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ENVIRONMENTAL EFFECTS ON THE RESPONSE OF SELF-POWERED FLUX DETECTORS IN CANDU REACTORS

by

G.F. LYNCH, R.B. SHIELDS and C.W. JOSLIN

Colloquium paper CI/02 presented at NUCLEX 75, International Nuclear Industries
Fair and Technical Meetings, 7-11 October 1975, Basel, Switzerland.

Chalk River Nuclear Laboratories
Chalk River, Ontario
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ABSTRACT

Self-powered flux detectors are playing an increasingly important role in the control and safety systems of CANDU-type reactors. In this paper we report on recent experiments to determine how local reactor conditions affect the output signals from self-powered detectors with vanadium, platinum and cobalt emitters. The results are interpreted in terms of variations in the local neutron, γ-ray and electron fluxes.

Résumé

Les détecteurs de flux auto-alimentés jouent un rôle de plus en plus important dans le contrôle et dans les systèmes de sûreté des réacteurs de type CANDU. Ce rapport concerne des expériences effectuées récemment pour déterminer dans quelle mesure les conditions locales des réacteurs influent sur les signaux provenant des détecteurs auto-alimentés dont les émetteurs sont en vanadium, en platine et en cobalt. Les résultats sont interprétés en fonction des variations se produisant dans les flux locaux de neutrons, de rayons gamma et d'électrons.

Zusammenfassung

Netzunabhängige Fluß detektoren spielen in der Steuerung und Sicherheit von CANDU-Reaktoren eine immer bedeutendere Rolle. Das vorliegende Referat berichtet über kürzlich durchgeführte Versuche zur Feststellung des Einflusses verschiedener Reaktorverhältnisse auf die Ausgangsimpulse von netzunabhängigen Detektoren mit Vanadium-, Platin- und Kobalt-Strahlern. Die Ergebnisse werden als Schwankungen des Neutronen-, Röntgenstrahlen- und Elektronenflusses ausgewertet.

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INTRODUCTION

Since their introduction over ten years ago, self-powered flux detectors have moved from the research laboratories to play a prominent role in the CANDU power-reactor program, and their use in control and safety systems is now well-established. As confidence in these detectors has grown, the number used in particular reactors has increased from a single stringer of 24 detectors in Douglas Point to over 200 in the latest generation of 600 MW CANDU-PHW* reactors, as shown in Table 1 below.

TABLE 1

SELF-POWERED FLUX DETECTORS IN CANDU REACTORS

REACTOR	YEAR IN SERVICE	NO. OF SELF-POWERED DETECTORS CONTROL	SAFETY	TOTAL	DETECTOR TYPES
NPD (25 MWe)	1962	--	--	--	--
DOUGLAS POINT (208 MWe)	1967	24	--	24	V
PICKERING (514 MWe)	1971	32	4	36	Co
GENTILLY-1 (250 MWe)	1971	42	26	68	V,Rh,Zr
GENTILLY-1 (250 MWe)	1974	60	54	114	V,Pt
BRUCE (732 MWe)	1976	82	78	160	V,Pt
GENTILLY-2 (600 MWe)	1979	130	72	202	V,Pt

This increased use of self-powered detectors has arisen from the requirement for more in-core flux measurements. For example, as reactor cores increase in size, less reliance can be placed on out-of-core instrumentation to provide the information required on spatial power distribution. Secondly, for CANDU reactors with boiling cooling, thermohydraulic measurements, e.g. of temperature and outlet quality, on individual coolant channels leave much to be desired. Thirdly, flux-tilt and regional overpower protective systems require prompt signals from many points located throughout the reactor cores. Because of their simplicity, ruggedness, reliability and long life in the harsh reactor core environment, self-powered detectors are well-suited to these applications.

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*CANDU-PHW ≡ CANada Deuterium Uranium - Pressurized Heavy Water coolant

Because of the important role of these detectors in reactor control and safety systems, it is essential that we understand their basic response mechanisms and how they are affected by various reactor environments and mounting arrangements. Since theoretical models describing the responses of self-powered detectors are still in their infancy [1], it is necessary to rely on experimental data to determine how detectors will respond to the various radiation conditions to which they may be subjected.

Our present studies have been limited to heavy-water-moderated, natural-uranium reactors and in this paper we summarize recent experiments aimed at improving our understanding of how various local core conditions affect the neutron, γ-ray and electron fluxes, and consequently the output signals from self-powered detectors. Many of these experiments have been performed for particular applications, but considered together they give a fairly broad picture of the behaviour of these detectors in various radiation environments.

2. SELF-POWERED DETECTOR TYPES

As shown in Table 1, several types of detectors have been used in CANDU reactors, including those with vanadium, rhodium, zirconium, cobalt and platinum emitters. There are advantages and disadvantages for each type, but current practice is to use Pt detectors for fast control and safety systems, and an array of slower-responding V detectors for determining reactor power distribution and local hot spots.

For the work described here, V, Co and Pt detectors are assumed to be representative of the three major detector-response mechanisms, viz., neutron-induced β-decay, neutron-capture γ-rays and external γ-rays, respectively [2]. The emitter diameters were 0.33 mm for V and 0.50 mm for both Pt and Co, and the sensitive length was 300 cm for all detectors.

3. FACTORS AFFECTING DETECTOR RESPONSE

The calibration of individual detectors is often carried out in research reactors, under conditions considerably different from those experienced in a power reactor. We have attempted to simulate conditions in CANDU power reactors using the heavy-water-moderated ZED-2 lattice-test reactor [3] and thus determine the effects of the power-reactor core environment on the various detectors.

3.1 Mounting Arrangement

For permanent installation in a power-reactor core, self-powered detectors are normally mounted in an assembly such as that shown in Fig. 1. The detectors are coiled on a 9.5 mm OD Zircaloy tube which is inserted into a 19 mm ID Zircaloy guide tube, normally installed in the moderator, midway between fuel channels.

Table 2 shows results obtained by inserting the three basic types of detector into tubes of various materials that might be used for detector mounting assemblies. The tubes were filled with D_2O moderator.

TABLE 2

SELF-POWERED DETECTOR RESPONSES TO VARIOUS MOUNTING MATERIALS IN ZED-2

MOUNTING MATERIAL	V	Pt	Co
FREE-HANGING	1.00	1.00	1.00
ZIRCALOY TUBE	1.00	1.00	1.00
ALUMINUM TUBE	0.97	0.93	0.91
304 STAINLESS STEEL TUBE	0.92	1.03	0.94
LUCITE ROD	0.97	1.00	0.99

For comparison, the results obtained when the detectors were strapped to the outside of a lucite rod are also listed. In all cases the detectors were straight and the signals with the detectors free-hanging are taken as the unperturbed values. To allow for changes between irradiations, the detector signals were normalized to a V reference detector, located in the moderator, five lattice pitches ($\sim$ 1.4 m) from the test position.

Zircaloy appears to have the smallest effect on the detector outputs. Aluminum depresses the signals in all cases and this presumably arises from the combination of three effects. The thermal neutron flux is slightly depressed by the presence of the aluminum.

The external electron flux is enhanced by β-decay of $^{28}\mathrm{A}\ell$, produced via the $^{27}\mathrm{A}\ell(n,\gamma)^{28}\mathrm{A}\ell$ reaction. The local γ-ray flux is enhanced by neutron-capture events. For aluminum, the second effect appears to dominate. With stainless steel, however, enhancement of the local γ-ray flux is important, as indicated by the 3% increase in the Pt detector signal.

When local flux measurements are required, the detectors are usually coiled to adjust their effective sensitive length. Variations in sensitivity of detectors under such conditions are shown in Table 3, where once again the uncoiled, free-hanging detector responses are taken as the unperturbed values.

TABLE 3

EFFECT OF COILING SELF-POWERED DETECTORS

DETECTOR CONDITION	V	Pt	Co
FREE-HANGING AND STRAIGHT	1.00	1.00	1.00
FREE-HANGING AND COILED	0.88	1.11	0.79
COILED ON ZIRCALOY	0.81	1.04	0.74
COILED ON ZIRCALOY + GUIDE TUBE	0.80	1.01	0.70
COILED ON LUCITE	0.84	1.09	0.79

Coiling a detector produces several effects, the relative importance of each depending on the type of detector. For V detectors, the major effect ($\sim$ 9%) is flux depression (discussed further in section 3.2 below), plus an enhancement of the electron flux into the detector from β-decay processes in adjacent turns ($\sim$ 3%). For Pt detectors, the higher γ-ray and lower neutron sensitivities result in the dominant effect being enhancement of the local γ-ray flux (due to neutron-capture events in adjacent coils), thus producing a signal increase of 11%. Neutron flux depression is also the dominant effect for the Co detector. However, the enhancement of the γ-ray flux due to neutron-capture events in adjacent coils leads to a further decrease in the signal, since Co has a negative γ-ray sensitivity [2].

Coiling the detectors on a Zircaloy tube has a much greater effect than might be expected from the results in Table 2. This is presumably due to the intimate contact between the coiled detector and the Zircaloy former, compared to occasional point contact when the detector is located inside a tube. The close contact allows transfer of Compton and photoelectrons from the Zircaloy former to the detector. With the detector inserted in a D_2O-filled tube the heavy water between the tube wall and the detector absorbs many of these electrons.

Coiling, plus the use of a Zircaloy guide tube, results in overall changes in sensitivity of -20% for V, +1% for Pt, and -30% for Co.

3.2 Effect of Detectors on the Neutron Flux

The neutron flux depression at the surfaces of self-powered detectors have been determined by Cu foil activation measurements and the results are shown in Table 4 below.

TABLE 4

NEUTRON FLUX DEPRESSION BY SELF-POWERED DETECTORS

DETECTOR TYPE	NEUTRON FLUX DEPRESSION %	
	DETECTOR STRAIGHT	DETECTOR COILED
V	2 ± 1	9 ± 1
Pt	2 ± 1	11 ± 1
Co	2 ± 1	17 ± 1

The flux perturbation extends about 3 cm from the surface of a detector, as shown in Fig. 2, and results from neutron absorption in the Inconel sheath as well as the emitter material. This is the major cause of the decrease in the response of neutron-sensitive detectors when they are coiled.

3.3 Local Perturbations

The flux distributions in CANDU reactor cores are highly structured because of the nature of the distribution of the fuel in the moderator. There are also other local perturbations arising from the distribution of reactor control devices. These disturbances affect the neutron, γ-ray and electron fluxes in different ways, leading to changes in the responses of the flux detectors.

For one particular application, it was necessary to install detectors in the gas annulus between the pressure and calandria tubes of certain fuel channels in a CANDU-BLW* reactor. A simulation was performed in the ZED-2 reactor, primarily to determine the effects of a refuelling operation. The results are shown in Table 5, where the channel filled with D_2O is taken as the reference condition.

TABLE 5

SELF-POWERED DETECTOR RESPONSES NEAR FUEL ASSEMBLIES

FUEL-CHANNEL CONTENTS	SELF-POWERED DETECTOR RESPONSE V	 Pt	 Co	Cu FOIL ACTIVITY
D_2O	1.00	1.00	1.00	1.00
H_2O	0.71	0.77	0.68	0.69
NAT UO_2 + H_2O	0.66	1.14	0.65	0.68
NAT UO_2 + AIR	0.56	1.15	0.55	0.59

The three basic types of self-powered detectors were used in the experiments. Each detector output was normalized to the output of a V reference detector and the foil activities normalized to the activities of similar foils, both of which were located in the moderator, five lattice pitches from the channel under test. The copper-foil activation measurements represent the relative thermal neutron flux at a point near the self-powered detectors.

The decrease in all detector signals when D_2O is replace by H_2O reflects the greater neutron absorption in the latter. The further reduction of the signals from the Co and V detectors, when the fuel is introduced into the channel, results from the additional thermal neutron flux depression, plus an increase in the local γ-ray flux, as indicated by the increase in the Pt detector signal. These results are consistent with the negative γ-ray response of Co and V detectors [2]. It is interesting to note that the Pt detector seems relatively insensitive to the type of coolant in the fuelled channel, although H_2O has a significant moderation effect compared to air (the Cu foils show a 14% higher thermal neutron flux). When these results are compared

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*CANDU-BLW ≡ CANada Deuterium Uranium - Boiling Light-Water coolant with fine-structure flux measurements through a similar fuel channel [4], it appears that Pt detectors reflect the local fission power more accurately than predominately neutron-sensitive detectors.

The response of a Pt detector, compared to that of neutron-sensitive detectors, in the vicinity of a rather black boron absorber, is shown in Fig. 3. In the unperturbed reactor core, the radial flux distribution measured by Pt is indistinguishable from that measured by V or Co detectors, or Cu foils. With the absorber installed, Pt reads somewhat higher than the other detectors close to the absorber as a result of the lower neutron sensitivity of Pt and also possibly enhancement of the local γ-ray flux, due to neutron-capture events in the boron. As a general rule, the relative responses of all three detectors may be regarded as the same (within a few percent) at distances greater than one lattice pitch from a control absorber.

Some CANDU reactors use booster (enriched U) fuel rods to shorten the Xe poison-out period. For example, booster rods will be used in the Bruce G.S. reactors, and local overpower trips have been provided, to protect against loss of regulation with the reactor heavily boosted or the flux distribution otherwise highly distorted.

Figure 4 shows the axial neutron-flux distribution, as determined by Cu foils, for an unperturbed, simulated (in ZED-2) Bruce core and the same core perturbed by a particular configuration of boosters. For the unperturbed lattice, the results from Pt, Co and V detectors all agree with the Cu foil data, within experimental accuracy. For the perturbed core, Co and V detectors agree with the Cu foil data but the behaviour of the Pt detector as it approaches the booster is the combined result of a rapidly increasing γ-ray flux near the fission source, and a decreasing thermal-neutron flux. However, once again it is interesting to note that at distances greater than one lattice pitch from the booster assembly, the Pt detector response matches the thermal neutron flux within 3.5%, even with full booster insertion.

4. DISCUSSION

The results from experiments to study the effects of mounting hardware indicate that care must be taken when considering the absolute calibration of self-powered detectors. It is important to define exactly the conditions under which the calibration is performed and ideally the detector signal should be related to the flux at that point with no detector present. The main changes in the responses arise from variations in the local neutron/γ-ray flux ratio, as well as an enhancement of the local electron flux, particularly when the detector is coiled on the mounting assembly. On balance, Pt detectors appear to be least affected by the mounting hardware.

The main effect of core perturbations on the responses of the detectors is also due to variations in the neutron/γ-ray flux ratio. However, these variations are usually significant only within one lattice pitch of the perturbation, even in extreme conditions, such as a highly-boosted lattice. Beyond this distance, the three basic types of detectors give, within experimental accuracy, the same flux distributions as those obtained from Cu foil activation measurements. Within one lattice spacing, the Pt detector reflects the local power condition better than neutron-sensitive devices. This results from the fact that the fission process in the fuel is the major direct source of γ-rays, whereas the immediate source of thermal neutrons is the moderator, one stage removed from the fission events.

Thus in conclusion, these experiments have led us to a basic understanding of the signals from self-powered detectors in a variety of configurations in CANDU power reactors and greater confidence in their use as absolute flux measurements in future applications.

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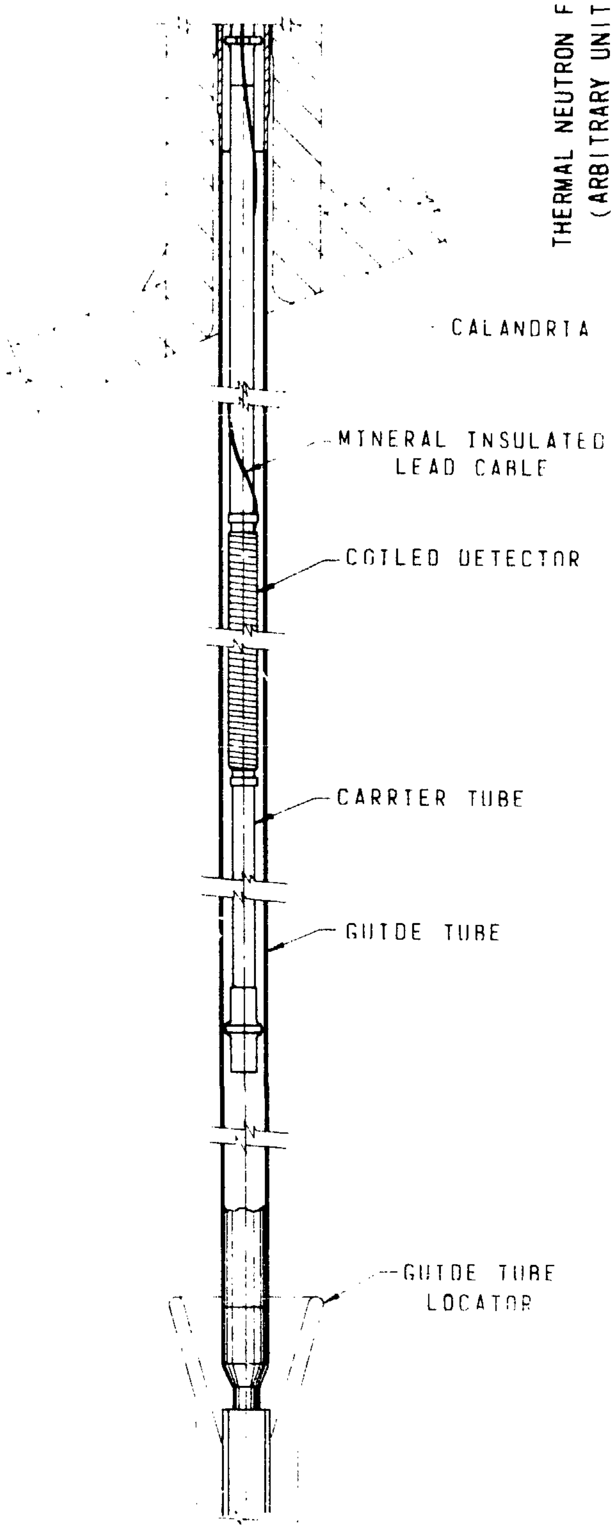

FIGURE 1 - TYPICAL DETECTOR MOUNTING ARRANGEMENT

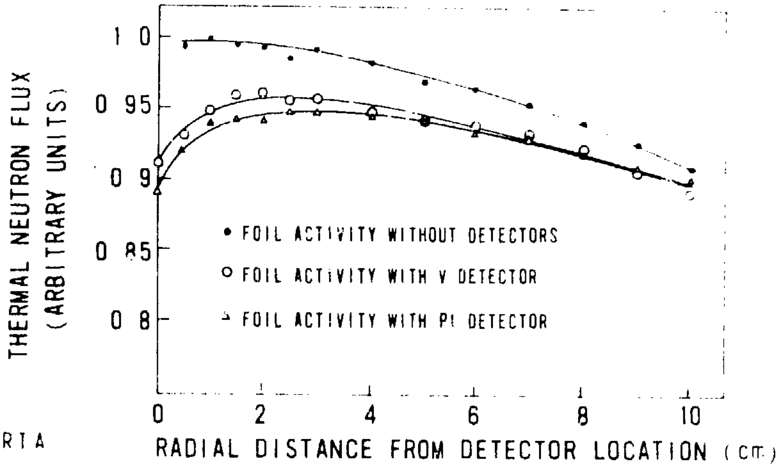

FIGURE 2 - NEUTRON FLUX PROFILE IN VICINITY OF DETECTORS

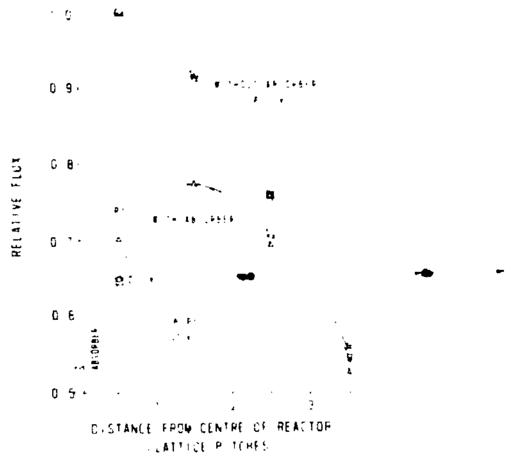

FIGURE 3 - DETECTOR RESPONSES IN VICINITY OF A CONTROL ABSORBER

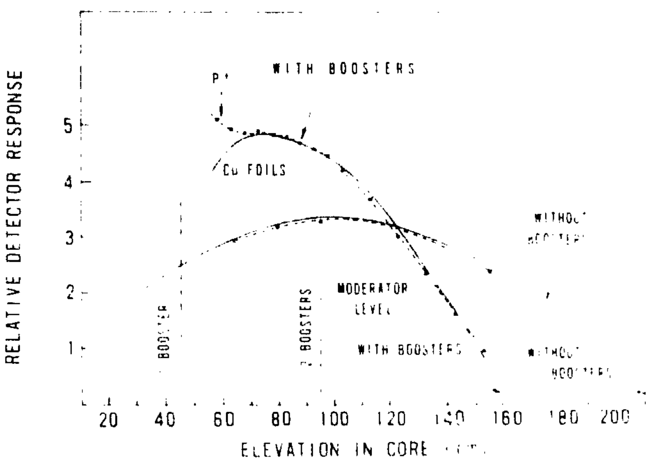

FIGURE 4 - AXIAL FLUX DISTRIBUTION AND Pt RESPONSE IN A BOOSTED LATTICE

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