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ENSURING NEGATIVE COOLANT-VOID REACTIVITY IN CANDU GENERATION III+

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ABSTRACT

It was established that the CANDU-NG model for Generation III+ had overall negative coolant-void reactivity in uniform voiding of all coolant channels. Reactivity is positive however, in the case of checkerboard voiding (when every second channel voids). Checkerboard voiding may be eliminated if channels from each geometric quadrant of the core are grouped to the same pair of inlet and outlet headers. Negative coolant-void reactivity and wide marketability remain thus ensured. Refuelling, structures, axial flux and exit burnup are not negatively affected.

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

1. INTRODUCTION

Checkerboard voiding (*i.e.*, when every voided channel neighbours a cooled one to its left, right top and bottom) introduces positive reactivity in CANDU-NG [1] or *early* ACR-700 of Generation III+. Reactivity decreases with uniform voiding of all channels. Solving the problem of checkerboard voiding in channel reactors is a conceptual task that has some precedents. The Indian AHWR [2] and the Soviet RBMK [3] are channel-reactor designs for which checkerboard voiding is not possible. This is achieved through one-directional flow and through grouping channels for in or outflow according to uniform geometric regions. Some ideas from AHWR and RBMK may be employed to eliminate the possibility for such unwanted reactivity increase in Generation III+ of CANDU reactors.

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2. DESIGNING WITH ONE-DIRECTIONAL FLOW

CANDU reactors have separate coolant (flowing in pressure tubes) and moderator (in a *calandria* barrel). Each tube is connected to one of the two *independent* coolant loops. A single loop with the reactor is presented in Figure 1.

It has been a design goal for Generation III+ of CANDU to have negative [4] coolant-void reactivity (CVR) or coolant-void coefficient. In ACR-700, CVR is positive for the equilibrium core in checkerboard voiding [5]. This outcome may be changed by further increasing burnable-poison concentration in the fuel, but this solution has a clear, negative economic impact. Another option is to eliminate checkerboard voiding altogether.

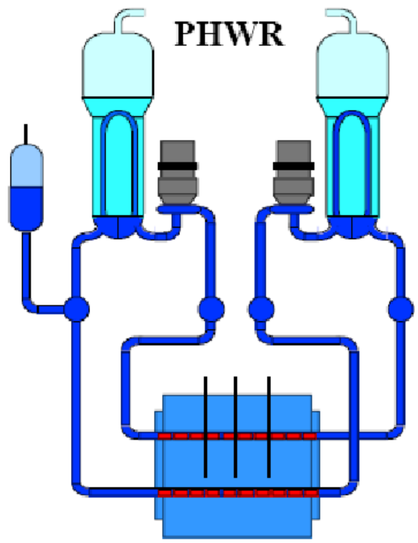

Figure 1. A Coolant Loop in a CANDU Reactor [6].

This may be achieved through one-directional coolant flow in every geometric quadrant of the core, though it is not the only solution. To avoid checkerboard voiding, each inlet or outlet header may be linked to all channels in a uniform quadrant of the core (in CANDU 6 and the standard ACR-700, it links to every second channel in half the core as on a checkerboard). From a mechanical point of view, the change is minimal and even makes piping simpler.

Thus, every coolant loop provides service to half a core (two vertically aligned quadrants). This distribution is shown in Figure 2. Channels marked in blue (left half) belong to one coolant loop, those in red (right half) belong to the other. Coolant flows in opposite directions through the upper and lower halves of the core (though both quadrants in the upper half connect to separate, *independent* loops, and so do those in the lower). In Figure 2, letters x are assigned to channels with flow from bundle position 12 to 1 (*i.e.*, channels in the upper half of the core), while letters o are assigned to those with flow from position 1 to 12 (channels in the lower half).

In the first seconds of large-break loss-of-coolant accident (LBLOCA), a single quadrant will be voided if there is only one large break in one coolant loop, which is the most probable LBLOCA scenario. This is the quadrant downstream from the break. Gradually, the whole loop will void (both quadrants up and downstream from break) affecting half the core.

A first challenge to one-directional flow in ACR-700 is directly related to refuelling. In the current models of CANDU, fuel is loaded in the direction of coolant flow, which is opposite in every second channel (checkerboard pattern). Two-directional loading allows a very flat flux shape to be achieved. If the flow pattern is changed, there may be need to load fuel against the direction of coolant flow in some channels (if two-directional loading is to be preserved, which is definitely advisable).

Fuel movement against the flow may have mechanical consequences, *i.e.* oscillations, affecting the channel integrity. A simple model for fluid-structure interaction [7] is adapted and applied to the channel of ACR-700 in order to study any possible effects. This model predicts that no complications should result from such movement.

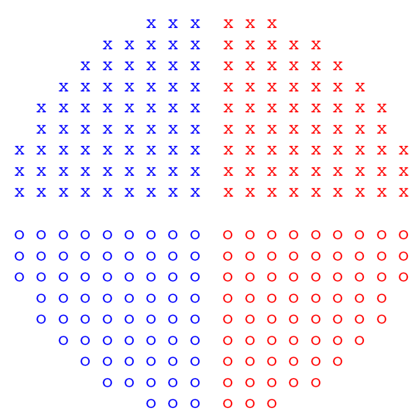

Figure 2. Channel Groupings on the Face of an *early* ACR-700.

Another possible challenge to one-directional flow is maintaining a flat axial shape of neutron-flux distribution and high exit burnup of the fuel. All simulations show no practical effect on these two parameters as two-directional refuelling easily compensates for any neutronic consequences of one-directional flow.

3. NEUTRONIC AND THERMALHYDRAULIC MODELS

The neutronic parameters are the same as those used to investigate the checkerboard effect and cross-section models for an *early* ACR-700 core [5]. The only difference lies in the local thermalhydraulic values. In the present study, coolant temperature and density, plus fuel temperature are assumed to vary along the fuel channel. For simplicity, the core is modelled as if channels in a quadrant were identical from a thermalhydraulic point of view.

Thermalhydraulic-parameter values are estimated on the basis of coolant temperature and density at channel inlet and outlet [8] plus channel-average values as used earlier [5]. Variation of values along the fuel channel was assumed similar to the variation [9] in CANDU 6. Bundle-average estimates for coolant density and temperature are shown in Figure 3 and Figure 4 respectively. Figure 5 displays the values for bundle-average fuel temperature.

Coolant enters channels at the front of bundle position 1 and exits at the end of bundle position 12 for quadrants in the lower half of the core (marked with o in Figure 2). The opposite is true for channels marked with x (invert the channel numbers in Figure 3, Figure 4 and Figure 5 for a representation of these cases).

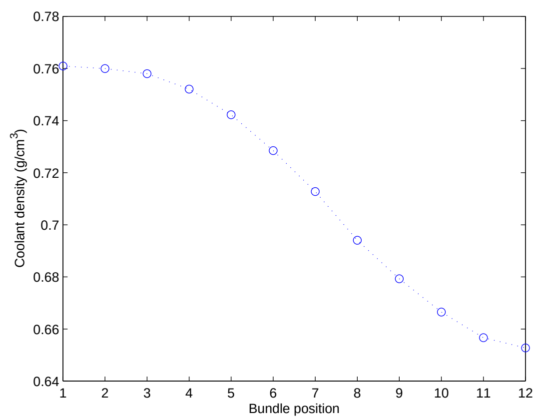

Figure 3. Coolant Density *vs.* Bundle Position for *early* ACR-700

Coolant-density and temperature for positions 1 and 12 are assumed those of channel inlet and outlet [8] for simplicity. Coolant-temperature variation along the channel [9] was adjusted to better fit fuel-temperature and coolant-density estimates.

CANDU-NG or *early* ACR-700 is a reactor of 700 MWe. It has a lattice pitch of 22 cm [4]. Fuel is enriched to 2.0% in 42 of the 43 bundle pins, while the central pin contains natural uranium plus 4.6% weight of dysprosium as described in previous publications [5, 10]. Cross sections were obtained from ENDF/B-VI through the E6MLIB library with energy discretisation into 89 groups. Self-shielding is based on the generalised Stamm'ler method.

The integral form of the transport equation is solved by DRAGON [11] using the collision-probability method. A buckling calculation with the homogeneous `B1` model plus multigroup non-leakage factors and without streaming [12] is imposed. Each fuel bundle has four concentric rings of fuel pins. Each pin is here subdivided into 3 regions (each region from a pin is studied together with identical regions of other pins in the corresponding ring). Coolant is subdivided into 24 regions and moderator into 12 for a total of 56 regions per lattice.

Homogenisation of cross sections *vs.* burnup was performed over the whole lattice geometry for each of the 12 local-parameter cases. Power level is assumed at an average value for simplicity, since no power-history variations were computed. Moderator cross sections were extracted for use in reflector cells of the reactor calculations. The simulation model of the whole core is similar to that used in CANDU 3 studies [13]. When simulating online refuelling, burnup dependence is interpolated in each of the 12 bundle positions of a reactor quadrant (each set of local thermalhydraulic parameters).

The reactor code DONJON [14] is used to perform static diffusion calculations in three dimensions. Reactor measurements are as previously described for the *early* ACR-700 [15]. No controller mechanisms are simulated and a reference k_{eff} value of 1.0040 is imposed to compensate for their absence. To simulate the result of two-directional online refuelling, a *time-average* model is used. Each of the 3024 fuel bundles (12 bundles per channel in 252 channels) has its own burnup. Online refuelling is iteratively simulated until the burnup distribution in the core satisfies imposed k_{eff} and axial-flux shape.

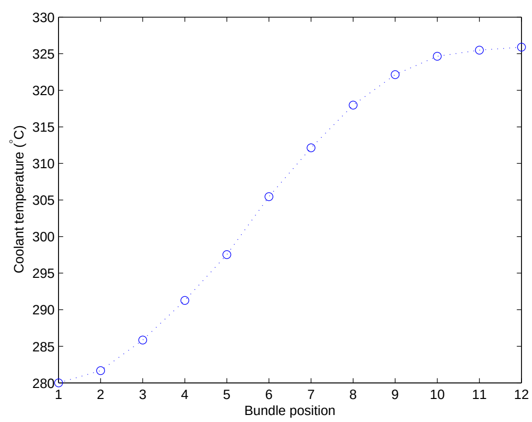

Figure 4. Coolant Temperature *vs.* Bundle Position for *early* ACR-700

This model produces a realistic representation of ACR-700 having undergone some operation and refuelling and attained an equilibrium state, which is maintained through further refuelling. Upon obtaining an *equilibrium core*, voiding is applied. The resulting k_{eff} is estimated anew by DONJON and CVR computed.

4. REFUELLING AGAINST COOLANT FLOW

The question in refuelling against coolant flow is to examine the fluidelastic stability behavior of concatenated fuel bundles forming a *fuel string*. If their movement against coolant flow reaches a threshold of relative velocity, oscillations may occur and have negative impact on tubes and structures in the medium and long run.

A basic model for *fuel strings* subject to axial flow was presented for an early CANDU model [7].

A vertical *fuel string* with central support tube in a channel was examined. Several important modifications are applied to this model for studying the present case. They are matter for separate publication and only briefly described here.

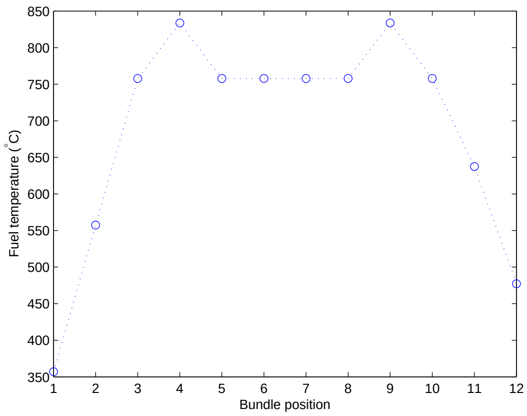

Figure 5. Fuel Temperature *vs.* Bundle Position for *early* ACR-700

ACR-700 *fuel strings* are horizontal with no central support tube. Translation and rotational springs model contact conditions at the bundle end-support plate. Contact between the bundle bearing pads and the pressure tube is modeled by a tangential spring. Typical stiffness parameters are assumed as earlier [7] for simplicity. However, pushing fuel against coolant flow might possibly change the effective contact stiffness [16] relative to the stationary string already examined [7]. This effect is taken into account by conservatively reducing the value of the tangential contact stiffness by a factor of 100.

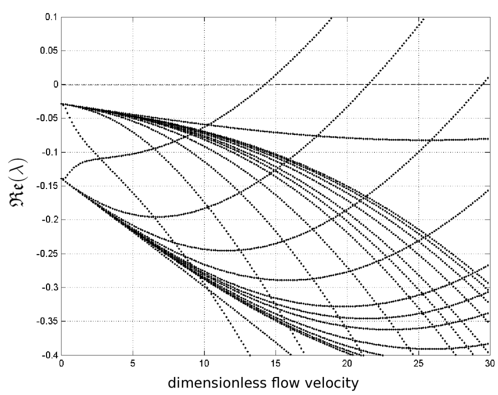

Figure 6. Stability-parameter variation $\mathfrak{Re}(\lambda)$ *vs.* dimensionless flow velocity

It is assumed that fuel takes several minutes (about 15 min) to move across a channel long some 6 m. Coolant is assumed to flow at about 10 m$/$s in the channel [17]. Therefore, for all practical purposes, the *fuel string* is a stationary system with respect to the surrounding flow. This is independent of whether fuel bundles move against flow, with it or do not move.

Moreover, the brink of instability for such a system, as predicted by the stability parameter $\mathfrak{Re}(\lambda)$ (plotted in Figure 6 *vs.* the dimensionless flow velocity λ) is attained at λ equivalent to relative flow velocity higher than 100 m/s. This value could not possibly be reached in a realistic refuelling process.

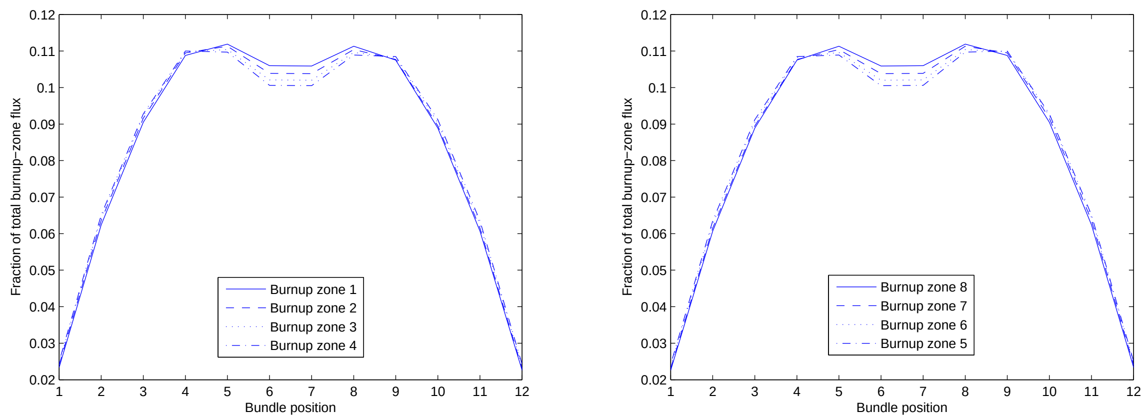

Figure 7. Axial Flux for ACR-700 Refuelled in *Four-Bundle Shifts*

The analysis shows that refuelling against coolant flow, has no practical structural or fluidelastic stability consequences as compared to refuelling in the direction of flow. While the modelling parameters are only approximate, the analysis is deemed conservative since inclusion of fluid-squeeze film and structural damping in the model would further stabilise the system. Moreover, the margin left from about 10 to 100 m/s is very significant indeed.

5. AXIAL FLUX SHAPE AND EXIT BURNUP

Uniform voiding introduces negative reactivity in an ACR-700 core [5]. Unidirectional flow produces uniform decrease of coolant density, *i.e.* voiding, in one extremity of each half of the core here. Voiding occurs towards bundle position 1 in the upper half, and towards position 12 in the lower half of the core. An interesting question should be whether it would affect the axial flux shape.

The variation of reactivity induced by such decrease in coolant density however, is less than 1% of that induced by replacing end-of-life with fresh fuel. Therefore, minor time adjustments in refuelling some channels are more than enough to compensate for unidirectional flow in the core (as long as two-directional fuelling is preserved). The axial flux shape over each burnup zone is presented in Figure 7.

The burnup zones are defined over four concentric half-rings of channels in each half of the core. They are numbered from outer to inner in the upper half (zones 1 to 4) and inversely in the lower half of the core (zones 8 to 5). Flux shape is computed for each individual channel and average values per burnup zone are produced. Results in Figure 7 are based on refuelling four fuel bundles (out of 12 in the channel) at once, *i.e.* using a *four-bundle shift*.

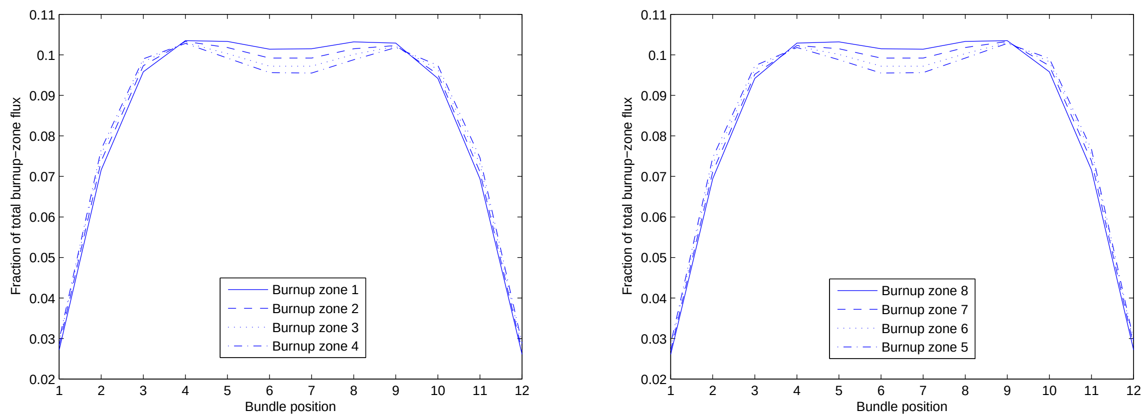

Figure 8. Axial Flux for ACR-700 Refuelled in *Two-Bundle Shifts*

Average exit burnup is, for all practical purposes, the same as what one obtains using the same model but with *checkerboard*-based flow (less than 0.2% difference refuelling in *eight-bundle shifts*). Also, average exit burnup increases about three times compared to that of natural-uranium CANDU 6 from Generation II. Moreover, models of Generation III+ use several times less heavy water for more competitive economics [18].

Further flattening of the flux shape is possible by using a *two-bundle shift* as seen in Figure 8. DONJON models predict however, the possibility for an economic penalty in exit burnup of about 1.5% lower than values for the *four-bundle shift*. Deciding whether to flatten or not the flux shape is, hence, an economic choice to be made by reactor operators.

Of course, *one-bundle shift* may also be used for further flatter flux shape. Beyond possible exit-burnup penalty however, this may also impose strong demands on the work of the fuelling machine (which is probably undesirable).

6. SIMULATION AND CVR RESULTS

The results for a simple CVR calculation in voiding a quadrant and a half of the core (break of a single pipe in one or both coolant loops respectively) are given on Table I. CVR is defined as the difference between perturbed and unperturbed reactivity or

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

Simulations here are for voiding from 100% to 0.01% coolant density in the affected portion of the core. Results are compared to those for a standard ACR-700 where flow direction is opposite in neighbouring channels [5]. Quarter-core voiding for that model is represented by checkerboard voiding over half a core (due to differences in piping).

A slightly negative CVR is achieved for the equilibrium core in the most probable LBLOCA scenario. CVR of the modified model for quarter-core voiding is -1.1 mk as opposed to $+1.4$ mk for checkerboard voiding in the standard ACR-700. If more channels are voided, CVR becomes further more negative. When both coolant loops start to void (*i.e.*, in the case of breaking several large pipes, *e.g.* in an earthquake), CVR remains clearly negative as seen in Table I, where the modified ACR-700 is affected by voiding in the upper half of the core (two quadrants belonging to separate loops).

Table I. CVR Results for Quarter and Half-Core Voiding

Reactor model	k_{eff} cool	k_{eff} quart	ρ_{cv} quart	k_{eff} half	ρ_{cv} half
ACR-700 standard	1.0040	1.0054^a	1.4	1.0005	-3.5
ACR-700 modified	1.0040	1.0029	-1.1	1.0015^b	-2.5

^{a} *checkerboard* half-core ^{b} two quadrants of same-direction flow

Voiding a full coolant loop, or even both loops, was already found to produce negative CVR in an equilibrium core of ACR-700 [5]. The remodelling, hence, clearly achieves the target of ensuring negative CVR in the reactor for every possible kind of accident. Proper choice of enrichment and burnable poison concentration in fuel ensure the same effect in a fresh core too [4, 19].

7. CONCLUSION

It is clear from these results that a simple repiping of ACR-700 permits to achieve the long-sought goal of guaranteed negative CVR and elimination of LBLOCA power pulse for pressure-tube reactors. CANDU reactors of Generation III+ so remodelled could not be excluded from international markets and jurisdictions requiring negative CVR. Further studies on voiding different configurations of quadrants or modelling exotic flow patterns (*e.g.*, one-directional flow in two concentric rings of channels styled after the burnup zones) may be conducted. A more important consequence of this work is that, thinking outside the frame of longstanding traditions in a series of reactor designs is not necessarily unhealthy.

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