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TITLE

SUBCRITICAL MEASUREMENTS OF THE WINCO SLAB TANK EXPERIMENT USING THE SOURCE-JERK TECHNIQUE

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ABSTRACT

Subcritical measurements of the WINCO slab tank using the source-jerk technique are presented. This technique determines subcriticality by analyzing the transient response produced by the sudden removal of an extraneous neutron source (i.e., a source jerk). We have found that the technique can provide an accurate means of measuring k in configurations that are close to critical (i.e., 0.90 < k < 1.0). As the system becomes more subcritical (i.e., k < 0.90), spatial effects introduce significant biases depending on the source and detector positions. A comparison between the measurements and Monte Carlo code calculations is also presented.

INTRODUCTION

Recent interest in measuring k in subcritical systems for which k << 1.0 has spurred the development of several new techniques and has reincarnated an old, but seldom used technique, the "source jerk." In this technique, a neutron source is placed into a subcritical system, and the neutron density is allowed to reach an equilibrium value proportional to the source strength and inversely proportional to the quantity (1 - k). The source is then rapidly ejected (or jerked) from the system, and the resultant transient is observed. The reactivity of the system is then inferred from the analysis of the transient data. In the past, there have been three analysis techniques: (1) the prompt-drop approximation, (2) the integral-flux method, and (3) the semi-explicit inverse kinetic technique.

PROMPT-DROP APPROXIMATION METHOD

Although it is not known who originally derived the prompt-drop approximation, the first reference to its use in measuring the reactivity of a subcritical system via the source-jerk technique was made by Jankowski, et al.[1] Using the nomenclature of Hetrick,[2] it can be shown that the reactivity of the system can be related to the sudden drop in power immediately following the source jerk via

$$\frac{\rho}{\beta} = -\left(\frac{n_0 - n_1}{n_1 - n_b}\right) \quad , \tag{1}$$

where ρ = reactivity [defined as (k - 1)/k], β = effective delayed neutron fraction, n_0 = initial equilibrium neutron density, n_1 = neutron density level obtained immediately after source jerk, and n_b = final equilibrium neutron density (see Fig. 1). In the derivation of Eq. 1, we assume that nonremovable neutron sources may be present in the system. These might include extraneous neutrons produced by spontaneous fissioning, photo-neutrons, etc. Note that the reactivity is measured in terms of "dollars" (i.e., ρ divided by β). This is an inherent characteristic of all reactivity measurements based upon the dynamic response of a reactor. The response is governed strictly by the ratio ρ/β, not ρ. It should also be noted that Eq. 1 is derived from the point-reactor model, and hence n_0 and n_1 are interpreted to be neutron densities proportional to the fundamental mode of the transient behavior of the neutron density.

Although this method works in principle, it has several shortcomings that limit its use. First, and foremost, it is

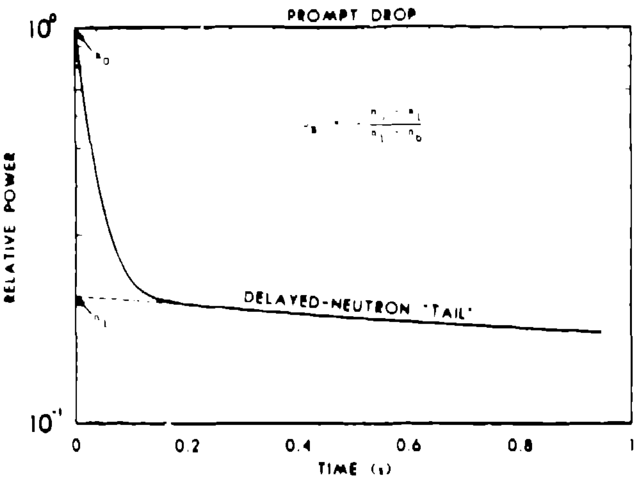

Fig. 1. Neutron density as a function of time, illustrating a source-jerk measurement of reactivity.

very susceptible to spatial effects produced by the rapid decay of higher flux harmonics present during the initial portion of the transient, the point in time at which n_1 is measured. Hence, a poorly positioned detector or source will yield a biased n_1, and an "apparent" reactivity that can be significantly different from the true reactivity of the system. Second, for highly subcritical systems, n_1 will be several orders of magnitude lower than n_0. The counting statistics at n_1 may become so low as to produce a large uncertainty in n_1 and a subsequently large uncertainty in the calculated ρ. And third, because the prompt-drop approximation assumes an instantaneous removal of the source, if the source is not removed in a time that is short compared to the shortest-lived delayed-neutron group, extrapolating back in time to find n_1 may become more tenuous, resulting again in a large uncertainty for ρ.

INTEGRAL-FLUX METHOD

A vast improvement to the prompt-drop approximation technique was introduced by Schmid.[8] Rather than just observing the initial behavior of the neutron density following the source jerk, the integral of the delayed-neutron tail following the source jerk is measured and related to the reactivity of the system. This relationship is derived as follows.

Immediately following the source jerk, it is assumed that the point-reactor equations for an arbitrary number of delayed-neutron groups are applicable. That is,

$$\frac{dn}{dt} = \left(\frac{\rho - \beta}{l}\right)n + \sum_i \lambda_i C_i + q_b \quad , \qquad (2)$$

and

$$\frac{dC_i}{dt} = \left(\frac{\beta_i}{l}\right)n - \lambda_i C_i \quad , \text{ for } i = 1,2,3,\ldots g \quad , \qquad (3)$$

where n = neutron density, t = time, C_i = delayed-neutron precursor density of i^{th} group, q_b = the final effective source strength, λ_i = decay constant of i^{th} precursor group, β_i = delayed-neutron yield of i^{th} precursor group, g = number of delayed-neutron groups, and l = neutron-generation time. Integrating Eqs. 2 and 3 from t = 0 to t = ∞ yields the following expression, which relates reactivity (in dollars) to the integral of the neutron density occurring during the decay of the delayed-neutron tail (Fig. 2):

$$\frac{\rho}{\beta} = \frac{(n_0 - n_b)}{\int (n - n_b)\,dt}\left[\frac{1}{\beta}\sum_i \frac{\beta_i}{\lambda_i} + \frac{l}{\beta}\right] \quad . \qquad (4)$$

The first term in the bracket on the right-hand side of Eq. 4 represents the weighted harmonic-mean decay constant for the delayed-neutron precursors. That is,

$$\frac{1}{\lambda_h} = \frac{1}{\beta}\sum_i \frac{\beta_i}{\lambda_i} \quad . \qquad (5)$$

It is obvious that λ_h is a function of both the effective relative yields and the decay constants of each delayed-neutron group for the reactor systems upon which the source jerk is performed. Therefore, some additional knowledge of

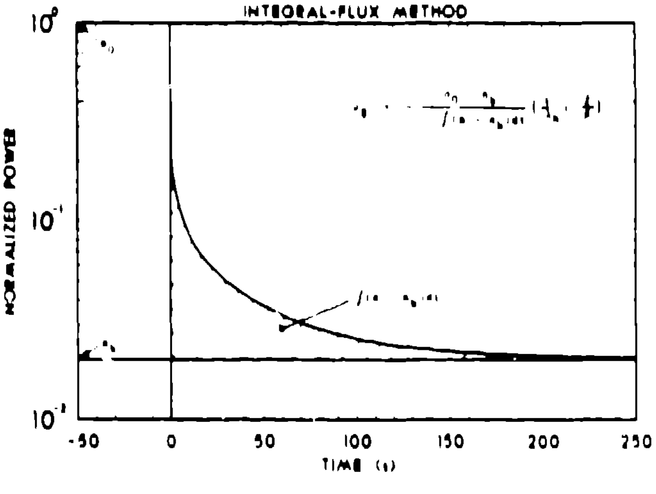

Fig. 2. Integral of the neutron density used in source-jerk analysis.

the reactor system is required to perform a reactivity measurement using this technique. Table I shows the typical values of λ_h, using the delayed-neutron parameters measured by Keepin, Wimett, and Zeigler.[4]

TABLE I. Delayed-Neutron Harmonic Mean Decay Constant

Energy	Fuel	$\lambda_h(s^{-1})$
Thermal	^{235}U	0.0767
Thermal	^{239}Pu	0.0648
Thermal	^{233}U	0.0543
1.45 MeV	^{235}U	0.0784
1.58	^{239}Pu	0.0683
1.45	^{233}U	0.0559

Because neutron generation times range from 10^{-3} to 10^{-8} for most reactors, the second term in the bracket on the right-hand side of Eq. 4 is usually negligible in comparison to $1/\lambda_h$. Contingent upon this condition being satisfied, Eq. 4 can be simplified to

$$\frac{\rho}{\beta} = -\frac{(n_0 - n_b)}{\lambda_h \int (n - n_b)\, dt} \quad . \tag{6}$$

Although this method represents an improvement over the prompt-drop approximation, in some respects it still suffers. First, additional information (i.e., λ_i and β_i) must be known to evaluate λ_h. Although the vast majority of reactor systems normally encountered can be well characterized by the values shown in Table I, the requirement of knowing the delayed-neutron parameters precludes using an integral-flux technique on "black-box" type systems. This is in contrast to the prompt-drop method. In that formulation, the only information necessary to measure the <u>dollars</u> subcritical is the initial equilibrium power level and the power level immediately following the source jerk.

Assuming that the additional information required is not a constraint, the integral method is still based upon the point-reactor model, and, as such, requires that the measured neutron densities n and n_0 must be proportional to the <u>fundamental</u> mode of decay throughout the entire transient if Eq. 6 is to yield the correct answer. This can only be accomplished by the judicious choice of both the source and detector position within the reactor system, particularly if k is well below 1.0. As with the prompt-drop method, a poorly positioned source or detector will yield an "apparent" reactivity that can be significantly biased from the true reactivity.

Several methods have been proposed to convert from an apparent (or spatially dependent) reactivity to the true reactivity of the system. In general, there have been two approaches. The first approach locates the source and detector(s) where the first harmonic is nullified, thereby allowing n and n_0 to be nearly proportional to the fundamental mode. However, this method presumes that this node position is known. For asymmetric systems, this presumption may be questionable. The second approach relates the true reactivity to an apparent reactivity via

$$\left(\frac{\rho}{\beta}\right)_t = f(\vec{r})\left(\frac{\rho}{\beta}\right)_r \quad , \tag{7}$$

where the correction factor f is a spatially dependent quantity that must be determined from either a direct measurement or a calculation of both the neutron and adjoint fluxes. To date, the adequacy of Eq. 7 has been shown to be successful for subcritical systems with k of 0.95 or higher.[5-11]

Although Eq. 7 corrects for the problem that arises from spatial effects, another potential problem plagues this method of analysis. If the source is not removed instantaneously, the integral of the neutron density may be altered significantly during the source-removal "ramp." For systems that are highly subcritical, the contribution to the integral during the source-removal ramp may be as large or larger than the contribution from the entire delayed-neutron tail. This results in an erroneous calculation of reactivity. To circumvent this potential problem, Spriggs and Pederson[12] proposed using a semi-explicit inverse-kinetic technique.

INVERSE-KINETIC TECHNIQUE

Rather than integrate Eqs. 1 and 2, it can be shown that the solution to that system of differential equations for a source-jerk transient in a system subcritical by ρ/β corresponds to

$$\frac{n - n_b}{n_0 - n_b} = \sum_j \frac{(\rho/\beta)\, e^{\omega_j (t - t_0)}}{\omega_j \left[\frac{l}{\beta} + \sum_i \frac{\lambda_i \beta_i}{\beta(\omega_j + \lambda_i)^2} \right]} \quad , \tag{8}$$

where ω_j equals the j^{th} root of the inhour equation, Σ_i represents the sum from i = 1 to i = g, and Σ_j represents the sum from j = 1 to j = g + 1. Equation 8 is valid for $t \geq t_0$, where t_0 represents an arbitrary time shift. For $t \leq t_0$, the reactor is at its steady-state value of n_0.

Equation 8 describes the time-dependent behavior of the fundamental mode neutron density. It is noted that the right-hand side of Eq. 8 is a function of the following parameters: ρ/β, β_i/β, λ_i, and l/β. The roots, ω_j, are known quantities that can be determined from the inhour equation once the above parameters are specified. As with the integral-flux method, this requires some additional information about the system upon which the source jerk is to be performed. If we assume that the delayed-neutron parameters are known, then the right-hand side of Eq. 8 becomes strictly a function of reactivity (in terms of dollars). Hence, given a power history produced by a source jerk in a well-defined system, it is possible to determine the system's reactivity by successfully iterating on ρ/β until the power history predicted by Eq. 8 matches the observed power history produced by the source jerk. To perform this iteration, a nonlinear least-squares fitting code has been adapted for this purpose.[13] Figure 3 shows an example of a source-jerk transient analysis using this technique.

Performing an analysis of a source-jerk transient using this technique improves the experiment in two ways. First, the result becomes only weakly dependent on the source-removal ramp time. This occurs primarily because the relative power, at times several seconds into the transient, is essentially identical to the relative power corresponding to a true step removal of the source. Hence, for source-removal ramp times of 1 s or less, the least-squares fit of the data following the source ramp will yield the same answer as if it were a true step change in source strength. Second, to perform an adequate least-squares fit, only a small portion of the total delayed-neutron tail is necessary. Hence, rather than having to observe the entire delayed-neutron tail as required by the integral-flux method, the initial portion of the transient (first 60 s or so) is more than sufficient, and will significantly reduce data acquisition time.

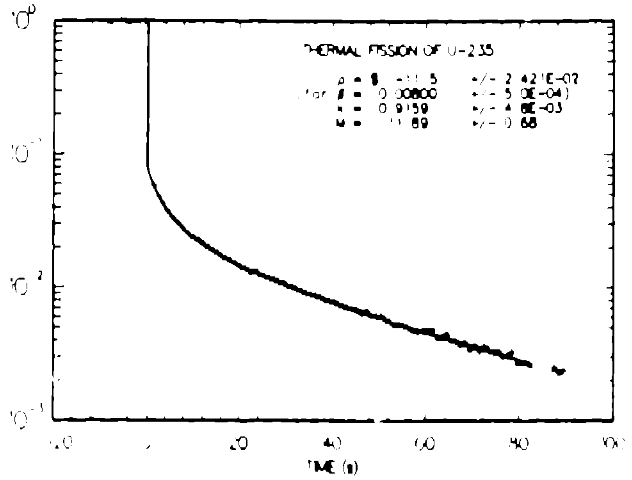

Fig. 3. Example of analysis of source-jerk transient using the inverse-kinetic method.

On the other hand, the inverse-kinetic method still suffers from the problems that plague both the prompt-drop and the integral-flux methods; namely, spatial effects can significantly bias the reactivity measurement.

RESULTS

Subcritical measurements were performed on the WINCO slab tank experiment at the Los Alamos Critical Experiments Facility (LACEF). This assembly comprises two "pancake" type tanks filled with highly enriched uranyl-nitrate solution (see Fig. 4). The reactivity of the system is adjusted by varying the gap between the two tanks.

A series of source-jerk measurements were performed using three different detector locations and three different

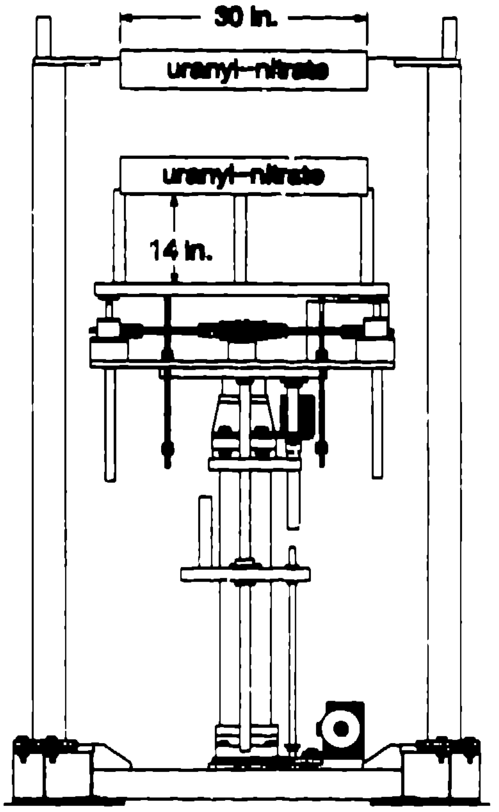

Fig. 4. WINCO slab tank.

source positions. A pair of detectors was placed in a horizontal position approximately 10 in. above the top tank, a second pair of detectors was placed in a horizontal position approximately 10 in. below the bottom tank, and a third pair was placed in a vertical position along the side of the two tanks.

Three source positions were used. All three positions were between the two tanks. The "top" position was located on the centerline of the tanks 1.25 in. below the top tank. The "bottom" position was located on the centerline of the tanks .25 in. above the bottom tank. The "center" position was located on the centerline of the tanks at the vertical midpoint between the two tanks. Source jerks were performed at five different gap positions, and the data were analyzed using the inverse kinetic technique. Table II shows the results of the measurements. The precision of each of the measurements shown in Table II was determined to be smaller than $.10. For cases in which k was > .92 the precision was on the order of $.02.

TABLE II. Reactivity ($) vs Air Gap (in.)

Air Gap (in.)	Source Position	Detector Position		
		Top	Side	Bottom
4	Top	.83	.84	.82
	Center	.87	.89	.86
	Bottom	.82	.84	.82
6	Top	6.85	6.62	6.71
	Center	6.85	6.82	6.83
	Bottom	6.66	6.73	6.92
8	Top	11.7	11.3	11.0
	Center	11.5	11.5	11.4
	Bottom	10.9	11.1	11.9
15.82	Top	23.4	25.2	19.7
	Center	22.6	26.0	22.8
	Bottom	19.0	23.1	24.3
22.84	Top	30.0	30.8	27.8
	Center	28.7	35.2	28.2
	Bottom	22.3	28.8	29.4

As can be noted, for separations of 8 in. or less (k > .9), the measured reactivity is relatively insensitive to detector and source positions. However, as k is decreased, spatial effects become more evident. This is most pronounced with the results obtained via the "side" detectors. This is to be expected for any source/detector positions in which the neutron source shines directly onto a detector (poor source/detector geometry), particularly at low multiplications (i.e., < 5). Poor source/detector geometries result in a significant change in detector efficiency following the source jerk, since most of the neutrons being counted by the detector originate from the source as opposed to originating from the assembly. On the other hand, at high multiplications (i.e., > 20), most neutrons being counted originate from the assembly, resulting in only minor changes in the detector efficiency when the source is jerked away. Hence, at high multiplications, poor geometries can be used with only minimal impact on the results.

When the source is located at off-center locations, spatial effects also become more pronounced at low multiplications. For example, at a spacing of 15.82 in. (see Table II), with the source located at the top of the air gap, the top detectors measured a reactivity that was $3.7 more subcritical than the bottom detectors measured. By comparison, when the source was located in the center, the difference between the top and bottom detectors was only $.20. This decrease in disparity can be explained by changes in the initial distribution of the delayed-neutron precursors. When the source is located at the center of the air gap, the flux in both tanks is equal, and hence, the initial precursor density in both tanks is equal. When the source is jerked out of the system, the flux in both tanks decreases at an equal rate and eventually assumes the fundamental mode decay rate. In contrast, if the source is located off-center, the initial flux in one of the tanks is higher than the initial flux in the other tank. This creates an initial non-symmetric precursor density. Following the source jerk, the tank with the higher initial precursor density "feeds" the other tank extra neutrons throughout the transient. Consequently, detectors located near the tank with the lower initial precursor density will measure a smaller reactivity relative to detectors located near the tank with the higher initial precursor density. In this situation, a true fundamental mode decay may never be obtained in either tank.

If the multiplication of the system is relatively high (i.e., > 20), then regardless of where the source is placed, multiplied neutrons will constitute the majority of the neutrons in the system, and as such, will establish a nearly fundamental mode flux distribution across the entire system. Under this condition, each tank starts with a nearly equal precursor density, resulting in both the top and bottom detectors measuring essentially equal reactivities.

As previously mentioned, reactivity measured via the source-jerk technique is measured in dollars ($). To convert $ to an absolute k, an effective delayed-neutron fraction must be determined or assumed.

For the case of the WINCO slab tanks, β was calculated using the method described by Keepin.[14] In this method, β is dependent upon the delayed-neutron energy spectrum and the buckling of the assembly (i.e., k). Because of the uncertainty associated with the measured delayed-neutron spectrum, a bounding calculation was performed for this assembly using two spectra: a "soft" spectrum as measured by Burgy,[15] and a "hard" spectrum as recommended in ENDF/B/V database. The results of this calculation are shown in Fig. 5. Using these values and the measured $ as shown in Table II (average of top and bottom detectors with source in center), k was determined for each gap separation. The results are plotted in Fig. 6 against results obtained from Monte Carlo code calculations for this system.

As can be seen from Fig. 6, the source-jerk results (in conjunction with the β calculation) show good agreement with two of the three Monte Carlo code results. For the case in which the results differ, it should be noted that the Monte Carlo calculations were low by ~0.02 Δk at critical. This bias remained consistent throughout the range of the calculations. Hence, correcting for the bias causes these data to agree with the other two Monte Carlo code calculations, which, in turn, agree with the source-jerk measurements.

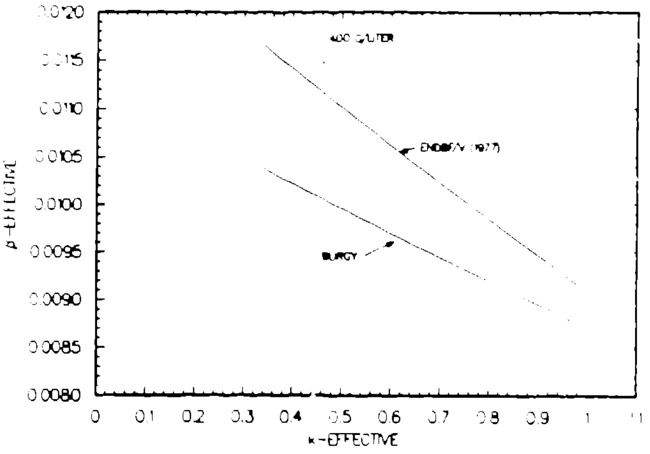

Fig. 5. β effective vs k-effective.

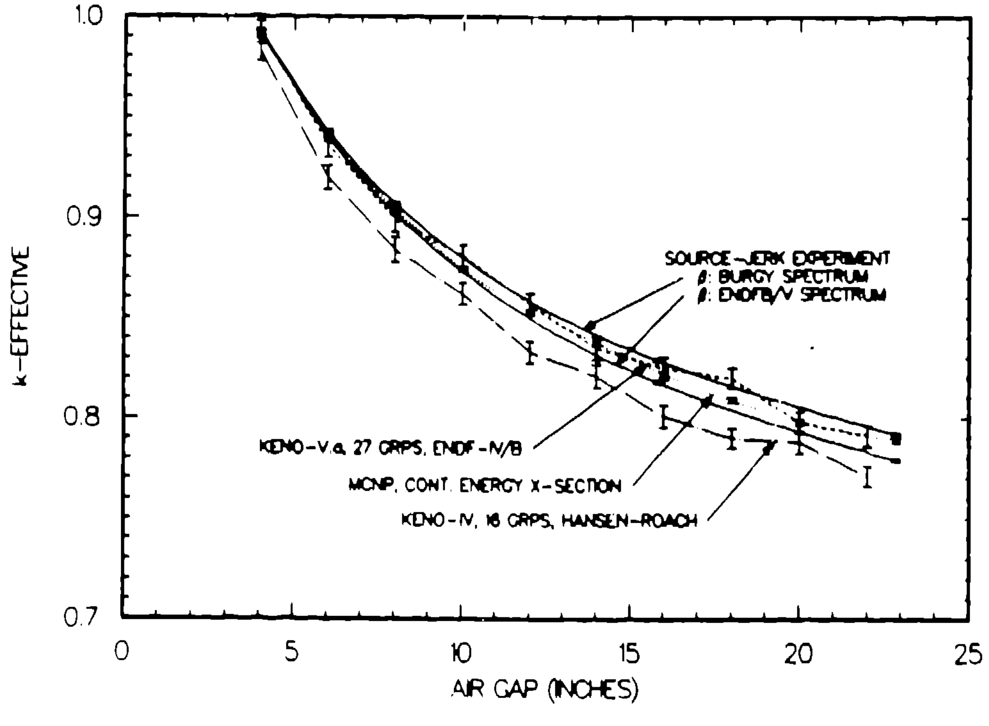

Fig. 6. Comparison between source-jerk measurements and Monte Carlo code calculations.

CONCLUSIONS

Measuring reactivity of a subcritical system by way of a source jerk is an easy and viable technique. It requires very little electronic equipment and can be performed in less than 30 min. Depending on the method chosen to analyze the transient data (i.e., the prompt-drop, the integral-flux, or the inverse-kinetic method), the results can be accurate for $k > 0.90$ and can be reasonably accurate in the range of $0.8 < k < 0.90$ if good source/detector geometries are chosen.

The only serious limitation to the use of the source-jerk technique arises primarily from biases introduced by spatial effects in far subcritical systems. However, with proper choice of source and detector position, these biases can be reduced to within acceptable limits.

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