ANALYSIS OF SEPTEMBER 2007, BRUCE A UNIT 3 SDS1 RUNDOWN TO ASSESS THE IMPACT OF EMPTY CHANNELS ON DETECTOR RESPONSES

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ABSTRACT

This paper documents the calculations performed using the Reactor Fuelling Simulation Program (RFSP-IST) code to model the recent Bruce A Unit 3 SDS1 (September 2007) power rundown test. The RFSP predicted power rundown profiles for both SDS1 and SDS2 in-core NOP and Ion Chambers are in very good agreement with the measured responses for most detectors.

Results confirm the conclusion of earlier validation studies with respect to overall RFSP accuracy of modeling SDS1 rundowns and show that the empty channels do not have a significant impact on the dynamic response of nearby detectors.

1. INTRODUCTION

Bruce A Unit 3 is operating with a number of empty (defuelled) channels to achieve the planned end of life for the plant. The main reason pertains to pressure tube (PT) axial deformation due to irradiation in fast neutron flux and particularities of Unit 3 design that can cope with limited PT expansion. In order to ensure the design is maintained, or more precisely the PT remains on end fitting bearings, the axial growth is significantly reduced by removing the fuel from specific channels. The absence of fuel in the channel reduces the fast flux in its pressure tube by an order of magnitude and practically stops the axial growth. Bruce Power has analyzed the safety and operational aspects of such non-standard operation. One aspect pertains to NOP detector responses in presence of defuelled channels and more specifically the dynamic response. The impact of empty channel on detector dynamic response is the subject of this paper.

A SDS1 rundown test was conducted at Bruce A Unit 3 on September 28, 2007. The reactor was manually tripped by Shutdown System One (SDS1) as part of the planned outage. In-core flux detector (ICFD) and Ion chamber (IC) signals from channels D, E, F, G, H and J, were recorded continuously during the reactor shutdown, along with rod positions and signals related to trip activation. At the present time, SDS1 uses vertical Straight Individually Replaceable (SIR) Platinum-clad Inconel detectors, while SDS2 uses horizontal Platinum (coiled) detectors.

The power rundown data resulting from the SDS1 trip was used in this analysis to investigate the general response of NOP detectors and in particular the dynamic response of NOP detectors close to empty (defuelled) channels. The analysis was performed with the CERBERUS module of the Reactor Fuelling Simulation Program (RFSP 3-04-04) code.

The code predictions were compared against measurements from SDS1 and SDS2 ICFDs. SDS1 and SDS2 NOP Detectors within one lattice pitch of empty channels have been analyzed separately and compared to the rest of detectors to extract potential impact due to the presence of the empty channels.

2. DESCRIPTION OF THE RUNDOWN TEST

At the start of the test, Unit 3 was operating at about 92.5%FP in steady state configuration. The power was reduced to 64%FP in 2.5 minutes and was held at that level for another 4.2 minutes after which SDS1 was manually tripped as shown in the **Figure 1**. The signals were sampled at a frequency of 500 Hz or at a time interval of 2 msec.

The power maneuver is important because, the ICFD detectors retain longer lived delayed components that affect their response during the trip.

The positions of the SORs (Shutoff Rods) and CAs (Control Absorbers) were recorded prior and during the trip. The voltage indications corresponding to rod positions are shown in **Figure 2** below for Bank 1. These voltages are used to calculate the rod positions using a non-linear formula.

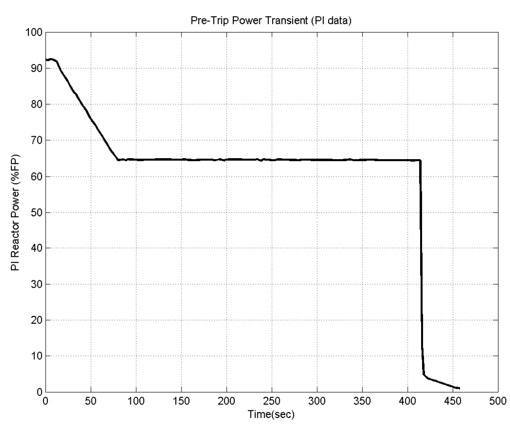

Figure 1. Flux/Power rundown evolution

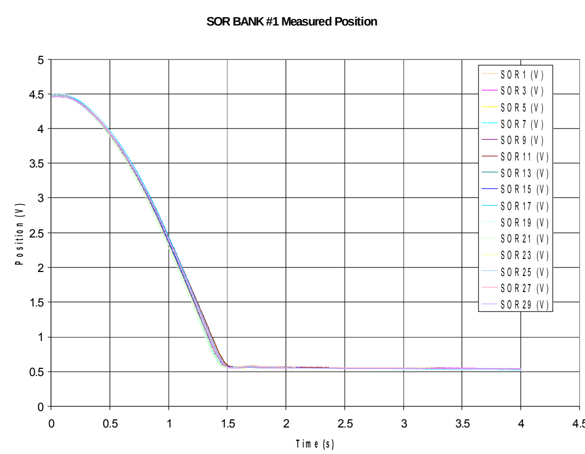

Figure 2. Sample SOR Insertion (Bank 1)

Sample SDS1, SDS2 and Ion Chambers signals collected during the trip are shown in **Figures 3 and 4** below. The SDS1 ion chambers, which are located on the top of the calandria vessel, responded first to the insertion of SORs and CA rods. The sequence of the NOP in-core flux detectors (ICFD) signal reductions indicates the effect of SOR insertion.

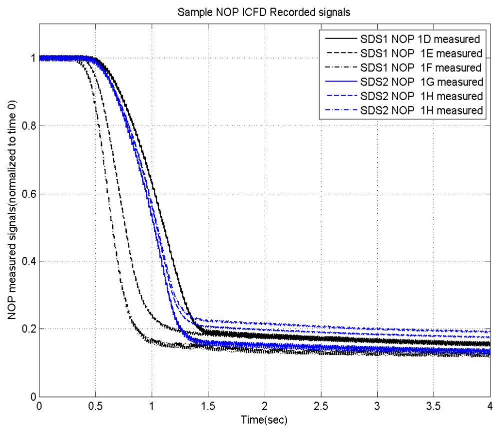

Figure 3. Sample measurement for ICFD

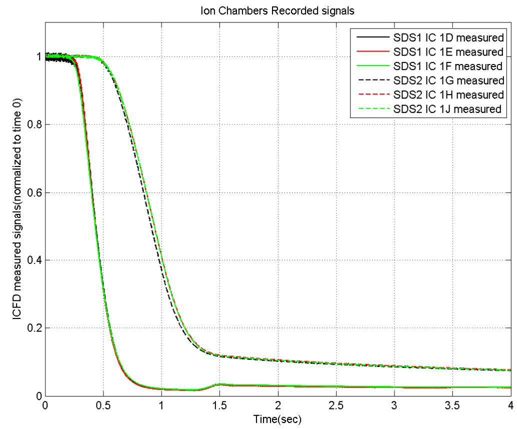

Figure 4. Ion Chamber measurements

3. METHODOLOGY AND ASSUMPTIONS

The current Bruce A model with a fine mesh of 48x60x33 was used. Fuel properties of the Natural Uranium bundles were derived using WIMS-IST. Device properties were based on calculations performed with DRAGON for major devices (i.e. ZCU and SOR/CAR) and converted from the existing 1.5 group MULTICELL for remaining structural materials. The ion chambers have been placed approximately in the middle of the reflector to be able to extract equivalent information to the actual ion chambers located out of core.

An equivalent core irradiation was established based on the preexisting operational configuration i.e. SORO states of September 27/28, 2007. The equivalent RFSP power matched the SORO target within 2% relative. This configuration included the empty channels present at that time, shown in **Figures 5 and 6** below along with potentially impacted NOP detectors.

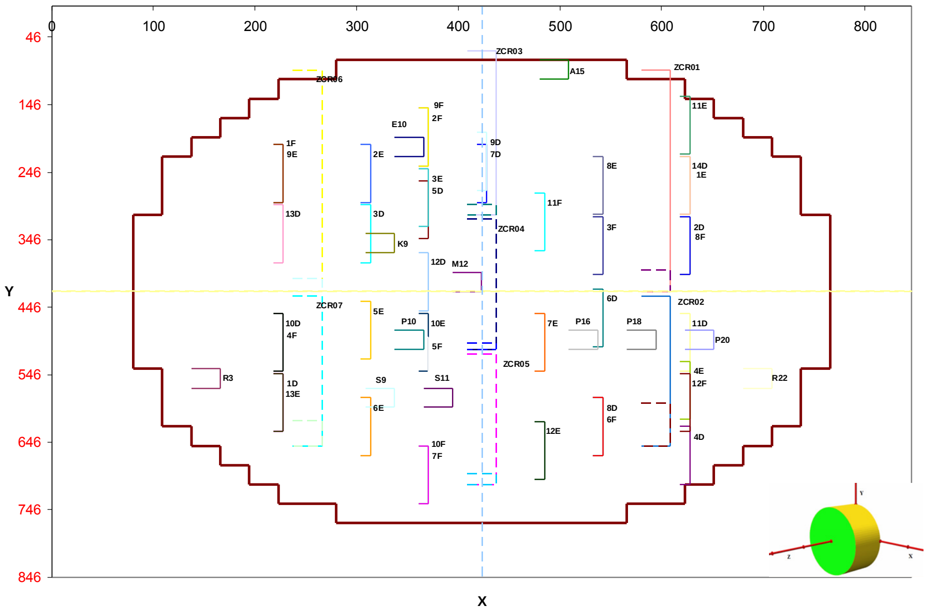

Figure 5. Unit 3 empty channels configuration and SDS1 detectors positions

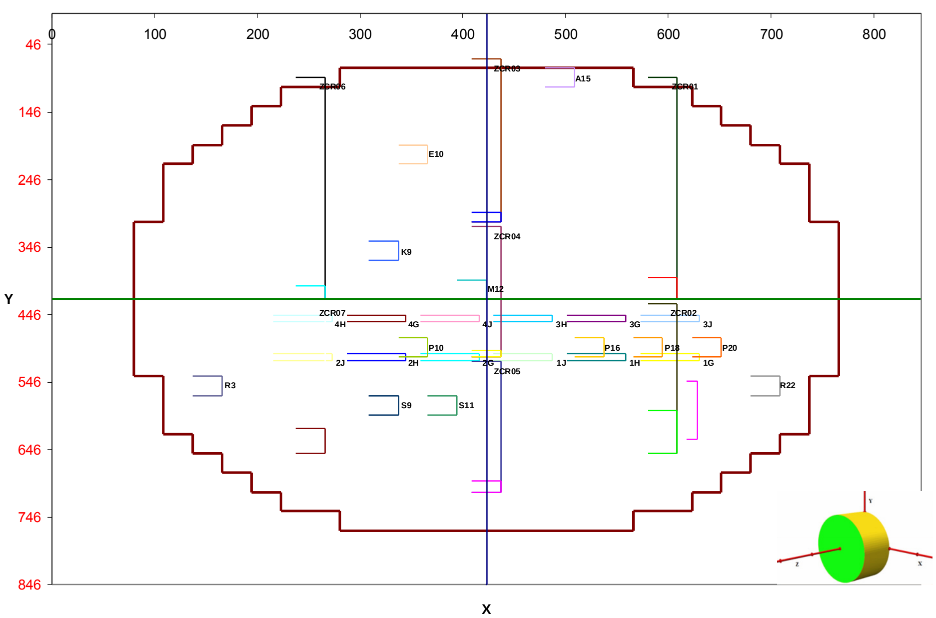

Figure 6. Unit 3 empty channels configuration and SDS2 detectors positions

All predicted responses are based on thermal neutron flux only, since gamma components are not simulated within RFSP. In general for high power operation this is reasonable, however at very low power gamma effects can cause differences that are not captured within RFSP. Such effects are affecting detectors regardless of the presence of nearby empty channels.

Detectors were assumed to have prompt fractions as estimated from measurement [1]. The delayed components yields have been modified proportionally to obtain the required prompt fractions. An additional effect known to affect and contribute to detector response is the lead cable which acts as a detector in itself and has its own prompt fraction. In general the lead cable contribution is small and was neglected in this work.

The *CERBERUS module was used to determine raw thermal fluxes and detector responses during the SDS1 transient. SOR and CAR drop curves measured in the test were used. Zone Controller levels at the time of trip were modeled as well. In order to account for contributions to detector responses from the pre-trip power maneuver a MATLAB model of detector response was developed and used in this analysis.

The following approximations have been used as their impact was considered small:

- Thermalhydraulic conditions determined for Large Break Loss of Coolant Accident analysis have been used. The thermalhydraulic conditions were considered steady during the trip i.e. constant and equal to the values in the initial steady state.

- The nominal isotopic conditions were used for moderator and coolant. The actual conditions were close to the nominal and no correction was deemed necessary.

- The fuel isotopic distribution as determined in the Time-Average model and used for the nominal case is different that the instantaneous one present in the core as predicted by SORO.

- The existing depleted bundles present in the core have not been modeled. There was a small number of depleted bundles located toward the channel outlet and would have a minimal impact on calculations.

- The water bundle SCM properties determined for Low Void Reactivity Fuel were available for this simulation. The water bundle properties are quite insensitive to specific modeling and neighbouring channel type.

- No RFSP simulation of the pre-trip power maneuver was performed. The effect on detectors was accounted for in a global sense i.e. the same for all detectors, as described below.

All incore flux detectors are sensitive to both neutron and gamma fluxes and have a dynamic response. Incident neutron and gamma radiation is converted to energetic electrons; the positive charge on the electrode produces a current when linked with an external circuit, however the generated current does not reproduce the incident neutron flux transient behavior. The delayed components due to delayed gammas from beta-active fission products are compensated through electronic compensation schemes to provide a response that matches the fuel power.

In general it is preferred to allow for operation at a lower power for a longer period of time in order for the detector delayed components to achieve the new equilibrium case. In Bruce A this is not possible due to lack of adjusters[1] hence the trip was initiated after about 4 minutes of steady state operation at about 64%. The pre-trip power maneuver was considered to correct the detector long term components. This correction was applied within MATLAB to determine detector responses considering both the power maneuver and the actual trip. Since the detector amplifier outputs were used to collect data, another correction was applied to account for amplifier time constant of 10 milliseconds presented in design documentation.

Analysis was performed at selected signal level crossings between 90% and 40%, equally spaced every 10%. The high level (90%) is the lowest value that has significance for the typical margin to trip (typical between 10 to 20%). The lowest value (40%) is well within the linear portion of the transient for all detectors and was chosen high enough to minimize the impact of low power response. Analysis was performed in both time and signal domain.

3.1 Modelling Of In-Core Flux Detectors Dynamic Behaviour

The equations characterizing the detector dynamic response to time dependent flux are:

$$D(t) = PF * \Phi(t) + \sum_{i=1}^{n} d_i(t) \quad \text{where} \quad PF = 1 - \sum_{i=1}^{n} a_i$$

$$\dot{d}_i(t) = \frac{(a_i * \Phi(t) - d_i(t))}{\tau_i}; i = 1, n$$

where D(t) and $d_i(t)$ is total detector response and ith delayed component respectively, to a flux $\Phi(t)$, a_i and τ_i are the amplitudes and time constants respectively of the ith delayed components of the detector out of the total n delayed components. PF is the prompt fraction. A MATLAB model was developed using the state-space solver. The RFSP predicts the flux at selected moments in time during the rundown ($\Phi(t)$) and also predicts detector responses. Same equations have been used to determine detector initial condition taking into account the power maneuver that took place in MATLAB.

The RFSP raw fluxes were used to determine detector response using MATLAB, taking into account the initial conditions i.e. the pre-trip power maneuver presented in Figure 1. The MATLAB model produces excellent results that match RFSP predictions within 2 ms for same detector level in time domain or within 0.25% normalized level for the same times i.e. in signal domain.

4. RESULTS AND DISCUSSION

Sample results of the analysis for NOP detectors are shown in Figure 7 (SDS1) and 8 (SDS2). Results for the ion chambers are shown in Figure 9. Each of these plots show the RFSP

[1] In general, CANDU reactors use the adjuster rods to overcome Xe poisoning that occurs after power reductions. Bruce A original design employed highly enriched U^{235} booster rods that to provide poison override capability. The booster rods are no longer in use hence the capability of maintaining operation after a power manoeuvring is quite limited since the only source of positive reactivity is provided by the light water Zone Controllers..

response, MATLAB corrected and the measured signal filtered to eliminate noise. Note that the detectors close (distance less than 1 Lattice Pitch or 28.575 cm) to empty channels are marked with a star *.

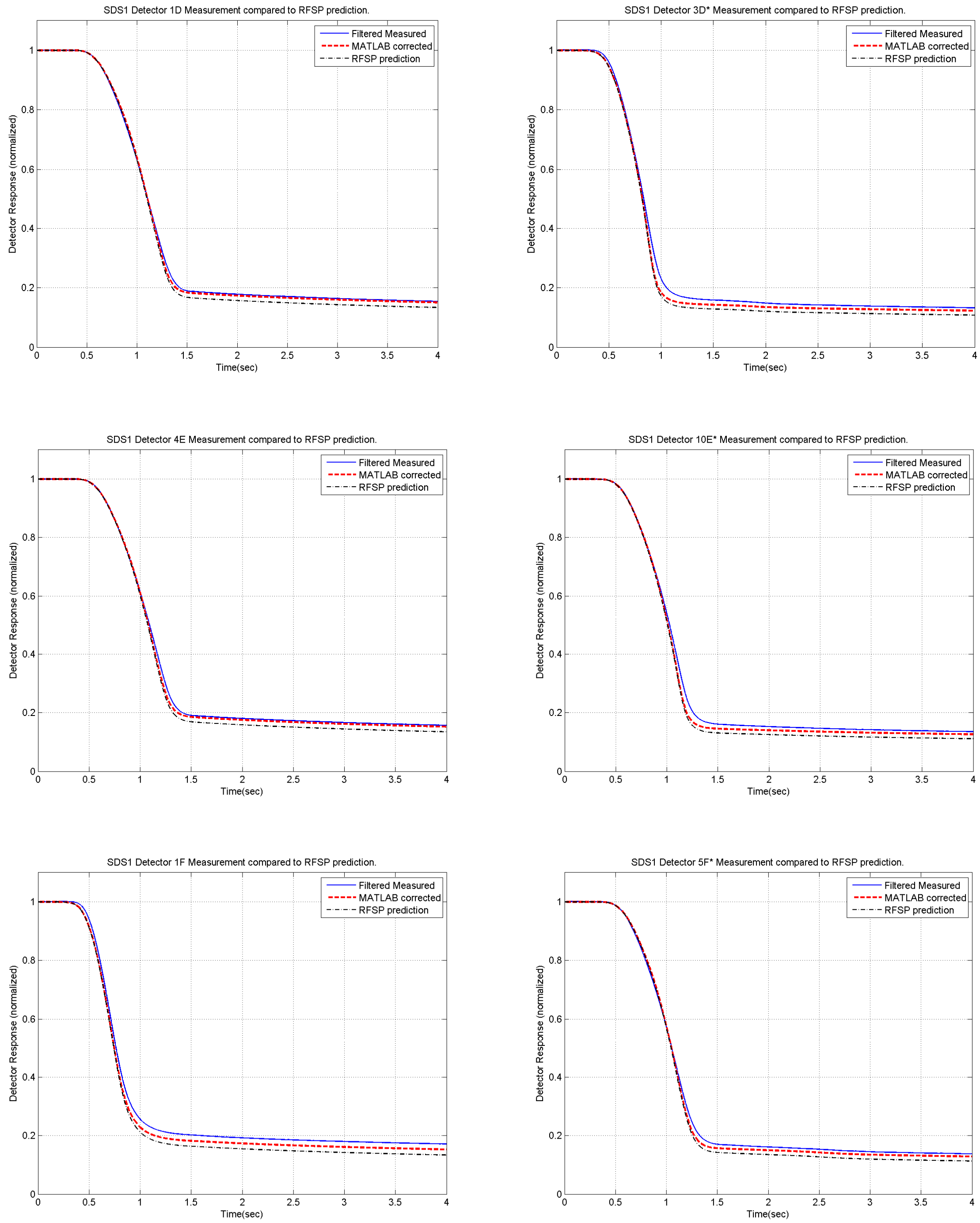

Figure 7. Sample of SDS1 NOP detector comparisons

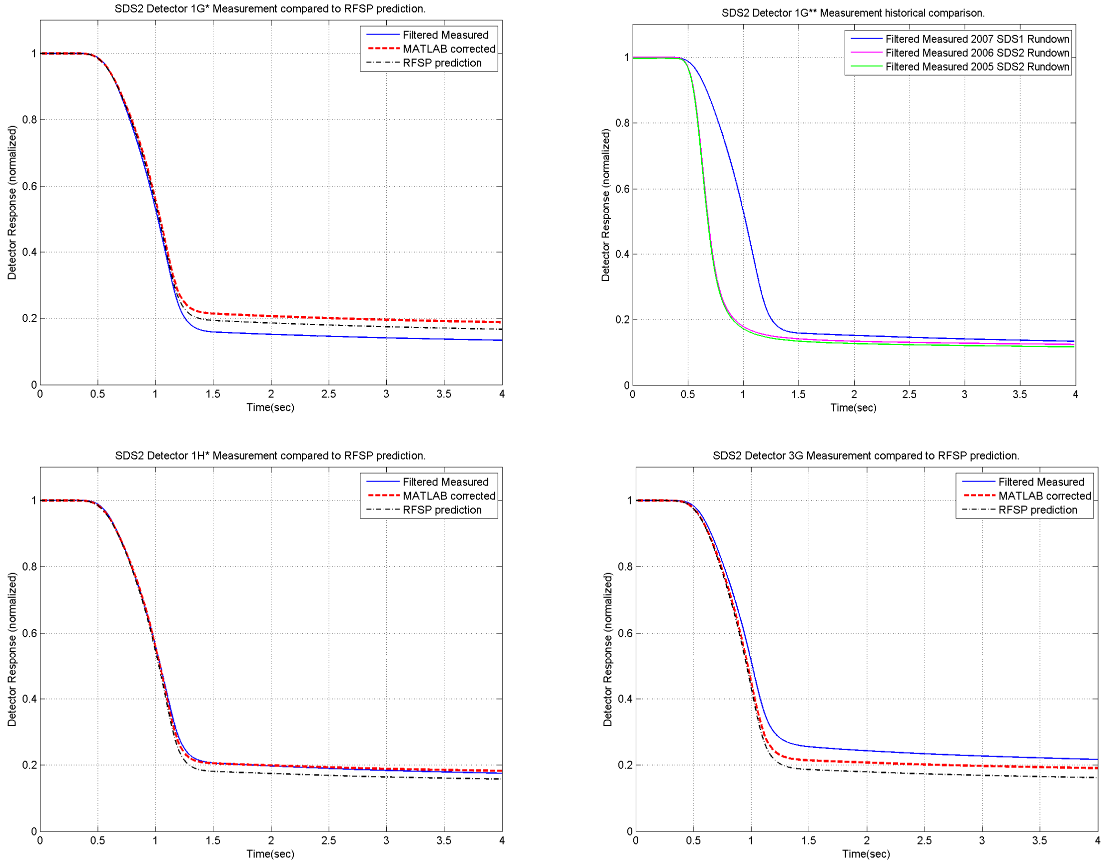

Figure 8. Sample of SDS2 NOP detector comparisons

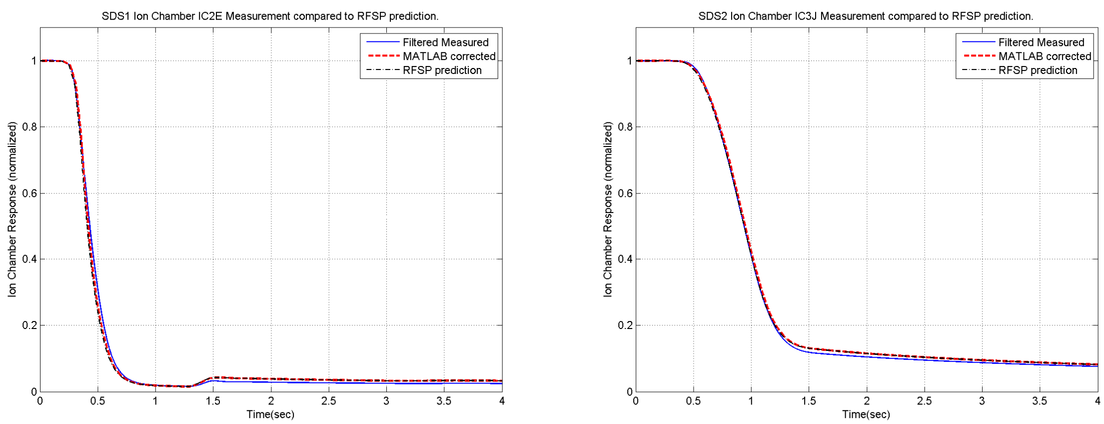

Figure 9. Sample of Ion Chamber comparisons

Integrated results are presented in **Table 1** for time-domain, and **Table 2** for signal domain for ICFD NOP SDS1, SDS2 and Ion Chamber detectors. These tables present the results of detectors grouped based on their proximity to defuelled channels (**FAR** if distance between empty channel and detector exceeds 28.575 cm or **CLOSE** otherwise.)

Table 1: Summary results –Time domain
Difference between Simulation and Measurement

	Power Maneuver Accounted		**No pre-trip maneuver**	
SDS1	**Mean (ms)**	**Std (ms)**	**Mean (ms)**	**Std (ms)**
ALL NOP SDS1	-3.5	18.4	-8.6	18.2
FAR NOP SDS1	-2.0	19.6	-7.1	19.3
CLOSE NOP SDS1	-9.0	11.9	-13.7	11.7
SDS1 IC	-17.6	13.4	-17.6	13.4
SDS2	**Mean (ms)**	**Std (ms)**	**Mean (ms)**	**Std (ms)**
ALL NOP SDS2	-14.7	15.2	-23.7	16.1
FAR NOP SDS2	-20.3	12.2	-29.3	13.7
CLOSE NOP SDS2	-3.3	14.5	-12.7	15.0
SDS2 IC	-4.7	5.2	-4.7	5.2

Table 2: Summary results –Signal domain
Difference between Simulation and Measurement

	Power Maneuver Accounted		**No pre-trip maneuver**	
SDS1	**Mean (%)**	**Std (%)**	**Mean (%)**	**Std (%)**
ALL NOP SDS1	-1.0	2.6	-1.7	2.7
FAR NOP SDS1	-0.7	2.6	-1.5	2.7
CLOSE NOP SDS1	-1.9	2.2	-2.6	2.4
SDS1 IC	-6.3	4.2	-6.3	4.2
SDS2	**Mean (%)**	**Std (%)**	**Mean (%)**	**Std (%)**
ALL NOP SDS2	-2.1	2.3	-3.4	2.8
FAR NOP SDS2	-2.8	2.0	-4.2	2.6
CLOSE NOP SDS2	-0.6	2.1	-1.9	2.5
SDS2 IC	-0.5	0.5	-0.5	0.5

In addition to the results presented above, several other sensitivity cases have been performed, with the effect of initial flux/power distribution considered as the most relevant. The results show that the nominal case with matched power distribution (i.e. using September 27 Unit 3 SORO channel powers in a RFSP model) improved the predictions by about 20ms for both SDS1 and SDS2 NOP detectors when compared to the case of a nominal Time-Average RFSP model with the same empty channel configuration. A similar improvement can be claimed for the SDS2 ion chamber mostly due to the significant differences in flux/power distribution. This sensitivity case supports the current methodology used in perturbation analysis that matches target channel power by deriving an equivalent Time-Average core irradiation.

For the nominal case (12 empty channels, pre-trip correction, matched power distribution and distributed TH conditions) , the SDS1 overall average is –3.5±18.4 ms time shift for all detectors i.e. simulation is faster than measurement by 3.5ms on average. This can be due to the effect of gamma flux at low power or local effects. Detectors far from empty channels have an overall time shift average of -2.0±19.6 ms, while the ones in immediate proximity of defuelled channels have an average of -9.0±11.9 ms.

SDS2 detectors exhibit an overall average of -14.7±15.2 ms. Detectors far from empty channels show an average time shift of -20.3±12.2ms, while the detectors close to empty channels have a better agreement of -3.3±14.5 ms.

The very good agreement between simulation and measurement in the time domain supports the fact that the effects related to the empty channels over detector response are well captured by the current tools. In general, the agreement for SDS2 detectors is not as good as for SDS1 detectors, similar to previous work [2].

The agreement in the signal domain is generally good to about 1 to 2% of the initial value. All the results for nominal case show a very good agreement, similar to [2].

5. CONCLUSIONS

Results confirm the overall RFSP accuracy of modeling SDS1 rundowns and show that the empty channels do not have a significant impact on the dynamic response of nearby detectors.

6. REFERENCES

1. C. Banica, “Analysis of the SDS1 Rundown Test in Bruce-3, September 2007”, December 18, 2007, Bruce Power report NK21-REP-63700-00016.
2. A.C. Mao, G. Gomes, “Validation of the Full-Two-Group Kinetics Calculation in RFSP Against the 1995 SDS1 Trip Test at Point Lepreau”, November 2002, COG-00-202.