# DYNAMIC MODELLING FOR SHUTDOWN-SYSTEM-1 DEPTH ANALYSIS

by

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## Abstract

*Shutdown system 1 (SDS1) depth has traditionally been analysed as a static all-effects calculation of the core condition 15 minutes after an in-core break, at which time operator action is credited. The postulated accident is intended to represent the most reactive core at that time and is arrived at by assuming that the discharging coolant is replacing and diluting heavily poisoned moderator as well as damaging nearby shutoff-rod guide tubes. The challenge is to demonstrate that SDS1 has sufficient reactivity worth to maintain this most reactive core subcritical. This paper describes a more accurate treatment of SDS1 depth through the time-dependent dynamic analysis of the event and demonstrates that the static calculation may underestimate the SDS1-depth margin or at least the time available before the core would become critical without operator action.*

## Introduction

Single-channel events which lead to channel failure and subsequent discharge of coolant into the moderator can, under certain operating conditions, provide the most limiting challenge to the depth of SDS1. It must therefore be shown that for these events SDS1 can shut down the reactor and maintain it subcritical until operator action can be credited to further increase the subcriticality. Note that this is an issue only when considering SDS1 acting alone. The action of either shutdown system 2 (SDS2) or the emergency core-cooling system (ECCS) would insert sufficient negative reactivity to ensure that the reactor is maintained subcritical.

Under the most pessimistic postulated conditions, it is assumed that the in-core break significantly damages nearby shutoff-rod (SOR) guide tubes, preventing those SORs from dropping into the core on actuation of SDS1. A further assumption is that the moderator is heavily poisoned with boron or gadolinium or both, such that the discharge of unpoisoned primary heat-transport system (PHTS) coolant into the moderator dilutes this poison and causes an increase in reactivity.

The traditional method of calculating the SDS1 depth under these conditions has been to model the core condition at 15 minutes effectively as a steady state, assuming the undamaged SORs are in the core, fixing the moderator poison and isotopic concentration to the values determined from the integrated discharge, and taking the coolant temperature and density and the fuel temperature from the CATHENA[1] transient calculation.

The implicit assumption in the steady-state (static) case is that the delayed-neutron precursors are in equilibrium with the shutdown flux distribution. In reality, the delayed-neutron precursor distribution depends on the past flux shape. The pre-event delayed-neutron source has a significant effect on the neutron flux shape and thereby on the neutronic importance of the shutoff rods, for example. Even long after the reactor is shut down there is some effect due to the long-lived delayed-neutron components such as the photoneutron groups.

In order to determine the effect of dynamic modelling on SDS1 depth, a stagnation feeder break from the CANDU 9 analysis has been run as a time-dependent transient using the RFSP[2] *CERBERUS module. This module solves the time-dependent neutron diffusion equation in its finite-difference form using the Improved Quasi-Static method[3].

## Method

The starting configuration for the calculation was chosen to maximize the poison level in the moderator. It represents a plutonium-peak core (at 40 full power days of operation) followed by a long shutdown and restart. The long shutdown increases the poison requirement to compensate for the decay of saturating fission products (xenon and rhodium). On the restart it is assumed that power is raised instantaneously and consequently no credit is taken for the reduction in poison to offset the fission-product build-up. In arriving at the starting point for the dynamic transient the history-based local-parameter methodology[4] of the core-tracking module (*SIMULATE) of the reactor fuelling simulation program (RFSP) was used. Also built into that methodology are fission-product drivers[5] which can model the saturating-fission-product transient in each fuel bundle, up to the start of the kinetics calculation.

A stagnation feeder break in a high power channel is assumed for the in-core break. The 25 SORs available (assuming 6 damaged rods + 1 unavailable) were inserted in the first 2 seconds. The transient was then simulated in 10-second steps to 1200 seconds. The 10-second time step was found to be close to the maximum possible for a stable solution of the Improved Quasi-Static method. At each step, the moderator boron and $D_2O$ isotopic concentration were calculated based on the integrated discharge from the PHTS into the moderator using values obtained from CATHENA. The delayed-mixing model was used to obtain the dilution factor at each time step. The moderator temperature at 10-second intervals was provided from MODSTBOIL calculations. The coolant density and temperature and fuel temperature were obtained from CATHENA at 10-second intervals. Fifteen delayed-neutron groups were used. The complete transient was also repeated without the 9 photoneutron delayed groups to determine their contribution to the dynamic reactivity. Modifications were made to the *CERBERUS module of RFSP to extend the input to handle a change of moderator temperature and purity in addition to the poison concentration which could already be modelled. To speed up the calculation, and allow for the large number of dynamic cases, the power and integrated-energy calculation for each bundle was bypassed for all the transient cases, as this does not affect the amplitude, flux and reactivity calculation.

The results of the dynamic calculation were compared with those of static calculations, previously performed corresponding to three snapshots: at 2 seconds (just after the SORs were inserted) and at 15 and 20 minutes after the start of the in-core break.

## Results

Figure 1 shows the integrated discharge of coolant into the moderator over the first 20 minutes (CATHENA calculation). Figure 2 gives the resulting poison dilution based on the delayed-mixing model. Figure 3 shows the moderator-temperature transient as a result of the hot coolant discharge (MODSTBOIL calculation).

Figure 4 shows the amplitude of the dynamic solution in *CERBERUS, which is an indication of the total core flux/power level. Figure 5 and Table 1 give a comparison of the static and dynamic reactivity for the SDS1 depth analysis. The dynamic reactivity at 15 minutes is -17.0 milli-k, compared with a static value of -8.7 milli-k. The reason for the increased worth is that the pre-event flux distribution is not depressed in the central core region and consequently there are more delayed neutrons available for absorption in the SORs in the dynamic case than in the static case. The initial reactivity worth (immediately following insertion) of the 25 SORs in the dynamic case was 1.6 times that of the static case, which is consistent with what is usually found in large LOCA or trip-test rundown analysis. Figure 6 and Table 1 demonstrate the contribution to the dynamic reactivity of the photoneutron groups. The photoneutrons contribute 17% of the difference between static and dynamic reactivity at 15 minutes and 33% of the difference at 20 minutes.

## Conclusions

It has been demonstrated that the RFSP *CERBERUS module can be used to dynamically model the neutronic transient associated with a single-channel event. The correct modelling of the delayed-neutron source is important in capturing the dynamic effects, and has implications on the SDS depth and the reactivity margin, even 20 minutes after shutdown. At longer times (30 minutes to 1 hour), the dynamic reactivity will eventually approach the static value as the effect of the pre-event delayed-neutron source becomes less important. However, as the accident is, in reality, a transient and not a static event, the dynamic calculation is the correct way of simulating the evolution of the situation in time. The dynamic modelling of the complete transient also allows us to show that there is no more-reactive core configuration at any point in the period before operator action is credited.

## References


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2. B. Rouben, "Overview of Current RFSP-Code Capabilities for CANDU Core Analysis", AECL-11407, 1996 January.
3. K.O. Ott and D.A. Meneley, "Accuracy of the Quasi-static Treatment of Spatial Reactor Kinetics", Nuclear Science and Engineering, Vol. 36, 1969, p. 402.
4. D.A. Jenkins and B. Rouben, "Calculation of 3-D Flux Distributions in CANDU Reactors Using Lattice Properties which Include the History of the Lattice", in Proceedings of the 12th Annual Canadian Nuclear Society Conference, Saskatoon, Saskatchewan, 1991 June.
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**TABLE 1**

**Dynamic versus Static Reactivity for SDS1 Depth Analysis**

| Core Condition | Static Reactivity (milli-k) | Dynamic Reactivity (milli-k) | Dynamic No Photoneutrons (milli-k) |
|---|---|---|---|
| Steady–State, Full Power, Time = 0 | 0.0 | 0.0 | 0.0 |
| 25 SORs In Core, Time = 2 s | -28.3 | -44.7 | -44.6 |
| Shutdown + 15 min | -8.7 | -17.0 | -15.5 |
| Shutdown + 20 min | -3.6 | -8.2 | -6.7 |

**FIGURE 1**
**Integrated Coolant Discharge**

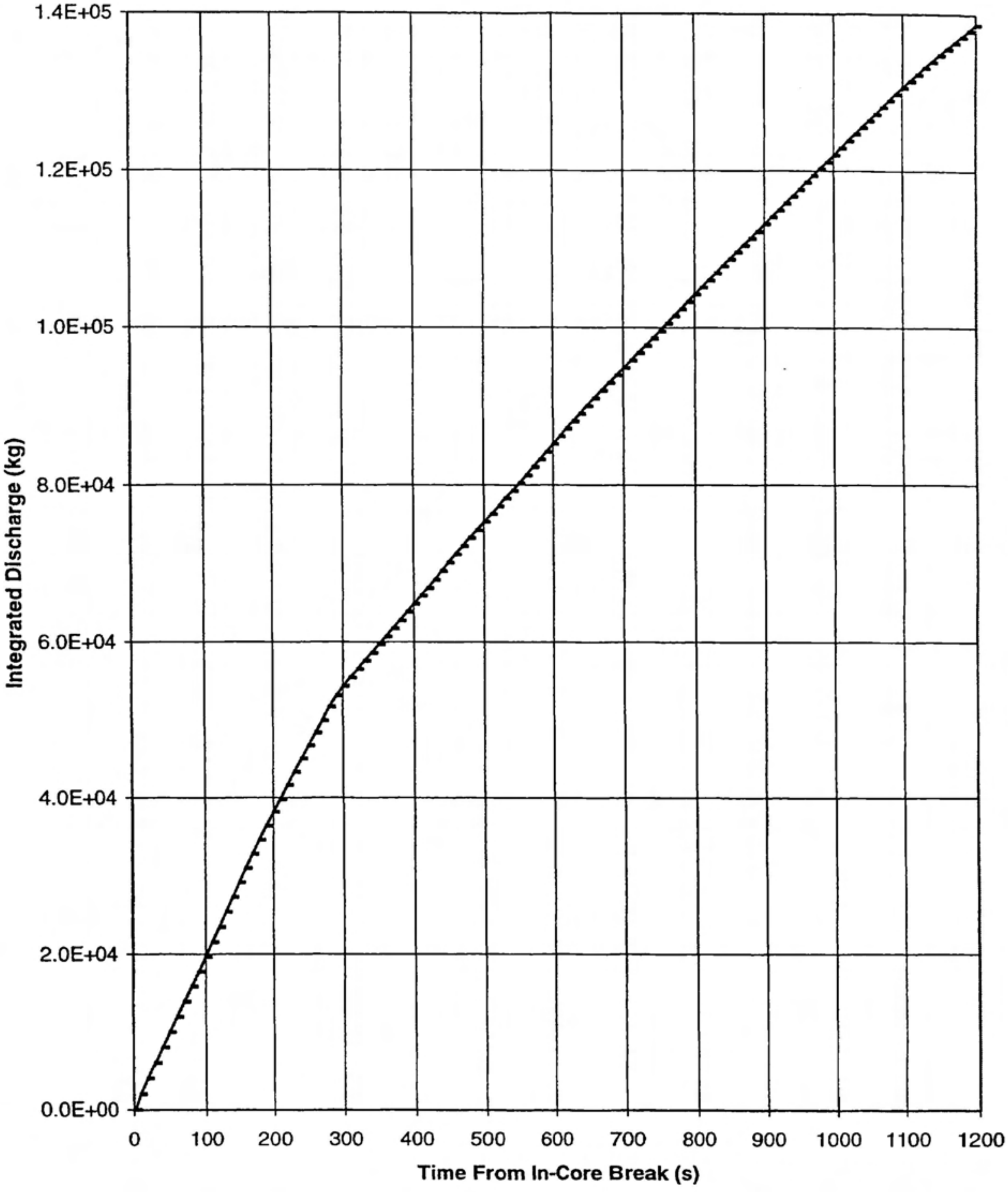


**FIGURE 2**
**Boron Concentration in Moderator**

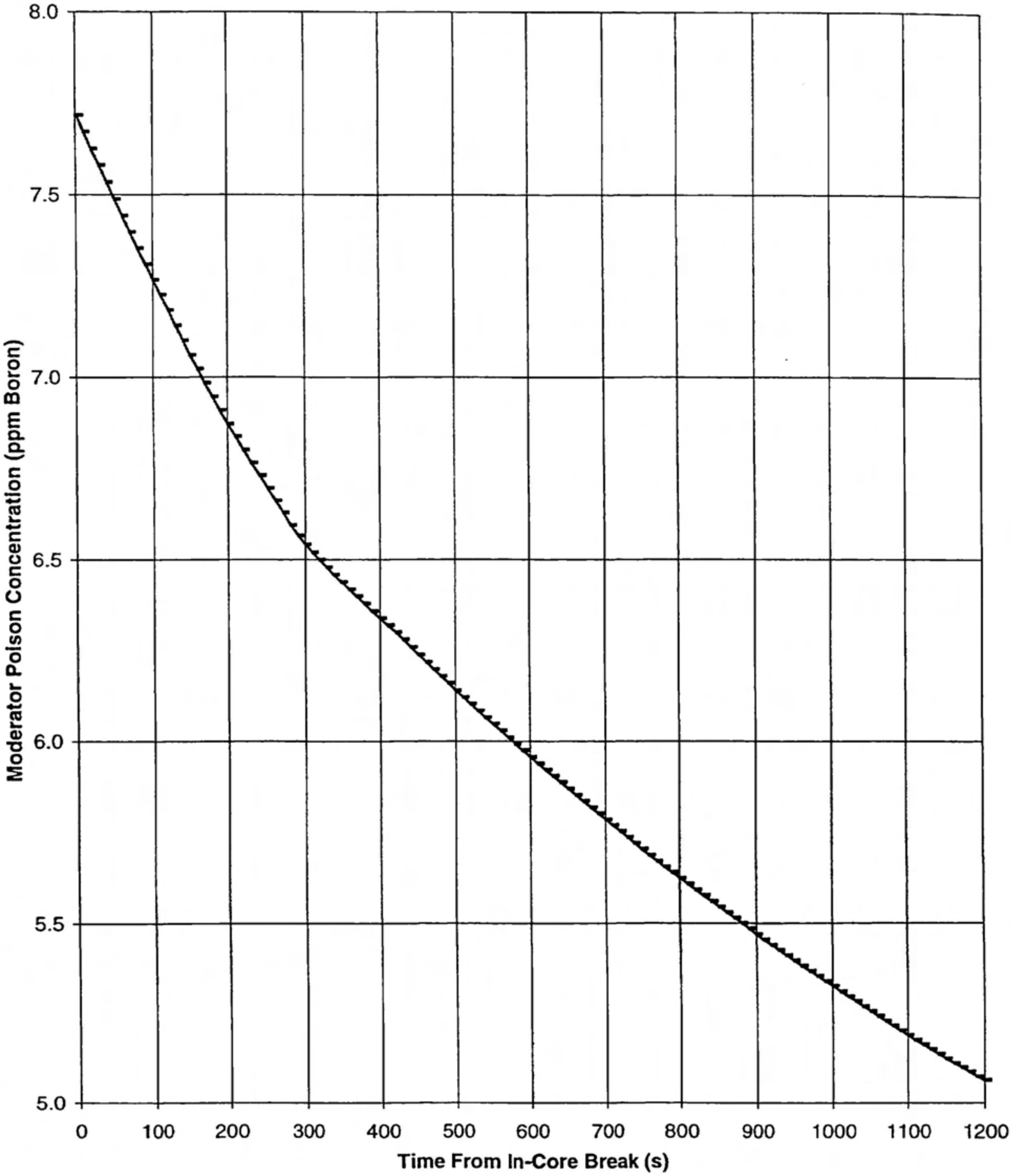


**FIGURE 3**
**Moderator Temperature**

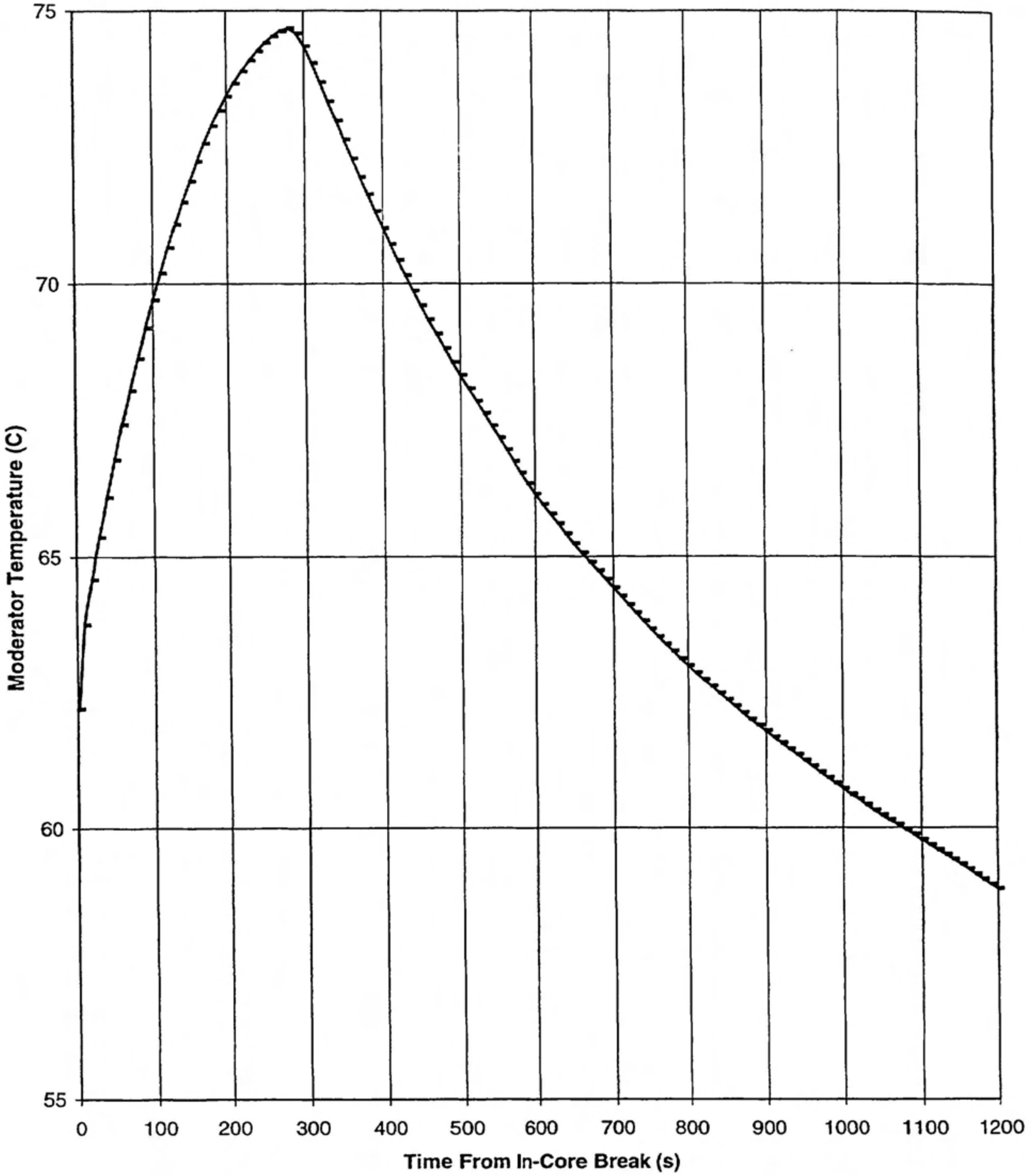


**FIGURE 4**
**Amplitude of Dynamic Solution**

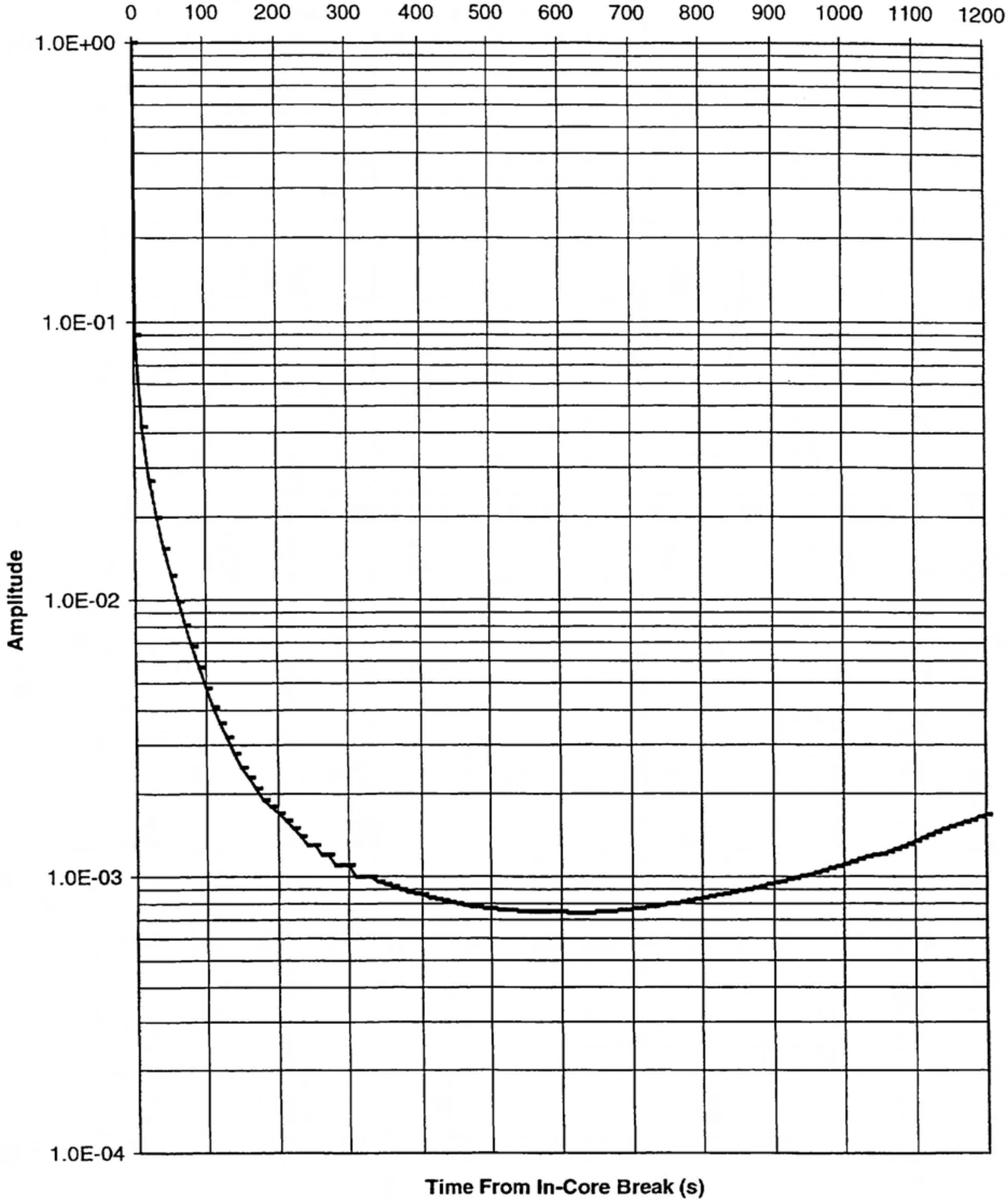
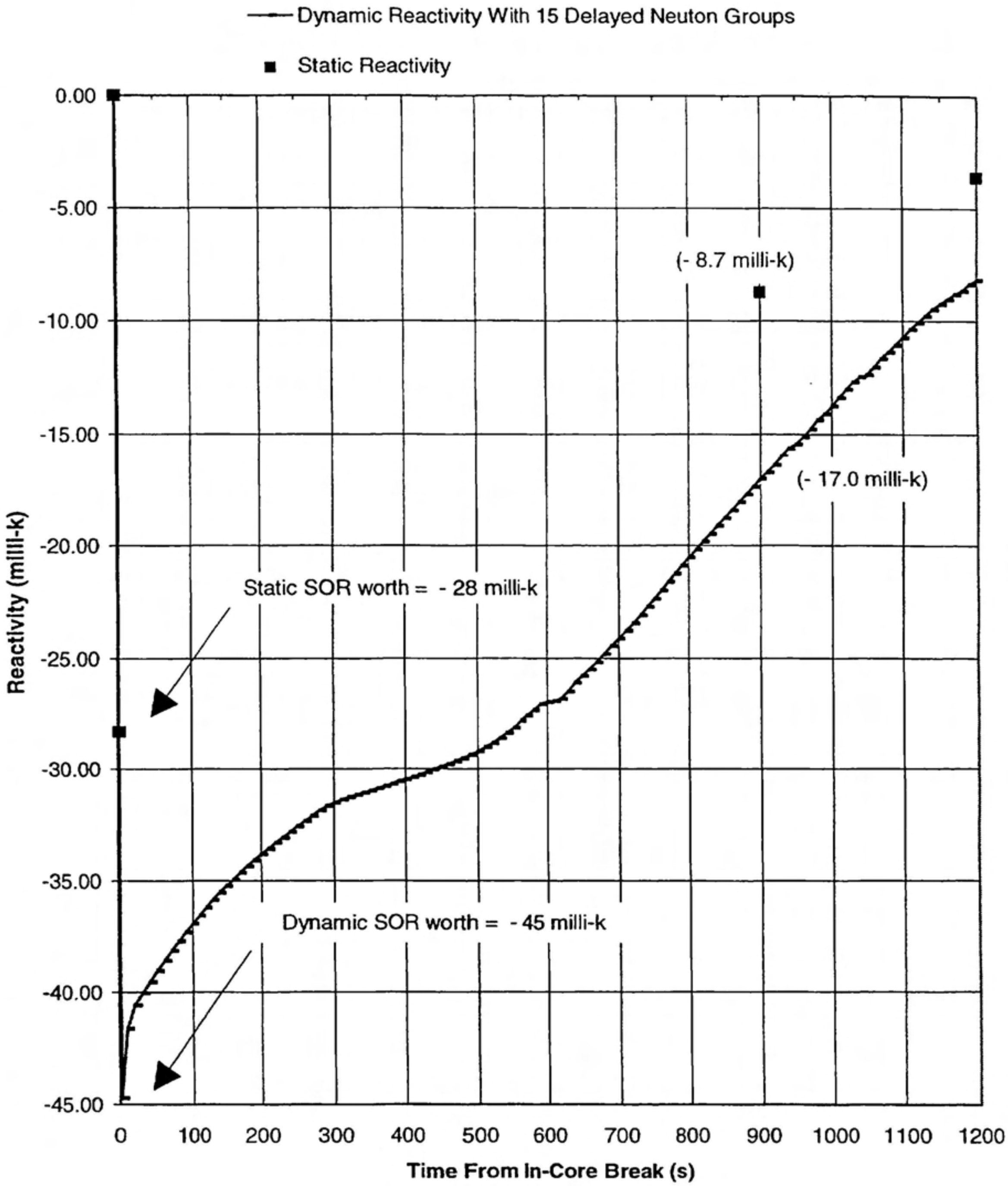


**FIGURE 5**

**Dynamic versus Static Reactivity for SDS1 Depth Analysis**



## FIGURE 6
## Comparison of Dynamic Cases with and without Photoneutrons