# TESTING THE DYNAMICS OF SHUTDOWN SYSTEMS INSTRUMENTATION IN REACTOR TRIP MEASUREMENTS

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## ABSTRACT

Periodic testing of the dynamics of the shutdown systems and their instrumentation is performed in the CANDU nuclear power plants of Ontario Power Generation (OPG) and Bruce Power. Measurements of in-core flux detector (ICFD) and ion chamber (I/C) signals responding to the insertion of shut-off rods (shutdown system No.1, SDS1), or to the injection of neutron absorbing poison (shutdown system No.2, SDS2) are regularly carried out at the beginning of planned outages. A reactor trip is manually initiated at high power and the trip response signals of ICFDs and I/Cs are recorded by multi-channel high-speed high-resolution data acquisition systems set up temporarily at various locations in the station. The sampling of the separate data acquisition systems are synchronized through the headset communication systems of the station. A total of 120 station signals can be sampled simultaneously up to 2500 samples per second. The effective prompt fractions of the ICFDs are estimated from the measured trip response. Effectiveness and the timeline of the trip mechanism are assessed in the measurement as well. The measurement can identify ICFDs with abnormally slow response (under-prompt) or overshooting response (over-prompt) at the beginning of the outage. The time required for the signals to drop to predefined fractions of their pre-trip values (level crossing time) is plotted as a function of detector position and compared against safety requirements. The propagating effect of shut-off rod insertion or poison injection on the flux is monitored by the level crossing times of ICFDs and ion chambers.

## KEYWORDS

In-core flux detectors, prompt fraction estimation, reactor power trip, safety system testing, trip effectiveness, detector fault monitoring.

# 1. INTRODUCTION

Data acquisition systems and signal processing techniques have been developed over the years at OPG to carry out periodic reactor power trip measurements. The tests are performed on a regular basis (approx. every two years in any given reactor unit), and their purpose is

- to estimate the effective prompt fractions of the shutdown system ICFDs, relative to the trip response of the ex-core ion chambers (100% prompt reference signals),
- to assess the effectiveness of the trip mechanism (poison injection, or insertion of shut-off rods) by measuring the timing of signal changes of ICFDs and I/Cs as a function of detector location, and
- to provide trip measurement data for validating safety analysis models and assumptions.

In the Darlington and Bruce CANDU stations, shutdown system No.1 utilizes the signals of three independent sets of 18 vertically located over-prompt self-powered flux detectors (Inconel) serving as neutron-overpower (NOP) protection signals. These ICFDs are sensitive to the thermal neutron flux only, and have a design prompt fraction value of 104.8%. Shutdown system No.2 has three independent sets of 17 horizontally located under-prompt self-powered flux detectors (Platinum-clad Inconel). These ICFDs have a mixed sensitivity to neutron and gamma fluxes and have a design prompt fraction value of 88.7%. In the Pickering CANDU station, both shutdown systems have under-prompt Platinum-clad Inconel self-powered flux detectors.

The effective prompt fraction of an ICFD is estimated from its measured trip response as the ratio between the normalized signal drop of the reference ion chamber and that of the ICFD signal, measured three seconds after trip initiation. Additional correction terms are applied to the result to remove the effects on the detector current of pre-trip power changes, the post-trip gamma background of fission products, and the delayed detector current component already active at 3 seconds after the trip. The combined effect of these three sources is in the range of 2-3%. The effective prompt fractions estimated from the trip measurements do change as detectors age, and they can significantly deviate from their initial values. Safety model calculations establish the minimum allowable limits of ICFD prompt fractions for various accident scenarios.

In addition to estimating the ICFD prompt fractions, the measured ICFD trip response signals are also used to assess the effectiveness and timing of the poison injection system in SDS2 trips. This is required at a two-year interval, as a station commitment to the regulator (Canadian Nuclear Safety Commission).

All ICFDs in Pickering-B Units 5, 6, and 7 were replaced between 1996 and 2000. The same trip test technique was used in the commissioning measurements of the new ICFDs. The prompt fractions of all new ICFDs were estimated in SDS1 trips, as part of the commissioning project. All safety system ICFDs and ion chambers were temporarily connected to the data acquisition systems. Their pre-trip noise signals at steady-state and their trip response signals were recorded. Follow-up noise measurements and trip tests are performed at the beginning of planned outages to identify possible changes in the dynamic response of ICFDs. In Unit 8, SDS1 trip test results obtained in 1993, 1998, and 2001 were used to support the deferral of the ICFD replacement project until 2004. The linear trend of prompt fraction reduction, seen in the above measurements, indicated that the worst-case predictions of all ICFDs would stay above the minimum allowable limit of 70% over the next three years.

ICFD noise signatures are also measured at steady-state high power before the trip. The noise analysis of ICFD signals provides information on the dynamics of the detectors, as well as, on the dynamic properties of the flux noise sources, such as fuel channel vibration, detector tube vibration, moderator density fluctuations, and the level fluctuations of “liquid zone control” compartments containing neutron absorbing light water. The measured multi-channel noise signatures of ICFD signals (auto and cross spectra, coherence and phase functions) characterize the dynamics and the general health of the instrument lines. The measurement of signal fluctuations at steady state is followed by the trip response measurement.

## 2. COMPARING THE EFFECTS OF SHUT-OFF ROD INSERTION AND POISON INJECTION

Figure 1 shows the first two seconds of the trip response signals of 24 ICFDs and 4 ion chambers, normalized by their pre-trip values. The signals were recorded during an SDS1 trip (shut-off rod insertion) in Pickering-B Unit 8 in 2001. The ICFD response signals measured during the first two seconds after trip initiation are clearly the products of the ICFDs' prompt current generating mechanism only, since the ICFDs' delayed components do not contribute to the detectors' trip response signals at that early stage. One can make two important observations in Figure 1:

- After the SDS1 trip, the ICFD signals dropped to 20-30% of their pre-trip values, while the reference ion chambers dropped to 3-5%. This resulted in an estimated ICFD effective prompt fraction range of 75-80%. The Platinum ICFDs in Pickering-B Unit 8 are more than 17 years old and their prompt fractions dropped from its design value (84.8%) significantly due to the burn-up of detector emitter.
- The bulk of the power reduction took place over an 800-msec time interval. This is a typical flux reduction time, measured when the insertion of shut-off rods (SDS1 trip) is initiated.

Figure 2 shows the first two seconds of the trip response signals of 33 ICFDs and 2 ion chambers, normalized by their pre-trip values. The signals were recorded during an SDS2 trip (poison injection) in Pickering-B Unit 6 in 2001. Similarly to the previous case, the ICFD signals measured during the first two seconds are generated by the ICFDs' prompt current generating mechanism, therefore the measured response can be used to estimate the ICFD prompt fraction. In comparison to the previous case, note that

- After the SDS2 trip, the ICFD signals dropped to the level of 8-15% of their pre-trip values, while the reference ion chambers dropped to 1% of their pre-trip levels. This resulted in an estimated ICFD effective prompt fraction range of 85-90%. In Pickering-B Unit 6, the old platinum ICFDs were replaced with new Platinum-clad Inconel ICFDs (hybrid encapsulated straight individually replaceable – HESIR) in 1996. These HESIR ICFDs are relatively new, and their effective prompt fractions were found to be close to their design value (88.9%).
- The bulk of the power reduction took place over a 400-msec time interval. This is a typical flux reduction time, measured when poison injection (SDS2 trip) is initiated.

The difference between the SDS1 and SDS2 trips is more obvious, when the SDS1 and SDS2 response signals of the same ICFD are compared. Such comparison is shown in Figures 3 and 4 for two ICFDs. The effect of the reactor trip on the flux is measured by the level crossing times of ICFDs. In the SDS2 trips, the poison (Gadolinium) is injected from the south side of the core, and it propagates toward the north side in injection nozzles (pipes). In the SDS1 trip, shut-off rods are inserted into the core from the top. In both cases, the level crossing times of ICFD signals are used to monitor the progress of the shutdown. The times needed for the ICFD signals to drop to certain pre-defined fractions of their pre-trip values are plotted as a function of ICFD position, then they are compared against location-dependent action limits and impairment limits.

The propagation effects of the SDS1 and SDS2 trips are compared in Figure 5. It shows the 50% level crossing times of ICFD signals as a function of detector position, measured in Pickering-B Unit 6 in an SDS1 trip (1996) and in an SDS2 trip (2001), both started from 60% full power. A similar comparison of trip effects was performed in Darlington Unit 1, and the results are shown in Figure 6. In both cases, the SDS2 trip was significantly faster. Comparisons of level crossing times related to other signal levels between 98% and 50% of the pre-trip values supported the same finding.

## 3. CONCLUSION

Reactor trip tests are performed on a regular basis to assess the health of in-core flux detectors and the effectiveness of the reactor shutdown systems. The techniques, combined with the pre-trip noise measurements carried out at full power steady-state, have provided a surveillance tool for monitoring the dynamics of safety systems.

## Comparing SDS1 and SDS2 Trips in Pickering-B

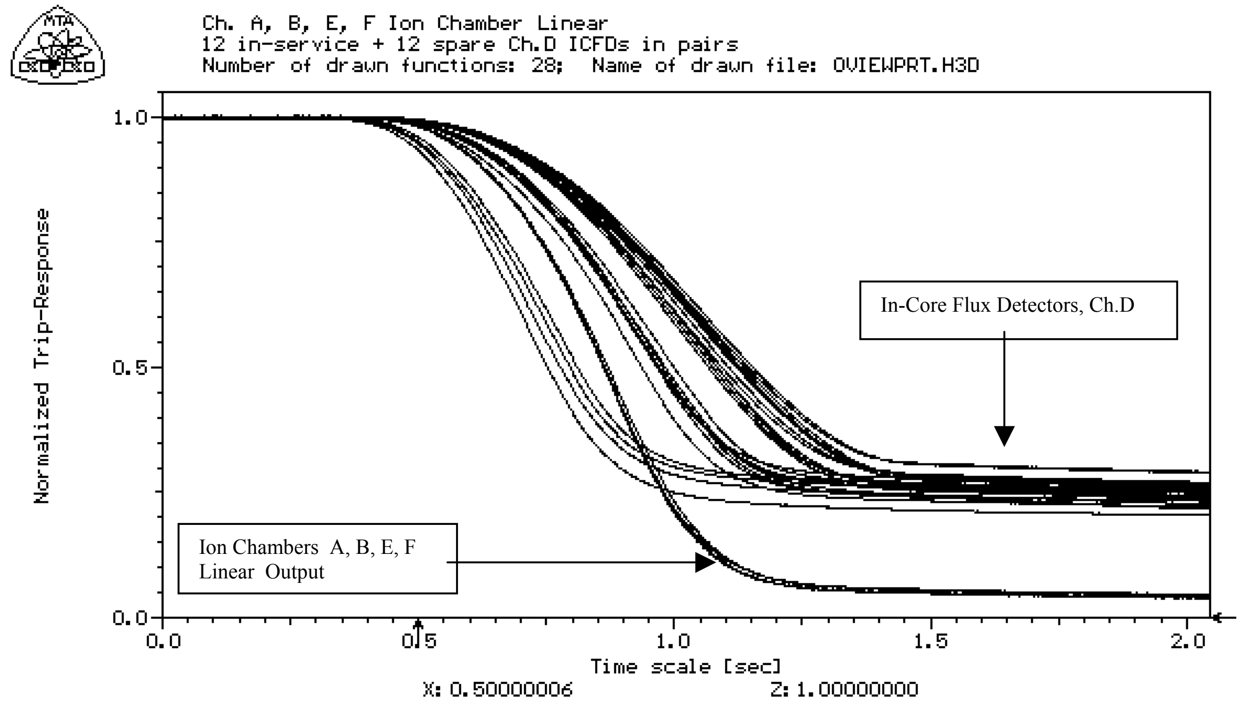

Figure 1. Normalized response of ion chambers and in-core flux detectors to an **SDS1** trip (shut-off rod insertion) from 60% full power in Pickering-B Unit 8 (trip at t=0)

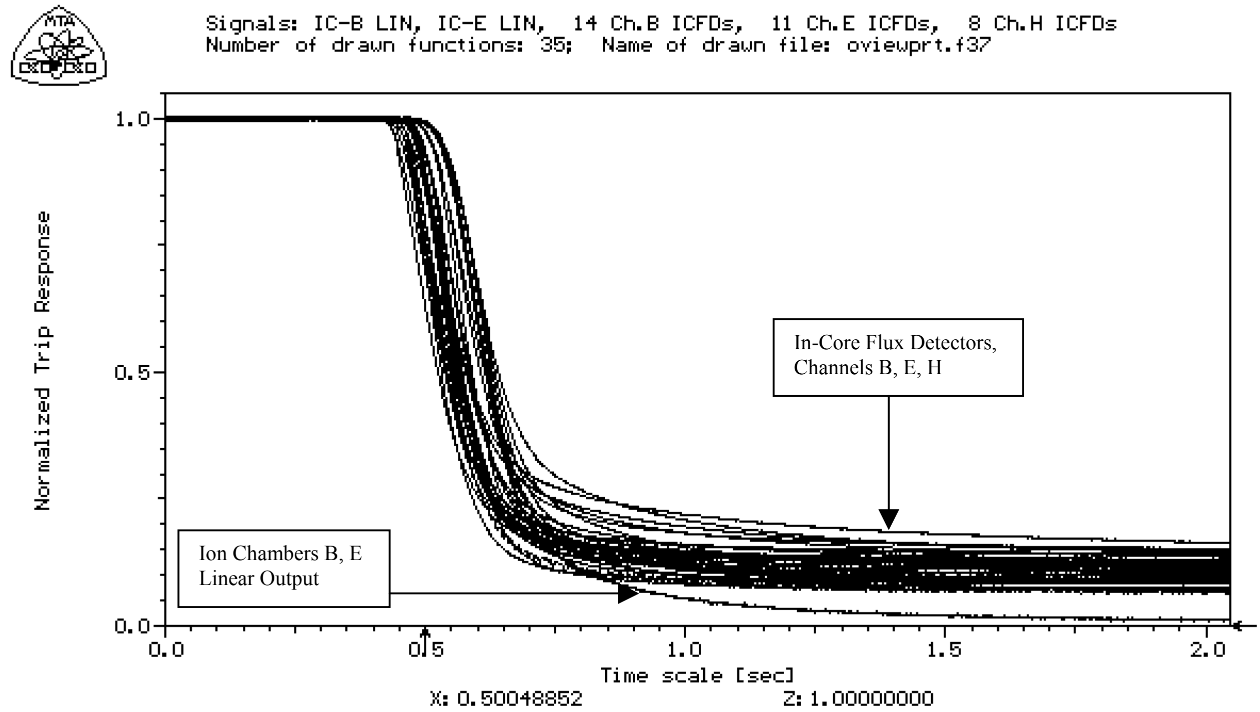

Figure 2. Normalized response of ion chambers and in-core flux detectors to an **SDS2** trip (poison injection) from 60% full power in Pickering-B Unit 6 (trip at t=0)

## Comparing SDS1 and SDS2 Trip Responses of In-Core Flux Detector Signals

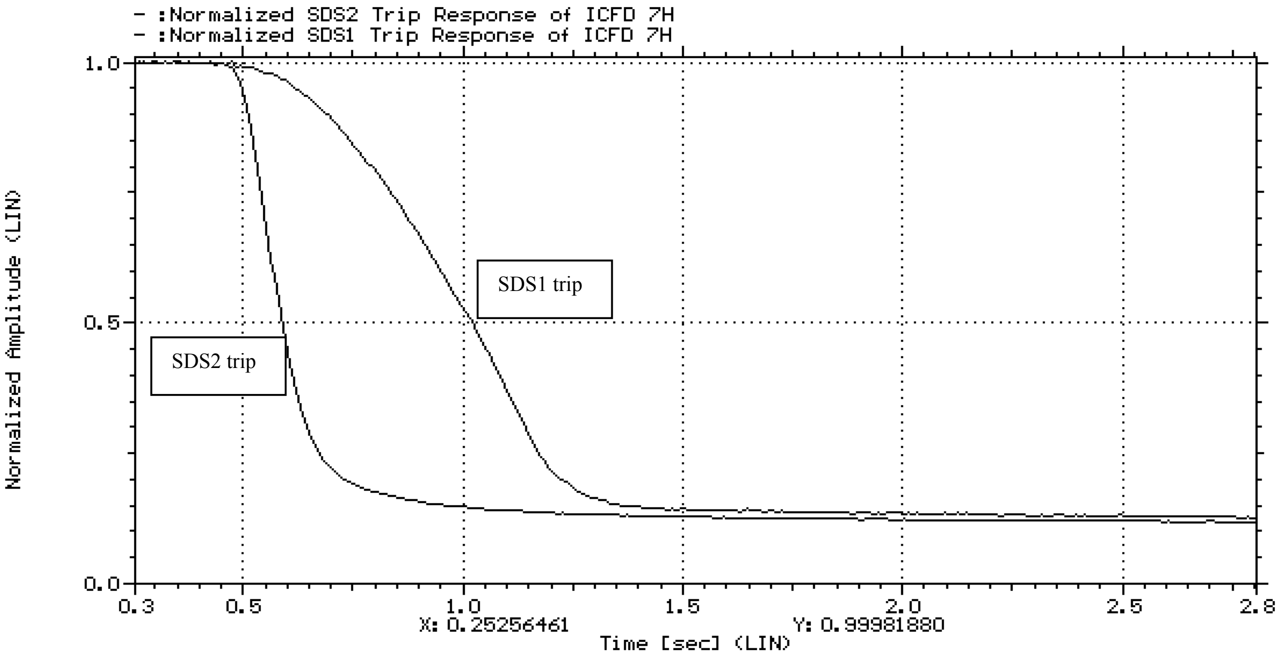

Figure 3. Comparing the SDS1 and SDS2 normalized trip response signals of under-prompt In-Core Flux Detector 7H of Channel H in Pickering-B Unit 6

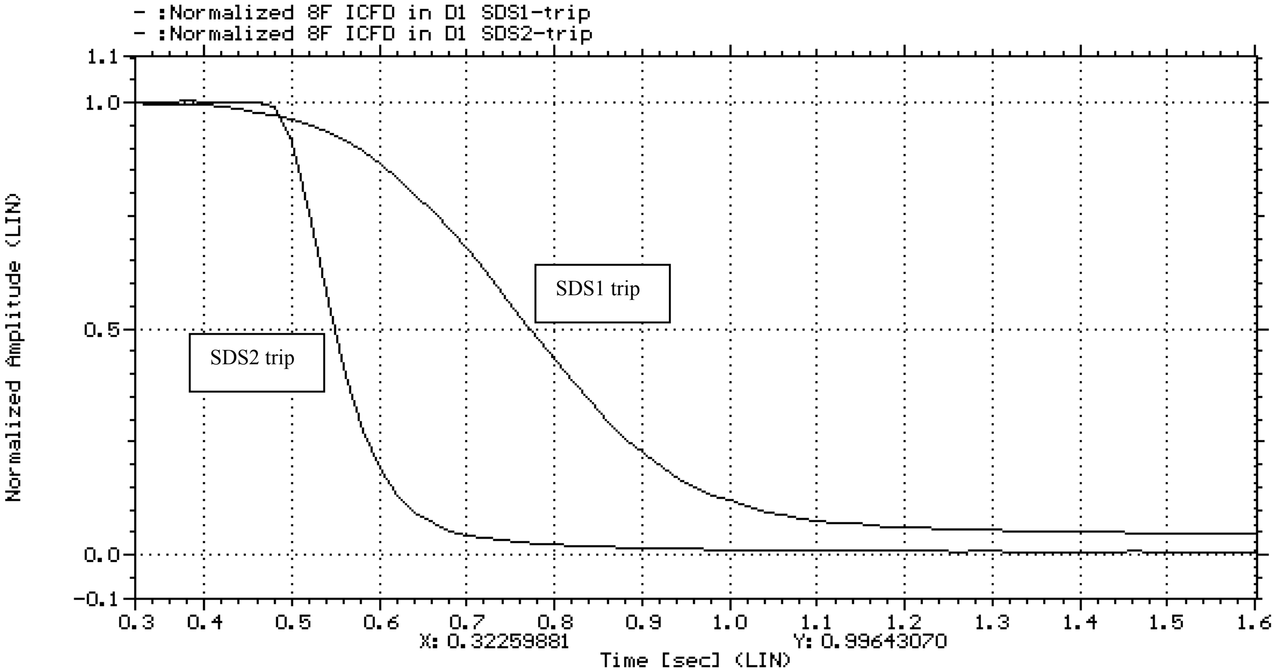

Figure 4. Comparing the SDS1 and SDS2 normalized trip response signals of over-prompt In-Core Flux Detector 8F of Channel F in Darlington Unit 1

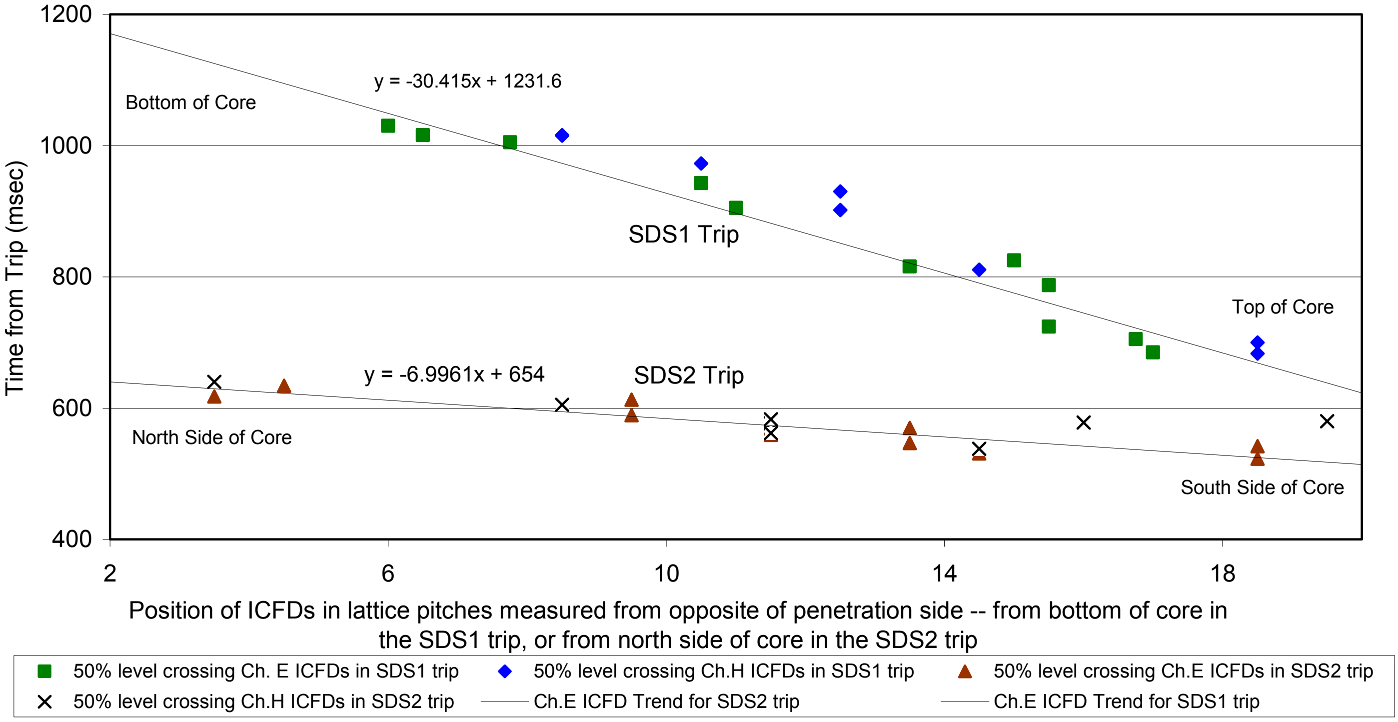

Figure 5. Comparing the 50% level crossing times of in-core flux detector signals as a function of detector position, measured in SDS1 (1996) and SDS2 (2001) trips from 60% full power in Pickering-B Unit 6

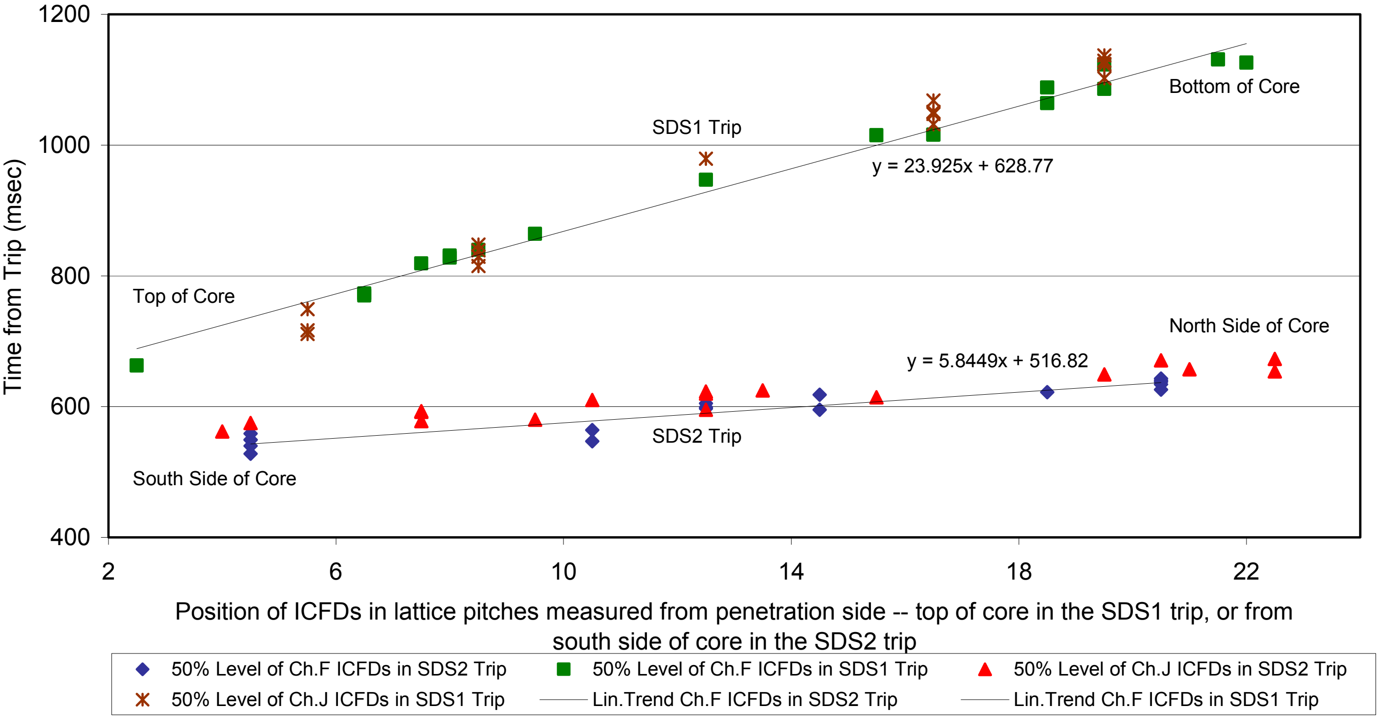

Figure 6. Comparing the 50% level crossing times of in-core flux detector signals as a function of detector position, measured in SDS1 (1995) and SDS2 (1998) trips from 60% full power in Darlington Unit 1