EVALUATION OF SLOW SHUTDOWN SYSTEM FLUX DETECTORS IN POINT LEPREAU GENERATING STATION

I: Dynamic Response Characterization

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Abstract

CANDU[1] reactors are protected against reactor overpower by two independent shutdown systems: Shut Down System 1 and 2 (SDS1 and SDS2). At the Point Lepreau Generating Station (PLGS), the shutdown systems can be actuated by measurements of the neutron flux by Platinum-clad Inconel In-Core Flux Detectors (ICFDs). These detectors have a complex dynamic behaviour, characterized by "prompt" and "delayed" components with respect to immediate changes in the in-core neutron flux. The dynamic response components need to be determined accurately in order to evaluate the effectiveness of the detectors for actuating the shutdown systems.

The amplitudes of the prompt and the delayed components of individual detectors were estimated over a period of several years by comparison of archived detector response data with the computed local neutron flux evolution for SDS1 and SDS2 reactor trips. This was achieved by custom-designed algorithms. The results of this analysis show that the dynamic response of the detectors changes with irradiation, with the SDS2 detectors having "prompt" signal components that decreased significantly with irradiation. Some general conclusions about detector aging effects are also drawn.

1. Introduction

The current SDS1 and SDS2 In-Core Flux Detectors at the Point Lepreau Generating Station are Straight Individually Replaceable (SIR) Platinum-clad Inconel self-powered detectors, housed in Helium Encapsulated SIR (HESIR) assemblies. The signal dynamics of the SIR detectors were measured, immediately after installation, via a manual reactor trip test in December 1992. The detector responses were confirmed to meet design specifications by comparing the measured signals to the design expectation from a full simulation of the reactor trip via a Reactor Fuelling Simulation Program (RFSP) [1].

Detector response data from trips in 1995, 1996, and 1997 were previously analyzed without the benefit of a full trip simulation. These analyses confirmed that some individual detector responses, as well as the SDS1 average response, deviated from the design expectation. The SDS1 "anomalous" detector response times however, were generally faster than the design expectation and hence were assessed not to be a problem in most cases. Some SDS2 detectors were found to be slower than expected. Subsequent examinations of reactor trips validate SDS2 detector sensitivity to possible dynamics degradation due to aging.

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This first part is an overview of the method used to obtain an accurate estimation of the detector response to neutron flux. The response of self-powered flux detectors does not instantly match changes in flux at the detector. For platinum-clad Inconel detectors, a significant portion of the signal will lag changes in flux by significant periods from about 4 seconds to about 2 days. The delayed part of the signal is assumed to be a linear combination of first order lag terms, also called delayed fractions. The lifetimes of the delayed fractions are given in the safety analysis of the reactor, while their amplitudes are computed by fitting the trip data to theoretical response.

2. Overview of the High-Speed Data Logging System

The Point Lepreau High-Speed Data Logging (HSDL) system is a system permanently installed at Point Lepreau, which continuously collects data from safety instrument signals, as shown in Figure 1. This system has several advantages:

a) Any reactor trip becomes an opportunity for safety system instrument verification. The results we report here come from both planned and unplanned reactor trips.
b) There are readily available data for plant upset diagnosis.
c) The high-speed data are necessary for demonstrating compliance with safety analysis time constants. This work is one of one of a series of AECL and PLGS works proving this point.

3. Trip Data Used

Detector and ion chamber output signal data was extracted from the data recorded by the Point Lepreau High-Speed Data Logging (HSDL) system. To ensure feasible computation, the amount of data collected on each reactor trip had to be reduced. This reduction was achieved using the PLGS System Engineers Data Extraction (SEDE) application, where data was presented at increasing time steps for increased time intervals. The data from each reactor trip was extracted in five separate data sets, as shown in Table 1. Each data set contained detector and ion chamber signals that were represented by a specific sampling time and interval; the time interval was centered symmetrically around the trip.

Table 1
Data Set sampling time and interval

Dataset	Sampling time (s)	Total duration
1	0.02	2 min
2	1	10 min
3	6	1 hour
4	60	10 hours
5	600	200 hours

4. General Assumptions

4.1 Detector and Ion Chamber Response Assumptions

The response of the detector itself, *F*, to the neutron flux Φ is assumed to be a linear combination [3] of prompt response and of delayed fractions. The Laplace transform of the detector response is:

$$F(s) = \left[\left(1 - \sum_{i=1}^{6} a_i \right) + \sum_{i=1}^{6} \frac{a_i}{1 + s\tau_i} \right] \Phi(s) \tag{1}$$

where τ_i are the delayed fraction lifetimes, assumed known, and a_i are the delayed fraction amplitudes, which are estimated from the detector response. This is an approximation because it is known that platinum-clad Inconel detectors respond to gamma radiation as well.

All the responses of the ion chambers are assumed to be prompt, with no delayed fractions. The signal to be analyzed is not the signal from the detector itself, but the signal output from the detector compensation system, as recorded by the HSDL and shown in Figure 1. The characteristics of the dynamic compensator, the ICFD amplifier, the trip comparator buffer amplifier and the HDSL isolator amplifier are all assumed known.

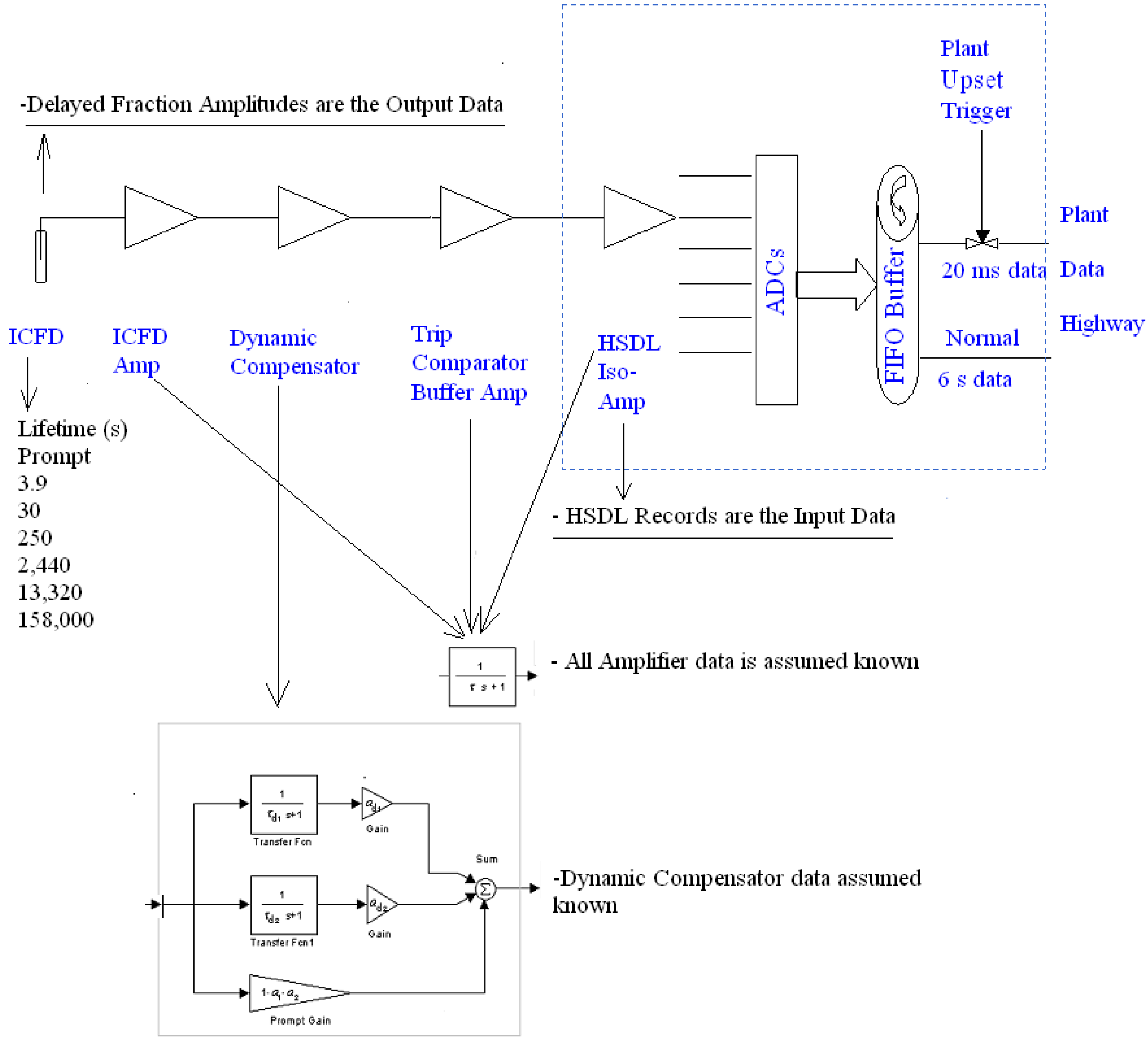

Figure 1 Schematic diagram for the safety system and of the permanently installed HSDL. The blue labels denote the components of the detector electronics loop and of the data logger. The black labels identify the inputs, the given data and the outputs of the computation of the amplitudes of the delayed detector fractions.

4.2 Shutdown Flux Assumptions

For the two types of shutdown, SDS1 (Shut-down rods are left to fall into the reactor core) or SDS2 (reactor poison is injected in the moderator), the following approximate methods were used:

a) The SDS1 shutdown flux evolution is assumed to be well approximated by the RFSP calculation.

b) The SDS2 shutdown proceeds by poison injection, which is controlled by fluid flow effects that are difficult to simulate. Fortunately, the shutdown time is short (0.15 s), which brings this closer to the instantaneous shutdown case (the similar time for a SDS1 shutdown is about 0.3 s). In this case, we assume that the signals in the ion chambers (located on the reactor core boundary) give an accurate and prompt representation of the flux value at their locations. During shutdown, the measured values of the ion chamber signals were found to be very close to time-shifted replicas of each other as shown in Figure 2. A simplifying hypothesis is that the normalized flux signal is a time-shifted replica of a unique standard signal.

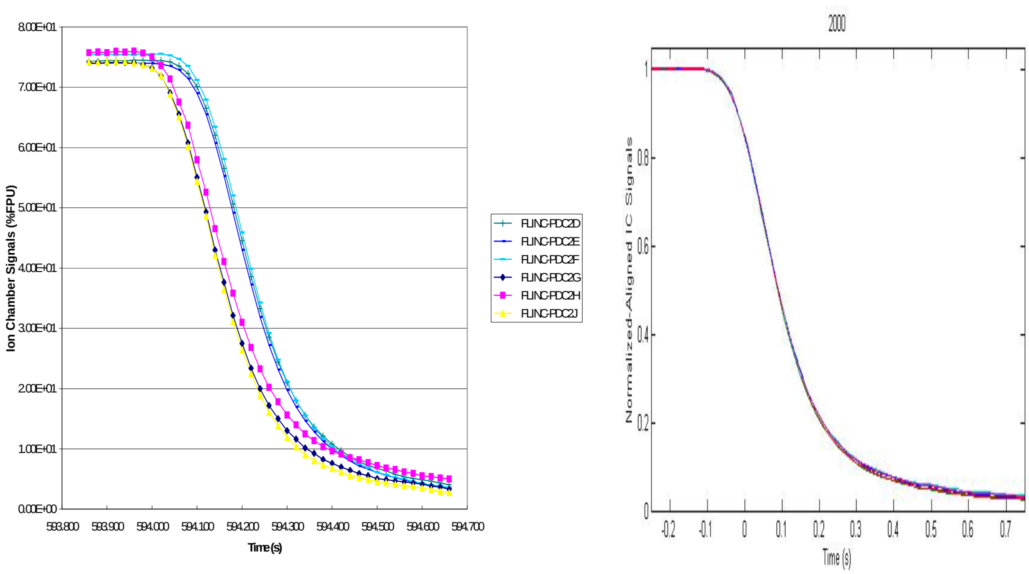

Figure 2 Ion chamber signals (SDS2 shutdown); on the right, the same ion chamber signals, normalized and shifted in time, plotted on top of one another. No curve fitting is used, except moving curves left or right with time shifts.

5. Calculation of the detector signal delayed fractions

5.1 Methods

The calculation of the detector-delayed fractions is built according to the following principles:

a) Approximate the effect of flux history on the detector response after trip, because there are long-lived delayed fractions in the detector response. This approximation is needed for all types of reactor trips.

b) Estimate of the delayed flux amplitudes. The estimation is done by solving a weighted least-square problem: fit the recorded detector response to a linear combination of compensated delayed fraction responses, which were computed from the local neutron flux.

c) Optimize weights so that the errors in the delayed amplitudes are as close to each other as possible.

d) Design the method so that it can be implemented easily using no matter what computer language.

5.1.1 Local Flux Approximations

An "ideal" shutdown would be characterized by a step function, with the flux at full power suddenly cut down to zero. As an ideal shutdown is not possible, we are left with finding the neutron flux by other means. For the two types of shutdown, the following approximate methods were used:

a) The SDS1 shutdown takes a relatively long time (around 0.35 s), quite far from the ideal case. Fortunately, the time dependent flux at each location in the reactor core can be computed accurately using RFSP. The RFSP results are given at relatively large time steps, so the flux values at intermediate times can be computed by means of spline interpolation. The time variables in RFSP and the trip data are "synchronized" once, so that the difference between the simulated and experimental ion chamber signals is minimal.

b) The SDS2 shutdown proceeds by poison injection, which is controlled by the fluid flow effects that are hard to compute. Fortunately, the shutdown time is short (0.15 s), which brings this closer to the ideal case, i.e., instantaneous trip. In this case, we assume that the flux at each location is a time-translated version of the "averaged" ion chamber signal.

5.1.2 Optimal Weights for Least-Squares

The weighted least-square fit has to have a set of 5 different weights, one for each data set. The criterion for choosing a weight optimization was to have the root mean square deviations of the fractions (prompt and 6 delayed) as close to each other as possible. The following objectives are satisfied by an optimal set of weights:

a) The root mean square deviations of the fractions (prompt and 6 delayed) shall be as close to each other as possible.

b) The algorithm has to be accurate and stable against missing data and against noisy data.

Basically the least-square method has to be as well conditioned as possible. Choosing a set of optimal weights acts in part as a preconditioning. The set of optimal weights is chosen so that the singular values of the pseudoinverse of the matrix A in the least-square fit

$$\min \| Ax - b \|^2 \tag{2}$$

are as close to each other as possible. We found that maximizing

$$\det\left[\frac{A^+ A}{Tr(A^+ A)}\right] \tag{3}$$

is a good way of satisfying this criterion. det is the determinant of a matrix, *Tr* is the trace of a matrix and A^+ is the transpose of A.

6. Amplitudes of the Detector Signal Delayed Fractions

The computational method was applied to results from several reactor trips. It was found that for most detectors, the prompt fraction decreases with reactor core age. Also, one can see that the SDS1 detectors (left two thirds on the plot) are clustered around the design value for prompt fractions, while the SDS2 detectors (right side of the plot) are all under the design value and the values are scattered.

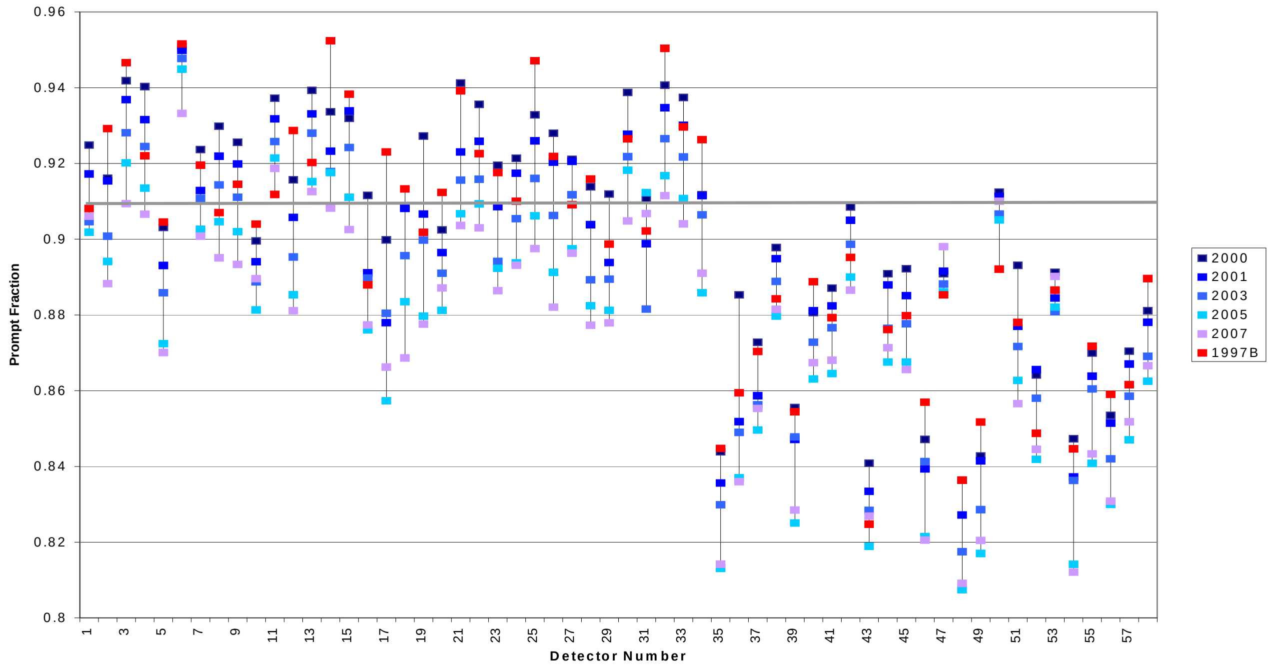

Figure 3 The prompt fractions for various shutdowns. The shutdowns in blue and green are SDS2 shutdowns, the red is a SDS1 shutdown. The grey line is the design value for prompt fraction.

One can see that the effects of aging between 1997 and 2007 are smaller than the spread between the SDS2 detectors.

Also, one can see that the effects of long time aging are similar for the SDS1 and SDS2 detectors. The large difference in behaviour establishes itself early in the life of the detectors and proceeds then in a relatively uniform manner.

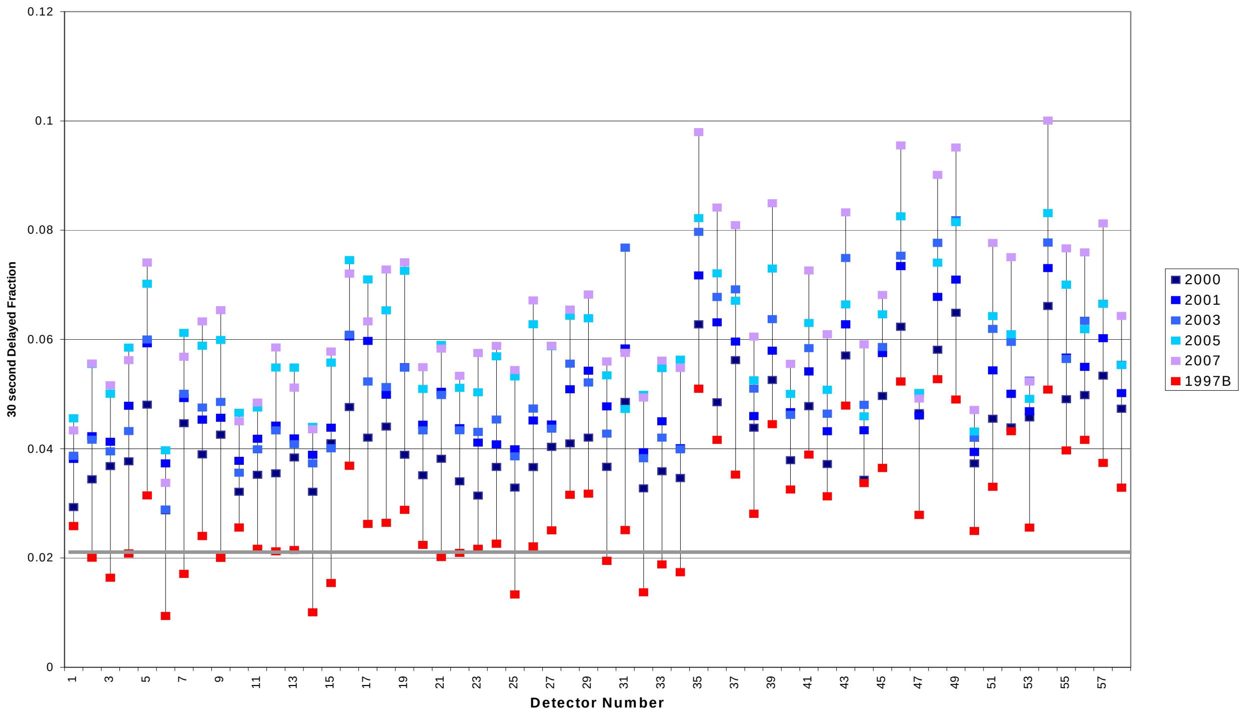

Figure 4 The f2 (30s) fractions for various shutdowns. The shutdowns in blue and green are SDS2 shutdowns, the red is a SDS1 shutdown. The grey line is the design value for the f2 fraction.

As the sum of all fractions equals one by definition, some fraction other than the prompt has to increase with increasing core age. It was found (see Figure 4) that the 30 s fraction increases strongly. Also the SDS2 detectors have a larger 30 s fraction than SDS1 detectors.

7. Conclusions

- Consistent and accurate results were obtained for the trips that yielded processable data.

- The signal of the detector was found to be fit with accuracy of +/- 3 % during the trip for SDS1 trips and +/- 0.6% afterwards. For the SDS2 trips, the accuracy is +/- 10 % during the trip, and the same as for SDS1 trip afterwards.

- The estimated delayed fraction amplitude for each detector errors are found to be smaller than the differences between the amplitudes of different detectors and small enough to allow one to observe the effects of detector aging on the detector characteristics between trips.

- The prompt fractions for the SDS2 detectors are significantly smaller than the design values and are widely spread.

- The spread in SDS2 detector prompt amplitudes is larger than the effects of aging on the prompt amplitudes. The aging effects on prompt fractions between 1997 and 2007 are similar between SDS2 and SDS1 detectors, basically all prompt fraction amplitudes go down in lockstep; therefore, the unknown cause for the SDS2 detector amplitude spread develops fast and then stays constant afterwards.

8. References

[1] B. Rouben, "Technology Transfer: Candu Fuel-Management Code RFSP", AECL document AECL-CONF-00531, AECL, Mississauga, Ontario, Canada, 1998, January 1.

[2] C. M. Bailey, R. D. Fournier, and F. A. R. Laratta, "Regional Overpower Protection in CANDU Power Reactors", International Meeting on Thermal Nuclear Reactor Safety, Chicago, Illinois, 1982 August 29 - September 2.

[3] C. J .Allan, N. H. Drewell, D. S. Hall, "Recent Advances in Self-Powered Flux Detector Development for CANDU Reactors", Proceedings of an international symposium on nuclear power plant control and instrumentation organized by the IAEA and held in Munich, 11-15 October 1982, pp. 505-520, IAEA-SM--265/8, 1983.