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INTERPRETATION OF SUBCRITICALITY MEASUREMENTS
WITH STRONG SPATIAL EFFECTS

A Thesis
Presented for the
Master of Science
Degree
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Carlos March-Leuba

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ABSTRACT

This thesis presents a technique to identify and isolate modal or spatial effects in frequency-domain quantities used for subcritical reactivity measurements using the ^{252}Cf -source-driven noise analysis technique. The ^{252}Cf technique is based on measurements of the system's response to a stochastic Cf neutron source with three detectors. Detector 1 measures the source fissions, while 2 and 3 measure the system's response at different locations. If point kinetics conditions are valid, it has been shown that the reactivity of the system can be related to the frequency-independent ratio of the cross power spectral densities between detectors. For some geometries and detector configurations, the point kinetics approximation is not valid; spatial effects (i. e. modal contamination) are important and special interpretation is necessary. Removal of these spatial effects has been accomplished in the past by parallel neutronic calculations of the modal contamination factors. This approach has been successful in simple geometries.

The approach taken in this thesis is to functionally fit the measured CPSDs using a model that accounts for the modal contamination. The fundamental-mode component of the measured quantities is extracted from the fit, and a fundamental-mode ratio is calculated. All the current theories can be now applied. Subcritical reactivities

can, in this way, be estimated using the existing proven theories even in cases where the geometry or the modal contamination would invalidate the point kinetics approximation.

To validate the model, data from experiments involving ^{235}U solution tanks is analyzed. How spatial effects can be diagnosed and isolated is shown. Finally, reactivity calculations are made using a previously developed two point kinetic model. The results obtained agree with Monte Carlo simulation using the code KENO.

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CHAPTER 1

INTRODUCTION

This thesis presents a technique to isolate modal contaminations caused by spatial effects in frequency-domain quantities used for subcriticality measurements with the ^{252}Cf method. This technique has been implemented in a computer code that: (a) analyzes data from ^{252}Cf experiments, (b) unfolds the contribution of the fundamental mode, and (c) calculates multiplication factors and related kinetics parameters.

1.1 Background

The ^{252}Cf technique for subcritical reactivity estimation is based on measurements of the system's response to neutron flux perturbations introduced by a stochastic Cf neutron source. Three detectors are used: Detector 1 measures the spontaneous fissions in the Cf source, while Detectors 2 and 3 measure the response of the system at two different locations. Using a point kinetics approximation, it can be shown that the reactivity of the system can be related to a frequency-independent ratio, P , defined as

$$P = \frac{G_{12}^* G_{13}}{G_{11} G_{23}}, \quad (1)$$

where G_{ij} represents the cross power spectral density (CPSD) between Detectors i and j , and $*$ denotes complex conjugate.

The ^{252}Cf method has been applied to arrays of tanks containing fissile solutions to estimate the kinetics parameters of the system. Previous work (1) has shown that, when point kinetics conditions are valid, the reactivity of the system can be estimated using the ^{252}Cf method. The complicated geometry of the tank arrays does not allow for the interpretation of the experiment with point kinetics models, because, spatial effects (i. e. higher modal contamination of the fundamental mode) arise. Removal of these effects is necessary to calculate subcritical reactivities under these conditions.

1.2 Spatial Effects

For certain detector and source locations, the point kinetics approximation is quite valid, and the results of the technique are very satisfactory (2-4); however, this approximation is not valid for some detector or source locations when spatial effects (i.e., higher modes) contaminate the fundamental flux, thus invalidating the point kinetics approximation.

1.3 Previous Work

Removal of spatial effects has been accomplished in the past by numerically calculating modal contamination factors (5) that relate the system's transfer functions for the fundamental flux to the transfer functions for the actual flux, including spatial effects. The measured ratio, P , needs to be corrected by these modal contaminations factors to yield the system's reactivity. This approach has shown to yield satisfactory results for systems with simple geometries such as cylinders (5), but the calculations become rather difficult for complex geometries.

1.4 Objectives of this Research

The approach taken in the present work is to unfold the fundamental-mode contributions from the overall system response without relying on parallel neutronics calculations; in this way, the fundamental-mode ratio, to which the point kinetics theory applies, can be estimated. For this purpose, a physical model that takes into account spatial effects and that is based on one-group time-dependent diffusion theory has been developed. The experimental transfer functions are fitted to this model to obtain the fundamental-mode components, which are used to estimate the fundamental-mode reactivity using the point kinetics theory previously developed (1). More

information about the system can be obtained using a two-point kinetics system (6). This alternative has been implemented in the code developed.

1.5 Original Contributions

The original contributions of this dissertation to the field of subcriticality measurements are:

1. General functional forms, which take into account spatial effects, have been developed for the power spectral densities measured using the ^{252}Cf technique.
2. The concept of fundamental-mode ratio has been introduced. This ratio can be interpreted as the ratio that would have been measured if only the fundamental mode were excited during the experiment.
3. The model has been implemented in a computer code. This code fits the experimental data to the functional forms developed in this thesis, calculates the fundamental mode, and, using a two point kinetics model previously developed (see Ref. 6), estimates the reactivity and related kinetics parameters.
4. Based on the analysis of the experimental data, a detailed study has been performed of spatial effects in this type of experiments. In particular, it has been determined when these effects arise and how they can be minimized.

CHAPTER 2

THE PHYSICAL MODEL

This chapter describes a model of the neutron dynamics in the presence of a ^{252}Cf source that describes the spatial effects observed in subcriticality measurements.

2.1 Background

In this section, the basic mathematical model representing the dynamics of the Cf-source driven space-dependent system is developed. For simplicity of algebra, the time-dependent one-group diffusion equation is used. This approximation contains all the physical information necessary to understand the spatial effects. Similar development could have been done starting from transport theory by introducing the adjoint flux to ensure the orthogonality of the modes.

The time-dependent one-group diffusion equation, including delayed neutrons, can be written as

$$\frac{1}{v} \frac{\partial \psi(t, \bar{x})}{\partial t} = [\nu \Sigma_f (1-\beta) - (\Sigma_a - \nabla D \nabla)] \psi(t, \bar{x}) + \sum_{\ell=1}^6 \lambda_{\ell} c_{\ell} + s(t, \bar{x}) \quad (2)$$

$$\frac{\partial c_{\ell}(t, \bar{x})}{\partial t} = \beta_{\ell} \psi(t, \bar{x}) - \lambda_{\ell} c_{\ell}(t, \bar{x}) \quad , \ell = 1, \dots, 6 \quad (3)$$

where $\psi(t, \bar{x})$ represents the neutron flux, $c_l(t, \bar{x})$ represents the precursors concentration for l^{th} -group of delayed neutrons, and $s(t, x)$ represents the Cf source fissions. ν is the average number of neutrons per fission, Σ_f is the fission cross section, Σ_a is the absorption cross section, D is the diffusion coefficient, β is the total effective delayed neutron fraction, and β_l and λ_l are the fraction and the time constants, respectively, of the l^{th} -group of delayed neutrons. All the above quantities are allowed to have a space dependency, but they are assumed constant in time.

Using this assumptions, the following steady-state eigenvalue equation for the space dependence of the flux results:

$$[K_m \nu \Sigma_f - (\Sigma_a - \nabla D \nabla)] \psi_m(\bar{x}) = 0 \quad (4)$$

where $\psi_m(\bar{x})$ is the m^{th} eigenfunction, which represents the shape of the m^{th} mode, and K_m is the eigenvalue corresponding to the m^{th} mode. Note that Eq. (4) is of the Sturm-Liouville type, thus, the eigenfunctions are orthogonal to each other; therefore, with the proper normalization,

$$\int d\bar{x} \psi_i(\bar{x}) \psi_j(\bar{x}) \nu \Sigma_f(\bar{x}) = \begin{cases} 0 & , \text{ if } i \neq j \\ 1 & , \text{ if } i = j \end{cases} \quad (5)$$

The space dependence of the flux and precursors concentrations, therefore, can be expanded in a series of the eigenfunctions to give the following expressions:

$$\Psi(t, \bar{x}) = \sum_{m=1}^{\infty} \phi_m(t) \psi_m(\bar{x}) \quad (6)$$

$$c_{\ell}(t, \bar{x}) = \sum_{m=1}^{\infty} c_{\ell m}(t) \psi_m(\bar{x}) \quad (7)$$

Substitution of Eqs. (6) and (7) in Eqs. (2) and (3), multiplication by the factor $v \Sigma_f \psi_m(\bar{x})$, and integration over the system's volume results in the following modal kinetics equations:

$$\frac{dn_m}{dt} = \frac{P_m - \beta}{\Lambda_m} n_m + \sum_{\ell=1}^6 \lambda_{\ell} c_{\ell m} + s_{\ell m} \quad (8)$$

$$\frac{dc_{\ell m}}{dt} = \beta_{\ell} n_m - \lambda_{\ell} c_{\ell m}, \quad \ell = 1, \dots, 6 \quad (9)$$

where the following definitions have been made:

$$n_m = \frac{1}{V} \phi_m = \text{modal neutron density,}$$

$$\rho_m = \frac{1 - K_m}{K_m} = \text{modal reactivity,}$$

$$\Lambda_m = \frac{1}{\Lambda K_m \overline{v \Sigma_f}} = \text{modal generation time,}$$

S_m is the effective source of the m^{th} mode, and it is given by the expression

$$S_m = \frac{\int d\bar{x} \, s(t, \bar{x}) \, v \Sigma_f(\bar{x}) \, \psi_m(\bar{x})}{\int d\bar{x} \, v \Sigma_f(\bar{x}) \, \psi_m^2(\bar{x})} \quad (10)$$

For $m=1$, the fundamental mode, Eqs. (8) and (9) reduce to the point kinetics equations. For higher values of m , we obtain modal equations similar in structure to the point kinetics equations for the fundamental mode.

Fourier transforming the modal equations requires solving an inhour equation with seven roots for each mode. We can, however, use the prompt approximation and obtain a solution of these equations valid for high frequencies (usually over 10Hz) :

$$N_m(\omega) = \frac{\tau_m S_m(\omega)}{1 + j\omega\tau_m} \quad (11)$$

where N_m and S_m are the fourier transform of the n_m and s_m , respectively. τ_m is the time constant of the m^{th} mode and is given by the expression

$$\tau_m = \frac{\lambda_m}{R - P_m} \quad (12)$$

Taking into account Eqs. (6) and (11), the space-dependent neutron density is given by the expression

$$\bar{N}(\omega, \bar{x}) = \sum_{m=1}^{\infty} \frac{\tau_m S_m(\omega)}{1 + j\omega\tau_m} \psi_m(\bar{x}) \quad (13)$$

2.2 Removal of Spatial Effects

From Eq. (13), we observe that the system's response to an arbitrary source is composed of a sum of modal terms. Spatial effects will affect the measurement if the fundamental-mode term ($m = 1$) is not dominant. To eliminate spatial (or modal) effects, the experiment might be designed in three different ways:

1. Minimize the effective source, S_m , of the higher modes by placing the source at the appropriate position. For instance, a centered source will eliminate all even modes because ψ_{2m} is zero at the source location [see Eq. (10)].
2. Minimize the effect of higher modes by placing the detectors at zeros of ψ_m [see Eq. (12)]. For example, centered detectors will eliminate even modes from the detection process.
3. If the modal reactivity, ρ_m , is very negative for higher modes compared to that of the fundamental mode (i.e., higher modes are highly subcritical), then the

amplitude of the modal contribution is reduced [see Eq. (12)]. For this reason, spatial effects may not be as important in systems close to criticality.

However, in some applications, the detector and the source positions are constrained by the geometry and the particular conditions. Consequently, modal contamination, leading to spatial effects, might be impossible to avoid.

2.3 Modal Contamination

As already stated, The ^{252}Cf technique uses three detectors: Detector 1 measures the Cf fissions, and Detectors 2 and 3 measure the response of the system. The system's reactivity can be related to a ratio, P [defined in Eq. (1)], which involves the CPSDs between source and detectors. Within the former point kinetics theory, the ratio is supposed to be constant in frequency and may require the calculation of modal contamination factors to interpret the results of the experiment. In this section, an expression for the ratio that accounts for these spatial effects is developed.

Introducing a point detector at position x_i , the count rate, D_i , at detector i is given by the expression

$$D_i(\omega) = W_i \sum_{m=1}^{\infty} \frac{\tau_m S_m(\omega)}{1 + j\omega\tau_m} \psi_m(\bar{x}_i) \quad , \quad i = 2, 3 \quad (15)$$

where W_i is the efficiency of the detector in counts per fission in the experiment.

For the case of the CPSD between the Cf source and Detectors 2 and 3, G_{12} or G_{13} , the source, S, can be considered to be a point source located at x_s . The CPSD between the ^{252}Cf source and Detector i becomes:

$$G_{1i}(\omega) = \sum_{m=1}^{\infty} \frac{A_{1i}^m}{1 + j\omega\tau} \quad , \quad i = 2, 3 \quad (16)$$

where the modal amplitudes, A_{1i} , are given by the expression

$$A_{1i}^m = G_{11}(\omega) W_i \left(\frac{I_c}{I} \right)_m \tau_m \psi_m(\bar{x}_i) \quad (17)$$

where $G_{11}(\omega)$ is the power spectral density (PSD) of the source and the factors $(I_c/I)_m$ represent the effectiveness of the Cf source for each mode, m, and are defined by the expression

$$\left(\frac{I_c}{I} \right)_m = \frac{S_m}{S} = \frac{\nu \Sigma_f(\bar{x}_s) \psi_m(\bar{x}_s)}{\int dx \nu \Sigma_f(x) \psi_m^2(x)} \quad (18)$$

To obtain an expression for the CPSD between the two detectors, the spatially distributed noise equivalent source, S_e (1), needs to be considered. The following expression is obtained:

$$G_{23}(\omega) = \left\{ S^* W_2 \sum_{m=1}^{\infty} \frac{\tau_m \left(\frac{I_e}{I} \right)_m \psi_m(\bar{x}_2)}{1 - j\omega\tau_m} \right\} \left\{ S W_3 \sum_{\ell=1}^{\infty} \frac{\tau_{\ell} \left(\frac{I_e}{I} \right)_{\ell} \psi_{\ell}(\bar{x}_3)}{1 + j\omega\tau_{\ell}} \right\} \quad (19)$$

where the factors $(I_e/I)_m$ represent the effectiveness of the noise equivalent source for each mode and are described by the expression

$$\left(\frac{I_e}{I} \right)_m = \frac{\int d\bar{x} \vee \Sigma_f(\bar{x}) \psi_m(\bar{x}) \frac{S_e(\bar{x})}{S}}{\int d\bar{x} \vee \Sigma_f(\bar{x}) \psi_m^2(\bar{x})} \quad (20)$$

Equation (19) can be rewritten in the following form:

$$G_{23}(\omega) = \sum_{m=1}^{\infty} \frac{A_{23}^m - j\omega\tau_m B_{23}^m}{1 + \omega^2\tau_m^2} \quad (21)$$

with

$$A_{23}^m = A_{11} W_2 W_3 \sum_{\ell=1}^{\infty} \tau_m \tau_{\ell} \left(\frac{I_e}{I} \right)_m \left(\frac{I_e}{I} \right)_{\ell} \left[\psi_{\ell}(\bar{x}_2) \psi_m(\bar{x}_3) + \psi_m(\bar{x}_2) \psi_{\ell}(\bar{x}_3) \right] X_{m\ell} \quad (22)$$

$$B_{23}^m = A_{11} W_2 W_3 \sum_{\ell=1}^{\infty} \tau_m \tau_{\ell} \left(\frac{I_e}{I} \right)_m \left(\frac{I_e}{I} \right)_{\ell} \left[\psi_{\ell}(\bar{x}_2) \tau_m(\bar{x}_3) - \psi_m(\bar{x}_2) \psi_{\ell}(\bar{x}_3) \right] X_{m\ell} \quad (23)$$

and

$$X_{m\ell} = \begin{cases} \frac{\tau_m(\tau_\ell - \tau_m)}{\tau_\ell^2 - \tau_m^2} & \text{if } m \neq \ell \\ 0.5 & \text{if } m = \ell \end{cases} \quad (24)$$

The noise equivalent source is distributed over the volume of the system because it is nearly proportional to the fission rate (1); therefore, higher modes do not affect G_{23} , because the Cf source is punctual and excites more modes. In other words, The A_{23} and the B_{23} terms are very small for $m > 1$ in most cases and the fundamental amplitude of the real part of G_{23} can be approximated as

$$A_{23}^1 = \tau_1^2 \left(\frac{I}{I} e \right)^2 \psi_1(\bar{x}_2) \psi_1(\bar{x}_3) \quad (25)$$

At this point we can defined two ratios: (a) the zero-frequency ratio, that can be calculated by evaluating equation (1) at low frequency and (b) the fundamental ratio, P_1 , defined as the ratio between fundamental-mode components of the CPSDs. The fundamental-mode ratio is frequency-independent and takes the simple form

$$P_1 = \frac{\frac{A_{12}^1}{1 - j\omega\tau_1} \frac{A_{13}^1}{1 + j\omega\tau_2}}{\frac{A_{11}^1}{1 + \omega^2\tau^2}} \quad (26)$$

The value of the fundamental ratio is not only independent of frequency, but it also does not depend on the amount of modal contamination or spatial effects. The PSD of the noise equivalent source takes a complex form, but it is approximately inversely proportional to reactivity (1). Therefore, the fundamental ratio, P_1 , can be related to the reactivity, while this is not necessarily the case for the zero-frequency ratio.

2.4 Model Predictions

Equations (16) and (19) describe the effects of modal contamination in ^{252}Cf subcriticality measurements. We observe that modes affect G_{12} and G_{13} [Eq. (16)] in an additive way. That is, the resulting CPSD contains the fundamental mode plus contributions from all higher modes. On the other side, the expression for G_{23} [Eq. (19)] contains cross terms between modes that might affect the measurement in a different way. In particular, if the two detectors are not located in symmetric (i. e. balanced) positions, then G_{23} might have an imaginary component due to these modal cross terms.

CHAPTER 3

IMPLEMENTATION OF THE MODEL

Based on the theory developed in the previous sections, a technique has been developed to separate spatial effects from the ^{252}Cf subcriticality measurements. This technique consists of performing least-squares fits to the measured data using functional forms developed in Chapter 1. To accomplish this, a computer code has been developed to help interpret the results of subcriticality experiments in the presence of spatial effects.

The fitting procedure extracts the fundamental-mode contribution from the raw data and generates the ratio, P_1 , of this fundamental mode. In essence, the fitted fundamental ratio is the ratio that would have been obtained if the source and the detectors had been located in an optimal position to excite and detect only the fundamental mode. The difference between the fundamental and the zero-frequency ratios is the modal correction factor that was previously obtained from detailed neutronics calculations (5). The functional forms used in the fitting algorithm are based on the formulas developed in Chapter 2, which reduce to

$$G_{ij} = \sum_{m=1}^M \frac{A_{ij}^m - j\omega\tau_m B_{ij}^m}{1 + \omega^2\tau_m^2} ; i = 1,2,3, j = 1,2,3 \quad (27)$$

where M represents the number of modes used in the fit.

To increase accuracy, the power spectral densities (PSD) are also included in the fit. Their functional form is

$$G_{ii} = \sum_{m=1}^M \frac{A_{ii}^m}{1 + \omega^2 \tau_m^2} \quad (28)$$

the source PSD, G_{11} , is fitted to a single constant term.

The results of the least-squares fits are usually very sensitive to the weights used. The optimal weights are the inverse variances of the measured function. Upper bounds of these variances are given by the expressions

$$d^2 R_{ij} = d^2 I_{ij} = \frac{1}{2} \left(\frac{G_{11} G_{22}}{N} + \frac{|G_{12}|^2}{N_C} \right) \quad (29)$$

$$d^2 G_{ii} = G_{ii}^2 \left(\frac{1}{N} + \frac{1}{N_C} \right) \quad (30)$$

where R and I stand for the real and imaginary parts of G, and N and N_C are, respectively, the number of fast fourier transform blocks used to calculate the data and calibration run that is used to remove the electronic transfer function from the data.

The results of these fits is a set of time constants, τ_m , and amplitudes, A_{ij} , for each of the observable modes. The fundamental-mode ratio, P_1 , is calculated from

the modal amplitudes using Eq. (26). The ratio, P , contains all of the modes and, thus, depends on frequency. Its value at zero frequency can be estimated from the fit to be

$$P_0 = \frac{\sum_{m=1}^M A_{12}^m \sum_{m=1}^M A_{13}^m}{A_{11} \sum_{m=1}^M A_{23}^m} \quad (31)$$

The previously calculated modal correction factors, M_C , can also be estimated from the fit as

$$M_C = \frac{P_0}{P_1} \quad (32)$$

The present technique provides an estimate of the fundamental-mode ratio, and thus allows for the interpretation of experimental data with nonoptimal source-detector configurations when spatial effects are relevant.

CHAPTER 4

APPLICATION TO EXPERIMENTAL DATA

This chapter presents some examples of the applicability of the present technique to interpret experiments with high modal contaminations. Three different experiment were analyzed:

1. One ^{235}U solution tank.
2. Two equal ^{235}U solution tanks.
3. Two different ^{235}U solution tanks.

The data was fitted and analyzed. How and when spatial effects arise was studied. Fundamental and zero-frequency ratio were calculated. How the reactivity can be calculated from these result is shown in chapter 5.

4.1 One ^{235}U Solution Tank Experiment

4.1.1 Model Validation

To validate the physical model developed in this thesis, data collected in a subcritical experiment based on a ^{235}U solution tank (3) was used. Measurements were taken with the ^{252}Cf source located at 3/4 height in the central axis, with the intention of exciting axial modes.

Three observable modes were found, whose associated break frequencies are 165, 225, and 370 Hz. It was concluded that they correspond to the first three axial modes, which are represented graphically in Fig. 1.

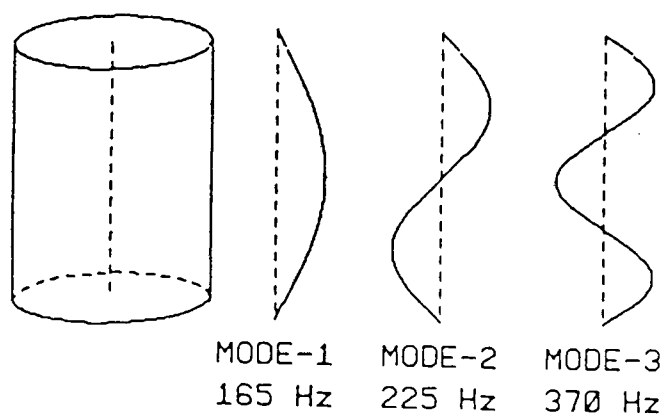
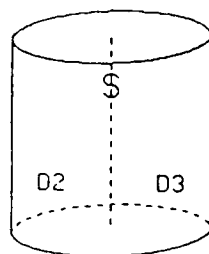
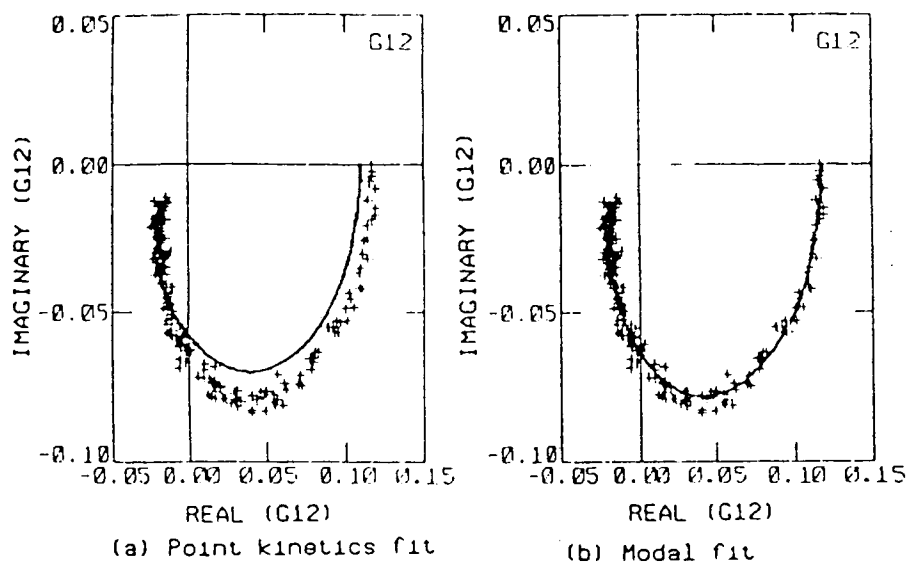


Fig. 1. Observable modes in the ^{235}U solution tank experiment.

The present physical model predicts the general structure of the frequency-domain quantities used in ^{252}Cf subcriticality measurements. In particular, the model predicts that G_{12} and G_{13} should have a structure given by Eq. (16). In contrast, the previously existing model (1) was based on the point kinetics approximation, which results in expressions for G_{12} and G_{13} which contain only the first term of the summatory in Eq. (16). The additional terms introduced by the present model represent the contributions to the system response from the higher modes. Consequently, the point kinetics approximation does not give an appropriate description of the system when spatial effects are relevant. For instance, Fig. 2 presents a polar plot of G_{12} with the detectors and source locations chosen to excite the second axial mode with a negative amplitude [see Fig. (1)]. Fig. 2a corresponds to a functional fit using the point kinetics model, while Fig. 2b shows the fitted CPSDs using the present model. With source placed axially at 3/4 height and the detectors at 1/4, the second axial mode is excited along with the fundamental mode; therefore, the point kinetics model (which describes only the fundamental) is not capable of representing this type of data. On the other hand, the fit using our model follows perfectly the trend defined by the unconverged data points (see Fig. 2), implying that



(c) Source-detector configuration

Fig. 2. Comparison between measured CPSD between source and Detector 2 (+++) and model (---).

this model is valid, and indeed, it represents the measured data with fair accuracy.

The CPSD between detectors, G_{23} , depends on the noise equivalent source, which is spatially distributed. For this reason, modal contaminations in G_{23} are not as pronounced as in G_{12} and G_{13} where the source is a delta function in space and excites higher modes. Consequently, in most cases, G_{23} is real, and the point kinetics approximation is fairly accurate. However, as shown in this work, The imaginary part of G_{23} , could be nonzero if Detectors 2 and 3 are located in unbalanced positions with respect to the modal symmetries [see Eq. (23)]. For instance, Fig. 3a shows the Bode plot of G_{23} with the two detectors balanced at the same height (1/4) and with the source located at 3/4 height; in this case, we observed that G_{23} is essentially real, but it has a strong functional dependence on frequency. In contrast, Fig. 3b shows G_{23} with detectors in unbalanced positions (1/4 and 3/4 height); in this case, we observed that, because the second mode changes sign, the two terms in Eq. (23) do not cancel, and G_{23} is clearly complex and has a well-defined imaginary part. In both cases, the present model is able to fit all data points, proving the validity of the model to represent the CPSD between detectors even in cases with high modal contamination.

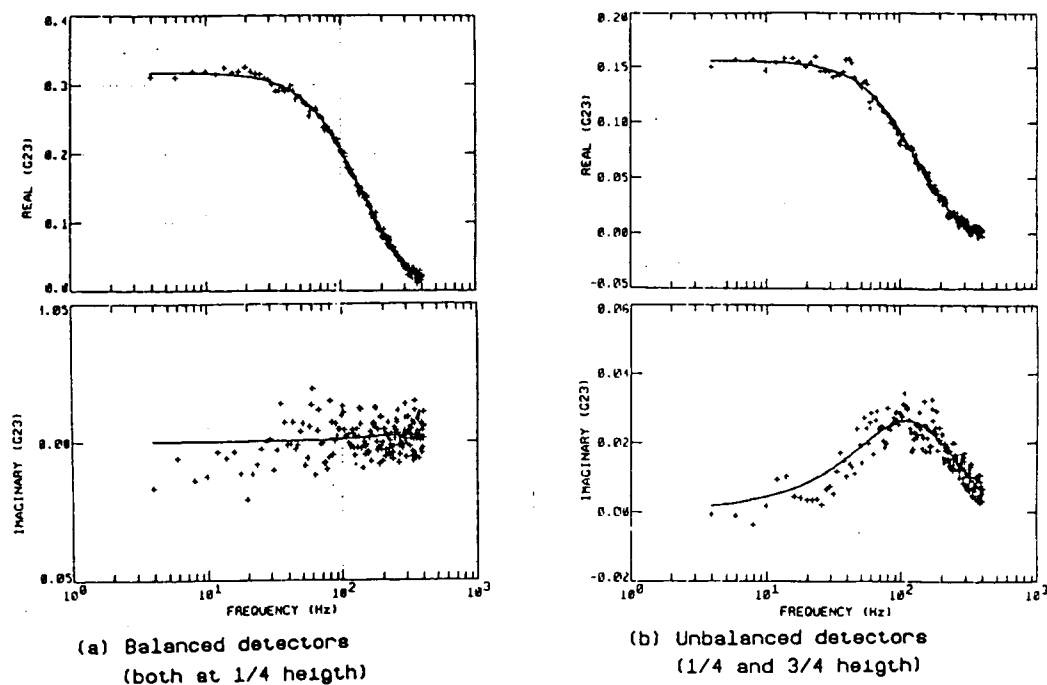


Fig. 3. The CPSD between Detectors 2 and 3 (G_{23}) becomes complex if detectors are unbalanced. The solid line shows the fit using the space-dependent model.

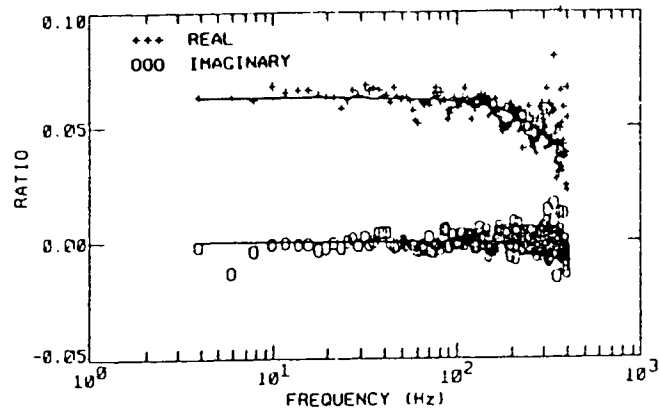
Point kinetics theory predicts that the ratio, P , should be real and constant in frequency; however, when spatial effects are important in the measurement, the measured ratios are certainly not constant and sometimes complex. The present model, however, is able to represent this feature of the ratio. As an example, Fig. 4 shows the measured and fitted ratios for the same source and detectors positions as in Fig. 3. We observe that the present model does an excellent job of representing the overall dynamic structure of the ratio in systems where spatial effects are important.

We conclude, thus, that the functional forms for the CPSDs and the ratios that are predicted by the model developed in this work are valid because they show satisfactory agreement with the measured functions.

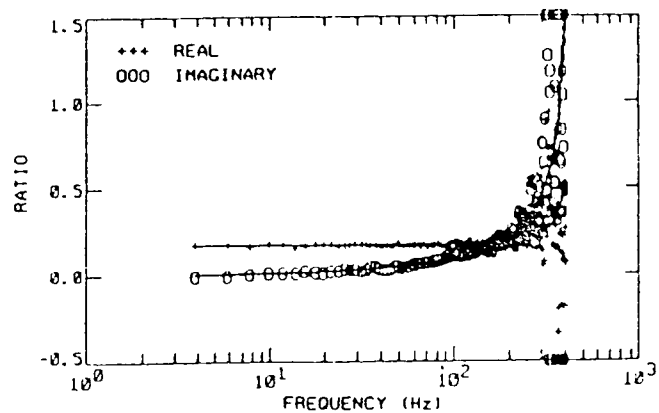
4.1.2 Study of Modal Contaminations

The differences observed in Section 4.1.1 between the measured data and the predictions of the point kinetics theory can be explained by the fact that the source-detectors configuration promotes modal contaminations. In this section we look at those modes in more detail.

Figure 5 presents the source-detector configurations for four of the runs in this experiment along with a graphical representation of the fitted modal amplitudes. In case (a) of Fig. 5, the detectors are centered;



(a) Balanced detectors (both at 1/4 height)



(b) Unbalanced detectors (1/4 and 3/4 height)

Fig. 4. The measured ratio P becomes complex for unbalanced detector positions. The space-dependent model fit (solid line) can represent these conditions.

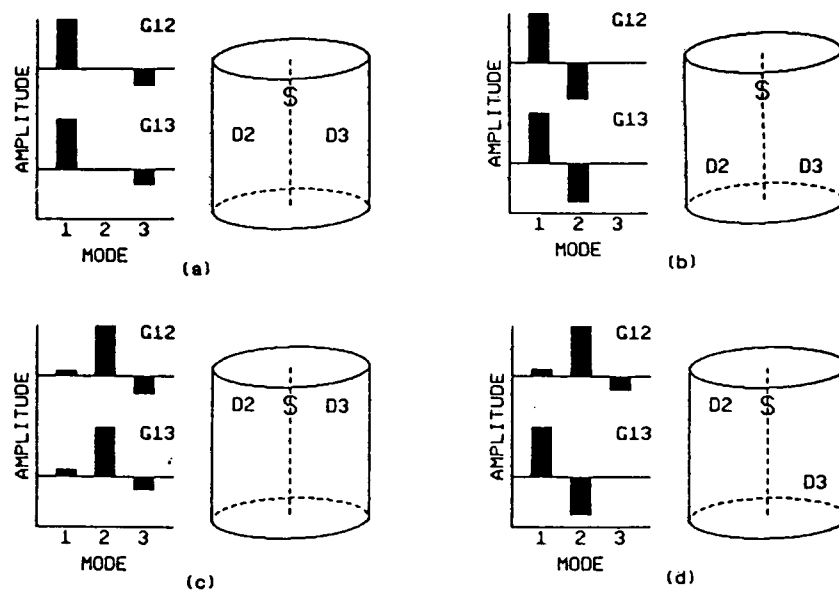


Fig. 5. Fitted modal amplitudes, A^m_{ij} , in the solution tank experiment with a single source.

thus, the second mode is not observable. The observed amplitude of the third mode is negative, as expected (see Fig. 1), and its magnitude is about 25% of the fundamental amplitude. The detectors location in case (b), (c), and (d) is such that the second mode is excited preferentially. In case (b), the second mode is negative, but the third mode is positive, as could have been predicted from Fig. 1. In case (c), however, the detectors are at the same level as the source; therefore, the second mode is dominant. Case (d) is a combination of cases (b) and (c) and shows similar behavior.

A different set of measurements were performed in the same cylindrical tank. In this case, two Cf sources are located at $1/4$ and $3/4$ of the central axis. Detector 1 is now considered to be the sum of both sources. This source configuration is symmetric with respect to the central plane, thus, eliminating contaminations from even axial modes. The fitted modal amplitudes are represented graphically in Fig. 6 along with the detector locations. We observe that the second mode, although it should not be excited in this configuration, has a small but observable amplitude; this could be due to a slight asymmetry in the position or strength of the sources. In any case, the second-mode amplitude is small compared to the first and third modes, even for detectors positions where the second

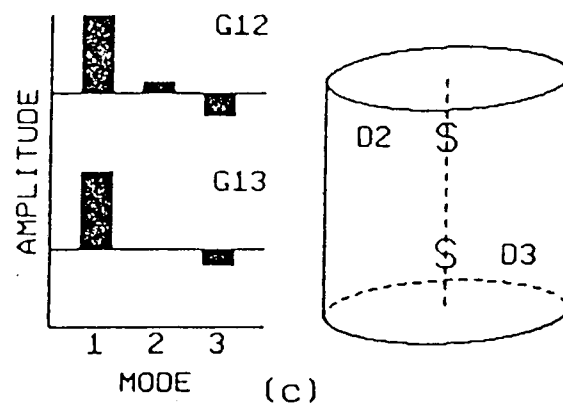
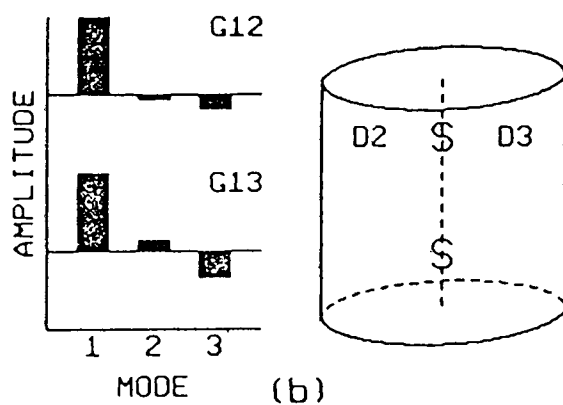
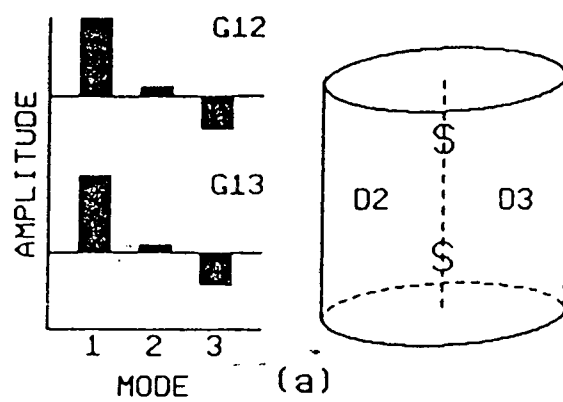


Fig. 6. With symmetric sources, the fitted amplitude for the second mode becomes negligible.

mode dominate the response with a single source (Fig. 5). These last results increase our confidence that the observed spatial effects are due to axial-mode contamination.

4.1.3 Measurements of Fundamental-Mode Ratios

The fitting technique described in Chapter 3 can be used to obtain fundamental-mode ratios directly from the data. The modal correction factor, M_C , can be calculated using Eq. (32) and compared to results of neutronic calculations.

Table 1 contains the results of the analysis of the solution experiment (3). We observe that although the zero-frequency ratio, P , varies from 0.132 to 0.222, depending on the source-detectors configuration, the fundamental mode ratio is essentially constant and equal to 0.2 for all cases. This observation agrees with the theory because tank reactivity does not depend on the location of source and detectors. The zero-frequency ratio, though, is affected by different source-detectors configurations, which may result in differing amounts of modal contamination. Note that the errors presented here are upper-bound estimates based on theoretical considerations of the maximum statistical error involved in the measurement of CPSDs, assuming that all errors during the calculations are uncorrelated; therefore,

Table 1. Results of the analysis of the solution tank experiment.

Configurations				Ratio	
S1	S2	D2	D3	Zero-Freq.	Fund.-Mode
3/4	---	1/2	1/2	0.141 ±5%	0.205 ±46%
3/4	1/4	1/2	1/2	0.132 ±4%	0.200 ±19%
3/4	1/4	3/4	3/4	0.155 ±5%	0.190 ±52%
3/4	1/4	1/4	3/4	0.222 ±5%	0.189 ±52%

they do not reflect the true error, which is most probably smaller. Nevertheless, the magnitude of these errors highlights the fact that extra information obtained from the fitting technique is obtained at the expense of an increase of statistical error; therefore, to increase precision, it is necessary increase the measurement time. This was done in the experience show in Section 4.3.

Modal contamination factors, M_C , have been computed from the two fitted ratios, and the resulting values are reported in Table 1. The M_C value for the first case in Table 1 was also computed as a separate neutronic calculation using the methodology described in Ref. 5. The computed value is 0.59 which, considering the errors involved, agrees satisfactorily with the 0.69 value obtained from the present fitting technique.

As seen in Chapter 2, the fundamental-mode ratio is almost proportional to the reactivity. The constant of proportionality, however, depends on the (I_C/I) factor that is defined in Eq. (1) and that represents the effectiveness of the ^{252}Cf source in its particular location. Typical values for (I_C/I) for cylinders range from 1.72 at the center to .26 with the source located at the top of the tank (4).

The present technique can also be used to map the values of (I_C/I) as a function of source location by

measuring the fundamental-mode ratio at each of these locations. The advantage of using the Fundamental-mode ratio is that spatial contaminations will be removed from the measurement.

As an example, Table 2 contains the fitted ratios from data obtained at the SHEBA facility with the source located at two axial levels (2). Four detector configurations have been analyzed at each source level. The weighted average of the fundamental ratios is $0.082 \pm 6\%$ and $0.102 \pm 7\%$ for the cases with the source located at $1/2$ and $3/4$, respectively. According to these measurements, the (I_C/I) factor should be 1.25 larger in the center of the cylinder than at $3/4$ height. In fact, detailed neutronic calculations yield (I_C/I) values of 1.44 and 1.09, respectively. That is, according to the calculations, The central (I_C/I) value should be 1.30 times larger than the (I_C/I) value at $3/4$ height level. We note in Table 2 that, similar to the cases in Table 1, the fundamental-mode ratio is fairly independent of the detector location (as predicted by the theory) but that the zero-frequency ratio varies (as the solution experiment) with the position of the detectors.

Table 2. Results of the analysis of the SHEBA experiment.

S. Height	Ratio		M _C	
	Zero-Freq.	Fund.-Mode	Measured	Calculated
3/4	0.071 ±6%	0.082 ±19%	0.86 ±25%	0.823
3/4	0.075 ±7%	0.082 ±32%	0.91 ±40%	0.811
3/4	0.071 ±7%	0.085 ±34%	0.84 ±41%	0.839
3/4	0.064 ±7%	0.079 ±30%	0.81 ±37%	0.812
1/2	0.076 ±6%	0.106 ±24%	0.72 ±30%	0.606
1/2	0.100 ±7%	0.115 ±38%	0.87 ±45%	0.825
1/2	0.077 ±7%	0.088 ±38%	0.88 ±45%	0.825
1/2	0.092 ±7%	0.104 ±31%	0.89 ±38%	0.825

4.3 Two Equal ^{235}U Solution Tank Experiment

4.3.1 Modal Contamination

So far examples of the effect of modal contamination in simple geometries have been presented. Spatial effects can be more pronounced in complex geometries. As an example, this section shows the analysis of data from an experiment based on two equal cylindrical ^{235}U solution tanks (4). The separation between tanks controls the amount of coupling between them, and it also affects the modal contamination. Following a similar procedure as in the previous section, two observable modes were determined for this experiment:

1. The fundamental, that is positive in both tanks.
2. The second mode, that is positive in the source tank and negative in the other tank.

These two modes are presented graphically in Fig. 7 along with the total flux, which is the sum of both modes. We observe that the effect of the negative second mode is to reduce the flux in the other tank. When the coupling is very small (i.e., large tank separation), the first and second modes have approximately the same amplitude and break frequencies, so the flux in the second tank tends to zero, while flux in the source tank approaches the one

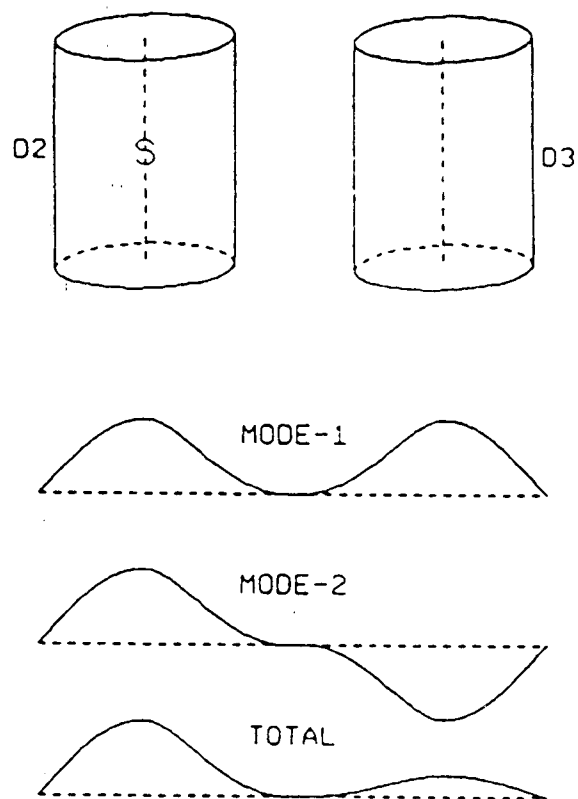


Fig. 7. Observable modes in the two ^{235}U solution tank experiment.

of an isolated tank. Contrary to the results presented in the previous section, no axial modes were observed. This was a consequence of the use of long axial detectors that average modal contributions and, thus, favor the observation of the fundamental mode.

Figure 8 presents, as a function of the tank separation, the relative amplitudes of the first and the second modes as seen by detectors located in the source and away tanks. Figure 9 plots values of the modal break frequencies for the two observable modes as a function of the tank separation. We observe that the two break frequencies are distinct when the coupling is strong, but as the coupling weak, the two break frequencies converge to a single value (1250 Hz) which corresponds to the break frequency of a single tank. The modal amplitudes are well defined when the two break frequencies are separated; the first mode is positive in both tanks and the second mode is negative in the away tank, as should be expected. As the break frequencies collapse to one, though, the individual values of the modal amplitudes become undefined, because the only significant quantity is the sum of the amplitudes (both break frequencies are the same so the problem of determining the amplitudes become singular). The sum of the modal amplitudes is always

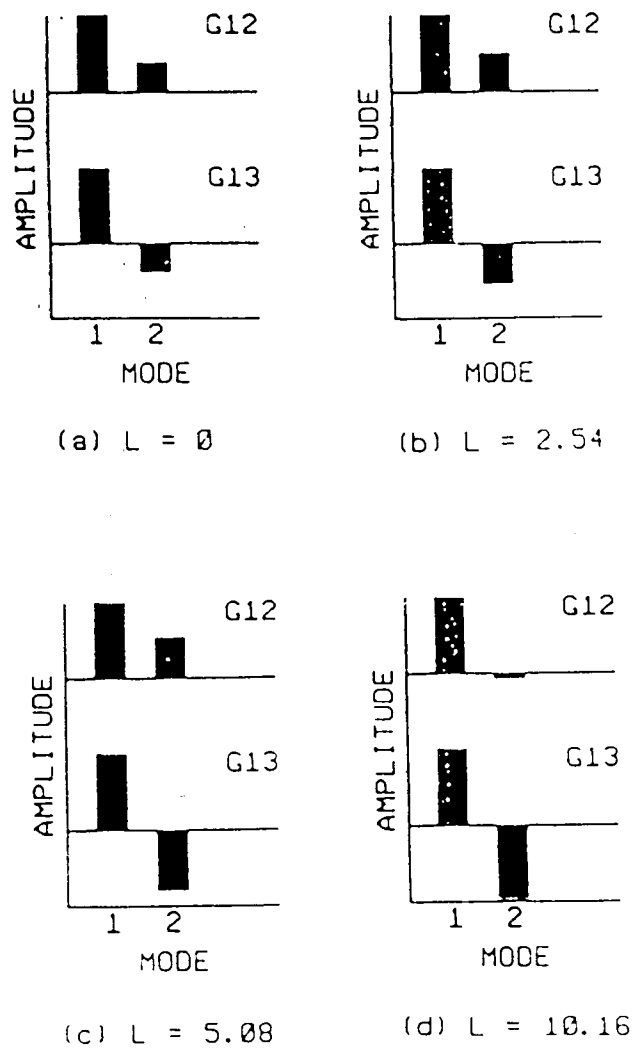


Fig. 8. Fitted modal amplitudes in the two ^{235}U solution tank experiment. L is the distance between tanks

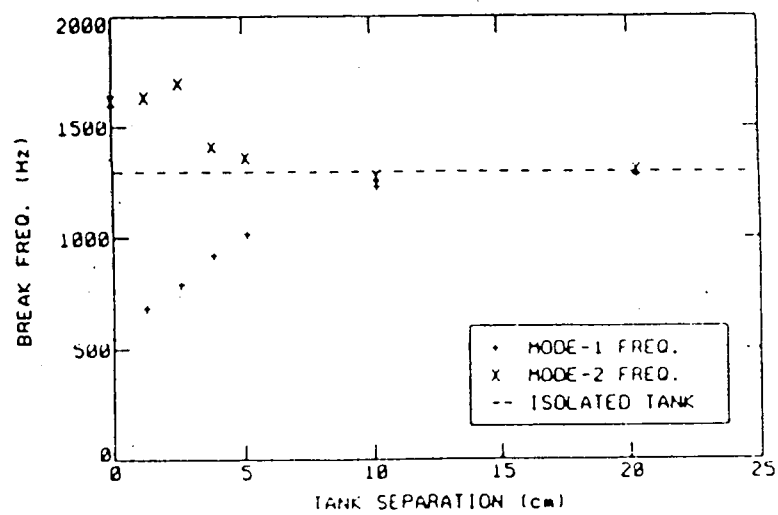


Fig. 9. Fitted break frequencies versus tank separation in the two ^{235}U solution tank experiment.

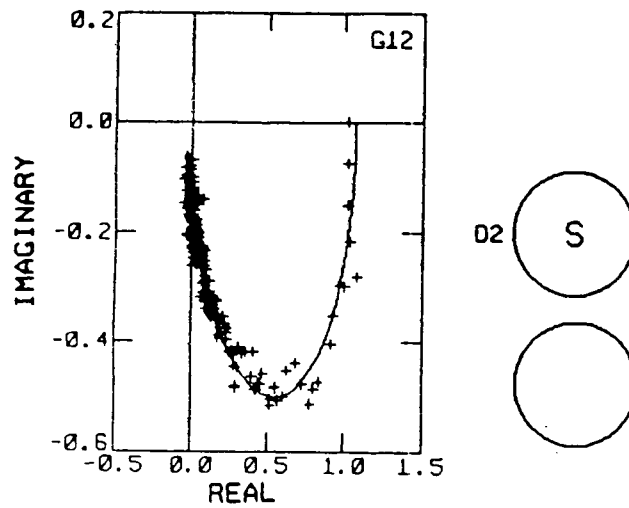
positive in both tanks, but it tends to zero in the away tank as the coupling weakens.

Spatial effects can also be observed directly in the frequency domain data. For instance, Fig. 10 shows a polar plot of the CPSD between the source and a detector placed on the source tank, Fig. 10a, or the away tank Fig. 10b. In a polar diagram, the plot of a single mode CPSD is contained in the fourth quadrant. The CPSD in case (a) behaves in this fashion, because the fundamental mode dominates. In case (b), The second modes has an important contribution and the polar plot of the CPSD cross the imaginary axes.

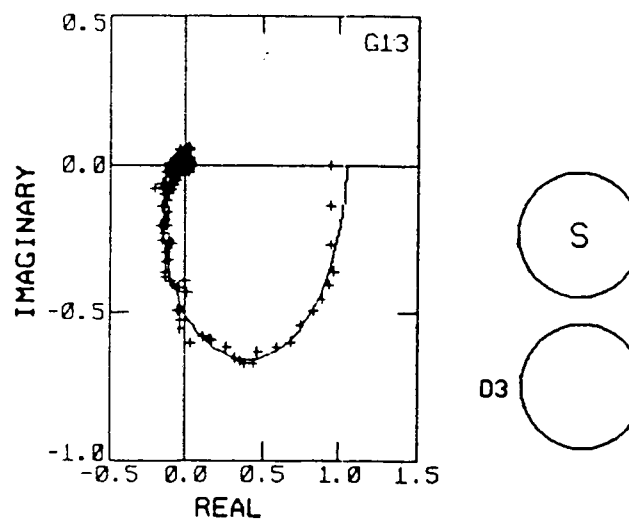
4.3.2 Fundamental-Mode Ratio Measurements

As predicted in Chapter 2 the on-line ratio, P , is not constant in frequency when spatial effects are important. For example, the ratio is essentially constant when the detectors are placed in the same tank as the source (see Fig. 11a), but it becomes frequency dependent when the two detectors are on the tank away (see Fig. 11b). The ratio might even become complex when the detectors are one in each tank (see Fig. 11c).

The present technique allows for the estimation of the fundamental-mode ratio from the fitted modal amplitudes, even in cases with strong spatial effects. Table 3 and 4 summarize the results of the analysis.



(a) Detector in source tank



(b) Detector in away tank

Fig. 10. The CPSD polar plot cross the imaginary axis when spatial effects arise

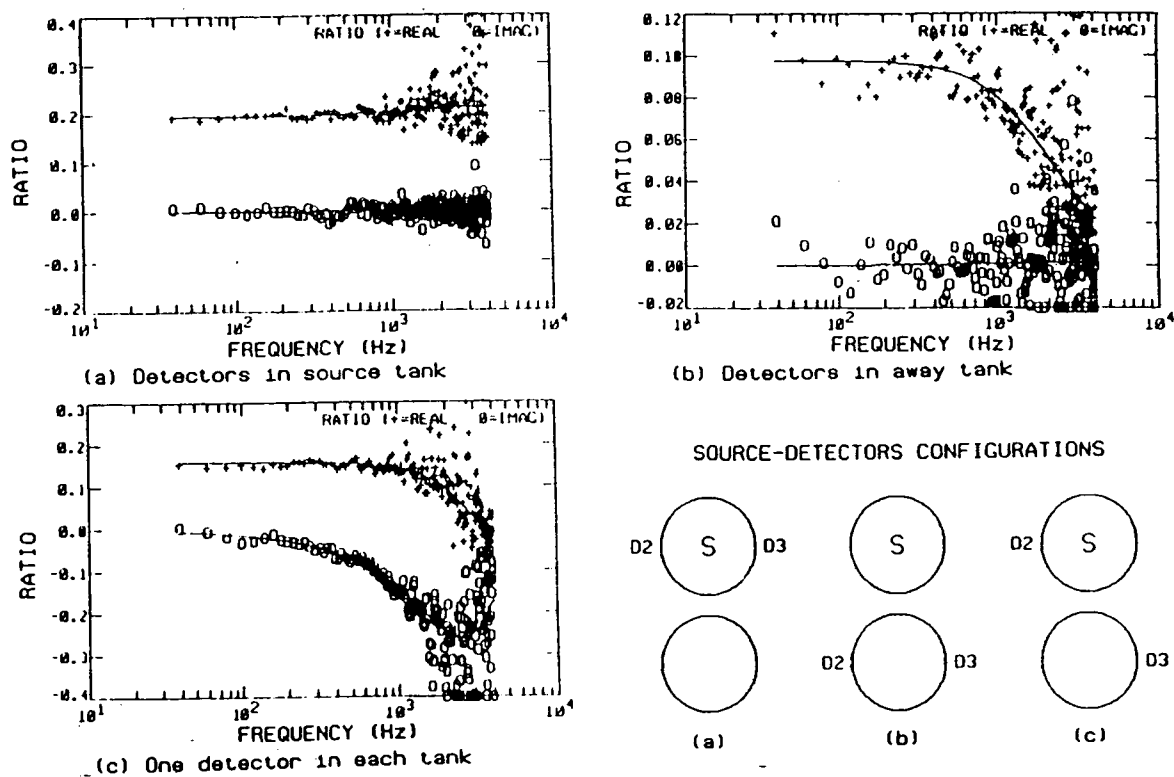


Fig. 11. Measured ratio for three different detector locations. The space-dependent model fit (solid line) can represent these conditions.

Table 3. On-line ratios. Two equal tank experiment.

Tank Separation (cm)	Source-Detector Configuration		
	1a	2b	3c
0.	0.16+/-5%	0.08+/-5%	0.14+/-4%
1.27	0.20+/-5%	0.10+/-6%	0.16+/-4%
2.54	0.22+/-5%	0.10+/-5%	0.18+/-5%
5.08	0.25+/-6%	0.11+/-6%	0.21+/-8%
10.16	0.28+/-6%	0.11+/-6%	0.24+/-14%
30.48	0.31+/-6%	0.08+/-5%	0.27+/-35%

- a two detectors in source tank
- b two detectors in away tank
- c one detector in each tank

Table 4. Fundamental-mode ratios. Two equal tank experiment.

Tank Separation (cm)	Source-Detector Configuration		
	1a	2b	3c
0.	0.16+/-4%	0.15+/-13%	0.15+/-11%
1.27	0.21+/-5%	0.20+/-18%	0.17+/-13%
2.54	0.23+/-5%	0.23+/-15%	0.20+/-16%
5.08	0.27+/-6%	0.39+/-31%	0.26+/-78%
10.16	0.30+/-6%	0.44+/-32%	0.60+/-530%
30.48	0.34+/-6%	0.50+/-26%	1.07+/-7500%
a two detectors in source tank b two detectors in away tank c one detector in each tank			

Figure 12 shows graphically the behavior of the fundamental-mode and on-line ratio (zero-frequency ratio) as a function of the distance between tanks. The values were calculated averaging the results for the different configurations. The on-line ratio first increases and then decreases as a function of distance. If the point kinetics interpretation was applied, we would conclude that the reactivity increases when the coupling decreases. A more reasonable result is given by the behavior of the fundamental-mode ratio. It increases with decreasing coupling, so the reactivity decreases. Actually, as is shown in Chapter 5, the values obtained for the reactivity using these results were compatible with the values obtained by Monte-Carlo calculations using the code KENO (6).

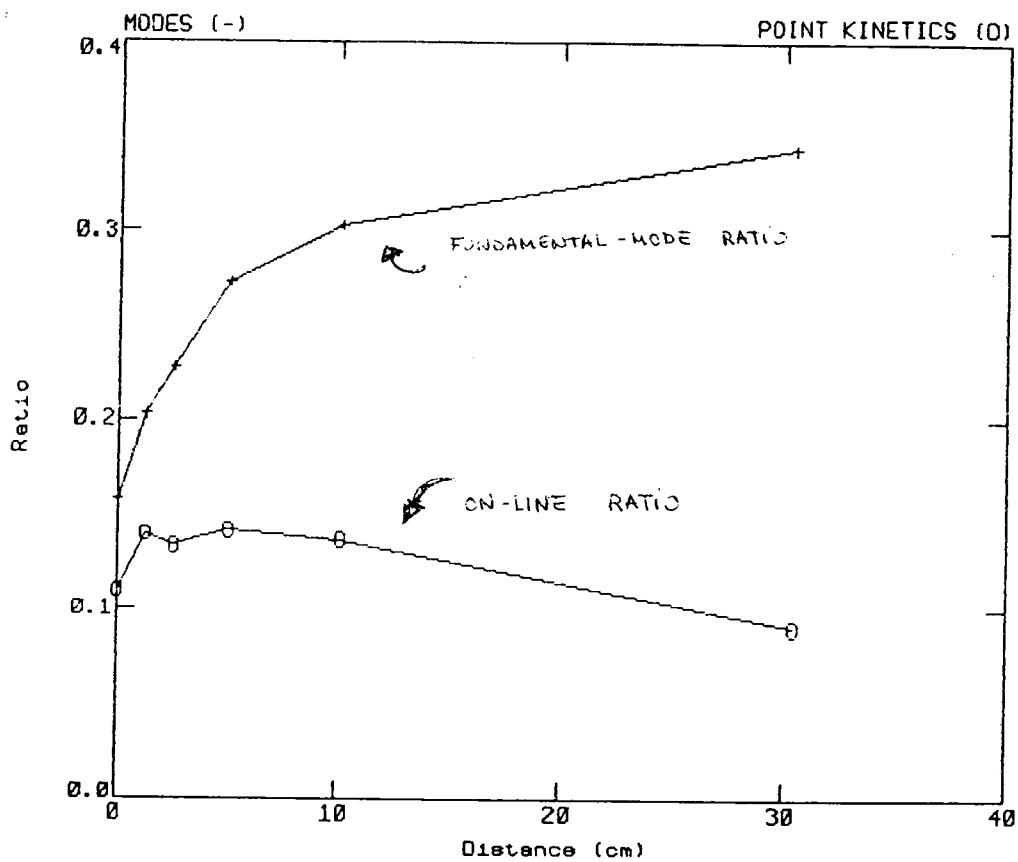


Fig. 12. Measured fundamental-mode ratio (-) and on-line ratio (O) versus distance between tanks.

CHAPTER 5

SUBCRITICALITY CALCULATIONS

In Chapter 4 it has been shown that modal contamination can be isolated, and the contribution of the fundamental mode to the CPSDs can be obtained from the raw data. In this Chapter it is shown how the previous results can be used to estimate multiplication factors and related kinetics parameters.

Several models have been developed to obtain the reactivity from the fitted ratio (1 and 6). The two point kinetics model developed by Felix C. Diffilippo (6) has been used for the present analysis. The advantage over the other models is that it allows an estimate of the interaction between tanks. The results obtained is shown to be compatible with the results of 27-group Monte Carlo calculations using the KENO code (6). The fitting technique presented in this thesis is also being used to analyze the ^{252}Cf data using a point kinetics model (1) with satisfactory results.

5.1 The Two-Point Kinetics Model

The model is presented in Ref. 6 and it is not an original contribution of this thesis. Details about it can be found in reference 6. In this section we only show

that using this model it is possible to relate the reactivity to the ratio introduced in this thesis. Additional information about the interaction between tanks can be obtained.

5.2 Implementation of the model

A computer code that fits the data to the functional forms for the CPSDs developed in this thesis, calculates the fundamental-mode ratio (see Chapter 2), and interprets the results using the two point kinetics model has been developed.

The reactivity is calculated from the fundamental-mode ratio using an iterative method, that allows, first, to unfold the modal contamination of the detector-field of view, and then, to calculate the reactivity. Details about how the model was implemented can be found in Ref. 6.

5.3 Application to experimental data

The program was validated using data from the experiments based on two ^{235}U solution tanks. Measurements were taken at different spacing between tanks. In the first set of experiments, both tanks had the same concentration of Uranium. Details about the position of the detectors and data fit are shown in

Chapter 4. In the second set of experiments, the tanks had different concentrations. The data could be analyzed in a bigger range of frequency and with better statistics; therefore, modal contaminations could be isolated with more precision. These are the reasons why the results are even better than in the first case.

5.3.1 Two Equal Tanks

Results of the analysis of experimental data are shown in Figs. 13 and 14. Figures 13 and 14 show respectively the values obtained for k_{eff} (multiplication factor) and l_{eff} (mean life), using the technique presented in this thesis, as a function of the distance between tanks and the results are compared with Monte Carlo calculations using the KENO code. the 16-groups and 27-groups libraries were used. These Monte Carlo calculations were made by Dr. E. Blakeman at ORNL.

5.3.2 Different Solution Tanks

The data was analyzed from an experiment based in the same geometries than the above and with the same detectors and source configurations, but this time, the tanks have different concentrations of Uranium. This asymmetry between tanks does not allow the model to obtain an estimate of the interaction between tanks. A further

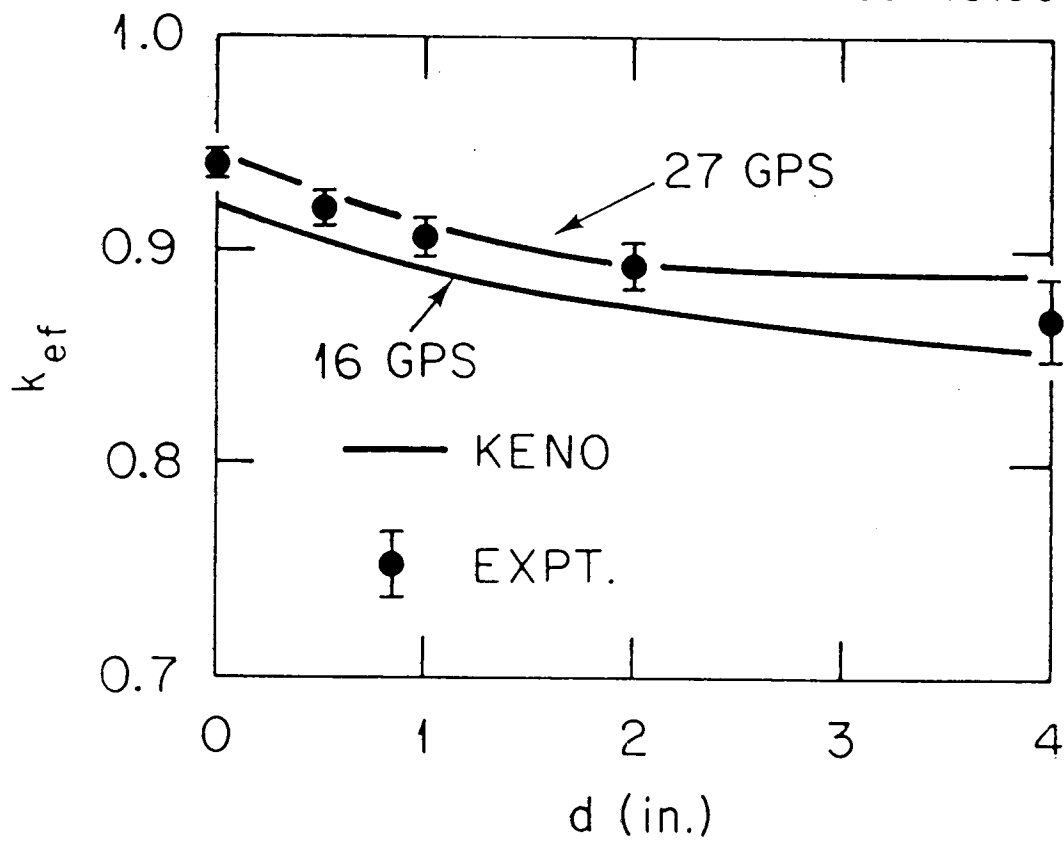


Fig. 13. Measured K_{eff} as a function of the distance between tanks.

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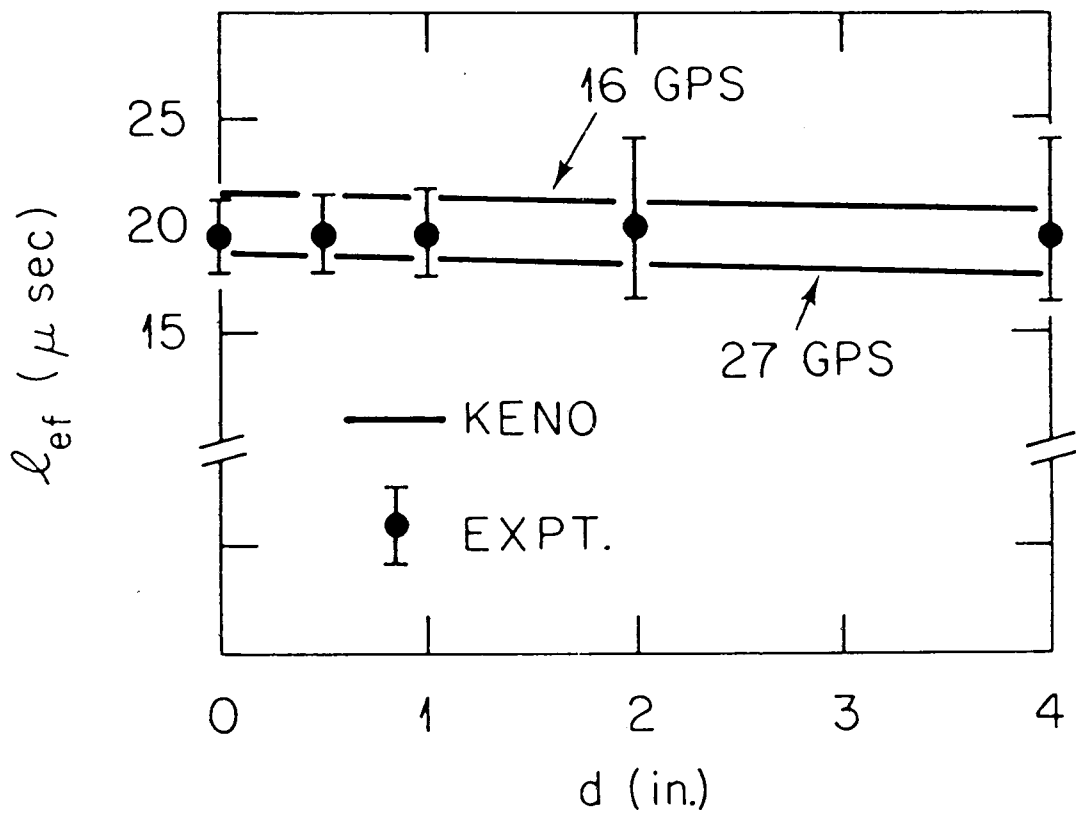


Fig. 14. Neutron mean life as a function of the distance between tanks.

development of the model will be necessary. On the other hand, the data was Fourier transformed using a different device. It gave a better resolution at high frequency; therefore, better statistics are obtained and the results are even better than in the two equal tanks.

Figure 15 shows values for k_{eff} as a function of the distance between tanks. Results are compared with Monte Carlo calculations using the KENO code with the 27-group library. The agreement between them is excellent. In this case, detectors were located in the tank without a source. Notice that, this time, the value of k_{eff} has been obtained without any average with other detector configurations. That proves that the removal of spatial effects can be accomplished using the technique presented in this thesis if good statistics are obtained for the measured quantities in the experiment.

Figure 16 shows values for k_{eff} as a function of the spacing between tanks in the case where the detectors were located one on each tank. In this case, it has been possible to fit the data even when the distance is bigger than 4 inches. The results agree with the KENO calculations again. When the distance is bigger than 4 inches, the coupling between tanks is weak, and, the first and second mode have almost the same break frequencies; therefore, the ability to differentiate

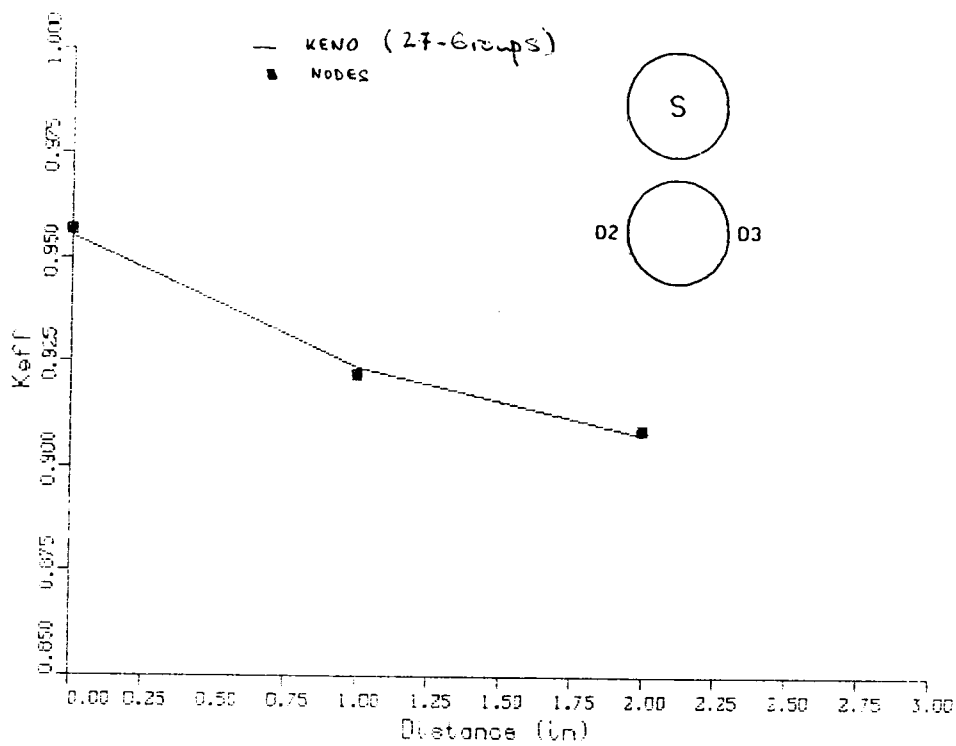


Fig. 15. Comparison between measured k_{eff} and k_{eff} calculated using the KENO code (Monte Carlo simulator). Two different tank experiment. Detectors on the tank without source.

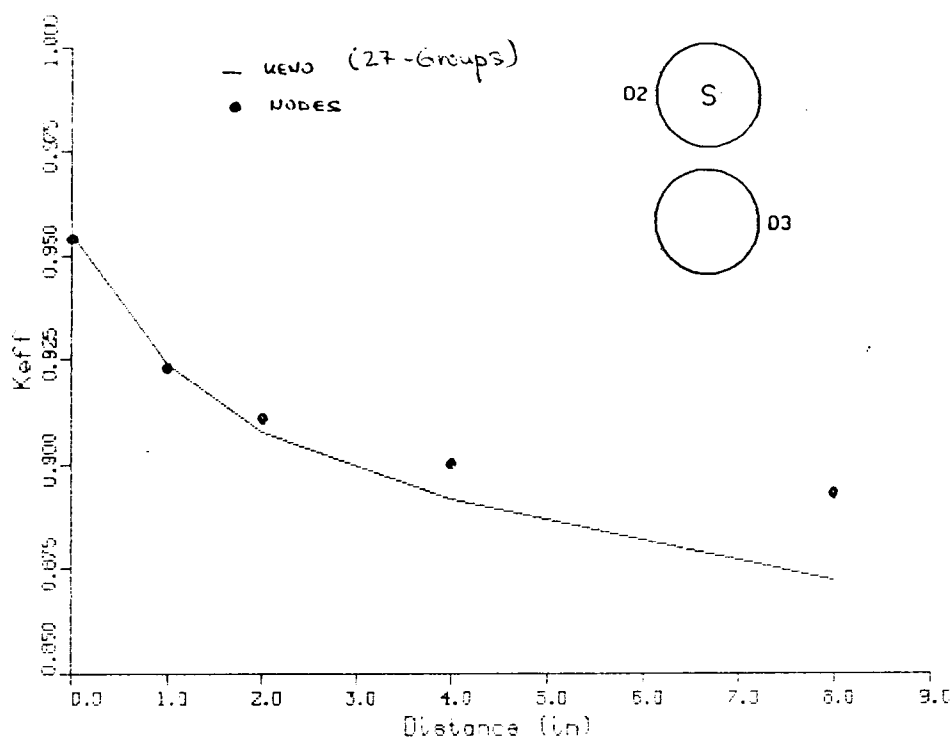


Fig. 16. Comparison between measured k_{eff} and k_{eff} calculated using the KENO code (Monte Carlo simulator). Two different tank experiment. Detectors unbalanced.

between the first and the second mode amplitudes decreases. This is the reason why the values of k_{eff} differ from the Monte Carlo calculations for distances bigger than 4 inches (weak coupling).

CHAPTER 6

CONCLUSIONS

This thesis documents the development of a space-dependent model to interpret the results of the ^{252}Cf subcriticality experiments when non optimal source-detectors configurations induce spatial effects. A study of how these spatial effects can be diagnosed and isolated has been performed. The concept of fundamental-mode ratio has been introduced, and a technique to calculate it has been implemented in a computer code. It has been shown how, from this ratio, it is possible to calculate the reactivity and other related kinetics parameters. Satisfactory agreement between the results of the techniques presented in this thesis and detailed Monte Carlo calculations has been obtained.

6.1 Model

A general space-dependent model of the ^{252}Cf experiment has been developed in Chapter 2. Using it, interpretation of subcriticality experiments has been made possible, by studying how spatial effects affect the measurement. It has been found that a way to minimize

these effects is to introduce symmetries in the experiment. For example:

1. A centered source minimizes contribution of the even modes.
2. Symmetry on the detector position cancels the imaginary part of the CPSD between detectors on the tank.
3. Higher mode effects can be minimize placing the detectors at zeros of the mode shapes.

But it is not always possible to choose the position of the detector in the experiment; therefore, a technique to isolate higher modes contribution has to be applied.

6.2 Implementation of the Model

A computer code has been developed. It fits the experimental data to the functional forms for the CPSDs developed in this thesis, and it isolates the contribution of the fundamental mode (fundamental-mode ratio). It can be applied to any geometry. Different models can be applied to obtain an estimate of the reactivity from this ratio:

1. Point kinetics model.
2. Two point kinetics model. This option has been implemented on the program and results are shown in Chapter 5.

6.3 Experimental Data Analysis

Data obtained from experiments based on tank arrays have been analyzed. In Chapter 4, experiment involving one ^{235}U solution tank, two equal tanks, and two different tanks, has been studied. How spatial effects affect the measured CPSD is shown. This study shows that an experiment can be diagnosed to be influenced by spatial effect when:

1. The measured ratio depends on the source and detectors position.
2. The ratio is not constant in frequency, or it is not real.
3. The CPSD polar plot are not contained in the fourth quadrant, and the plot cross the imaginary axes.

Chapter 4 shows how the fitting technique developed here is able to isolate the contribution of the fundamental-mode and obtain a ratio independent of frequency and detectors position. Once the isolation is performed, the previously developed analysis technique to obtain an estimate of the reactivity, based on point kinetics approximation, can be applied.

6.4 Subcriticality Calculations

In Chapter 5, the calculation of the multiplication factor and related kinetics parameters in experiments involving two interacting tanks is presented. The result agree with Monte Carlo calculations using the code KENO with a 27-group library.

Given these results, it can be concluded that subcriticality measurements using the ^{252}Cf frequency-domain methodology are possible even in cases that violate assumptions for the previous theory (point kinetics). Using the present technique, fundamental-mode ratio can be measured directly from the data without the need for parallel neutronic calculations to correct for modal contamination; therefore, reactivity calculations are again possible.

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LIST OF REFERENCES

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VITA

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