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Detector Response in a CANDU® Low Void Reactivity Core

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ABSTRACT

The response of the in-core flux detectors to the CANFLEX® *Low-Void-Reactivity Fuel (*LVRF) [1] bundles for use in the CANDU® reactor at Bruce nuclear generation station has been studied. The study was based on 2 detector types – platinum (Pt)-clad inconel and pure inconel detectors, and 2 fuel types – LVRF bundles and natural-uranium (NU) bundles. Both detectors show a decrease of *thermal-neutron-flux to total-photon-flux* ratio when NU fuel bundles are replaced by LVRF bundles in the reactor core (7% for inconel and 9% for Pt-clad detectors). The ratio of the *prompt component* of the net electron current to the *total* net electron current (PF_e) of the detectors however shows a different response. The use of LVRF bundles in place of NU fuel bundles in the reactor core did not change the PF_e of the Pt-clad inconel detector but increased the PF_e of the pure inconel detector by less than 2%.

The study shows that the inconel detector has a larger prompt-detector response than that of the platinum-clad detector; it reacts to the change of fluxes in the reactor core more readily. On the other hand, the Pt-clad detector is less sensitive to perturbations of the neutron-to-gamma ratio. Nevertheless the changes in an absolute sense are minimal; one does not anticipate a change of the flux-monitoring system if the NU fuel bundles are replaced with the CANFLEX LVRF bundles in the core of the Bruce nuclear generating station.

METHODOLOGY

The neutron-to-gamma ratio was calculated with the MCNP™ transport code version 4C [2]. In the analysis, the neutron-to-gamma ratio was defined as the ratio of the *total thermal-neutron flux in the emitter and the Pt-clad (for Pt-clad detector only)* to the *total photon flux in the same regions*. The total photon flux includes photons generated from prompt-neutron capture reactions, prompt-fission reactions, and fission-product decay photons. For prompt-capture photons originating from the dysprosium-doped central fuel pin of the LVRF bundle, the calculation was done separately because the neutron cross-section library in MCNP did not have the prompt gamma source for dysprosium (Dy). Implicit in the calculation is that the delayed components due to activation of the lead cable, the detector, and other structural materials are unimportant and do not affect the calculation of the prompt fraction, PF_e.

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The detector response was evaluated based on the calculated PF_e. The PF_e was defined as the ratio of the *prompt component* of the net electron current to the *total* net electron current (which includes the prompt component and a contribution to electron current from fission product decay). In this methodology, the detector signal was assumed to be directly proportional to the sum of electron currents across the detector insulator.
As will be shown, prompt fractions estimated using this methodology qualitatively reproduce and quantitatively approximate the observed behaviour of the detectors. Notwithstanding this, the calculation is still approximate as it leaves out a few second-order current-producing terms like activation decay gammas from the lead cable and detector materials in the derivation.

MCNP Model

Derivations of the neutron-to-gamma ratio and the PF_e were based on the results generated with MCNP. The MCNP model was a standard CANDU lattice cell with an in-core detector placed at the lattice edge. Two lattice models were generated to simulate separately the NU and the LVRF fuel bundles, see Figure 1.

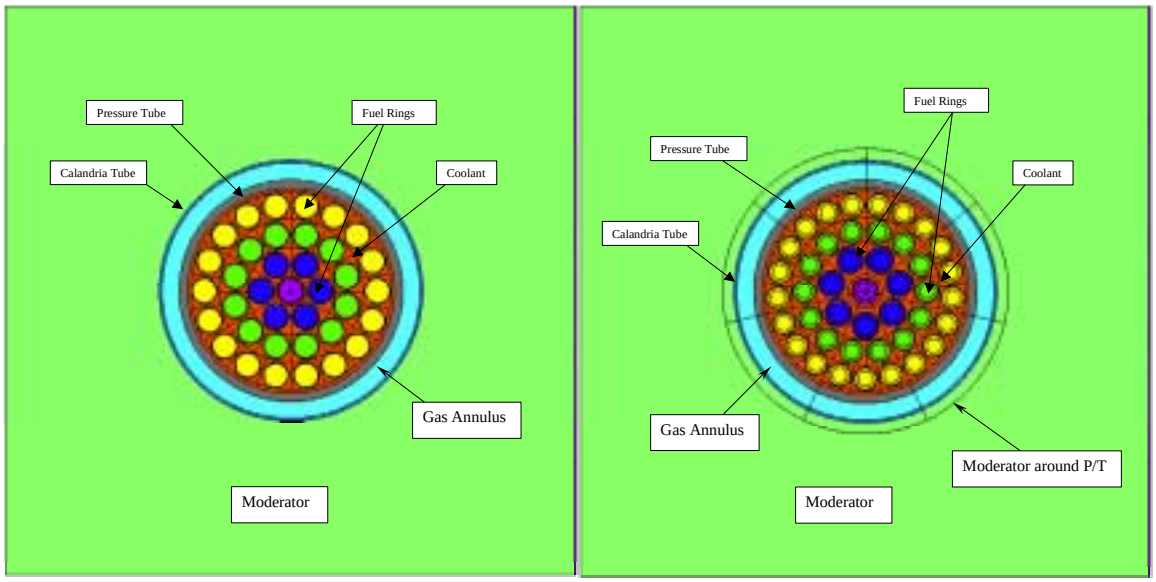

Figure 1 MCNP Models of a NU & a LVRF CANFLEX Bundles

The NU fuel bundle has 37 natural-uranium elements. The LVRF CANFLEX fuel bundle has 43 elements. The CANFLEX bundle has different pin sizes from the 37-element bundle with the inner 2 rings of fuel (8 elements) having a larger diameter than the pins of the outer 2 rings of fuel (35 elements). The pressure-tube (P/T) and calandria-tube dimensions are the same for both fuel-bundle types in a 286-mm square lattice, and the fuel bundle was located concentrically in the pressure tube. In both lattices, the in-core detector was placed at the edge of the fuel lattice. Unlike the 37-element bundle that has all natural-uranium fuel elements, the central element of the LVRF fuel bundle is made of natural uranium and dysprosium (Dy) oxide, with all the other fuel elements enriched to 1 wt-% of ^{235}U. The amount of Dy and enrichment is determined primarily by the magnitude of void reactivity reduction and burnup required [1].

MCNP Calculation Mode

The simulation was performed in the two calculation modes: criticality-search (*kcode*) and fixed-source (*sdef*) modes. The *kcode* calculation determined the neutron fluxes, the prompt portion of the photon fluxes, and all prompt-neutron capture reactions in the detector. The *sdef* calculation determined the delayed-gamma contribution to the photon fluxes, and all delayed reactions in the detector. In both calculation modes, the neutron-photon-electron coupling option in MCNP was used to determine the electron currents entering and leaving the detector regions.

The default cross-section library of MCNP does not come with Dy data; in the simulation, an AECL generated cross-section data for Dy was used. However, the AECL library does not have gamma-production data therefore prompt-gamma release from Dy absorptions was not credited in the *kcode* calculation. To include the missing gamma contribution, a *sdef*-calculation was done using the reaction rates from the *kcode* calculation and the standard capture-gamma spectra of the Dy nuclides. This extra *sdef*-calculation was to simulate the gamma-particle transport from the central element of the LVRF bundle to the detector.

Detector Prompt Fraction

In Figure 2 electron currents at the outer surface of the emitter and the inner and outer surfaces of the collector are identified. The focus is on the electron currents that cross the outer surface of the emitter (J_e^{net}) and the inner surface of the collector (J_c^{net}). Any electron exchange at the outer surface of the collector would never be measured across the resistance between the emitter and collector (J_o^{net}); any loss or gain at this outer surface will be neutralized by a compensating charge exchange via the ground.

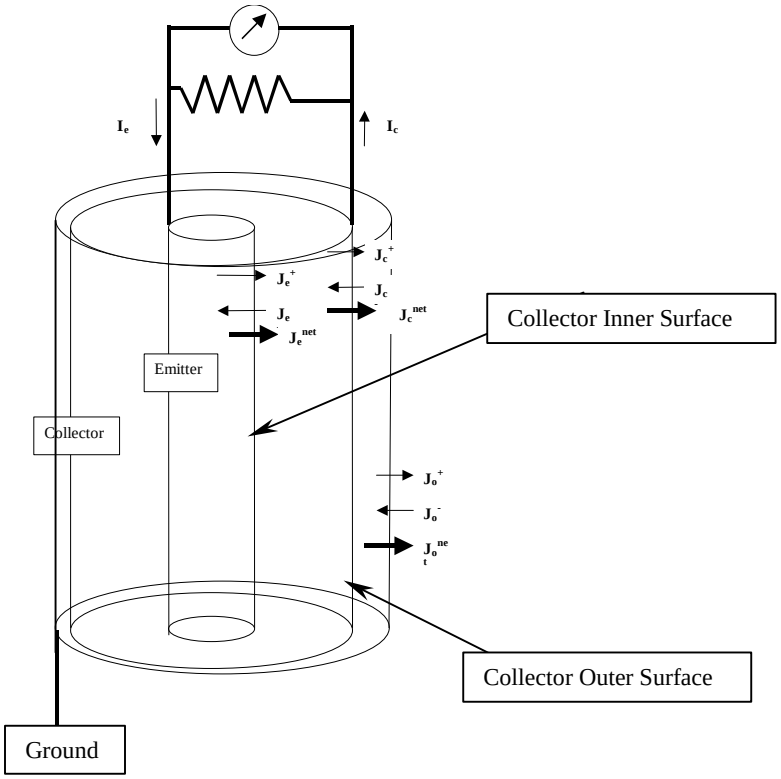

Figure 2 Schematic of the Electron Flow in the In-core Detector

However, at the emitter a net loss of electrons will generate a compensating flow of charge through the resistance from ground and that flow will register at the meter. In a similar fashion a gain of electrons at the inner surface of the collector will leave the insulator with a positive charge that can be neutralised by a flow of charge from the collector through the resistance to the emitter. That flow of charge will also register at the meter.

Thus the voltage measured across the meter reflects the passage of electrons on the emitter side of the meter, I_e, and on the collector side, I_c. For the directions of current shown in Figure 2, the currents, I_e and I_c, reinforce each other. That is, if either of the currents were zero then a signal would still register across the meter and its sign would be the same.

The electron currents are evaluated between the two interfaces of the insulator, i.e., the emitter-insulator interface and the insulator-collector interface. This net flow of electrons across the insulator was assumed to be directly proportional to the detector signal. Electrons leaving the collector externally in the well-tube direction are not considered because this surface is generally grounded and will not affect the current measured.

The detector PF_e was determined as the ratio of the *prompt component* of the net electron current to the *total* net electron current (which includes the prompt component and a contribution to electron current from fission-product decay) at 1 second after shutdown. In the simulation, the detector signal was assumed to be directly proportional to the sum of electron currents across the insulator located between the emitter and collector, which is proportional to the difference of the net electron currents that travel across the insulator to the collector.

$$PF_e = \frac{(\textit{prompt component of net electron current})}{(\textit{prompt component of net electron current}) + (\textit{delayed fission product component of net electron current})}$$

$$= \frac{J^{net}(prompt)}{J^{net}(prompt) + J^{net}(FP\ delayed)}$$

where

PF_e = Prompt fraction calculated based on the electron currents

$J^{net}(prompt)$ = Net electron current arising from prompt reaction rates (excluding delayed contribution from fission product decay)

$J^{net}(FP\ delayed)$ = Net electron current arising from delayed contribution due to fission product decay

In the equation above, J^{net} due to decay gammas from activation product was excluded. Unlike the vanadium detector which rely on activation-product decays, the self-powered detectors rely on (n,γ,e) and (γ,e) reactions. At shutdown, especially for short decay times of 1 second, electron currents generated by (γ,e) reactions due to fission-product decay gammas are many times larger than currents generated by β decay of Mn or Cr impurities in the inconel. Therefore the definition of PF_e does not include the currents due to activation-products in the denominator without large error.

RESULTS

The calculated neutron-to-gamma ratio for the inconel detector drops from 2.43 to 2.24 in going from NU fuel bundles to Bruce CANFLEX LVRF bundles in the core; the same ratio for the Pt-clad inconel detector drops from 2.36 to 2.21.

Compared to a standard natural-uranium core, in a LVRF core the estimated PF_e of the inconel detector increases slightly from 1.007 to 1.025 and the PF_e for the Pt-clad inconel detector remains essentially constant, changing very slightly from 0.912 to 0.913. The calculated results for the NU core are close to the measured values of 89% for the Pt-clad detector and 1.033 to 1.019 for the inconel detector in the Bruce B CANDU reactors.

CONCLUSION

Using the LVRF fuel, the thermal neutron flux in the lattice is expected to drop because the fission-to-capture ratio increases due to fuel enrichment. The calculated results show that a decrease in the thermal neutron flux would lead to a decrease in thermal-capture events and, consequently, a smaller number of prompt-capture gammas.

The more important detector-response parameter in terms of reactor control is the prompt fraction PF_e. The observed trends show that the PF_e of the inconel detector increases slightly, by less than 2%; and that of the Pt-clad detector remains rather constant. The results imply that the inconel detector has a larger prompt detector-response than the platinum-clad detector and will react to the change of flux in the core more readily. On the other hand, the high Z, i.e., the electron enhancing, property of platinum makes the Pt-clad detector less sensitive to small perturbation of the neutron-to-gamma ratio.

Although the calculated PF_e's are preliminary, there is minimal prompt-component change in going from NU fuel bundles to Bruce CANFLEX LVRF bundles in the core, i.e., no change or a slight increase in PF_e; no change of the flux-monitoring system is anticipated. Moreover, there is no change in performance to the delayed time constant as the fission-product decay-gamma release, the principal contributor to the delayed component, remains almost the same for the two types of fuel bundles due to the comparable burnup.

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