Behaviour of Aged and New Flux Detectors in Darlington Reactors

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Abstract

In-core neutron flux detectors are used for protective and safety functions in the Darlington NGS “A” CANDU reactors. This paper presents new observations regarding the aging of flux detectors, including response to fuelling, response to unit shutdown and indicators of detector noise. Comparisons of detector signals before and after replacement confirm previous assumptions about aging effects.

1. Introduction

All CANDU reactors in operation use a large number of self-powered, in-core flux detectors (ICFD) for the reactor regulating (RRS) and shutdown systems (SDS). For the Darlington NGS “A” CANDU station, RRS and SDS1 utilize vertically oriented, Inconel self-powered flux detectors, while SDS2 utilizes horizontally oriented, Platinum-clad Inconel detectors. The safety function of the Neutron OverPower (NOP) detectors in SDS1 and SDS2 is to protect against a local (regional) power increase for various postulated accidents.

The Inconel detectors are slightly overprompt and have a nominal (design) prompt fraction of about 104% at the beginning of their life [1]. Platinum-clad Inconel detectors are underprompt: their design prompt fraction is about 89% and their signal is made consistent with power increases by Dynamic Signal Compensators. The dynamic response of any ICFD changes during its lifetime due to changes in detector materials due to burn-out and burn-in, as well as changes in its local neutron and gamma flux environment. At Darlington, prompt fractions (PFs) are estimated following a reactor power rundown test at the beginning of each planned outage, usually completed by firing SDS2 from 59%FP. Analysis of responses to rundown has confirmed consistent, slow changes in detector dynamics over time [1].

The objective of this paper is to present recent information obtained after replacing a number of detectors. Comparisons of detector signals before and after replacement are employed to confirm previous assumptions on aging effects.

2. Response to Fuelling

Specific NOP detectors had been noted to have an increased response to fuelling of channels in their immediate vicinity. The exaggerated response to localized flux increases exhibited by some detectors resulted in a number of SDS channel trips. The SDS2 (Platinum-clad Inconel) detector G03 was replaced in both Units 1 (2011) and 2 (2010). The decision for replacement was initially based on the increasing trend in prompt fractions (PF) estimated from rundown tests: in one case the PF even increased above 100%. Note that, in this case, "replacement" means that a new detector was inserted in a spare well, while the old detector was kept in its original well after disconnection from the loop.

Figure 1 presents one Unit 2 example: responses of NOP detector 3G to three regular (8 bundle push) fuelling operations of the adjacent fuel channel E21, at comparable discharge burnups. The top graph represents the response of the aged detector (2009, few months before replacement), while the lower graphs present the response of the new detector (smooth, red graph, 2010) and mid-age detector (2000). It is clear that the response of a new detector to fuelling is not just smaller, but its signal contains much less "noise" than an aged detector.

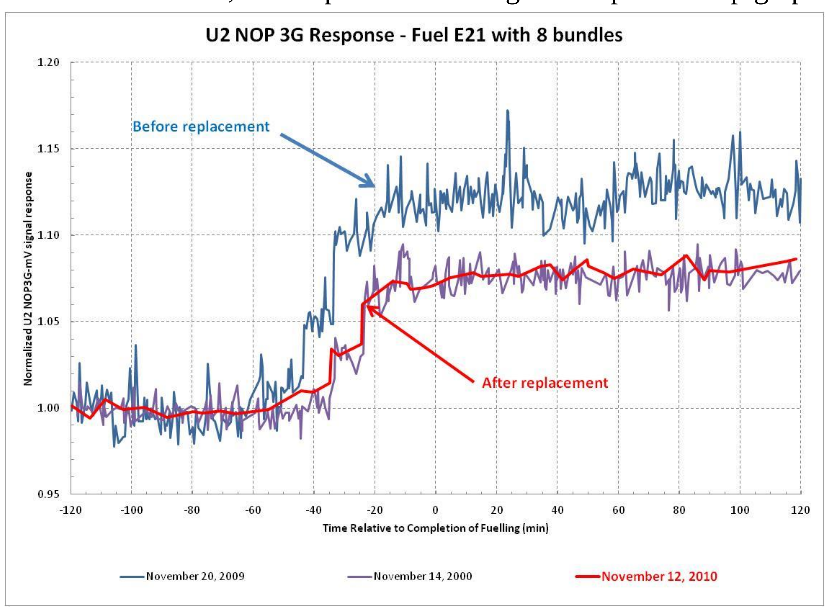

Figure 1 - Response of Detector 3G to Fuelling of Adjacent Channel E21

The increased "noise" (variability) is presented in Figure 2 below; please refer to sections 4 and 5 for more details on calculation. For both Units 1 and 2, there was a significant decrease in detector signal variability after replacement (2010 – 2011). The 3G detectors were not replaced in Units 3 and 4 because their behaviour and their estimated prompt fractions are normal, a difference currently attributed to the different detector batches.

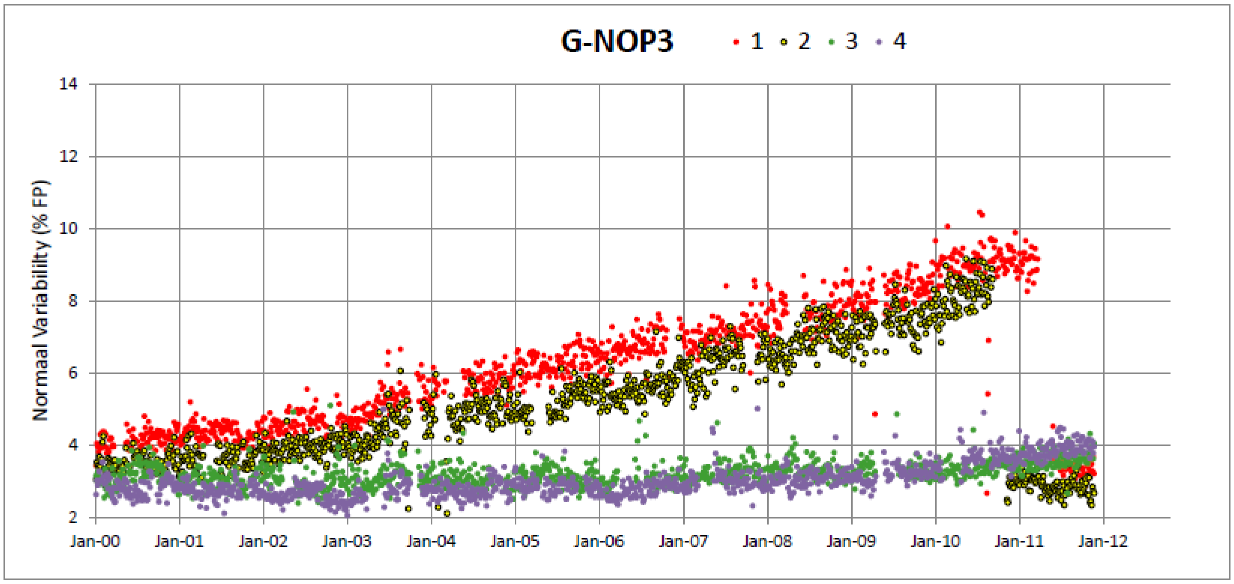

Figure 2 - Noise of Detector 3G in all Darlington Units

3. Response to Reactor Shutdown

Some Inconel (vertical) detectors are also overly responsive to changes in neutron flux and their overpromptness is growing worse in time. Although this aging mechanism is in the safe direction, the exaggerated promptness of these detectors has caused regulating problems during power reductions (multiple RRS detectors irrational low) and a number of SDS1 channel trips. Figure 3 presents the dynamic response of two different Unit 3 RRS (Inconel) detectors to a SDS2 trip from 59%FP. Both zone 5 and 12 detectors belong to RRS channel "B" and are located in the bottom of the core.

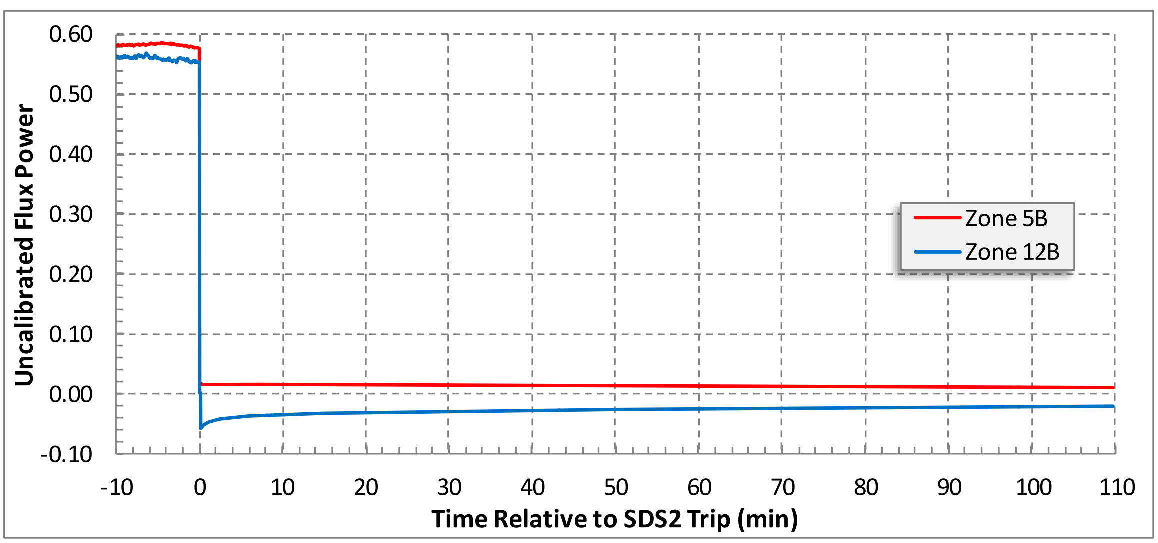

Figure 3 – Response of Inconel Detectors with Different Prompt fractions to Reactor Shutdown From 59%FP

The 5B detector (red) was slightly underprompt (estimated PF of 98%)[1], while the 12B detector was "too overprompt" (estimated PF of 108%) at the time of the trip. The 5B signal remained positive, while the 12B signal dropped to about -5% and slowly recovered over the next few hours.

4. Detector "Noise"

In addition to changes in prompt fraction, both vertical Inconel and horizontal Pt-clad Inconel detectors have exhibited increasing signal variability ("noise") over time. To quantify noise, the range of a specific detector signal was calculated every two hours for one full day, and the median value was selected to eliminate other effects (such as testing, maintenance, fuelling, and moderator temperature fluctuations). This procedure was repeated every 3 ½ days for 12 years. These data are shown in Figure 2 above for detector 3G (horizontal Pt-clad Inconel) in all four units. Similar observations have been made for other detectors. Figure 4 below shows the noise trend for detector 7J (horizontal, Pt-clad Inconel).

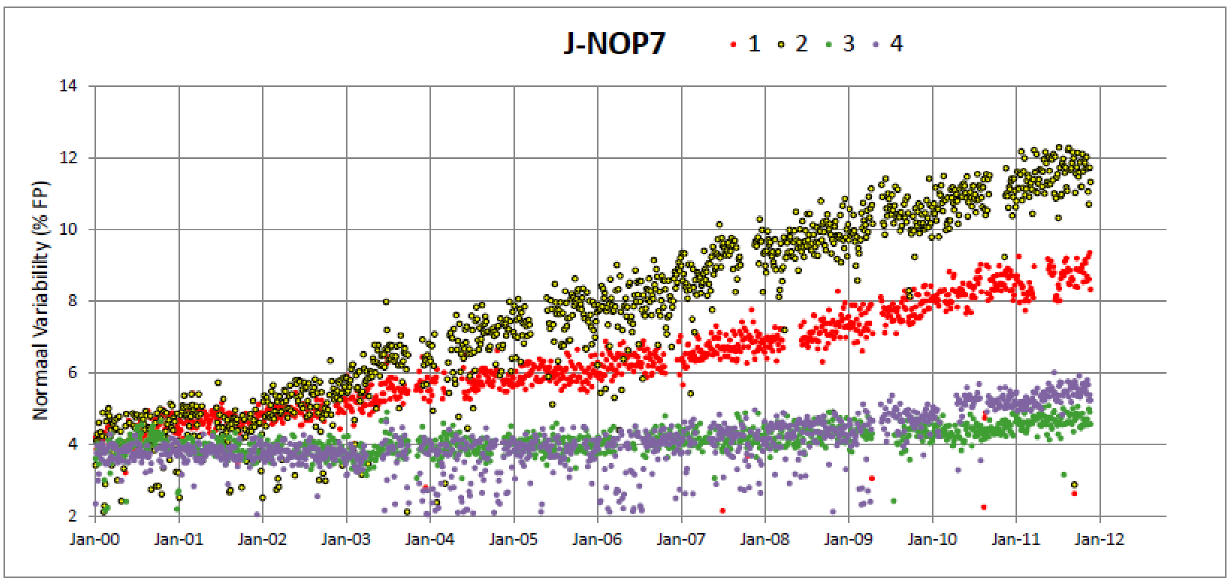

Figure 4 – Noise of detector 7J (Pt-clad Inconel) for all Darlington Units

This detector exhibits similar behaviour to detector 3G, albeit with more severe signal variability. Once again Units 1 and 2 detectors 7J display significantly increasing noise compared to Units 3 and 4, although Units 3 and 4 noise begins to trend upward after approximately 2008. Increasing noise is not

[1] A small residual effect exists due to overlap with multiple RRS detectors in the same location: the initial prompt fraction for the new RRS Inconel detectors can be slightly lower than 104%.

limited to Pt-clad Inconel detectors, as shown by Figure 5. In this case, detector 18D (vertical Inconel) signal variability is seen to increase, but the effect is mostly limited to the Unit 3 detector.

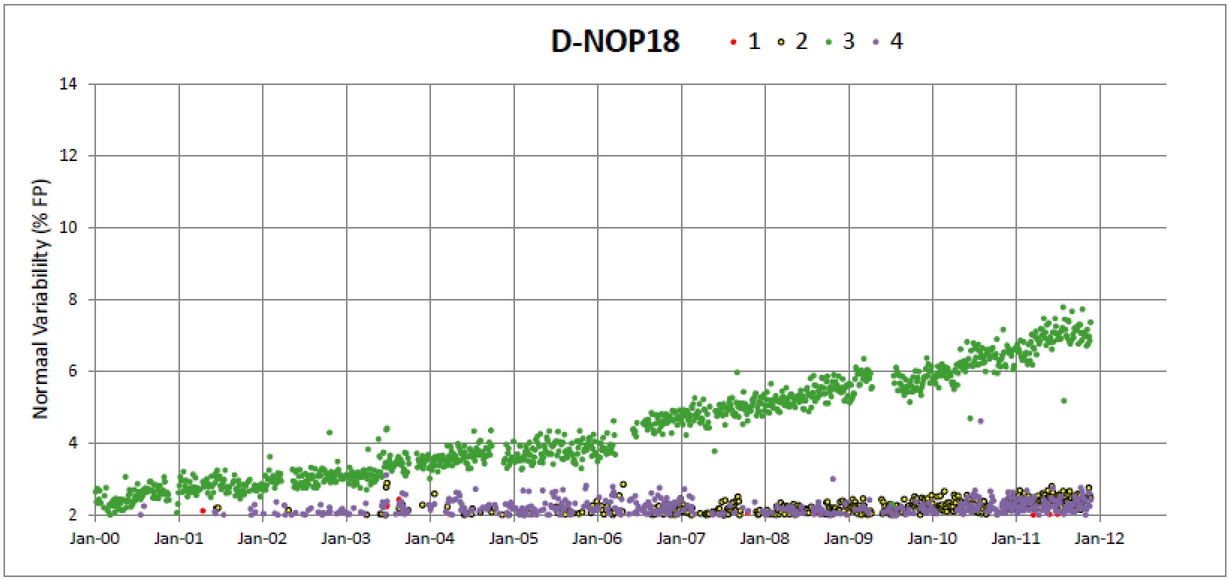

Figure 5 – Noise of detector 18D in all Darlington Units

Recently completed detector replacements in Unit 3 further illustrate the reduction in signal variability of new compared to aged detectors. Figures 6(a) through (h) show examples of detector noise measured in the same manner as described above, covering a period of time prior to and following replacement. After replacement, both vertical Inconel, and horizontal Pt-clad Inconel detectors exhibit significant reduction in signal variability. One potential explanation for this is that the detectors lose sensitivity as they age. This is discussed further in the following section.

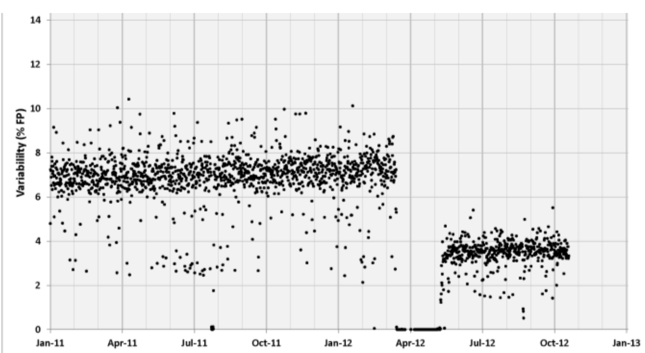

Figure 6(a) – Unit 3 detector 11D (Inconel)

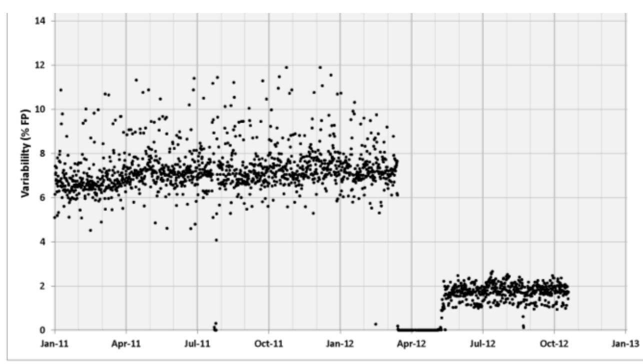

Figure 6(b) – Unit 3 detector 18D (Inconel)

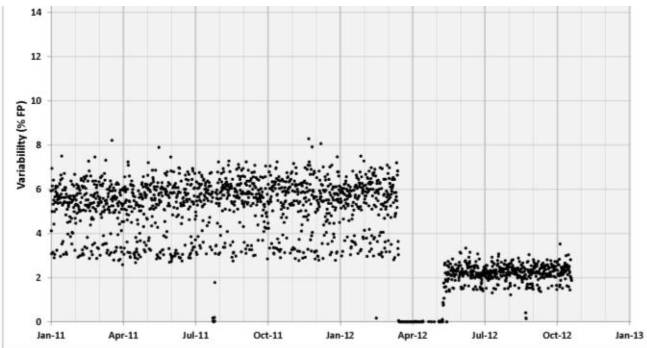

Figure 6(c) – Unit 3 detector 10E (Inconel)

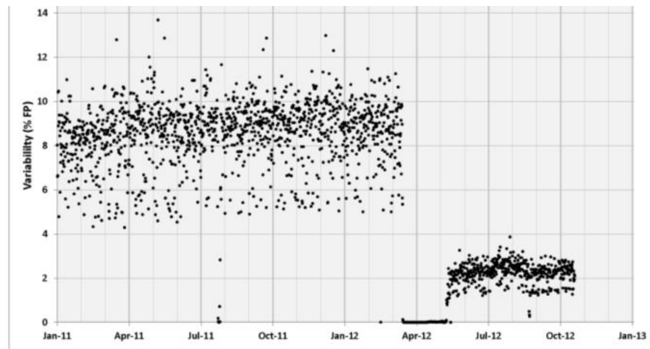

Figure 6(d) – Unit 3 detector 15E (Inconel)

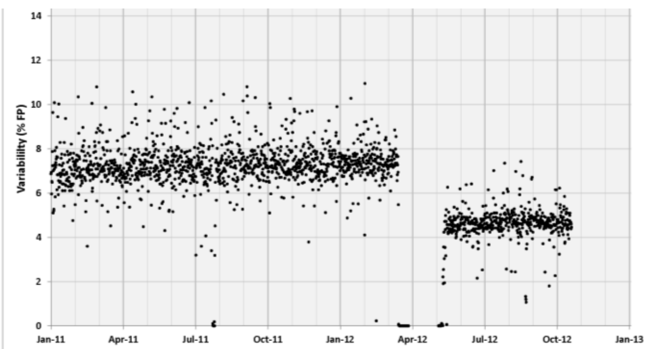

Figure 6(e) – Unit 3 detector 10F (Inconel)

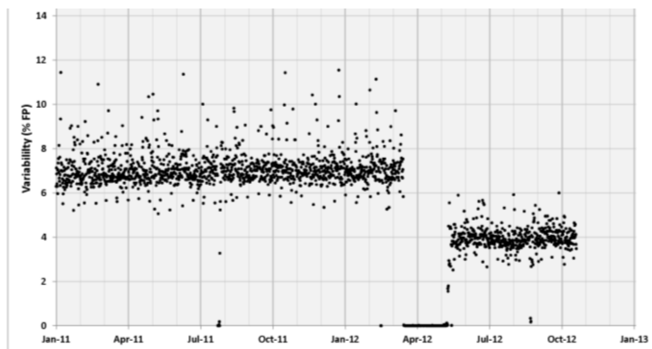

Figure 6(f) – Unit 3 detector 1H (Pt-clad Inconel)

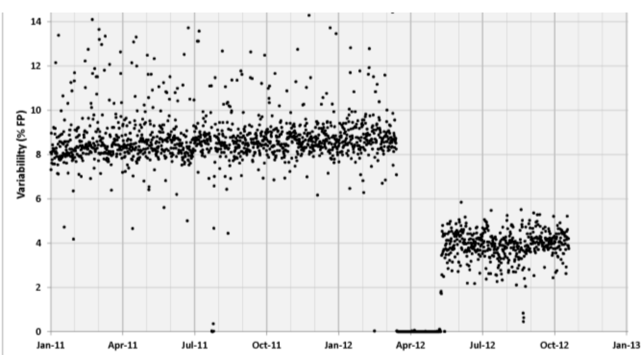

Figure 6(g) – Unit 3 detector 4H (Pt-clad Inconel)

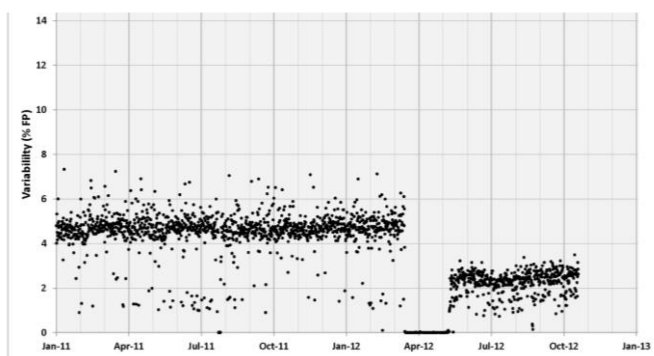

Figure 6(h) – Unit 3 detector 12H (Pt-clad Inconel)

5. Detector Amplifier Gains for New and Aged Detectors

Gradual loss of detector sensitivity may account for some of the increased signal variability observed in certain aged detectors. In order to perform their safety-related function, detector signals are routinely normalized and calibrated to a Required Detector Setting (RDS) based on reactor power and several other factors. This is accomplished by manually adjusting the detector amplifier gains such that the output signal falls within an acceptable range. Subsequent fine calibrations are then performed typically every 12 hours by adjusting software gain settings in the Shutdown System computers. Examination of amplifier normalization records following outages has revealed significant gain reductions where detectors have been replaced, indicating a significant increase in the current produced by the detector itself. This is illustrated in Table 1. For comparison, the average amplifier setting change for normalization during the 3 months prior the 2012 Unit 3 outage was +4% with standard deviation 9%, when excluding replaced detectors. In general, it can be seen that the vertical Inconel detectors tend to require larger gain reductions following replacement than the horizontal Pt-clad Inconel detectors. This is consistent with theoretical expectations for Inconel detectors only in qualitative terms – their sensitivity was predicted to increase over the first few years (peak value about 45 % higher than initial) and return to the initial value after 15-18 years of exposure.

Table 1: Amplifier gain reductions for replaced detectors

Year	Unit	Detector	Type	Amplifier Setting % Change
2012	3	10E	Inconel	-79.5%
2012	3	9E	Inconel	-72.4%
2012	3	15E	Inconel	-64.5%
2012	3	11D	Inconel	-59.5%
2012	3	6F	Inconel	-59.1%
2013	4	8F	Inconel	-49.7%
2012	3	10F	Inconel	-48.5%
2013	4	15E	Inconel	-44.5%
2013	4	5D	Inconel	-41.1%
2012	3	1H	Pt-clad Inconel	-36.8%
2012	3	18D	Inconel	-30.7%
2013	4	15F	Inconel	-28.4%
2012	3	4H	Pt-clad Inconel	-25.5%
2012	3	12J	Pt-clad Inconel	-23.0%
2012	3	1J	Pt-clad Inconel	-22.5%
2012	3	10G	Pt-clad Inconel	-15.5%
2012	3	12H	Pt-clad Inconel	-12.8%

The gradual loss of sensitivity due to aging effects combined with regular normalization and calibration results in a gradual increase in the amplifier gains required to maintain detector signals at RDS. Assuming the noise component remains relatively constant with time, the net effect is a reduction in neutronic signal-to-noise ratio. As the amplifier gain is increased, the noise component is amplified along with the weakened signal. Over time, this manifests as increased signal variation, as seen in the previous figures. It follows that upon replacement, a detector is restored to its full initial sensitivity, so amplifier gain is reduced and the signal-to-noise ratio is improved and signal variation reduced.

6. Current Status

Since 2005, analysis confirmed that a statistically-significant correlation exists between the detector prompt fraction and lead cable length. Moreover, the correlation coefficient appears to increase as the detectors age [1]. Changes in local gamma/neutron ratio and an increased contribution from the lead cable were identified as other possible contributors to the observed changes in dynamic behaviour. The analysis is complicated by obvious differences between various detectors in one reactor unit or between the same detector in different units. The fast transient provided by SDS2 power rundowns and the current methodology remains the best method to quantify the detector prompt fraction, a vital dynamic parameter for explaining the observed detector responses to local neutron flux changes.

For both safety reasons (some low prompt fractions) and production reasons (trips or margin to trip alarms caused by exaggerated promptness), Darlington started in 2012 a program to replace 2-3 detectors in each SDS channel during each planned outage. Preference was given to detectors exhibiting significant aging effects: low currents, unexplained high variability (noise), low or very high prompt fractions. The partial replacement program was successful in reducing the number of margin to trip alarms and the risk of channel trips due to excessive detector response.

7. Conclusions

Aging of flux detectors used in Darlington reactors has introduced technical and operational challenges beyond the effects predicted in previous studies. Estimates of prompt fractions from planned power rundowns, responses to fuelling, responses to unit shutdown and indicators of detector noise led to a better understanding of these aging effects.

Comparisons of detector signals before and after replacement have confirmed these aging effects. Replacements of most affected detectors will continue and a complete set of new detectors will be used after the refurbishment outage.

8. References

[1] C. Banica and R. Slovak, "Empirical Observations on the Aging of Flux Detectors at Darlington", Proceedings of the 32nd Annual Conference of the Canadian Nuclear Society, Niagara Falls, Ontario, Canada June 5 - 8, 2011.