CONCERNS ABOUT THE DYNAMIC RESPONSES OF IN-CORE FLUX DETECTORS

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ABSTRACT

CANDUs are determining the dynamic responses of flux detectors by a method open to question. It ignores relative changes in local flux conditions, which are significant during trips. Calculated prompt fractions (PFs) are widespread. The SIR detector development calculated the PF change with irradiation on a physical basis. Measurements were made over many years. The current results do not agree with the 1996 predictions. Some values are below the safety analysis limit. This has resulted in detector replacement, imposition of CPPF penalties on trip margins, additional safety analyses and other actions. This paper shows that such measurements are not required.

1. INTRODUCTION

All CANDU reactors now use straight, individually replaceable (SIR) in-core flux detectors (ICFDs) for reactor spatial control, flux mapping[1] and the overpower trip of SDS1 and SDS2. The detectors, coaxial cables with magnesium-oxide insulation, are mounted in vertical and horizontal neutron flux monitoring (NFM) units or flux detector units (Figures 1a and 1b) located throughout the large reactor core. These detectors are self-powered—the (thermal) neutron flux and gamma radiation field cause a net flow of electrons from the central electrode (emitter) to the 3 mm OD sheath (collector). A long 1 mm OD coaxial lead cable conducts the signal current from the emitter, to connect with its field cable in the NFM connector housing.

Prompt-responding ICFDs have an Inconel or a platinum-clad Inconel emitter (Figures 2). The Inconel detector is fully neutron sensitive and responds promptly to changes in neutron flux, except for a small (~4%) negative delayed component produced by the manganese impurity in Inconel. The platinum-clad detector has a mixed response. About 70% of the signal is produced by neutron absorption and 30% is due to reactor gamma radiation, one-third of which is delayed. So the dynamic response of the Inconel detector is 104% prompt, and the platinum-clad detector is about 90% prompt. Signal dynamic compensators are provided in the flux detector amplifiers of SDS1 and SDS2 to make the response fit the power-in-fuel response, to a hypothetical step increase in neutron flux (Figure 3).

The SIR detector design was proposed on April 1, 1975, and a joint AECL-Ontario Hydro ICFD development program began in January 1976 (Cuttler and Medak 1992). It continued intensively for several years. Detectors with different emitter materials and dimensions were

[1] CANDU 6 reactors use thermal neutron flux-mapping detectors with vanadium emitters. Their dynamic response is determined by the beta decay of V^{52} (3.7 minute), which is too slow for spatial control and overpower protection.

constructed and tested to optimize performance. Comprehensive tests were carried out to determine and understand neutron and gamma sensitivities and dynamic responses to changes in reactor power. The change in detector characteristics due to long-term irradiation was calculated[2] and measured over a long period (> 15 years) to validate predictions. By June 1978, AECL had carried out sufficient analysis and had enough measured data from tests in the NRU reactor to recommend changing the reference design of the Bruce B ICFDs from encapsulated coiled to the SIR type. Good long-term performance of the prototype SIR NFM in Bruce Unit 4 provided ongoing confidence in this decision. Darlington Engineering subsequently requested this design change. The coiled ICFDs in the other CANDU stations were later replaced by the SIR type.

A comprehensive technical specification was prepared for procuring SIR ICFDs that specified all the factors that introduce variation in detector response, such as Inconel composition, dimensions and tolerances. Qualification tests, acceptance tests and a manufacturing quality assurance program with inspections were specified to provide confidence that the detectors to be installed in the reactors would be uniform and of high quality.

Bruce B prototype ICFDs were left in the NRU reactor for long-term studies. In December 1998, four platinum-clad ones were removed after 15-17 years of irradiation and examined at the Post-Irradiation Examination facility at Chalk River. Two classes of tests were performed: the visual inspection and signal continuity tests (two failed detectors), and the material condition tests to examine for signs of actual or impeding breakdown in their construction. The sheaths of all detectors and their lead cables appeared to be in good condition; however, there was evidence of material deterioration (Jones et al 1999).

Since the beginning of the SIR detector development program in 1976, many measurements and analyses of ICFD performance have been made, in the NRU reactor and also in Bruce Unit 4. The most recent and most authoritative information on the predicted and measured performance characteristics of ICFDs appears in the comprehensive 110-page report that AECL prepared for the CANDU Owners Group (McAllindon et al 1996).

2. CONDITION ASSESSMENT OF BRUCE B DETECTORS

A condition assessment of the Bruce B NFMs in 2011 revealed that the NFM units and their detectors are performing well after about 25 years of irradiation. Very few ICFDs have failed, considering there are 28 platinum-clad for reactor control, 54 Inconel for SDS1 and 48 platinum-clad for SDS2, in each of the four reactors. In 2005 one vertical detector was replaced in Unit 5. In 2004 all the detectors in the Unit 5 horizontal NFM 3 failed after the helium vent valve was left open after flushing. Prior to that, only three SDS2 detectors had failed (Sur 2002).

[2] The known chemical compositions of the detector materials were used to identify the concentrations of all the nuclides. Their thermal neutron cross sections were used along with the thermal neutron flux in Bruce B reactors to calculate the transmutations that would occur over 20 years of irradiation. This yielded good predictions for the change of detector sensitivities and dynamic responses.

Detector sensitivities did increase during the first few years of irradiation and then decreased gradually, according to the predictions that were based on calculations and measurements. As shown in Table 1, the dynamic response (prompt fraction) of the platinum-clad ICFDs was predicted to decrease by 5% after 20 years of irradiation (McAllindon et al 1996, Table 3).

Table 1 – Predicted changes in detector sensitivity and prompt fraction with irradiation
(mean flux of 2 x 10^{18} n/m^2/s)

Time (a)	Relative Sensitivity I(t)/I(0)			Prompt Fractions Fp	
	Platinum	Pt-clad Inconel	Inconel	Platinum	Pt-clad Inconel
0	1.00	1.00	1.00	87%	88%
1	0.94	1.09	1.26	87%	89%
2	0.89	1.12	1.38	86%	90%
4	0.78	1.10	1.42	84%	89%
10	0.61	0.96	1.23	79%	88%
20	0.51	0.80	0.92	75%	85%

The condition assessment activity identified that Bruce B (and other CANDU stations) has been carrying out a test prior to each maintenance outage that includes a measurement of the dynamic response of each Inconel and platinum-clad detector. The method being used is open to question, as discussed in Section 3. The PFs have a wide spread; some are even below the safety analysis limit. This has led to mitigating actions, such as: the replacement of many detectors, the imposition of CPPF penalties on trip margins, additional safety analyses and other actions.

The prompt fraction (PF) of the dynamic response is defined as the detector signal 1 second after a step increase in neutron flux, normalized by the total change in detector signal after the delayed components have decayed to zero. A large step increase in neutron flux is difficult to execute, so the PF of a detector was measured during the ICFD development program by placing a small fission chamber in the TFD (central) well tube beside the detector. The NRU reactor was tripped (fast shutdown) while recording the signals from the fission chamber and the flux detector (McAllindon et al 1995, Figure 11). The fission chamber is assumed to respond promptly to changes in neutron flux at the detector. So the normalized change in the detector signal, one second after the start of the trip, divided by the corresponding normalized change in fission chamber signal was taken to be the prompt fraction of the detector (Figure 4). Many such tests have been carried out; consistent reproducible results were measured. The out-of-core ion chambers were not used for the reference measurement of the neutron flux change at the in-core detector because they cannot "see" the local flux variations that occur in core during the trip.

3. PRESENT METHODOLOGIES FOR MEASURING DYNAMIC RESPONSE

In the mid-1990s, a procedure was proposed by signal noise analysts for measuring the dynamic response of the ICFDs. The signals of all the in-core detectors and the out-of-core ion chambers of the large reactor were connected to fast data loggers. Then the reactor was shut down quickly (prior to a planned maintenance outage), usually by tripping SDS2 (liquid neutron absorber injection) and the signals were recorded during the power rundown. The methodologies use the ion chambers as the reference measurement of the in-core flux.

The ion chambers are assumed to record the bulk flux change accurately despite their out-of-core position. The effective prompt fractions are calculated by assuming, that for times greater than 1.0 seconds after the trip, the ion chambers reflect the magnitude of the step change in neutron flux, and the ion chamber signal provides a record of the average neutron flux response throughout the reactor power rundown. In large CANDU reactor cores, it is not clear how the out-of-core ion chamber rundown signals can reflect the changing local flux conditions of the individual in-core detectors.

The PF values measured by this method are spread over a wide range, from about 120% down to 98% for Bruce B Inconel ICFDs; whereas a change from 104% to about 100% is expected after irradiation for more than 25 years. Platinum-clad detector PFs range from about 90% down to 75%; however, AECL predicted a PF change from 90% to 85% after 20 years of irradiation. (The implied uncertainty of AECL's PF calculations/measurements appears to be 1%.) No physical or other explanations, supported by facts, have been provided for the unexpected wide spread in the measured PF values. The materials and processes for manufacturing the Bruce B detectors were carefully controlled.

Other CANDU stations have been performing these measurements using the same methodology. The PFs measured at Point Lepreau (Anghel et al 2009) do not appear to be reproducible for each measurement. The PFs measured at Darlington (Banica and Slovak 2011) are likewise difficult to explain in physical terms. Attribution of PF anomalies to differences in the detector batches and degradation in storage was not supported by data. Material composition information is available from the manufacturer. Detector and lead cable dimensions and tolerances were specified, and the manufacturer complied with them.

4. CONCLUSIONS AND RECOMMENDATIONS

The assumptions of the present measurement methodology are questionable and may be invalid. The spread in the PF values could be due to the variation in the local reactor conditions at the individual in-core detectors.

It should be recognized that there really is no need to measure ICFD PFs routinely because the dynamic responses of these detectors have been well characterized in the detector development program. Both the initial measured values and the calculated values after 20 years of irradiation are based on the known composition of the detectors and their physical characteristics. No valid new analyses and measurement information have been provided to challenge the data in Table 1.

If there is a good reason to believe that the actual PFs are significantly different than the values in Table 1, then a PF measurement should be done on one or two ICFDs to resolve the issue, by the same method that was used during the ICFD development program. A small fission chamber should be placed, in the TFD well tube, beside the ICFD to measure the same flux change during the power rundown.

The following novel method could be tested. An operator could insert a neutron absorber rod (cadmium or boron-10), in the TFD well tube, beside a platinum-clad ICFD. This would cause a local (stable) neutron flux depression. While recording the ICFD signal, withdraw the absorber rod quickly to produce a local flux excursion (like the withdrawal of an ion chamber shutter). This would provide the PF for the platinum-clad detector for a positive flux excursion. This test could be repeated many times (on-power) to improve the accuracy of the measurement.

5. REFERENCES

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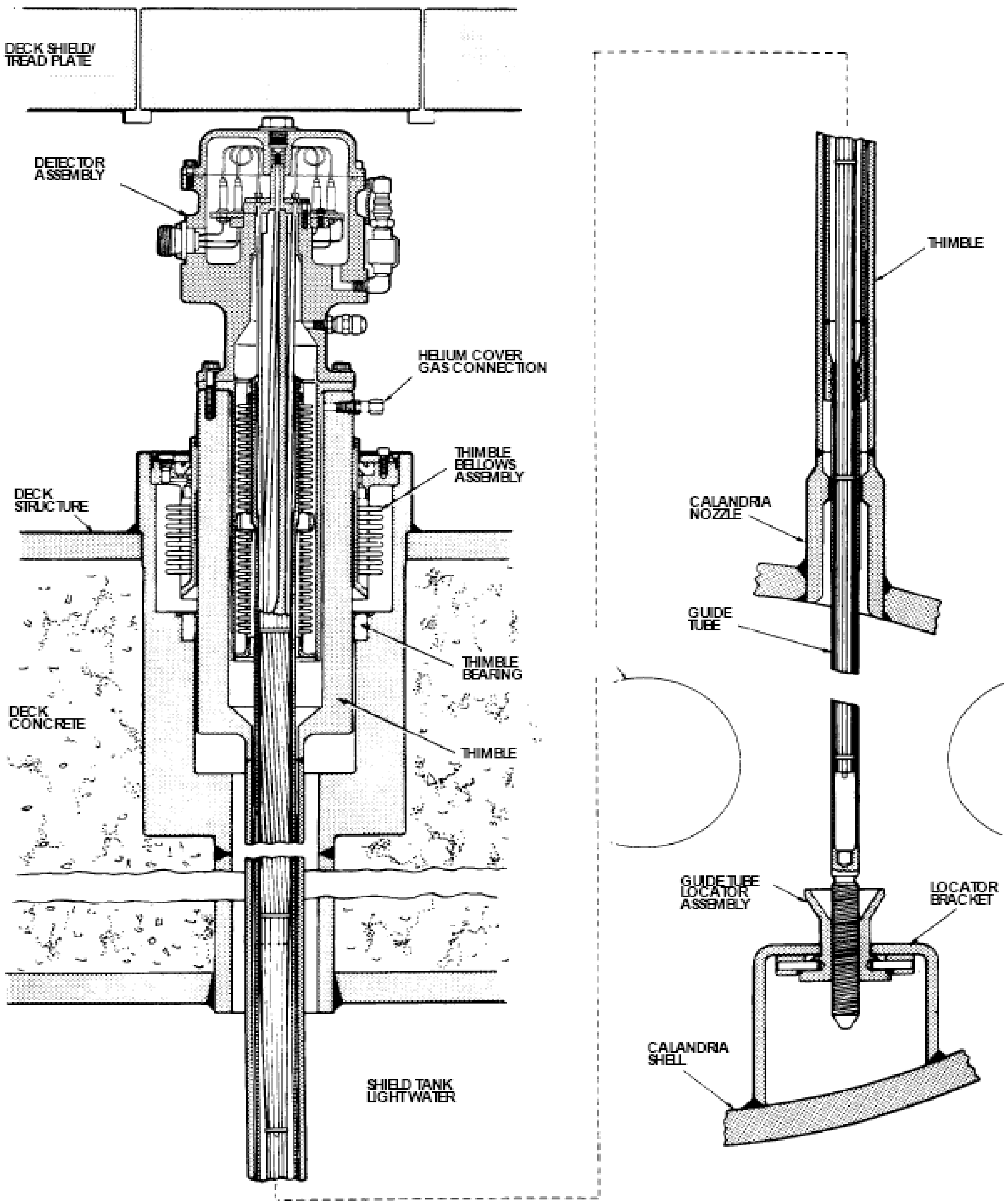

Figure 1a – Bruce B vertical neutron flux monitoring (or VFD) unit

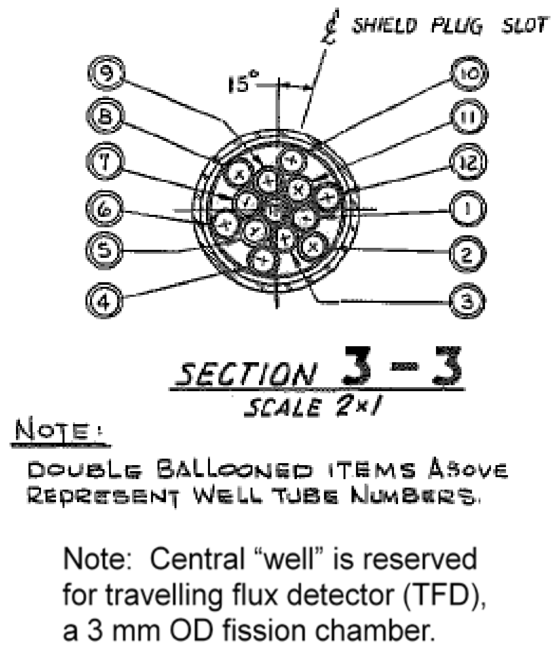

Figure 1b – Bruce B vertical neutron flux monitoring unit, layout of detector wells

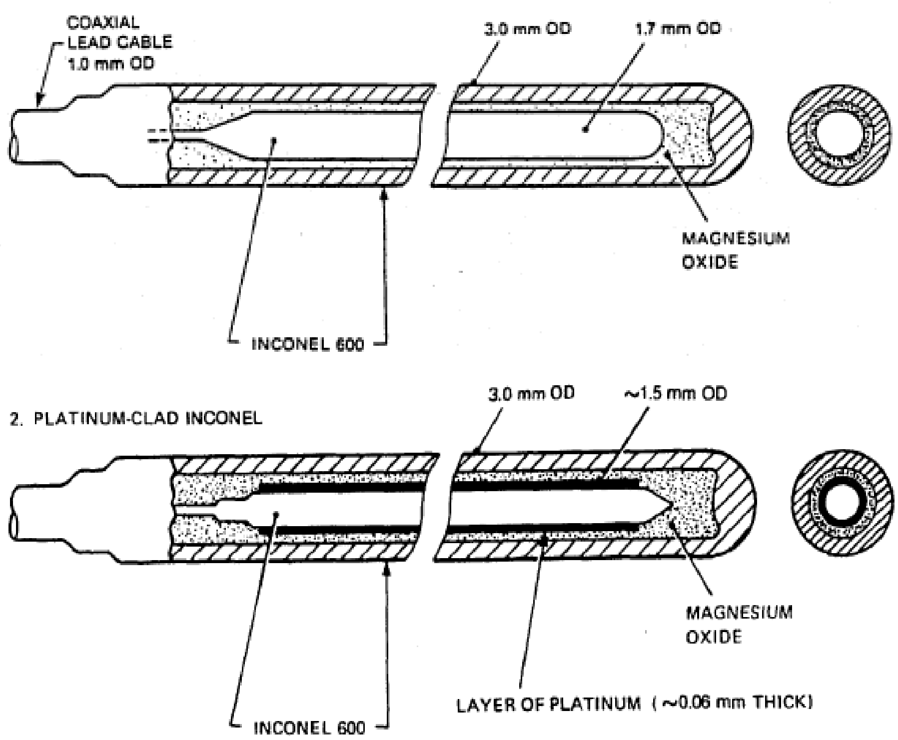

Figure 2 – Inconel and platinum-clad flux detectors

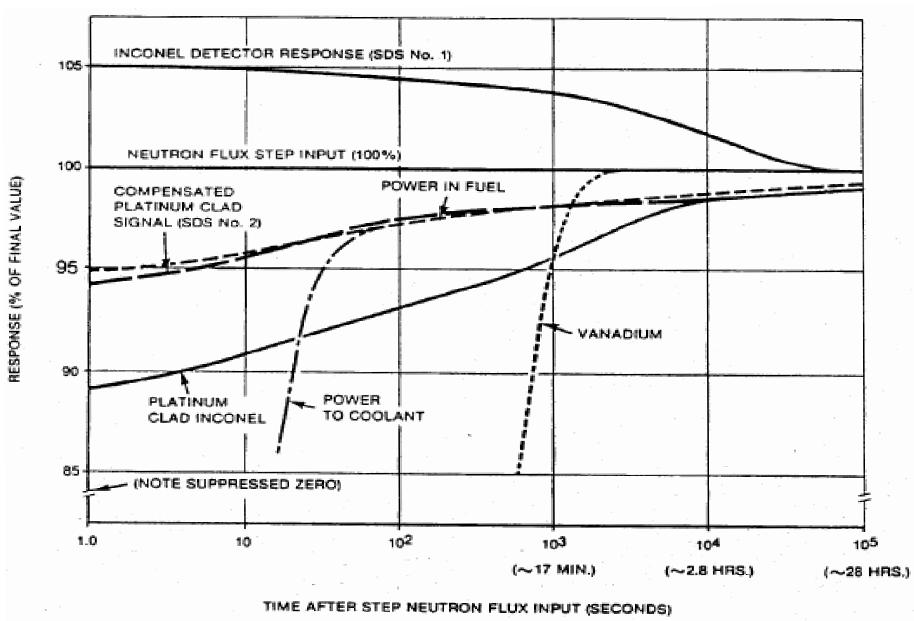

Figure 3 – Dynamic responses of SIR in-core flux detectors

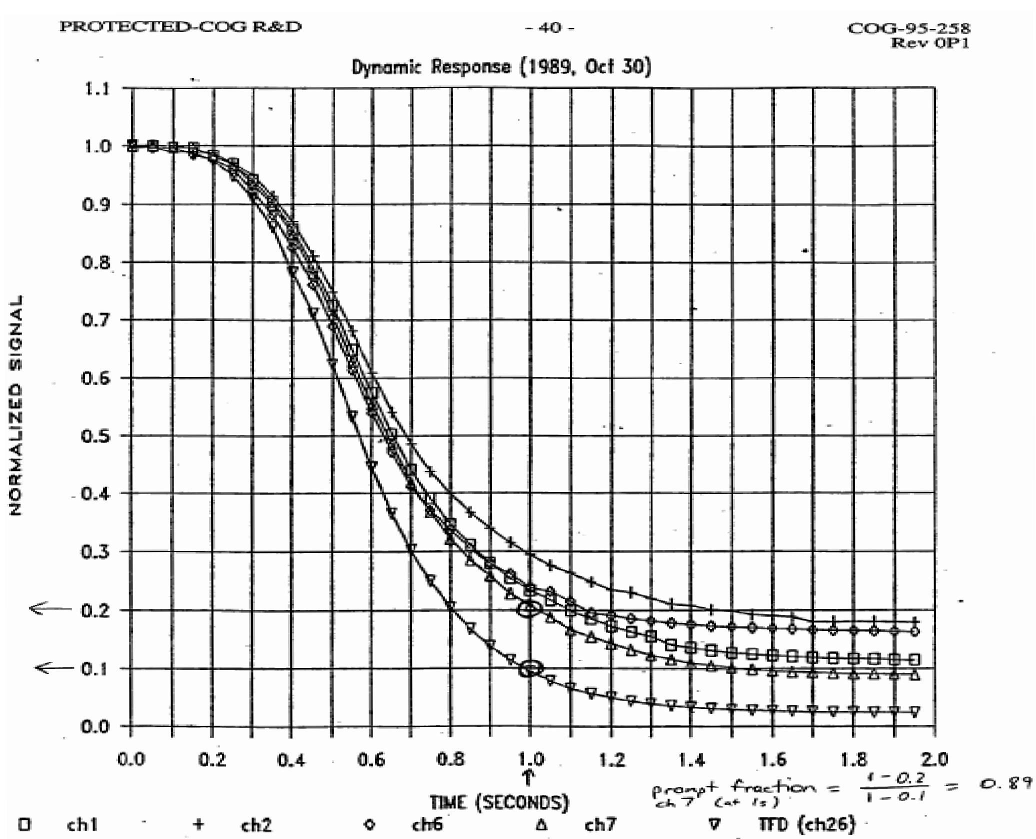

Figure 11. Determining Prompt Fraction from Rundown Curve (data shown here are from NRU measurements taken Oct 30, 1989)

Figure 4 – Measuring detector dynamic response (prompt fraction) during NRU trip