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# On-line determination of the prompt fraction of in-core neutron detectors in CANDU reactors

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This paper describes a new method for determining the prompt fraction of in-core neutron detectors in CANDU reactors. The method is based on noise analysis, and thus does not require any perturbation of the reactor operation. This method is therefore very well suited to on-line monitoring, and could detect early detector degradation as the detectors age. The prompt fraction estimation of the in-core neutron detectors is of prime importance in CANDU reactors, since these detectors are used by the reactor shutdown systems, and should consequently respond very quickly to any flux change.

This new method is based on the fluctuations of the light water levels in the water compartments at a frequency of roughly 0.25 Hz. These fluctuations are due to the control cycle of the regulating system of the reactor, and are equivalent to a spatially-distributed noise source of variable strength. The induced neutron noise can be monitored by the in-core neutron detectors, but only the prompt component of these detectors is able to follow these fluctuations at 0.25 Hz. Comparing the measured detector signals to the neutron noise estimated by core calculations allow determining the prompt fraction of the detectors.

***KEYWORDS: prompt fraction, neutron detector, noise analysis, dynamic reactor transfer function, core calculations***

## 1. Introduction

Permanently installed in-core neutron detectors are used in the two independent Shutdown Systems (SDSs) of CANDU reactors to prevent local over-power in the reactor core. The basic design function of the detectors is to detect a sudden increase in flux caused by any of a number of postulated accident scenarios. The detectors must respond to flux increases within the expected time interval stipulated by accident analysis.

The detectors are self-powered neutron detectors, producing a measurable current at high-power operation. Under steady-state conditions, the generated current is proportional to the local thermal neutron flux. In case of a transient in neutron flux, the current signal of the detectors lags behind the flux change, since the current generating processes of the detectors include slow-responding components, causing signal delays. The flux-to-current dynamic transfer function of the detectors consists of a large prompt response and a series of smaller exponentially delayed components, with either positive or negative amplitudes, making the detectors either under-prompt or over-prompt.

Experience has showed that the dynamic response of the detectors changes during its lifetime due to material changes (burn-up) and defects. In order to ensure that the detectors can respond fast enough to an accident and the reactor is shut down in time, it is necessary that the prompt component be always above the minimum allowable limit. Therefore the periodic testing of the prompt fractions of all safety-related neutron detectors is a requirement.

Prompt fraction measurements are performed regularly at the beginning of planned outages by tripping the reactor from high power. The effective prompt fractions are estimated from the measured trip response of the detectors and ex-core ion chambers. Similarly, trip measurements are also performed during the commissioning of new detectors to obtain a set of baseline values for prompt fractions.

A new method is proposed in this paper for determining the prompt fractions of in-core neutron detectors. The estimation is based on the comparison of dynamic parameters derived from the following two areas: (1) simultaneous measurements of instrumentation signal fluctuations (noise) at steady state, and (2) a detailed dynamic simulation of neutron flux noise in a CANDU core. A unique CANDU feature, namely the control of local power distribution by light water compartments, is utilized to gain measurement information on detector prompt fractions at steady-state operation.

At steady-state normal operation of CANDU reactors, the neutron absorption is controlled by 14 light water compartments (vertical pipes) with adjustable levels. Similarly to the control rods in a LWR, the light water acts as a neutron absorber in a CANDU reactor since the moderator is made of deuterium. The 14 water levels are constantly adjusted by the Reactor Regulating System (RRS) computer. Due to the control cycle, the level of the light water in the 14 pipes naturally oscillates around the desired mean value at a frequency of roughly 0.25 Hz. The 14 water level signals are directly measured by differential pressure transmitters and their signals can be readily recorded in the instrument rooms of the station. These measurements showed that the fluctuations of the water levels are highly correlated at 0.25 Hz. The 14 light water levels constitute therefore a noise source, or more precisely a 14 point-like absorber of variable strength type of noise source. The fluctuations of the in-core neutron detectors induced by the fluctuations of the 14 light water levels can be also measured along with the level signals. Therefore these simultaneous noise measurements are to be used to estimate the prompt fraction of the in-core neutron detectors while the reactor is at steady-state conditions. This could be achieved by comparing the measured detector signal noise to the neutron flux noise calculated by the so-called neutron noise simulator developed at the Department of Reactor Physics, Chalmers University of Technology [1]. The difference in amplitude between the normalized noise of detector signal and the normalized noise of calculated neutron flux is due to the deviation from 100% of the prompt fraction of the detectors. Therefore, the scaling factor between the two transfer functions at the 0.25 Hz frequency is related to the prompt fraction of the detector. The delayed components of the detector current are not fast enough to contribute to the detector signal at 0.25 Hz.

In the following, a quick overview of the liquid zone controllers in CANDU reactors is carried out. The main characteristics of the neutron detectors used for the shutdown systems are then touched upon. Emphasis is put on the dynamics of these detectors, as well as on the present method used for determining their prompt fraction. Furthermore, the effect of the fluctuations of the liquid zone controllers on the detector signals is highlighted. The noise-based method is finally presented, focusing on the required modeling tools and its advantages compared to the current method.

## 2. Characteristics of the liquid zone controllers

In a CANDU reactor, there are usually six ways of controlling the reactivity of the core (besides the on-line refueling) [2]. Four of these are used for normal control functions, including controlled shutdown, and two are used by special safety systems for rapid shutdown during accidental conditions.

The RRS controls the reactor under normal operating conditions via 14 liquid zone controller compartments (filled with light water at adjustable level), 21 movable adjuster rods (made of stainless steel or sometimes cobalt), 4 mechanical control absorbers (made of cadmium sandwiched in stainless steel), and some moderator poison (soluble boron used in the initial core, or gadolinium nitrate after reactor shutdown).

There are in addition two special SDSs: SDS-1, consisting of 28 cadmium shutoff rods falling into the core from above, and SDS-2, consisting of high-pressure poison injection into the moderator through six horizontally-oriented nozzles.

The liquid zone controllers are actually the main devices used for controlling the reactivity under normal conditions, and are meant to provide a continuous and fine control of the reactor power. They are made of six tubes within the reactor core, which contain in total 14 compartments into which light water is introduced. These compartments thus control each a separate region of the core. A second use of the light water compartments is therefore the control of the spatial power distribution. A layout of the position of the light water compartments is depicted in Figure 1. As can be seen in this Figure, the water compartments are distributed evenly through the core, providing a control of the whole core. The four tubes located close to the core periphery contain two water compartments, whereas the two tubes located in a more central location contain three water compartments. In a CANDU reactor, where heavy water is used as both coolant and moderator, the light water acts as a neutron absorber. The quantity of water in each compartment is controlled by an inlet valve specific to each compartment, whereas the water is forced out of the compartment at a constant rate by some helium cover gas pressure. The level of light water in each compartment is thus controlled by varying the relative value of the in-flow and out-flow rates of light water into that compartment. The 14 water level signals are directly measured by differential pressure transmitters.

The RRS adjusts the light water level in each compartment depending on the signals from neighboring in-core self-powered detectors (depicted as VFDs in Figure 1, where VFD stands for Vertical Flux Detector). To determine the required adjustment of the light water compartments, the RRS compares the 14 instantaneous detector readings to a set of reference readings corresponding to some desired power distribution. Due to the control cycle of the RRS, the light water level in each compartment oscillates around the desired level at a frequency of roughly 0.25 Hz.

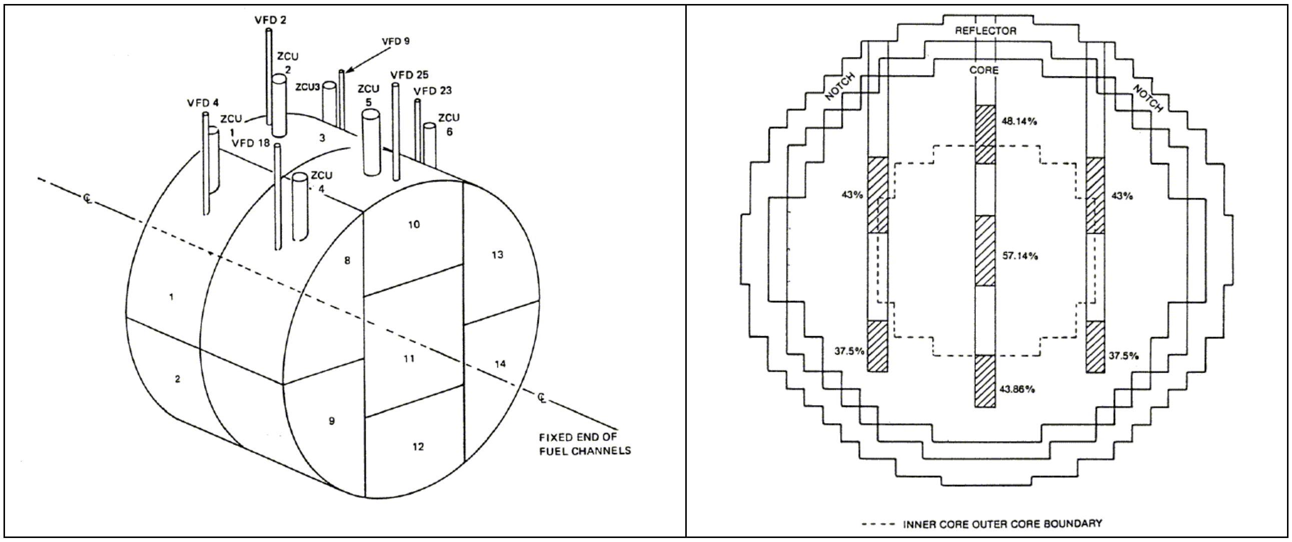


**Fig. 1** Overview of the position of the tubes (abbreviated as ZCU – Zone Control Units) containing the light water compartments (on the left hand-side), and overview of the position of the water compartments in each tube (on the right hand-side). [2]

Consequently, the fluctuations of the light water levels at 0.25 Hz are equivalent to fluctuations of the material constants of the core at the position of the water compartments, and can thus be considered as a 14 point-like absorber of variable strength type of noise source, whereas the reactor is still running at nominal operating conditions [3]. This can be easily seen in Figure 2, where the fluctuations of the water level in two different compartments of the Darlington Unit 3 CANDU reactor are analyzed. The normalized Auto-Power Spectrum Densities (APSDs) of the fluctuations of the water level around the mean value, i.e. the water level noise, for these two water compartments clearly exhibit a broad peak around 0.25 Hz. Furthermore, the coherence between the two signals at that frequency is very high, whereas the phase of the Cross-Power Spectrum Density (CPSD) between the two water level compartments is close to 0 deg. It can also be seen that the slow fluctuations in zone levels below 0.1 Hz are totally independent (zero coherence). This can be explained by the independent control of the liquid zone levels by the RRS, which affects only the relatively slow changes, i.e. low frequencies. This behavior at frequencies below 0.1 Hz is clearly different from the characteristics of the spectra at 0.25 Hz.

These fluctuations are expected to affect the neutron flux throughout the core, and the neutron detectors should therefore monitor the corresponding fluctuations of the neutron flux.

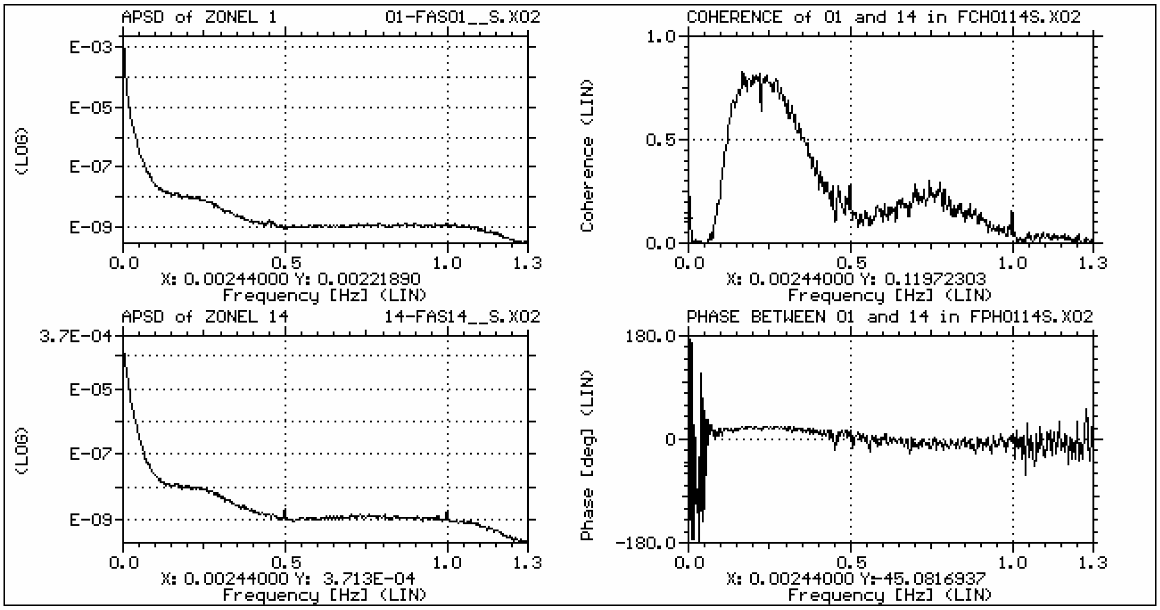


**Fig. 2** Normalized APSDs, coherence and phase functions of noise signals of liquid zone levels from zones #1 and #14 measured in the Darlington Unit 3 CANDU reactor

## 3. Characteristics of in-core neutron detectors used for the shutdown systems

There are many ways of monitoring the neutron flux in a CANDU reactor. The neutron flux is measured by In-Core Flux Detectors (ICFDs) of the self-powered type, and by ion chambers [2].

The ICFDs are distributed in several sets throughout the core: a set of fast-response Platinum detectors for zone power, needed by the zone control system, a set of fast-response Inconel detectors needed for local overpower protections on SDS-1, and a set of fast-response Platinum-clad Inconel detectors for local power protection on SDS-2. The ion chambers, whose facing surfaces are coated with boron-10, housed in a gas-filled vessel and which are 100% prompt, are located in separate housings on the sides of the reactor and are connected either to SDS-1 or SDS-2 (for SDS-1, each housing also contains one RRS ion chamber, but in a separate cavity within the housing).

Each ion chamber trips its logic channel of the corresponding SDS when the measured rate of change of the logarithm of the flux exceeds a pre-determined setpoint. Similarly, the protection-system logic channel can be tripped when any of the in-core neutron detectors connected to the corresponding SDS reaches a pre-determined setpoint. The in-core detector system connected to the SDSs is thus sometimes called the Regional Overpower Protection (ROP) system. Therefore, it is essential that the ROP system responds very quickly to changes in neutron flux. The in-core neutron detectors belonging to SDS-1 are actually vertical flux detectors, whereas the in-core neutron detectors belonging to SDS-2 are horizontal flux detectors. An overview of the position of the ICFDs used for the SDSs is given in Figure 3.

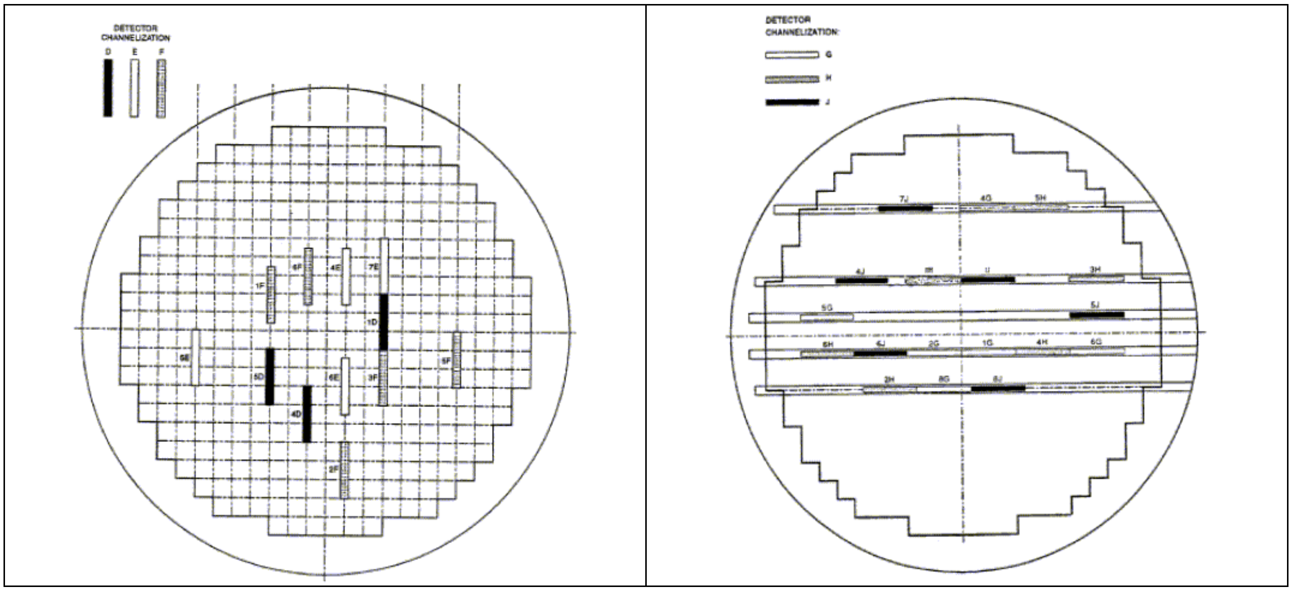

**Fig. 3** Overview of the position of the ICFDs used by the SDSs (Vertical Flux Detectors – or VFDs – for SDS-1 on the left hand-side, and Horizontal Flux Detectors – or HFDs – for SDS-2 on the right hand-side). [2]

In the following, the characteristics of the ICFDs used in SDS-1 and SDS-2 of the Darlington units are presented.

The Inconel ICFDs, i.e. the neutron detectors associated to SDS-1 and to the RRS, are over-prompt self-powered neutron detectors (104.8% design prompt fraction), and are almost entirely neutron sensitive. The emitter of these detectors absorbs neutrons and emits gammas at the time of capture via the (n, γ) reaction on Ni-58 contained in the Inconel. These gammas, via photoelectric effect and Compton interactions, produce an outward flow of charge which generates a current. This (n, γ, e) neutron-capture is a prompt interaction. The Inconel ICFDs have also a delayed contribution coming from (n, β) decay in the emitter, which has a small negative contribution to the detector current, and from the delayed reactor gamma-field through (γ, e) prompt interaction, which has only a minus 0.7% contribution to the detector.

The Platinum-clad Inconel ICFDs, i.e. the neutron detectors associated to SDS-2, are under-prompt self-powered flux detectors (88.7% design prompt fraction) and they have a mixed neutron/gamma sensitivity through (n, γ, e), (n, β), and (reactor γ, e) interactions, with approximately 60% and 40% contribution, respectively. The prompt (n, γ, e) sensitivity is about the same as that of the Inconel ICFDs, while the added, positive gamma sensitive process (reactor γ, e) is prompt and it arises from the interactions in the platinum cladding. Therefore, the Platinum-clad Inconel ICFDs are 1.5 times as sensitive as the Inconel ICFDs are. The relatively large delayed current is caused by (n, β) decay and by the delayed portion of the reactor γ-field. Approximately one third of the reactor γ-field is delayed with respect to the thermal neutron flux.

The above current producing processes are represented by the transfer function of the ICFD (gamma/neutron flux as input, and detector current as output). The transfer function is defined by one prompt component and five exponential delayed components with the design parameters given by Tables 1 and 2, for the Inconel and the Platinum-clad Inconel ICFDs respectively.

**Table 1** Nominal characteristics of the ICFDs used in SDS-1 of the Darlington units

| | Prompt | Delayed 1 | Delayed 2 | Delayed 3 | Delayed 4 |
|---|---|---|---|---|---|
| Time constant (sec) | 0.0 | 95.5 | 1538.5 | 13333.3 | 333333.3 |
| Amplitude (%) | 104.85 | -1.0 | -0.4 | -3.3 | -0.15 |

**Table 2** Nominal characteristics of the ICFDs used in SDS-2 of the Darlington units

| | Prompt | Delayed 1 | Delayed 2 | Delayed 3 | Delayed 4 | Delayed 5 |
|---|---|---|---|---|---|---|
| Time constant (sec) | 0.0 | 3.9 | 30 | 250 | 2440 | 170000 |
| Amplitude (%) | 88.7 | 1.5 | 2.3 | 1.6 | 4.5 | 1.4 |

In the time domain, the detector output voltage signal $V_D(t)$ is modeled via the convolution of the time dependent neutron flux, $\phi(\boldsymbol{r}_D,t)$, and the detector impulse response function, $h_D(t)$. The latter comprises the prompt fraction $p_D$ and the $N_D$ number of delayed components with time constant $\tau_{n,D}$ and relative amplitude $k_{n,D}$, respectively $(n=1,\ldots,N_D)$.

$$h_D(t) = p_D\delta(t) + \sum_{n=1}^{N_D} \frac{k_{n,D}}{\tau_{n,D}} \exp(\frac{-t}{\tau_{n,D}}) \tag{1}$$

where $\delta(t)$ is the Dirac-delta function, and $p_D + \sum_{n=1}^{N_D} k_{n,D} = 1$.

The voltage for a detector $D$ is thus given by:

$$V_D(t) = C_D \int_{-\infty}^{t} h_D(t-t') \times \phi(\boldsymbol{r}_D,t')dt' + V_{D,0} \tag{2}$$

where $C_D$ is the detector flux-to-voltage conversion factor and where $V_{D,0}$ is a constant voltage offset, measured at zero power (i.e. zero current). Equations (1) and (2) yield

$$V_D(t) = C_D\left[ p_D\phi(t) + \sum_{n=1}^{N_D} \frac{k_{n,D}}{\tau_{n,D}} \int_{-\infty}^{t} \phi(\boldsymbol{r}_D,t') \exp(-\frac{t-t'}{\tau_{n,D}})dt' \right] + V_{D,0} \tag{3}$$

Due to neutron and gamma irradiation, the prompt fraction of the ICFDs used in the SDSs will slightly decrease as the detectors age. Periodic tests are thus planned to verify that the prompt fraction of these detectors remain higher than some prescribed limit, which depends on various accident scenarios. The effective prompt fractions are estimated from the measured trip response of the detectors as the ratio between the normalized signal drop of a reference 100% prompt ion chamber and that of the ICFD signals, measured three seconds after trip initiation [4]. Additional correction terms are applied to the result to remove effects on the detector current of pre-trip power changes, the post-trip gamma background of fission products, and the delayed detector current component already active at 3 seconds after the trip. The combined effect of these three sources is in the range of 2-3%. This method requires a perturbation of the reactor, since the reactor has to be tripped.

In the frequency domain, the fluctuations of the detector signals around the mean value, i.e. the so-called noise, will satisfy the following equation:

$$\delta V_D(\omega) = C_D\left[p_D + \sum_{n=1}^{N_D}\frac{k_{n,D}}{1+j\omega\tau_{n,D}}\right]\delta\phi(\boldsymbol{r}_D,\omega) = T_D(\omega)\delta\phi(\boldsymbol{r}_D,\omega) \tag{4}$$

whereas the mean value will fulfill the equation given by:

$$V_D = C_D\left[p_D + \sum_{n=1}^{N_D} k_{n,D}\right]\phi(\boldsymbol{r}_D) + V_{D,0} \tag{5}$$

which, due to the fact that $p_D + \sum_{n=1}^{N_D} k_{n,D} = 1$, further simplifies into:

$$V_D = C_D\phi(\boldsymbol{r}_D) + V_{D,0} \tag{6}$$

The nominal dynamic transfer functions of the ICFDs, i.e. the transfer functions given by Eq. (4), are represented in Figure 4 for both the SDS-1 and SDS-2 systems of detectors. Due to the time constants of the delayed components, it can be noticed that the normalized gain of the detector transfer functions is equal to the detector prompt fraction for frequencies larger than the cut-off frequency corresponding to the fastest delayed components, i.e. typically for frequencies larger than 0.1 Hz.

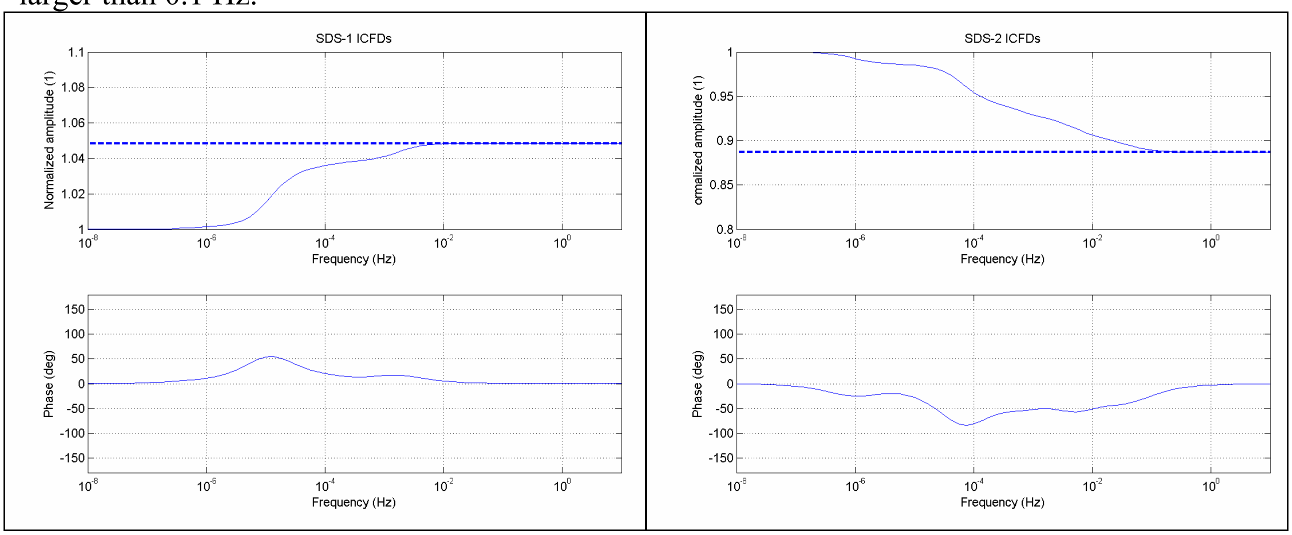


**Fig. 4** Calculated Bode diagrams of the normalized nominal dynamic transfer function of the ICFDs used in SDS-1 (on the left hand-side), and in SDS-2 (on the right hand-side). The dashed lines represent the relative prompt fraction of the detectors.

## 4. Method for the on-line determination of the prompt fraction of the ICFDs

Another possibility of determining the prompt fraction of the ICFDs arises with the fluctuations of the light water level in the zone control units. As mentioned previously, these fluctuations are equivalent to a spatially-distributed variable absorber type of noise source. The corresponding induced neutron noise should therefore be monitored by the ICFDs. As can be seen in Figs. 5 and 6, there is a very high coherence between the ICFDs noise and the zone level noise at a frequency of roughly 0.25 Hz, i.e. the frequency corresponding to the fluctuations of the light water level in the compartments. This high coherence is demonstrated within the same zones (see Fig. 5), and even between different zones (see Fig. 6), thus suggesting the coupling between the fluctuations of the level of the light water compartments and the measured neutron noise over the whole core. Furthermore, there is clearly an out-of-phase behavior between the neutron noise and the water level noise, since the phase of the CPSDs in Figs. 5 and 6 is close to ±180 deg. This is in agreement with the fact that more water in the water level compartment leads to increased absorption, and thus to a decrease of the neutron flux. As can be seen in Fig. 7, the neutron flux noise signals from different zones are also correlated with zero phase difference this time, except below 0.1 Hz, where the slow flux changes are determined by the control actions of the RRS, and which are independent in the 14 zones.

Consequently, both the noise source, i.e. the fluctuations of the water level in the 14 light water compartments, and the induced neutron noise can be measured. Assuming that the noise source corresponding to the fluctuations of the water level in a given compartment can be written formally as $\delta S_L(\omega)$ in the frequency domain, the induced neutron noise in the 2-group diffusion approximation at the frequency $\omega$ can be estimated from the following inhomogeneous equation [1]:

$$\left[\overline{\overline{D}}(\boldsymbol{r})\nabla^2 + \overline{\overline{\Sigma}}(\boldsymbol{r},\omega)\right]\times\begin{bmatrix}\delta\phi_1(\boldsymbol{r},\omega)\\ \delta\phi_2(\boldsymbol{r},\omega)\end{bmatrix} = \left[\overline{\overline{D}}(\boldsymbol{r})\nabla^2 + \overline{\overline{\Sigma}}(\boldsymbol{r},\omega)\right]\times\overline{\delta\phi}(\boldsymbol{r},\omega) = \overline{\delta S}_L(\omega) \quad (7)$$

where the matrix $\overline{\overline{\Sigma}}(\boldsymbol{r},\omega)$ is given as:

$$\overline{\overline{\Sigma}}(\boldsymbol{r},\omega) = \begin{bmatrix}-\Sigma_1(\boldsymbol{r},\omega) & \nu\Sigma_{f,2}(\boldsymbol{r},\omega)\\ \Sigma_{rem}(\boldsymbol{r}) & -\Sigma_{a,2}(\boldsymbol{r},\omega)\end{bmatrix} \quad (8)$$

and the different coefficients are defined as:

$$\Sigma_1(\boldsymbol{r},\omega) = \Sigma_{a,1}(\boldsymbol{r}) + \frac{i\omega}{v_1} + \Sigma_{rem}(\boldsymbol{r}) - \nu\Sigma_{f,1}(\boldsymbol{r})\left(1 - \frac{i\omega\beta_{eff}}{i\omega+\lambda}\right) \quad (9)$$

$$\nu\Sigma_{f,2}(\boldsymbol{r},\omega) = \nu\Sigma_{f,2}(\boldsymbol{r})\left(1 - \frac{i\omega\beta_{eff}}{i\omega+\lambda}\right) \quad (10)$$

$$\nu\Sigma_{a,2}(\boldsymbol{r},\omega) = \nu\Sigma_{a,2}(\boldsymbol{r}) + \frac{i\omega}{v_2} \quad (11)$$

All the notations have their usual meaning. The Department of Reactor Physics, Chalmers University of Technology developed a code to calculate the spatial distribution of the flux noise induced by any type of noise source and for any heterogeneous reactor core [1], i.e. the code actually performs the inversion of Eq. (7). Formally, the code calculates the so-called dynamic reactor transfer function $\overline{\overline{G}}_{dyn}$, fulfilling the following Equation:

$$\overline{\delta\phi}(\boldsymbol{r},\omega) = \overline{\overline{G}}_{dyn}(\boldsymbol{r},\boldsymbol{r}_L,\omega)\times\overline{\delta S}_L(\omega) \quad (12)$$

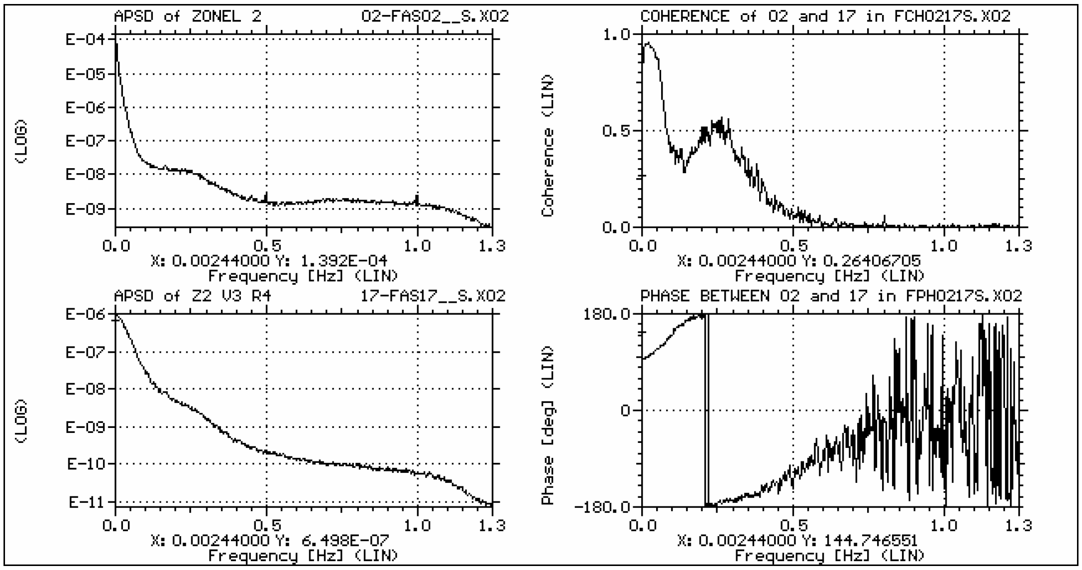


**Fig. 5** Normalized APSDs, coherence and phase functions of the liquid zone level noise and ICFD noise measured in zone #2 in the Darlington Unit 3 CANDU reactor

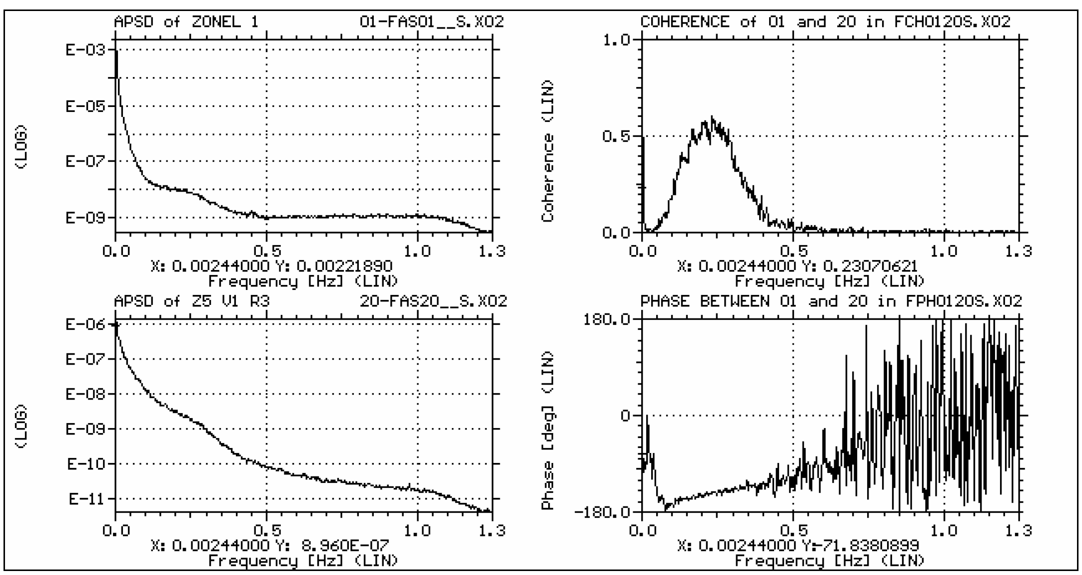


**Fig. 6** Normalized APSDs, coherence and phase functions of the liquid zone level noise from zone #1 and ICFD noise from zone #5 in the Darlington Unit 3 CANDU reactor

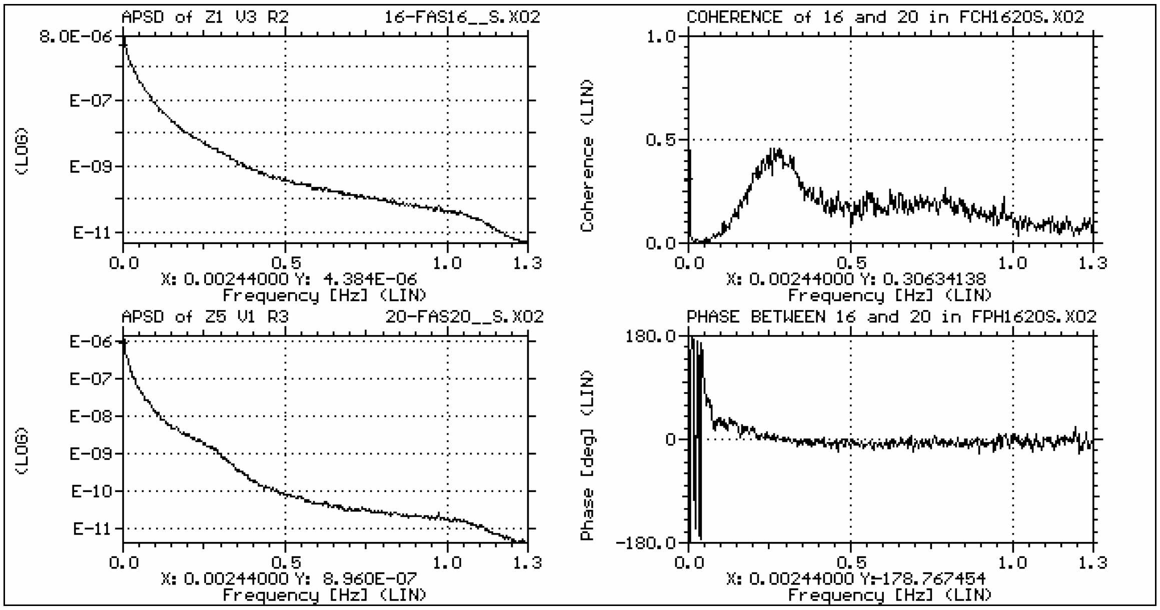


**Fig. 7** Normalized APSDs, coherence and phase functions of ICFD noise signals from zones #1 and #5 in the Darlington Unit 3 CANDU reactor

This code also calculates, among other things, the static flux in the 2-group diffusion equation, solution of the following homogeneous equation:

$$\left[\overline{\overline{D}}(\boldsymbol{r})\nabla^2+\overline{\overline{\Sigma}}(\boldsymbol{r})\right]\times\begin{bmatrix}\phi_1(\boldsymbol{r})\\ \phi_2(\boldsymbol{r})\end{bmatrix}=\left[\overline{\overline{D}}(\boldsymbol{r})\nabla^2+\overline{\overline{\Sigma}}(\boldsymbol{r})\right]\times\overline{\phi}(\boldsymbol{r})=0 \tag{13}$$

where

$$\overline{\overline{D}}(\boldsymbol{r})=\begin{bmatrix}D_1(\boldsymbol{r}) & 0\\ 0 & D_2(\boldsymbol{r})\end{bmatrix} \tag{14}$$

$$\overline{\overline{\Sigma}}(\boldsymbol{r})=\begin{bmatrix}\dfrac{\nu\Sigma_{f,1}(\boldsymbol{r})}{k_{eff}}-\Sigma_{a,1}(\boldsymbol{r})-\Sigma_{rem}(\boldsymbol{r}) & \dfrac{\nu\Sigma_{f,2}(\boldsymbol{r})}{k_{eff}}\\ \Sigma_{rem}(\boldsymbol{r}) & -\Sigma_{a,2}(\boldsymbol{r})\end{bmatrix} \tag{15}$$

Consequently, combining Eqs. (4) and (12), one can write the following equation giving the ICFD signal noise from the noise source, i.e. the fluctuations of the level in the light water compartments, as:

$$\begin{aligned}\delta V_D(\omega)&=T_D(\omega)\delta\phi(\boldsymbol{r}_D,\omega)=T_D(\omega)\times[1\quad 1]\times\begin{bmatrix}\delta\phi_1(\boldsymbol{r}_D,\omega)\\ \delta\phi_2(\boldsymbol{r}_D,\omega)\end{bmatrix}\\ &=T_D(\omega)\times[1\quad 1]\times\overline{\overline{G}}_{dyn}(\boldsymbol{r}_D,\boldsymbol{r}_L,\omega)\times\overline{\delta S}_L(\omega)\end{aligned} \tag{16}$$

For frequencies higher than the cut-off frequencies of the fastest delayed components of the ICFDs, one actually demonstrated earlier that:

$$\delta V_D(\omega)=T_D(\omega)\delta\phi(\boldsymbol{r}_D,\omega)=C_D p_D\delta\phi(\boldsymbol{r}_D,\omega)\quad\text{for}\quad\omega>>1/(2\pi\tau_D) \tag{17}$$

where $\tau_D$ is the shortest time constant of the ICFD delayed components. Recalling Eq. (6) giving the detector static value as a function of the measured static neutron flux, one can use Eq.

(17) to get:

$$\frac{\delta V_D(\omega)}{V_D - V_{D,0}} = p_D \frac{\delta\phi(\boldsymbol{r}_D,\omega)}{\phi(\boldsymbol{r}_D)} = p_D \times [1 \quad 1] \times \frac{\overline{\overline{G}}_{dyn}(\boldsymbol{r}_D,\boldsymbol{r}_L,\omega)}{\phi(\boldsymbol{r}_D)} \times \overline{\delta S}_L(\omega) \quad \text{for} \quad \omega >> 1/\tau_D \tag{18}$$

which can be rewritten in a more compact form as follows:

$$\delta F_D(\omega) = p_D \overline{G}(\boldsymbol{r}_D,\boldsymbol{r}_L,\omega) \times \overline{\delta S}_L(\omega) \quad \text{for} \quad \omega >> 1/\tau_D \tag{19}$$

with

$$\delta F_D(\omega) = \frac{\delta V_D(\omega)}{V_D - V_{D,0}} \tag{20}$$

and

$$\overline{G}(\boldsymbol{r}_D,\boldsymbol{r}_L,\omega) = [1 \quad 1] \times \frac{\overline{\overline{G}}_{dyn}(\boldsymbol{r}_D,\boldsymbol{r}_L,\omega)}{\phi(\boldsymbol{r}_D)} \tag{21}$$

This opens up the possibility of determining the prompt fraction of the ICFDs, since the left hand-side of Eq. (19) can be determined from the time signals of the ICFDs, whereas the only unkown parameter of the right hand-side of Eq. (19) is the prompt fraction $p_D$ ($\delta S_L(\omega)$ can be estimated from the time signals of the water level compartments, whereas $\overline{G}(\boldsymbol{r}_D,\boldsymbol{r}_L,\omega)$ is determined by core calculations as explained above).

The situation is nevertheless slightly more complicated since one ICFD monitors the contribution of the fluctuations of all the water level compartments, as well as the contribution from other noise sources that are completely independent of the fluctuations of the water level compartments. This can be formally written as:

$$\delta F_{D_i}(\omega) = p_{D_i} \sum_{j=1}^{14} \overline{G}(\boldsymbol{r}_{D_i},\boldsymbol{r}_{L_j},\omega) \times \overline{\delta S}_{L_j}(\omega) + \delta N_{D_i}(\omega) \quad \text{for} \quad \omega >> 1/\tau_D \tag{22}$$

where the index $D_i$ refers to a given ICFD, whereas the index $L_j$ refers to a given water level compartment. Furthermore, $\delta N_{D_i}(\omega)$ represents the independent flux noise recorded by the ICFD $D_i$.

Multiplying Eq. (22) by $\overline{\delta S}^*_{L_k}(\omega)$ where the star denotes the complex conjugate, and making use of the Wiener-Khinchin theorem, allows eliminating the independent flux noise $\delta N_{D_i}(\omega)$, so that one obtains for the Cross-Power Spectrum Density (CPSD):

$$CPSD_{D_i,L_k}(\omega) = p_{D_i} \sum_{j=1}^{14} \overline{G}(\boldsymbol{r}_{D_i},\boldsymbol{r}_{L_j},\omega) \times CPSD_{L_j,L_k}(\omega) \quad \text{for} \quad \omega >> 1/\tau_D \tag{23}$$

As for Eq. (19), the only parameter that is unknown in Eq. (22) is the prompt fraction $p_{D_i}$, all the others quantities being determined from measurements or from calculations. The prompt fraction estimation can thus be carried out at the frequency of 0.25 Hz, i.e. the frequency corresponding to the fluctuations of the water level compartments, since this frequency is larger than the cut-off frequency of the shortest time constant of the delayed components.

## 5. Conclusion

The fluctuations of the water level in the zone control units of CANDU reactors offer a unique opportunity to determine, via noise analysis, the prompt fraction of the in-core flux detectors, without perturbing reactor operation, i.e. without tripping the reactor as required by the present way of measuring the prompt fraction. This technique could be applied on-line, at any time during normal high-power steady-state operation. Possible early degradation of the in-core flux detectors as they age could be easily detected.

At-power noise measurements are planned in the future to test the applicability of this new noise-based method. By using an appropriate data acquisition systems (removal of the mean value, anti-aliasing filtering, amplification and A/D conversion), a sufficient accuracy of the light water level noise and the neutron noise measured by the in-core neutron detectors can be achieved. These at-power noise measurements of the 14 light water levels and the in-core neutron detectors will allow determining the level of sophistication of the core model required for the calculations, especially the level of heterogeneity of the reactor necessary to achieve the expected accuracy of the prompt fraction estimation. The noise-based estimates of detector prompt fractions can be validated by comparing them to detector design values or to prompt fraction results obtained from reactor trip tests.

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