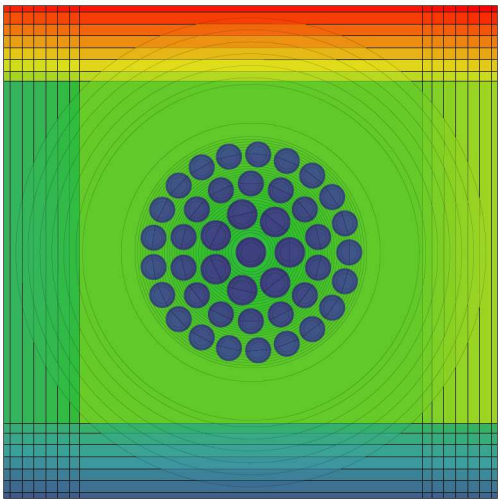

Figure 1. DRAGON Model of *early* ACR-700 Lattice.

Deterministic LBLOCA studies with a reactor code usually rely on homogenised cross-sections from lattice calculations. To generate these cross-sections, infinite arrays of identical lattices are commonly simulated. Corrections for heterogeneous cores are applied later [5].

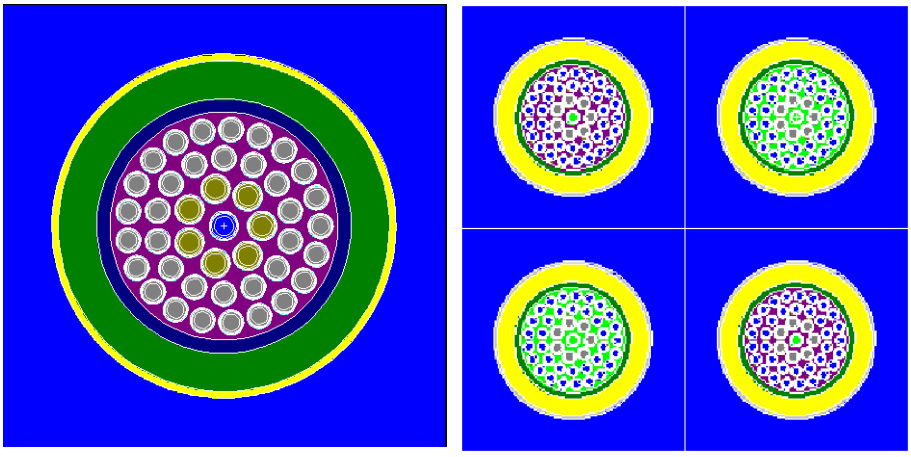

Figure 2. MCNP Model of ACR-700 Lattice and 2×2 *Colorset.*

It is logical to simulate the heterogeneous core using cross-sections generated in heterogeneous *colorsets* instead of applying approximations. This approach produces differences in CVR estimation of about 80% the expected β_{eff} for ACR-700 compared to the uncorrected case.

Moreover, estimated CVR is negative if uncorrected but positive with *colorset* cross-sections [3] in an equilibrium core. Monte-Carlo results here validate the approach.

3. METHODOLOGY USED

Calculations are performed in MCNP [6] for a two-dimensional (2D) core of the *early* ACR-700. No reactivity devices are considered, of course, as they require three-dimensional modelling for CANDU. Parallel models in the reactor code DONJON [7] are prepared too (and also in its developmental Version4 of DONJON [8] and TRIVAC [9]). Homogenised cross-sections for DONJON are generated with DRAGON in its Version4 [10] using ACR-700 *colorset* models already validated [11] against reciprocal MCNP and Tripoli [12] Monte-Carlo models.

For the uniformly cooled or voided reactor core, cross sections are generated in single-lattice models with DRAGON using *reflective* boundary conditions and homogenisation over the whole geometry. For the checkerboard-voided core, cross-sections are generated in a 2×2 *colorset* of lattices (2 voided and 2 cooled) with *translational* boundary conditions. Homogenisation is performed over each pair of equal-state lattices in the four-element *colorset*.

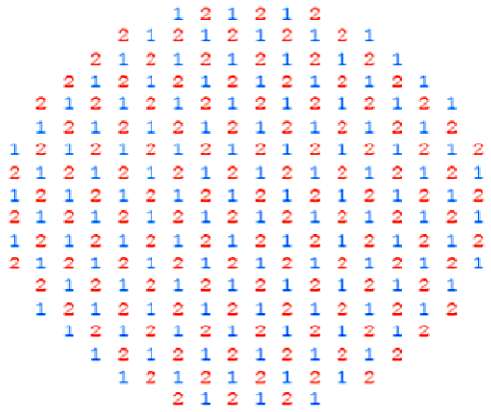

Figure 3. Checkerboard-Voiding Pattern over ACR-700 Channels.

As in the earlier model [11] ACR-700 has a lattice pitch of 22 cm. Fuel is uranium dioxide in bundles of 43 pins. The central pin has natural uranium plus 4.6% of dysprosium. This pin and the surrounding first ring of seven pins are of diameter 0.627 cm (0.675 cm with cladding). The outer two rings of fuel (with 14 and 21 pins respectively) have pin diameters of 0.533 and 0.575 cm in and out of cladding. Fuel density is higher in the central eight pins 10.12 *vs.* 9.825 g/cm^3 in the outer positions. All pins except the central one have uranium enrichment of 2.0% in weight.

The pressure tube enclosing fuel and coolant has inner and outer radii of 5.169 and 5.769 cm, which are the same dimensions as those for CANDU 6 of Generation II. The calandria tube, surrounded outwards by moderator, has radii of 7.5 and 7.8 cm respectively. Between the two tubes is a helium-filled gap. Materials for both tubes are same as in CANDU 6. Coolant is light water and moderator is heavy water. No boron is assumed in either (indeed, in CANDU reactors

coolant needs no boron addition, while the separate moderator may have a minimal unfiltered concentration not treated here).

Fuel temperature is assumed at 687°C, coolant and moderator temperatures at 300.6 and 50.6°C, while pressure and calandria-tube temperatures are assumed at 300 and 80°C respectively. In DRAGON calculations, each fuel pin is subdivided in four concentric, annular regions for optimised self-shielding effects. The whole geometry is subdivided into a total of 389 regions seen in Figure 1. The MCNP models are presented in Figure 2, where coolant in the channels is coloured purple (upper-left and lower-right lattices), while green represents voiding (the other two lattices).

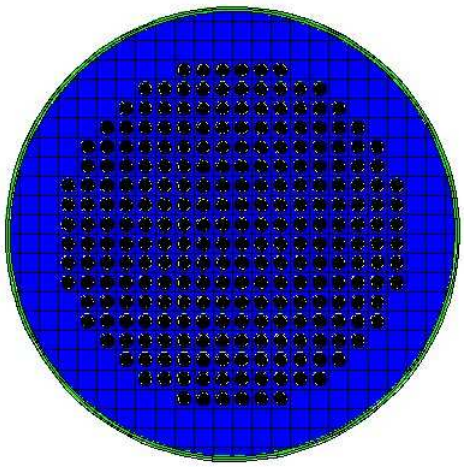

Figure 4. MCNP Model of *early* ACR-700 Reactor.

Nuclear data were used as generated previously [11] for DRAGON and MCNP, from 22 nuclides in JEF-2.2 evaluations collapsed to 172 groups. Self-shielding in the lattice and *colorset* calculations uses physical probability tables [13] with a *subgroup* approach. DRAGON solves the transport equations in its integral form through the characteristic method. The solution is approached as an eigenvalue problem with the homogeneous `B0` model without streaming nor leakage-compensation (which is appropriate to compare with MCNP lattices or *colorsets* where leakage is not modelled).

A 2D ACR-700 core is modelled in DONJON and in MCNP. The outer boundary is assumed void. The fuel channels (lattices) of the DONJON model are shown in Figure 3. Reflector ring of about 55 cm thickness is modelled but not shown there. The reactor radius is assumed 253 cm to inside of *calandria* shell. There are 252 fuel channels or lattices. Channels marked by 1 and 2 in Figure 3 are respectively cooled and voided for checkerboard CVR evaluation. For a uniformly cooled or voided reactor, both numbers represent the same respective kind of channels, of course.

In MCNP, 10 million neutron histories are used for the simulation. Also, a double-layer *calandria*

shell of 2.86 cm per layer is modelled around the reflector (same material as for *calandria* tubes is used for simplicity). No *calandria* shell is modelled in DONJON. A fresh-fuel core is considered in both cases. The MCNP reactor model is presented in Figure 4.

DONJON solves here the static diffusion equation with a dual variational formulation in tracking [14]. Void boundary conditions are considered. Results from the simulations with DONJON and (its developmental Version4 plus TRIVAC) are for all practical purposes the same.

4. SIMULATION RESULTS

With MCNP, a uniformly cooled, voided and checkerboard-voided reactor states are computed fully independently from any lattice calculations. With TRIVAC and DONJON, single-lattice cross sections are used to compute uniformly cooled and voided reactor states. A checkerboard-voided reactor state is computed with cross sections from a *colorset*.

Table I. CVR Results for Reactor Calculations

Code used	k_{eff} cool	k_{eff} void	ρ_{cv} void
MCNP	1.23374 ± 0.18 mk	1.24111 ± 0.19 mk	4.81 ± 0.17
DONJON	1.23478	1.24170	4.51

Code used	k_{eff} cool	k_{eff} CB[a]	ρ_{cv} CB[a]
MCNP	1.23374 ± 0.18 mk	1.24427 ± 0.18 mk	6.86 ± 0.17
DONJON	1.23478	1.24604	7.32

[a] *checkerboard* voiding with *colorset* cross sections

CVR is computed as

$$\rho_{\text{cv}} = \left(\frac{1}{\text{k}_{\text{cooled}}} - \frac{1}{\text{k}_{\text{voided}}} \right) \times 1000 \text{ mk},$$

while standard deviations on CVR values for MCNP results are obtained as

$$\sigma_{\text{cv}} = \sqrt{\frac{\sigma^2_{\text{cooled}}}{\text{k}^4_{\text{cooled}}} + \frac{\sigma^2_{\text{voided}}}{\text{k}^4_{\text{voided}}}}$$

and all values are given in Table I for MCNP and DONJON reactor calculations. Values for lattice and *colorset* evaluations underlying DONJON results are given in Table II, where CVR for checkerboard voiding is computed on the basis of *single-lattice* cooled results and checkerboard-voided *colorset* values.

This approximates the strategy used in DONJON, where the cooled core is evaluated with *single-lattice* cross sections rather than data from a uniformly cooled *colorset* to simplify and speed transport calculations. The loss of precision is 0.04 mk in CVR for transport calculations with DRAGON with respect to MCNP (comparing results in Table II with those already published).

An interesting outcome is that DONJON k_{eff} evaluations deviate from those of MCNP somewhat less than DRAGON estimations. The maximal deviation for k_{eff} in Table I is 1.77 mk in absolute value. The corresponding maximum deviation for DRAGON calculations in Table II is 2.50 mk.

Table II. CVR Results for Underlying Lattices

Code used	k_{eff} cool	k_{eff} void	ρ_{cv} void
MCNP	1.25556 ± 0.17 mk	1.26374 ± 0.18 mk	5.16 ± 0.16
DRAGON	1.25348	1.26160	5.14

Code used	k_{eff} cool	k_{eff} CB[a]	ρ_{cv} CB[b]
MCNP	1.25556 ± 0.17 mk	1.26774 ± 0.18 mk	7.65 ± 0.16
DRAGON	1.25348	1.26524	7.41

[a] *checkerboard*-voided *colorset* [b] *colorset vs.* cooled single lattice

DRAGON calculations were computed anew for the present study and are visibly closer to MCNP values than originally [11]. More precisely, the result for CVR voiding single lattices in Table II is for all practical purposes identical between DRAGON and MCNP (0.02 mk difference for standard deviation of 0.16 mk). This is probably due to improvements in the developmental Version4 of DRAGON [10].

The highest deviation from MCNP in DONJON calculations of k_{eff} and CVR are obtained for the checkerboard-voided core (at 1.77 mk and 0.46 mk respectively). These results are based on *colorset*-generated cross sections.

Traditionally, *single-lattice* cross sections have been used for the checkerboard voided core. The resulting k_{eff} is 1.24251 and CVR is 5.04 mk, which is a clear underestimation of the Monte-Carlo values of 1.24427 ± 0.18 mk and 6.86 ± 0.17. Approximate compensations that may be implemented in the reactor code [5] also continue the underestimation tradition for CVR.

The *colorset*-based approach, on the other hand, provides a safe but reasonable *overestimation* with k_{eff} of 1.24604 and CVR is 7.32 mk. It is clear that this approach [3] is fairly appropriate for evaluating CVR in Generation III+ of CANDU reactors on the basis of *colorset*-generated homogenised cross-sections.

5. CONCLUSION

Generating homogenised cross sections for reactor calculations on CANDU models of Generation III+ should take into account heterogeneity at best through *colorset* models in the transport code. Models surveyed thus far have a tendency to somewhat underestimate CVR in checkerboard-voided cores of CANDU for Generation III+. The present allows precise evaluations with slight conservative bias. Further work would be to investigate what exactly in the development of DRAGON Version4 caused improvement in the transport calculations and whether *superhomogenisation* [15] with a reactor-styled geometry in the transport code would further improve estimations.

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