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PHOTO-NEUTRON EXPERIMENT PERFORMED IN ZED-2

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1. INTRODUCTION

A review of existing data on delayed neutrons was recently undertaken by Laughton [1]. A major recommendation of that review was that delayed photo neutron group yields and half lives measured by Baumann [2,3] be used for PHWR kinetics calculations in place of earlier data measured by Bernstein [4,5]. This recommendation was based, in part, on Laughton's analyses of a rod-drop experiment performed by French [6] in the ZED-2 reactor. Laughton found that French's experimental results were equally well described by kinetics calculations using either Baumann's or Bernstein's data in combination with the direct-delayed-neutron data recommended by Blachot [7]. Laughton noted that Baumann had been critical of Bernstein's data because of shortcomings in Bernstein's experimental method. Baumann argued that Bernstein had used differences of delayed neutron yields from systems with and without deuterium present to derive his photo neutron data, resulting in an accumulation of large relative error. In particular he was dubious of Bernstein's value for the yield of the 2.5-s photo neutron group, suggesting that it is much too high.

Laughton commented that the French data provided nothing that could be used to validate the yield of photo neutrons at very short times as French's data acquisition apparently did not begin until 66 seconds following the rod drop. Another shortcoming of the French data as far as CANDU physics is concerned is that the lattice used for the experiment was hexagonal at a 30-cm spacing. The moderator-to-fuel ratio was therefore slightly lower than that of the square 28.575-cm (11.25 inch) CANDU pitch, which suggests that yields of photo neutrons would be underestimated compared to a power reactor.

This paper presents results from a rod-drop experiment performed in the ZED-2 reactor. The lattice used for the experiment comprised 28-element CANDU-type assemblies arranged in a square array at a 28.575-cm spacing. Data were obtained for the relative flux (power) versus time following the rod drop up to 3000 seconds (50 min).

An analysis of the data was performed using point kinetics calculations to yield flux (power) as a function of time and inverse point kinetics calculations to yield reactivity as a function of time. Two sets of calculations were performed, one set using the photo neutron data of Baumann and the other using the Bernstein data. Both sets of calculations employed the Blachot direct delayed neutron data.

2. EXPERIMENT

Figure 1 shows a plan view of the lattice used for the rod-drop experiment. It comprised 88 assemblies arranged in a square lattice with a centre-to-centre spacing of 28.575 cm. The inner 64 assemblies contained 28-element UO_2 fuel bundles. The remaining 24 assemblies were positioned in the outer-most ring and contained 19-element uranium metal fuel.

The shutoff rod consisted of a cadmium cylinder that was completely sealed in an annular aluminum casing. The shutoff rod was attached to a stainless steel cable that connected the rod to the shaft of a motor suspended from a beam above the lattice.

Flux-map experiments were performed before the rod drop to determine the perturbation to the distribution of neutrons in the lattice due to the shutoff rod. This information was to determine a detector location with minimal perturbation due to the insertion of the shutoff rod. Copper foils were positioned along the K-beam (see Figure 1) at three elevations near the maximum axial flux. Cu foils are useful neutron detectors because the cross section curve for Cu^{63} capture is approximately one-upon-v and Cu^{64} activation data are fairly insensitive to the spectrum shape of the neutrons inducing the activity.

Two irradiations were performed, one with and one without the shutoff rod suspended in the reactor. Figure 2 shows a plot of the activation data obtained from the two irradiations and Figure 3 is a plot of the ratio of the Cu activation data. The data in Figure 2 are averaged over the three axial locations where measurements were made. The data are normalized such that the volume-integrated power is unity for both the perturbed (rod in) and unperturbed (rod out)lattice. The ratio curve in Figure 3 crosses unity just before the position 2.5 pitches from the location of the shutoff rod (positions N0, L0, K5E and K5W in Figure 1).

The reactor was operated at a power of 100 Watts (nominal) for two hours and the data acquisition started about 10 seconds before the shutoff rod was dropped into the reactor. The rod drop was initiated by turning off a supporting electromagnet, resulting in the rod falling under its own weight into the reactor. The motor was positioned along the beam and the length of the attached cable was adjusted, so that when the rod was fully inserted its absorbing region was positioned at the location of the peak in the unperturbed flux. A calibrated potentiometer was used to record the axial position of the rod vs time and Figure 4 shows a plot of the rod elevation during the drop.

3. RESULTS

In analyzing the experiment, once a set of direct-delayed plus photo-neutron group parameters is chosen the objective is to determine the effective photo-neutron yield fraction relative to that of the prompt and direct-delayed neutrons. This effective yield is represented by a single parameter, ε, that accounts for gamma-ray degradation and absorption in the fuel and leakage from the reactor as well as the relative worth (i.e. importance) of the photo neutrons to that of the prompt and direct delayed neutrons. It can be determined by using it as a free parameter to obtain the best fit to the expected reactivity vs time curve using an inverse point kinetics analysis of flux vs time data. Alternatively it can be determined by varying it to obtain the best fit comparing a point-kinetics calculation directly to the data.

The absolute yields of the photo-neutron delayed neutron groups are proportional to epsilon

Direct point kinetics analysis requires independent knowledge of the reactivity worth of the rod as well as the variation of reactivity vs time during the rod insertion. Inverse point kinetics analysis requires no such independent knowledge and actually yields that information directly. All that is required is a knowledge of how the relative power (or flux) varies with time before, during and after the rod drop.

The definition of reactivity is:

$$\rho(t) = \frac{k(t)-1}{k(t)}$$

where ρ(t) is reactivity and k(t) is k-effective, the effective multiplication factor. Before the rod drop the reactor is critical (i.e. k(t) = 1) and reactivity remains constant with a value of zero. When the rod makes contact with the moderator reactivity starts decreasing with time and the reactor becomes subcritical. After the rod is fully inserted the reactor remains subcritical (i.e. k(t) < 1) but reactivity again remains constant with time, at a value that depends on the macroscopic cross section of the shutoff rod.

Figure 5 compares the variation of reactivity vs time derived from inverse point kinetics analyses using the two competing sets of photo-neutron data. In analyzing the experiment the relative power vs time obtained from the ion chambers is used as input and the parameter ε is varied until the resulting curves of reactivity remain constant with time for the period following the rod drop. The value of epsilon is varied assuming values between zero and one. By adjusting epsilon, the absolute yield of the photo neutrons in each group, β_i, is varied relative to the yield of direct delayed neutrons from U^{235} fission and U^{238} fission. This in turn causes a change in the value of Beta, the delayed neutron fraction, which is the sum of all direct delayed neutrons plus photo neutrons.

The top two curves in Figure 5 were derived using the data of Blachot and Baumann. The top curve was determined from the inverse point kinetic analysis and the second curve was derived from a period measurement (see below). The bottom two curves were derived using the data of Blachot and Bernstein.

In order to determine the reactivity worth of the shutoff rod in a different way two period measurements were performed, one with the shutoff rod out of the core and one with the rod in the core. The procedure is to initially operate the reactor at a very low power. Moderator is pumped into the calandria to make the reactor supercritical and the reactor power increases with time as it asymptotically approaches an exponential growth. The reactor period, T, is defined as one e-folding time once this asymptote has been achieved. The period is then used as input into the in-hour equation [8]

$$\rho = \frac{\Lambda}{T} + \sum_{i=1}^{ngroups} \frac{\beta_i}{1 + \lambda_i \cdot T}$$

to determine ρ, the reactivity worth of the extra moderator inducing the rate-of-rise. In the above expression Λ is the neutron life time, T is the reactor period, ngroups is the number of delayed groups, β_i is the absolute yield of the i^{th} delayed group and λ_i is the decay constant of the i^{th} group. The values of β_i depend upon the values of ε that are assumed in calculating the absolute yields. The difference in moderator levels with the reactor critical and supercritical is then used to derive the level coefficient of reactivity (LCR) for both the unperturbed (rod out) and perturbed (rod in) cores. The average LCR value then defines the worth of the rod through the difference in moderator critical heights for the perturbed and unperturbed cores.

Both the absolute delayed-neutron yields of Bernstein plus Blachot and Baumann plus Blachot obtained from the inverse point kinetics analyses were used in the in-hour equation to determine rod worth values and these are plotted along with the inverse point kinetics curves for comparison. The data plotted in Figure 5 demonstrate that the magnitude of the reactivity worth of the rod is dependent upon the delayed neutron data that are used for the analysis.

Figures 6 and 7 are plots directly comparing point kinetics calculations to the power-vs-time experimental data. The calculations plotted in Figure 6 employ the Bernstein photo-neutron data while the calculations in Figure 7 employ the Baumann data. The calculations assume rod-worth values derived from the respective inverse point kinetics analyses and reactivity is assumed to vary linearly with time for the 3.2 second interval between the rod contacting the moderator and full insertion (see Figure 4). Various values of ε are assumed in the calculations to show the sensitivity to this parameter. The best fit ε values from the inverse point kinetics analyses give the best agreement between the point-kinetics calculations and the power-vs-time experimental data, as expected.

The reactivity-vs-time data (Figure 5) show what appear to be non-point kinetics effects for about the first ten seconds following the shutoff rod hitting the moderator. As a test of the inverse point kinetics model it was decided to feed the output from pure point kinetics calculations into the inverse point kinetics calculation to determine if the above effects are meaningful. The best-fit calculations plotted in Figures 6 and 7 provided the input for this test and the resulting reactivity vs time curves are plotted in Figure 8. These curves suffer from the same problem as the analysis of the measured data for the first ten seconds following the rod entering the core, implying that the apparent non-point kinetics effects are not real but are an artifact of the numerical model used for the inverse point kinetics analysis.

The best-fit ε values derived using the Bernstein and Baumann photo-neutron data were found to be 0.460 and 0.194, respectively. Sensitivity calculations indicate that these values are accurate to about +/- 2%. However, both sets of calculations were found to be equally successful in describing the experimental results. As Laughton pointed out in his review the major difference between the two sets of photo-neutron data is in the short-lived (<144 s) group parameters. However, it turns out that these differences are compensated for by differences in the prompt response to the shut-off rod insertion in the two analyses. The period measurement to determine the worth of the rod shows a 0.12 mk difference depending on whether Bernstein's or Baumann's data are used in the in-hour equation. This rod-worth difference also shows up in the inverse point kinetics analysis of the rod drop experiment. The two sets of photo-neutron data are identical for the long-lived groups (>144 s) and the differences in ε and ρ allow for the two inverse point kinetics analyses to successfully keep ρ(t) constant following the rod drop.

The conclusion is that, based on this study, no recommendation can be made as to whether Baumann's or Bernstein's delayed photo-neutron parameters should be used for CANDU transient analysis.

ACKNOWLEDGEMENT

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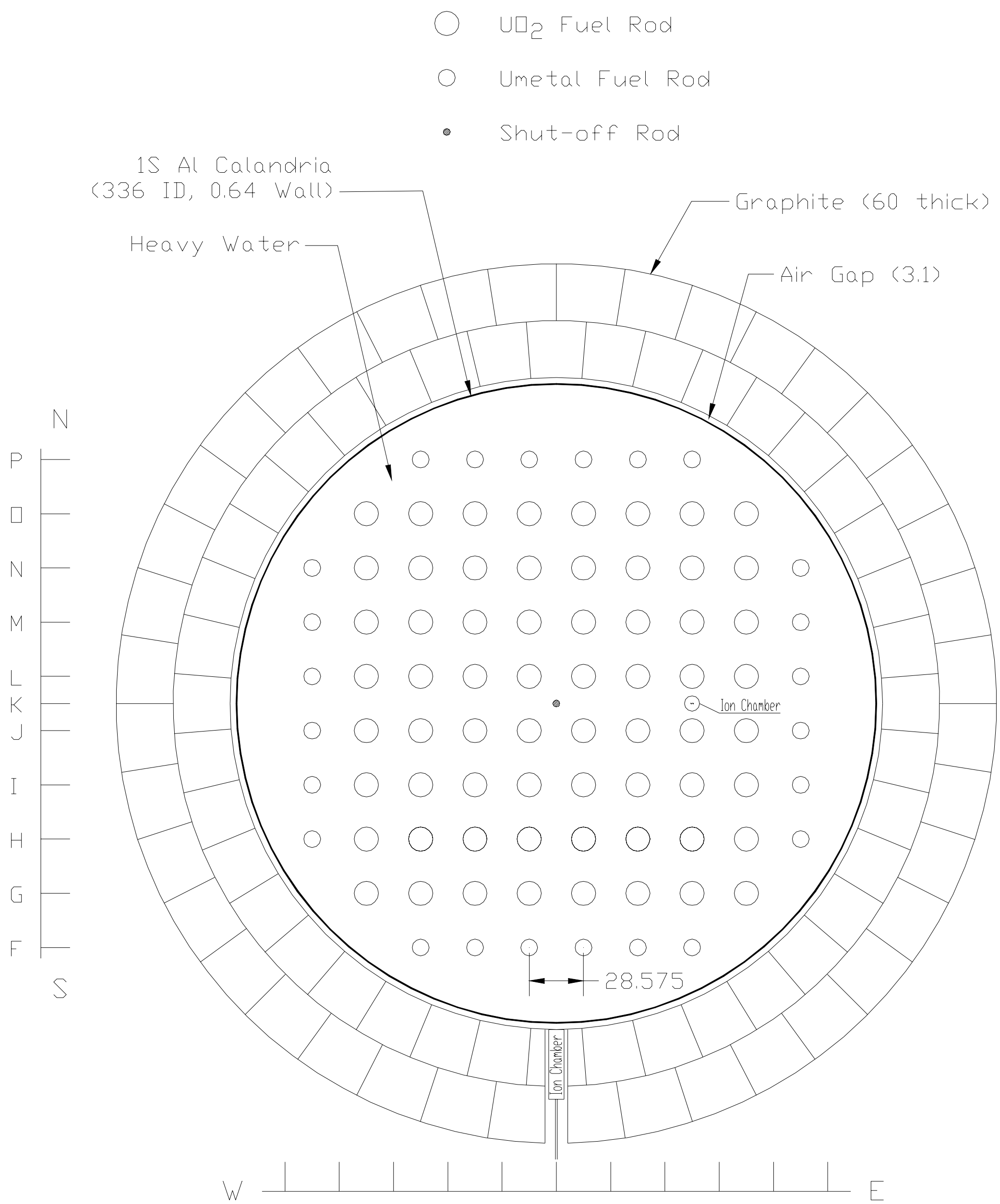

Figure 1 - Plan view of the lattice used for the rod drop

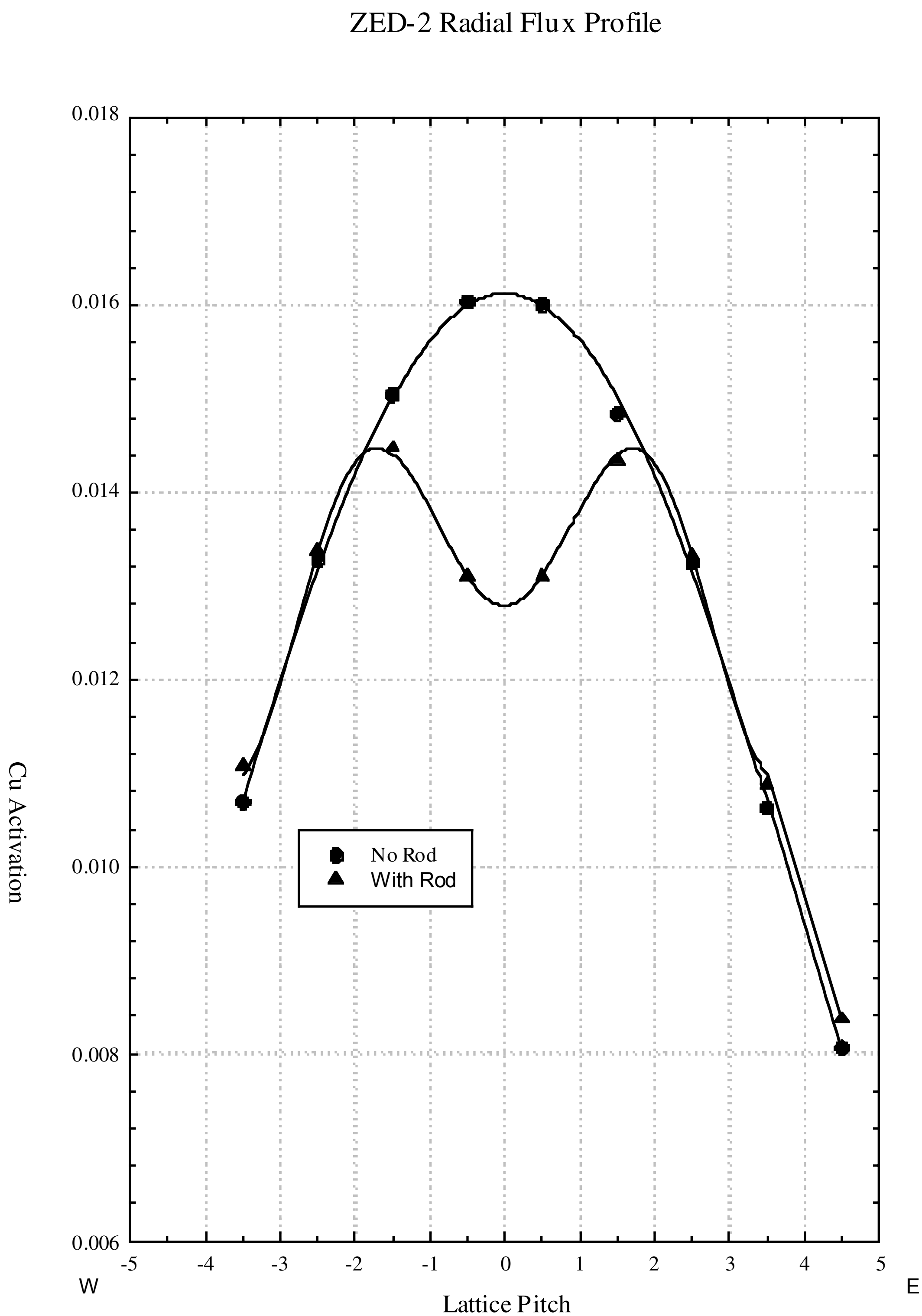

Figure 2 - Cu activation data from the flux map

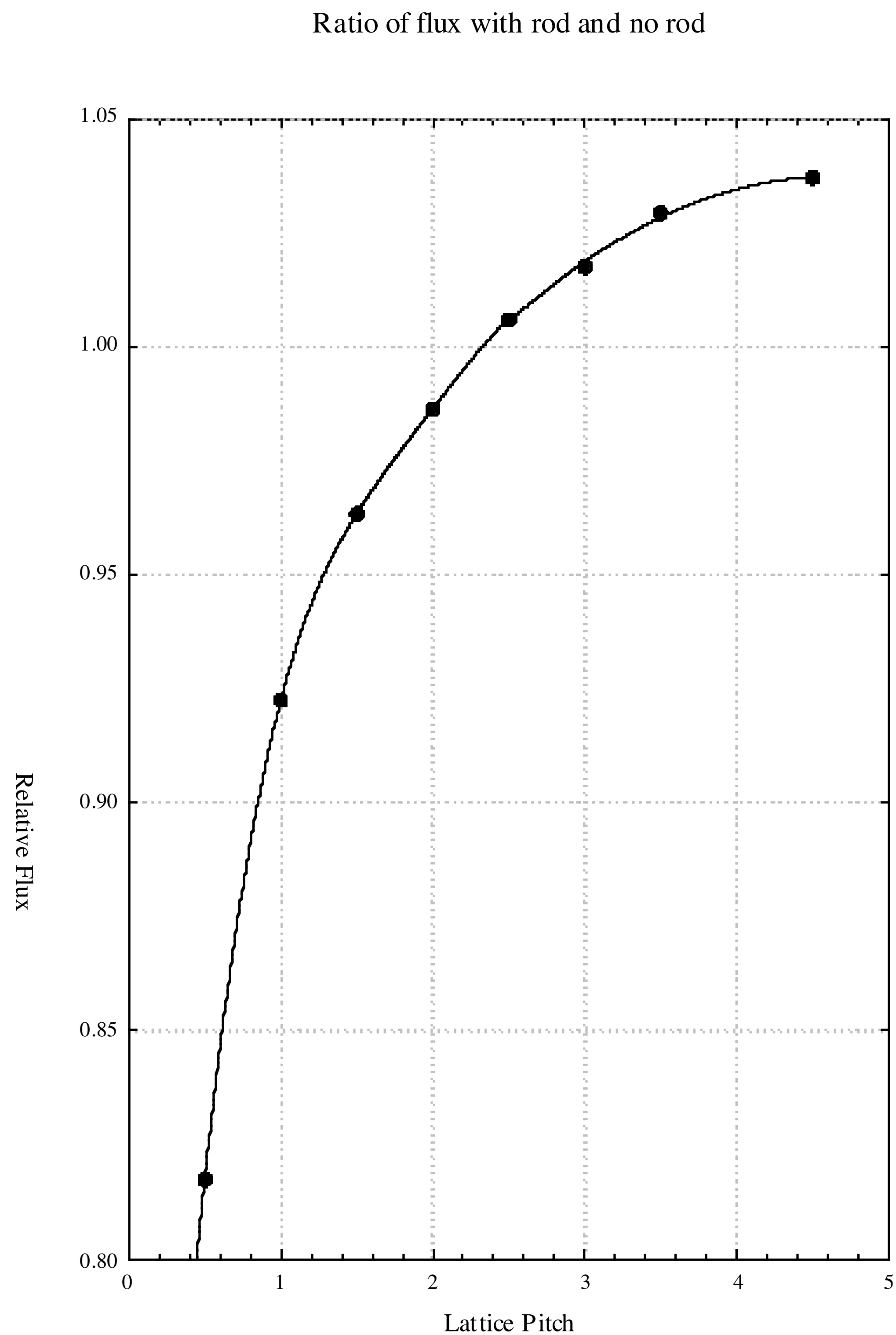

Figure 3 - Flux ratio with the rod in and out

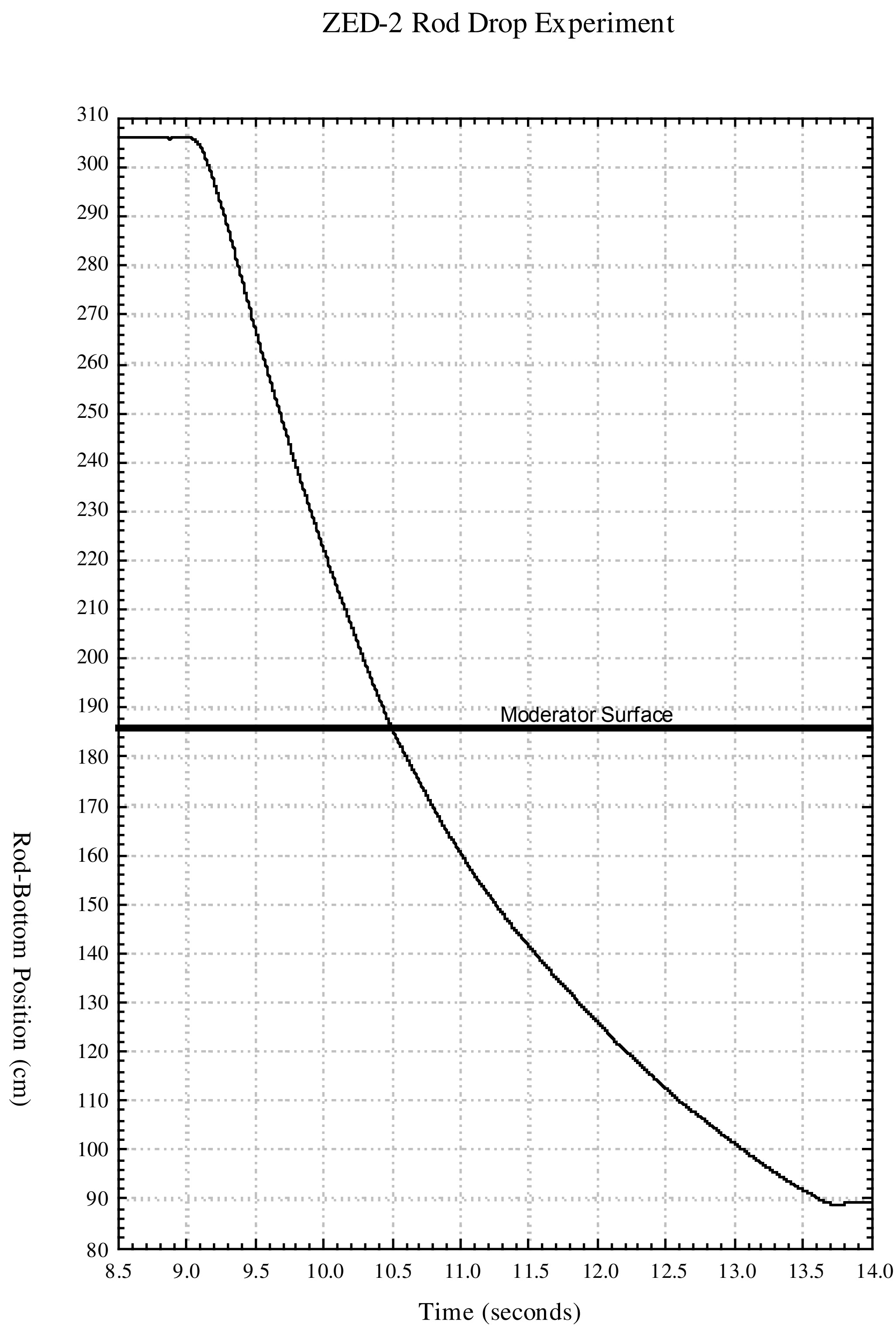

Figure 4 - Shut-off rod axial position during the rod drop

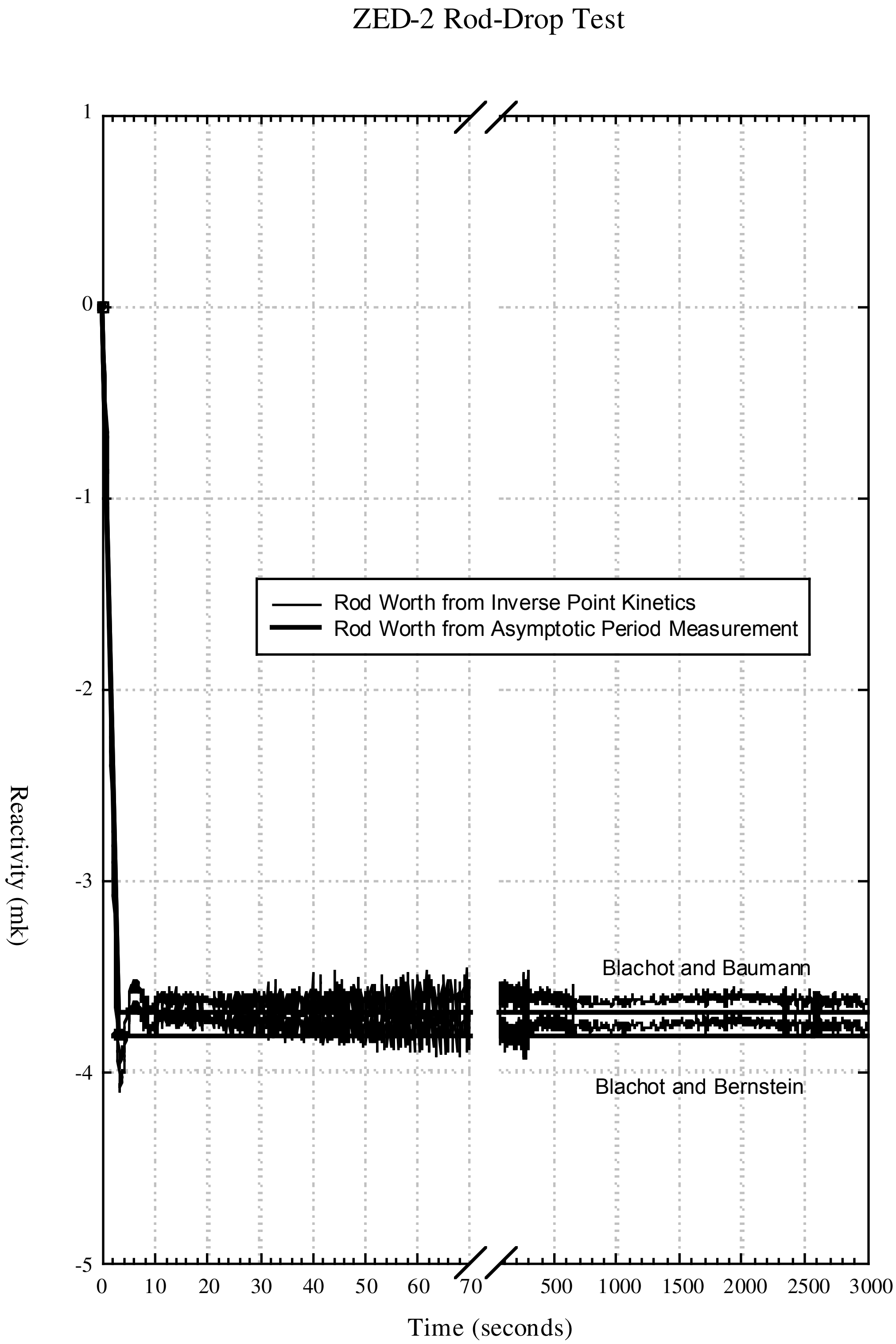

Figure 5 - Reactivity vs time derived from the inverse point kinetics analysis

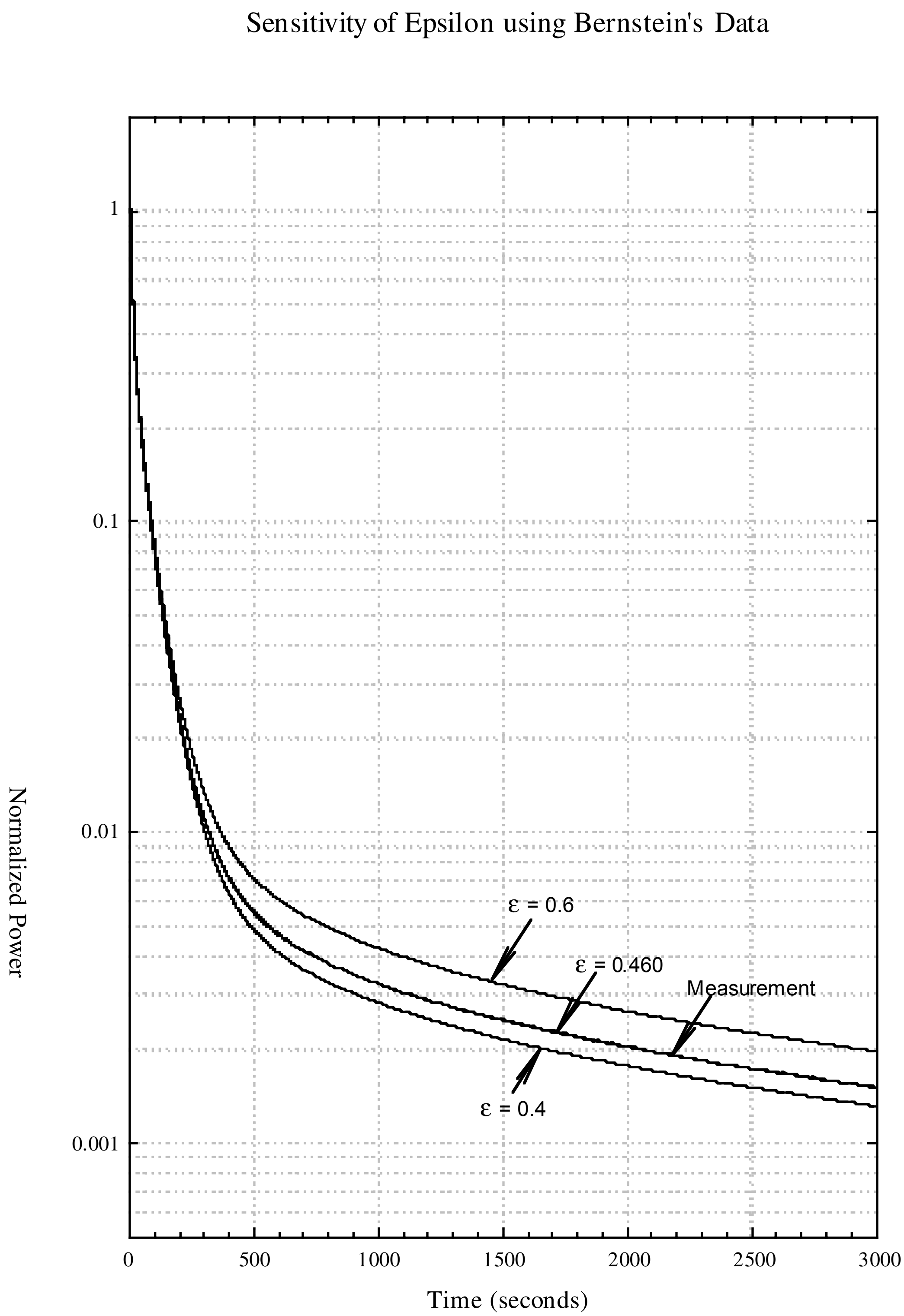

Figure 6 - Power vs time using Bernstein's photo-neutron data

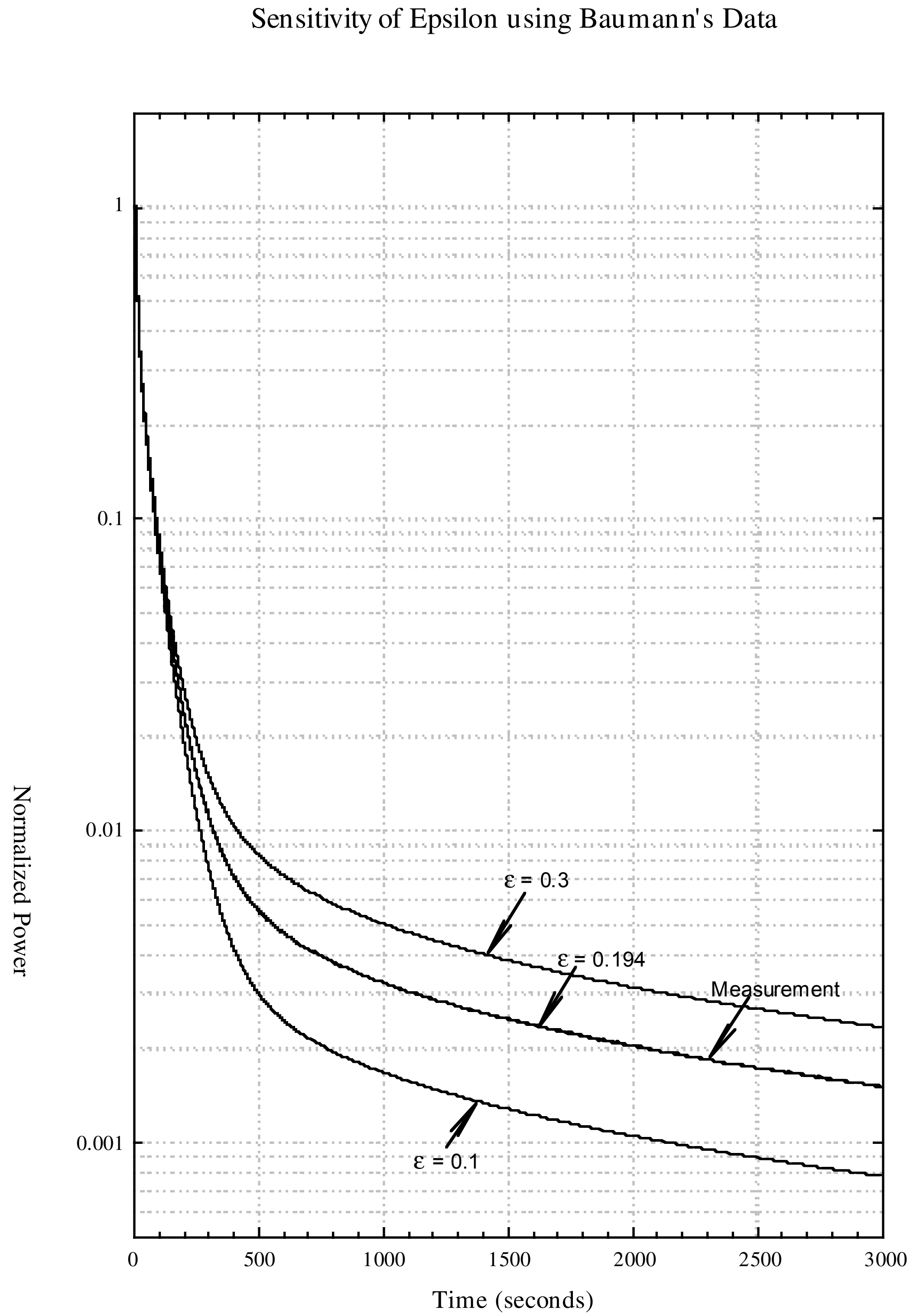

Figure 7 - Power vs time using Baumann's photo-neutron data

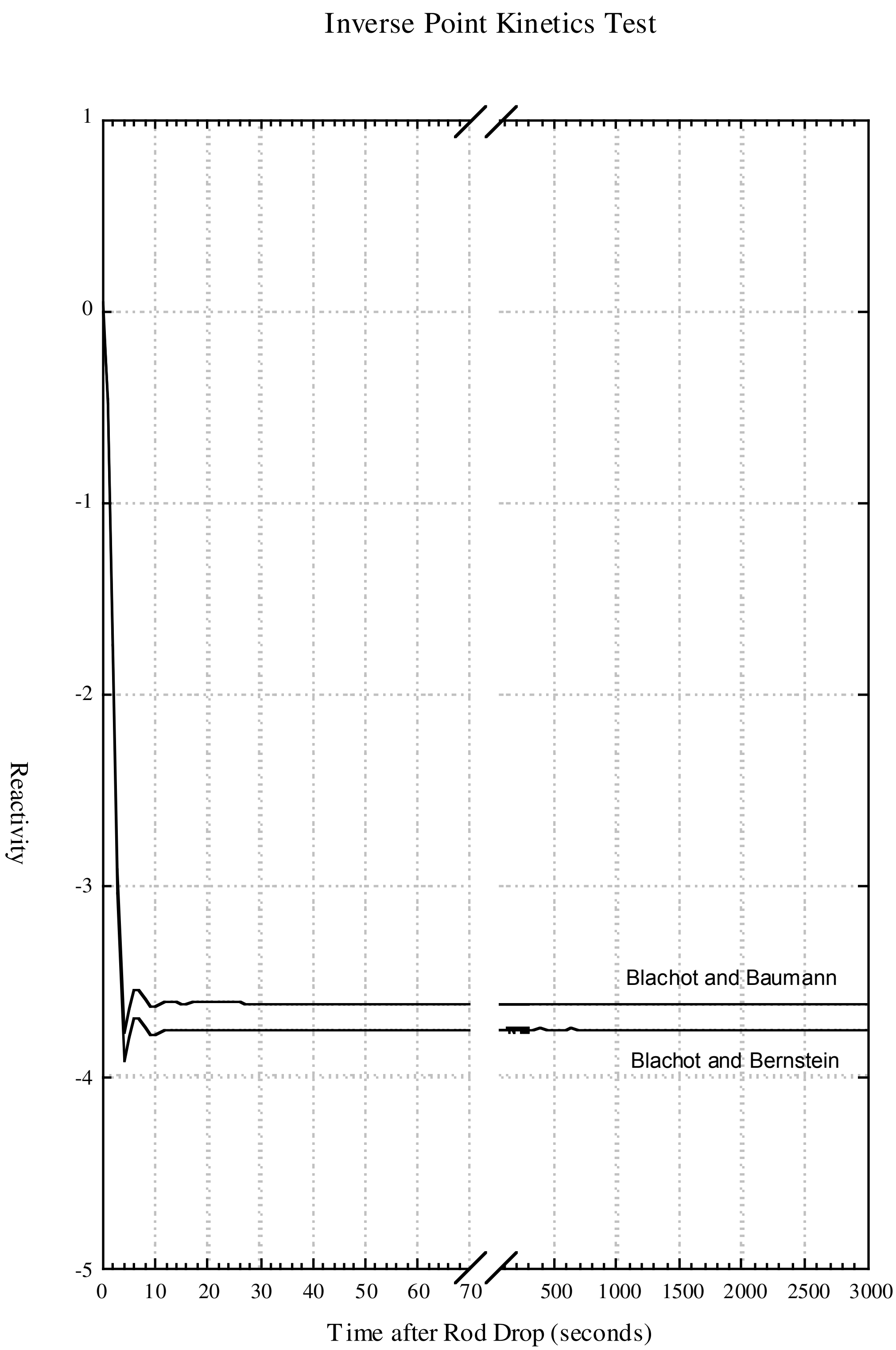

Figure 8 - Calibration test of the inverse point kinetics model