Impact of Lattice Geometry Distortion due to Ageing on Selected Physics Parameters of a CANDU Reactor

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Abstract

In this paper, results related to a limited scope assessment of the geometry-distortion-induced effects on key reactor physics parameters of a CANDU reactor are discussed. These results were generated by simulations using refined analytical methods and detailed modeling of CANDU reactor core with aged lattice cell geometry.

KEYWORDS: CANDU-6, Irradiation Induced Geometry Distortion, Reactor Physics Parameters, Monte Carlo Calculations

1. Introduction

The core geometry changes in time due primarily to irradiation induced distortions. These include pressure tube diametric creep, channel sag and channel elongation.

Pressure tube diametric creep results in the fuel bundle sitting at the bottom of an enlarged pressure tube, which leads to a series of changes in physics and thermal hydraulics characteristics, including an increase in coolant void reactivity, azimuthally asymmetric element power distribution, coolant volume, sub-channel flow pattern, flow by-pass, critical heat flux and critical channel power.

Channel sag leads to lattice irregularities, which is equivalent to variations in lattice pitch. The spacing from a channel to its neighbors deviates from the original lattice pitch by the difference in the relative sag. Channel sag increases the distance that the shutoff rods have to travel to achieve an effective reactivity bite. This may lead to degraded shutdown system reactivity drop performance. Furthermore, channel sag leads to changes in the position of the in-core devices and detectors relative to the channels, which may have an effect on the flux shape and detector readings.

Channel elongation extends the free end of the pressure tube, and could lead to the bundles being shifted out of core towards one end. In postulated accidents, where there is a break in the upstream inlet headers, the increased distance between bundles may result in a shifting of the fuel string, with the potential for increased impact forces and positive reactivity effect in the cores fueled against the coolant flow. Differences in channel elongation and latch displacement

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could lead to uneven power distributions (axial flux tilts) which may impact the effectiveness of neutron overpower protection system.

Current design and safety analyses have not, in general, explicitly included the effects of the irradiation-induced lattice-geometry distortions. That is, modeling and reactor control assume a static (pristine) core configuration, though this is not necessarily the case.

While some significant effects, such as the increase in positive void reactivity and positive reactivity due to fuel string relocation, have been addressed in safety analysis of most limiting design-basis events, such as large break LOCA events, most of the effects related to lattice-geometry distortions were judged to be of negligible in magnitude and not included in the modeling.

To explore some of these issues, a limited scope assessment of the geometry-distortion-induced effects using more refined analytical methods is carried out.

2. Lattice Cell Simulations

The effect of pressure tube creep and sag due to radiation aging on the physics parameters was first determined [1] in a CANDU lattice cell with a focus on the following physics parameters: the fission density in each fuel annulus and pin, coolant void reactivity, atom density of plutonium isotopes. The simulations were carried out using the lattice cell code HELIOS 1.7 [2].

The reference model consisted of a two-dimensional (2-D) representation of half of a CANDU lattice cell containing the fuel pins, the pressure and calandria tubes, and the moderator region. In developing the perturbed geometry models, both the geometry distortion (diametric creep) and the pressure tube shift (pressure tube sagging at a given axial position) were analyzed. It was shown that the 2-D modeling of the pressure tube sagging does not affect the physics parameters considered in this study. Therefore, the perturbed geometry models used for assessing the effect of aging on the lattice cell parameters include only the diametric creep of the pressure tube. For these models, the computational mesh was refined to ensure that mesh inconsistency between the reference and perturbed models does not lead to numerically unphysical differences in the cell parameters. Two values of the diametric creep (2.5% and 5% of nominal) were considered.

It was found that the fission density per annulus increases in the first three inner annuli and decreases in the fourth (outermost) annulus with increasing creep. The absolute value of the change slightly decreases with the burnup. There is an increase in the pin fission density in downward direction (of the fuel bundle shift relative to the pressure tube geometrical center) and a decrease in the opposite direction. The pin that is nearest to the bottom of the pressure tube sees the largest increase whereas the pin farthest from the bottom of the pressure tube sees the largest decrease in all perturbed cases. The absolute value of the change in the pin fission density slightly decreases with burnup.

It was also observed that the coolant void reactivity increases with increasing creep. The magnitude of the increase varies with burnup, with values between 0.7mk and 1.2mk for the 2.5% creep case, and between 1.4mk and 2.3mk for the 5% creep case. The infinite medium multiplication factor (k_∞) for both creep models is smaller than that of the reference model. The absolute value of the change in k_∞ increases with increasing creep. The magnitude of the increase gradually reduces with burnup.

The effect of the geometry perturbation (diametric creep) on all studied parameters of the lattice cell is almost linear (e.g., the magnitude of the change for the 2.5% creep case is almost half of that corresponding to the 5% creep case).

3. Simulations of a Simplified CANDU Subregion

The pressure tube creep and sag due to radiation aging in a selected subregion [3] of a typical CANDU core is modeled in the current study by using the continuous-energy Monte Carlo code MCNP [4]. In the radial direction, the size of the region is limited to 4 x 3 channels from the middle of the core. Periodic boundary condition is used on the lateral sides. In the axial direction, all 12 fuel bundles are explicitly modeled. Vacuum boundary condition is used in the axial direction. The bundle averaged fuel burnup is taken such that the average burnup of the sub-region is 4GWd/TU. Six adjuster rods in the sub-region are also modeled.

The channels considered in the model are J13 to J16, K13 to K16 and L13 to L16, as illustrated in Fig. 1. The 37 fuel pins and their clad, pressure tube, gap and the calandria tube are represented in detail for each of the 12 fuel bundles in each channel. Three of the six adjuster rods modeled are inserted midway between columns 13 and 14, and the other three between columns 15 and 16. The central rod of each set of three adjuster rods is located exactly at the middle of the channel, with the other two rods placed at a distance of 80 cm on either side of it. Each adjuster rod consists of a stainless steel cylinder in a tube, with moderator filling the gap in between. In the configurations where the adjuster rods are fully withdrawn, the moderator fills up the space previously occupied by the adjuster rods.

3.1 Representation of the Channel Distortions

The channel distortions are modeled based on available experimental data and by using additional assumptions. Experimental data from measurement of strain rate of the pressure tubes is used to estimate a bounding value for the pressure tube diametric creep. The measurements indicated that the pressure tube has a maximum diametrical strain at locations that correspond to a certain bundle position from the refueling end. The strain decreases approximately linearly on either side to zero at the ends of the pressure tube. It is decided to use the maximum diametrical strain of the pressure tube of 5% as an upper limit at the position of the maximum diametrical strain bundle position from the refueling side. The radial creep is linearly decreased to zero at both ends of the pressure tube. The change in the thickness of the pressure tube is ignored. The calandria tube dimension is assumed to be unaffected by the pressure tube creep. The pressure tube is assumed to remain concentric to the calandria tube. The fuel bundle is assumed to sit at the bottom of the pressure tube.

In this simulation, a channel sag of 80 mm at its center is taken as an upper limit. The MCNP sagged models for the subregion illustrated in Fig. 1 are shown in Figs. 2 and 3.

Figure 1 CANDU 6 Subregion Model

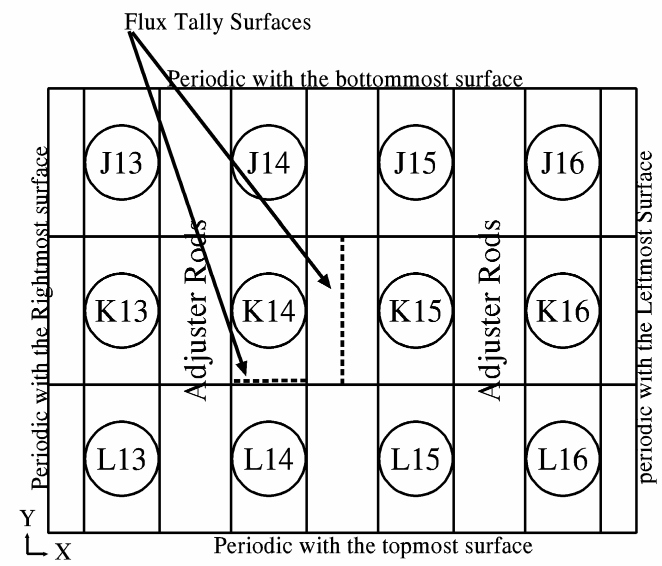


Figure 2: MCNP sagged model: Cross sectional view in the X-Y plane

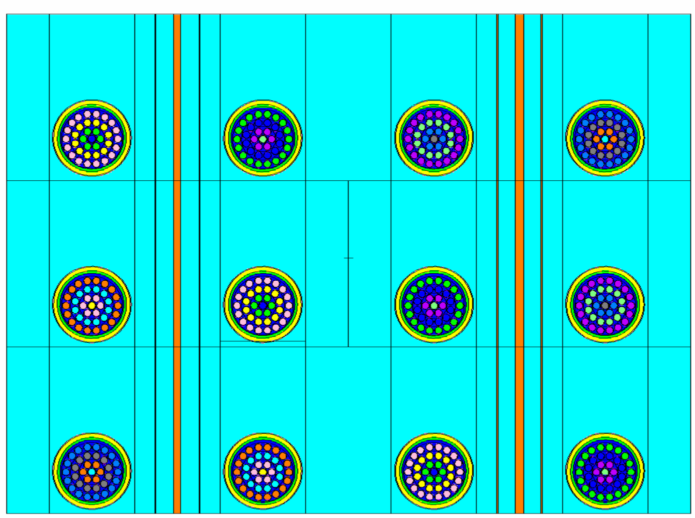
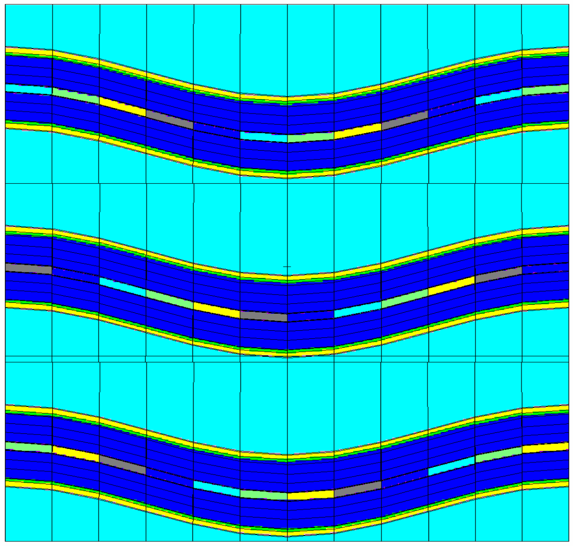


Figure 3: MCNP sagged model: Cross sectional view in the Z-Y plane



3.2 MCNP Results

Fifty million neutron histories (500 neutron generations with 100,000 neutrons per generation) are simulated in each of the calculations with MCNP. The multiplication factors and the flux and fission rate tallies are used to asses the effect of aging of the CANDU channels on the safety parameters of interest for the study. The main parameters under consideration are the coolant void reactivity and the neutron flux seen by the detectors traversing the lattice boundaries. The multiplication factors in each of the calculations is converged to about 0.07 mk (1 mk = 0.001) and the flux and fission density tallies are converged to <1%.

The following main results are noted:

- For the core configurations with all the adjuster rods fully inserted, the coolant void reactivity increases by 1.1 ± 0.1 mk due to core aging. When the adjuster rods are fully withdrawn, the coolant void reactivity increases by 0.6 ± 0.1 mk.
- Increased fission rate due to voiding is observed only for the uranium isotopes where as the plutonium isotopes show a reduction in the fission rates.
- A reduction in the flux levels and a pronounced change in the neutron spectrum are predicted at location of horizontal detectors which traverse below fuel bundles 4 to 9 in the sagged channels.
- The predicted flux levels at the vertical detector locations are unaffected by sagging.
- The predicted radial and azimuthal power peaking factors are unaffected by sag and creep.

4. Simulations of a CANDU Core

MCNP simulations of a full CANDU core with and without channel deformation were carried out to determine the effect of creep and sag on the following: coolant void reactivity, flux at detector locations, channel/bundle power profile in the core, maximum channel and bundle power, and reactivity worth of the reactivity devices.

4.1 Approximations and Simplifying Assumptions

The data set used to develop the MCNP model was based on conditions of an operating CANDU reactor. Certain approximations and simplifying assumptions were made to reduce the very high complexity of the model. The main approximations were:

- Same burnup distribution was used in both reference (unperturbed model) and perturbed model.
- The distribution of burnup was binned into 111 burnup bins each of ~100 MWd/TU bin width. An average burnup was calculated for each bin and this value was assigned to each of the bundles with a burnup value in the bin. The average burnup of each bin was specified to conserve the sum of bundle burnups in the bin. Fuel isotopic number densities were calculated by linear interpolation.
- Fuel, moderator and coolant temperatures were assumed to be uniform in the core.
- In modeling the aged core, a bounding value of 6% maximum creep and 80 mm of maximum sag were used. The distribution of creep and sag among the channels were assumed to be linearly proportional to the time averaged channel power, with the maximum value among the channels set to the postulated bounding values.
- The creep was discretized into 7 bins (0.5mm bin width). The maximum sag was discretized into 40 bins (2 mm bin width).
- Sagged channels were represented as a combination of 12 straight segments with each segment tilted with respect to the previous one.
- Crept pressure tube outer radius were adjusted to preserve Zr mass.

4.2 Results and Conclusions

MCNP simulations were performed in the reference (unperturbed) configuration as well as in several distorted core configurations, namely, coolant voided, checker board voided, adjusters out, zones drained, zones full, SORs in, CARs in, SORs half in. Three hundred million active histories were used in each of the first 4 cases to achieve a one standard deviation (1σ) statistical uncertainty of ±0.03 mk in k-effective. In the rest of the cases, 150 million active histories were used to achieve a $1\sigma = \pm 0.04$ mk.

Fission energy deposition tallies were scored for all bundles in the core. Individual pin powers were tallied in channels L12 and M12. Cell averaged flux tallies were scored in each of the segments of the detector thimble tubes. Tally convergence was verified by comparing tallies at 100, 200, and 300 million histories.

The main results of these simulations were:

- Channel distortions caused the core coolant void reactivity increase by 0.8 mk
- Channel distortions caused the coolant void reactivity increase by +0.5 mk when the core is voided in a checkerboard pattern
- The predicted worth of adjusters increased by 0.3 mk when the shut-off rods are halfway inserted. Changes to the worth of other reactivity devices were not predicted.

- The predicted thermal flux values in the horizontal detector locations (HFD1, HFD2, and HFD3) were lower by about 10% in the channel sagged geometry.
- The predicted thermal fluxes at the vertical flux detectors in the top half of the core were higher by ~5-6%. A corresponding decrease was seen at the bottom half of the core
- For the same total power from the reactor, the predicted bundle powers for the top channels of the core were higher by 10% compared to the undistorted core. These channels are low power channels located in the first few rows of the core. A corresponding decrease was predicted for bundle powers in the channels at the bottom of the core. The zone powers show ~14% top high tilt
- The predicted axial form factors were unaffected
- The predicted power distribution in the fuel pin rings was unaltered by the assumed changes

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