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Fundamental Mode Sources in Approach-to-critical Experiments,

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INTRODUCTION

The 1/M method is commonly used in approach-to-critical experiments to ensure criticality safety. Ideally, a plot of 1/M versus amount of nuclear material or separation distance will be linear. However, the result is usually a curve. If the curve is concave up it is said to be conservative, since the critical mass is underestimated. However, it is possible for the curve to be non-conservative and overestimate the critical mass. This paper discusses one of the factors contributing to the shape of the 1/M curve and how it can be predicted and measured.

Two source distributions, producing the same number of spontaneous fission neutrons, will not necessarily contribute equally towards the multiplication of a given system. For this reason equally sized units added during an approach-to-critical will have different effects on the multiplication of the system. A method of denoting the relative importance of source distributions is needed. One method is to compare any given source distribution to its equivalent fundamental-mode source distribution. An equivalent fundamental-mode source is an imaginary source distributed identically in space, energy, and angle to the fundamental-mode fission source that would produce the same neutron multiplication as the given source distribution.

A factor, denoted as g* and defined as the ratio of the fixed-source multiplication to the fundamental-mode multiplication, is used to relate a given source strength to its equivalent fundamental-mode source strength (Spriggs, et al., 1999).

$$g^* \equiv \frac{M_{fs}}{M_f} \tag{1}$$

A method of predicting and measuring the equivalent fundamental-mode source strength, g*S, was tested on the XIX-1 core on the Fast Critical Assembly at the Japan Atomic Energy Research Institute. (Spriggs, et al., 1999) The results showed a 30% difference between measured and calculated values. However, the XIX-1 reactor had significant intermediate energy neutrons. The presence of intermediate energy neutrons may have made the cross section set used for predicted values less than ideal for the system.

This paper shows that applying this method to Flattop, a fast uranium assembly where the cross section set is well characterized, produced much better agreement. The experimental value of the equivalent fundamental-mode source strength was only 5% higher than the predicted value. The method was also applied to the Flattop fast plutonium system. There, the experimentally measured value was 4% lower than the predicted value.

EXPERIMENT

Experimental Theory

The efficiency of a given detector is the count rate, C, divided by the neutron loss rate of the system, N/τ (where N is number of neutrons and τ is neutron lifetime), as given by

$$\varepsilon = \frac{C}{\left(\frac{N}{\tau}\right)} \tag{2}$$

Rewriting in terms of count rate with the fixed-source multiplication, M_{fs}, times the source rate, S, representing the neutron loss rate, (N/τ), the equation becomes

$$C = \varepsilon\left(M_{fs}S\right) \tag{3}$$

Rearranging equation 3 to substitute $g^*/(1-k_{eff})$ for M_{fs} yields

$$C = \frac{\varepsilon g^* S}{1-k_{eff}} \tag{4}$$

For a system containing only an intrinsic source, the count rate would be expected to be

$$C_i = \frac{\varepsilon\left(g_i^* S_i\right)}{1-k_{eff}} \tag{5}$$

where the subscript *i* denotes intrinsic. With the addition of a calibrated neutron source, the count rate would be

$$C_{pi} = \frac{\varepsilon\left(g_i^* S_i + g_p^* S_p\right)}{1-k_{eff}} \tag{6}$$

where the subscript *pi* denotes point plus intrinsic.

The efficiency of the detector, ε, can be eliminated by dividing C_{pi} by C_i. Eliminating ε and rearranging yields

$$g_i^* S_i = \frac{g_p^* S_p}{\left(\frac{C_{pi}}{C_i} - 1\right)} \tag{7}$$

Furthermore, Spriggs, et al. (1999) shows the ratio of count rates to be approximately equal to the ratio of slopes of count rate versus inverse reactivity in the vicinity of delayed critical, yielding

$$g_i^* S_i = \frac{g_p^* S_p}{\frac{m_{pi}}{m_i} - 1}, \tag{8}$$

where m_i is the slope of a plot of detector count rate versus inverse reactivity for the system containing only intrinsic sources and m_{pi} is the slope for the system containing a calibrated source in addition to the intrinsic sources. The point source is a calibrated source whose strength, S_p is known. The g_p^* can be calculated deterministically. Therefore, $g_i^*S_i$ remains the only unknown. Using the slope of a line of many points instead of just one count rate improves statistics, especially for low count rate systems.

FLATTOP

Flattop is natural uranium reflected critical assembly located at Los Alamos National Laboratory in Technical Area 18. It has interchangeable cores including oralloy (93.5% U-235) and plutonium (93.80% Pu-239). The total fissile mass is adjustable with mass adjustment buttons placed on the sides of the core and/or small cylinders of material that can be inserted into a glory hole.

A core is set upon its associated natural uranium pedestal and is placed against a stationary hemisphere of natural uranium. To drive the assembly critical, two quarter-spheres of natural uranium, referred to as safety blocks A and B, are hydraulically driven in against the core. Then three control rods made of natural uranium can be driven via stepper motors into the stationary reflector from below. There are two "small" rods, G and E, and one "large" rod, F. These rods increase reactivity by increasing reflection and decreasing leakage.

Flattop Oralloy Core

The oralloy core consists of two enriched uranium pieces held together with enriched uranium screws (See Figure 1). The sphere has an outer diameter of 12.12 cm (4.770 in). The top half of the sphere is covered by a split cap. The lower part of the cap, roughly ring-shaped, is natural uranium. The upper part of the cap is oralloy. The cap brings the outer dimension of the core up to the inner dimension of the reflector.

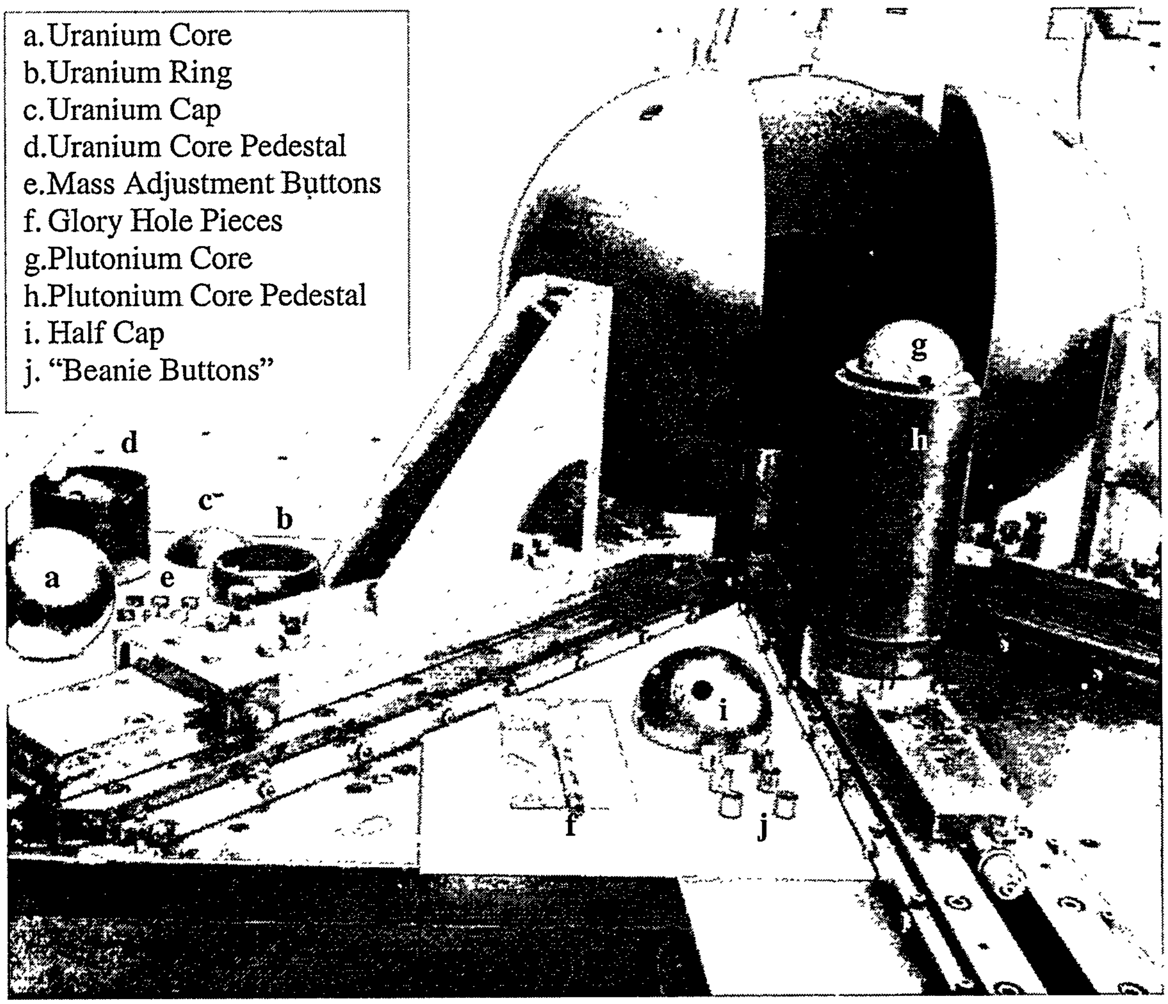

Figure 1: Flattop Components for Uranium and Plutonium Cores

The pedestal for the oralloy core contains space for mass adjustment buttons below the core. These mass adjustment buttons can be either oralloy or natural uranium.

For this experimental setup, there were ten oralloy buttons and one natural uranium button.

The orally core has a glory hole with diameter of 2.54 cm (1 in). There is a glory hole adapter, also made of oralloy, which reduces the diameter of the glory hole from 2.54 cm (1 in) to 1.27 cm (.5 in). For this experiment, the glory hole is loaded with oralloy pieces. There is a void in the center of the glory hole maintained by a thin-walled aluminum can. A source can be placed inside the aluminum can as required by experiment. The total mass of oralloy components, 18,339 g, will be used in the development of the computational model.

Flattop Plutonium Core

The plutonium core consists of two hemispherical pieces; their combined diameter is 9.08 cm (3.576 in). Because the plutonium core has a different (smaller) outer radius than the uranium core, it sits in its own pedestal. Like the uranium core, the plutonium sphere is covered by a cap to increase its diameter to that of the hollow in the reflector. The cap consists of a hemisphere with openings for "beanie buttons." Some "beanie buttons" are natural uranium while others are plutonium. For this experimental configuration, the natural uranium buttons were used.

The plutonium core has a 1.27 cm (.5 in) glory hole. All plutonium pieces, including the core and the glory hole pieces, are clad with 5 mils (.0127 cm) of nickel. The total mass of plutonium components, 6,033 g, will be used in the development of the computational model.

Experimental Method

The experimental method for measuring g*S uses fissile material in a slightly subcritical configuration such that the fundamental mode is excited. A neutron detector is used to measure the count rate at several subcritical configurations. Then a calibrated neutron source is placed within the assembly, and a new count rate is measured at various subcritical configurations. The ratio of the slopes of count rate versus inverse reactivity, along with the known strength of the source, yields a value of the intrinsic equivalent fundamental-mode source strength, g*S, according to equation 8.

COMPUTATIONS

Computational Theory

In equation 1, g* was defined as the ratio of fixed source multiplication to fundamental-mode multiplication. Because the fundamental-mode multiplication is customarily defined as

$$M_f = \frac{1}{1-k_{eff}}, \tag{9}$$

the factor g* can be defined as

$$g^* = M_{fs}\left(1-k_{eff}\right), \tag{10}$$

where values for k-effective and the fixed source multiplication, M_{fs}, are calculated using a deterministic code.

Several properties of g* are of additional interest in manipulating the output of the computational model. As mentioned earlier, g* is the factor that converts a given source distribution to an equivalent fundamental-mode source. Therefore, the g* calculated for each region, g_I*, is multiplied by the source strength of the isotope present in that region to yield a fundamental-mode source strength, Q_i, defined as

$$Q_i = g_i^* S_i . \qquad (11)$$

These fundamental-mode source strengths may be added together to yield the total fundamental-mode source strength, Q

$$Q_{total} = \sum Q_i \qquad (12)$$

The effective g* is calculated as the source strength weighted average of the individual values of g_i*.

$$g^* = \frac{\sum_i g_i^* S_i}{\sum_i S_i} \qquad (13)$$

For the purpose of this experiment, however, it is the predicted and experimental values of Q, or g*S, which are compared.

Use of DANTSYS in Calculations

The first calculation performed using a deterministic code is a k-eigenvalue solution that gives the k-effective of the system as modeled. In DANTSYS, this is accomplished by setting the *ievt* flag to one (Busch, 1996). The systems were modeled at slightly subcritical configurations with k-effective values of 0.990 to 0.999.

A fixed source multiplication must be calculated for each fixed source distribution present in the system. Each combination of region and isotope is considered as a separate source distribution. For example, U-238 is present in both the uranium core and the reflector, but at different concentrations. U-238 in the core will be considered as one source distribution and U-238 in the reflector will be considered as a separate source distribution. Fixed source multiplication calculations are performed by setting the *ievt* flag to negative one and entering a spontaneous fission source distribution (Alcouffe, et al., 1995).

The Hansen-Roach 16-group cross section set was used in all calculations. This is consistent with and allows comparison with the earlier work of Spriggs, et al.

Spontaneous Fission Rates

The spontaneous fission source rate is calculated using the spontaneous fission half-lives and the average prompt neutron multiplicities given in Table 4.

Table 1: Spontaneous Fission Data

Isotope	half life(y)	%SF	ν_p	S(n/kg/s)
^{235}U	7.03E+08	7.00E-09	1.86	1.04E-02
^{238}U	4.47E+09	5.45E-05	2.00	1.36E+01
^{239}Pu	24110	3.00E-10	2.24	1.54E+01
^{240}Pu	6563	5.75E-06	2.15	1.04E+06
^{241}Pu	14.35	2.40E-14	2.25	2.07E+00
^{252}Cf	2.645	3.092	3.77	2.31E+15

In addition to the spontaneous fission source rate, the spontaneous fission spectrum varies by isotope. A spectrum for each isotope is included in the DANTSYS input deck to be used in the computational model. The spectra for the isotopes present in the two Flattop systems are shown in Table 5 using the Hansen-Roach energy group structure.

Table 2: Spontaneous Fission Spectra

Group	Energy Range	^{235}U	^{238}U	^{252}Cf	^{239}Pu	^{240}Pu	^{241}Pu
1	3 -20 MeV	0.186	0.140	0.275	.227	.196	.211
2	1.4 – 3 MeV	0.364	0.362	0.353	.361	.364	.362
3	0.9-1.4 MeV	0.174	0.190	0.149	.162	.171	.167

4	0.4 – 0.9 MeV	0.179	0.200	0.146	.163	.175	.169
5	0.1 – 0.4 MeV	0.083	0.093	0.067	.075	.081	.078
6	17 – 100 keV	0.013	0.014	0.010	.011	.012	.012
7	3 – 17 keV	0.001	0.001	0.000	.001	.001	.001
8-16	3 keV & below	0.0	0.0	0.0	0.0	0.0	0.0
	Average Energy	1.89 MeV	1.69 MeV	2.31 MeV	2.07 MeV	1.93 MeV	2.00 MeV

RESULTS

Data for the uranium and plutonium cores are shown in Figure 1 and Figure 2, respectively. The lower line represents the data for a system with intrinsic sources only. The steeper line represents the data for the system with a point source added.

The calculated value of the equivalent fundamental-mode source strength, g*S, was 1,800 neutrons per second for the uranium system. The experimentally determined value was 1,890 neutrons per second, 5% higher.

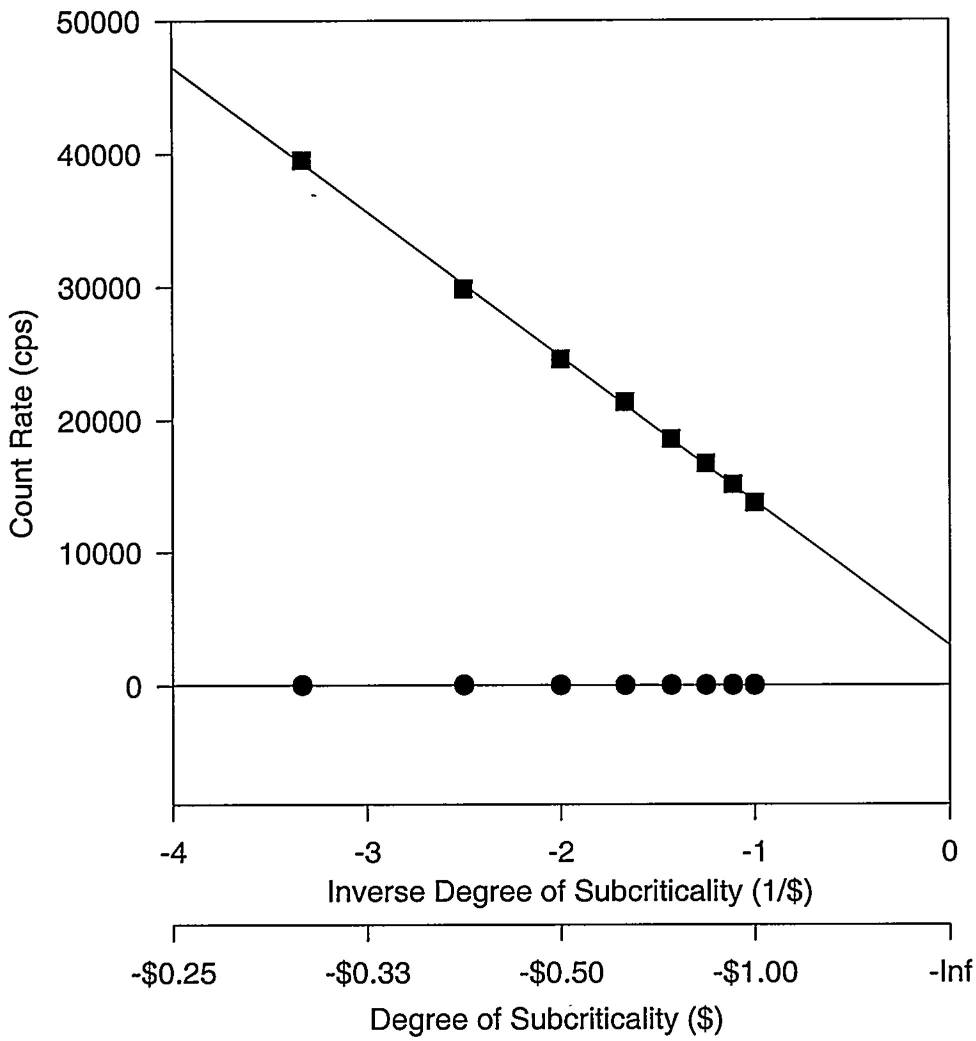

Figure 2: Count Rate vs. Inverse Reactivity for Uranium Core

For the plutonium system, the calculated value of the equivalent fundamental-mode source strength, g*S, was 375,000 neutrons per second. The experimentally determined value was 359,000 neutrons per second, 4% lower.

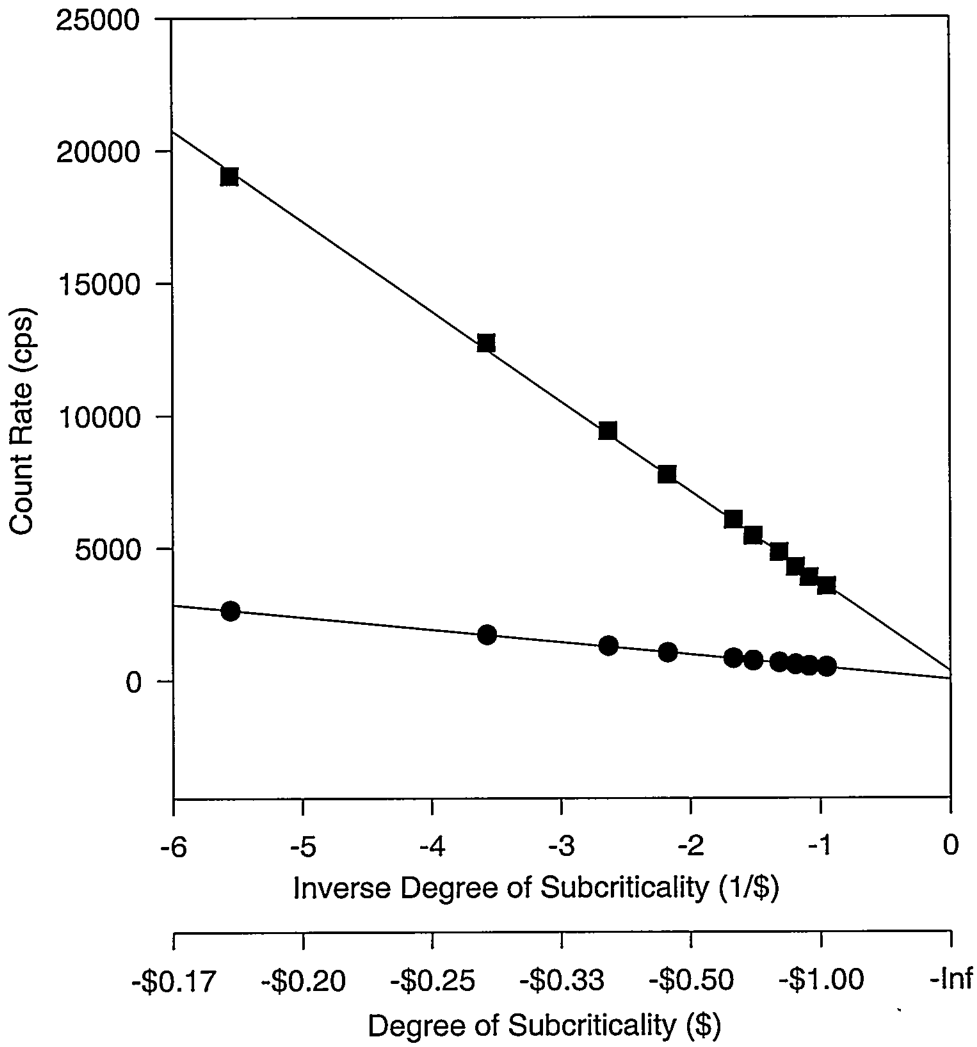

Figure 3: Count Rate vs. Inverse Reactivity for Plutonium Core

DISCUSSION

Using the computational and experimental methods described above to compare calculated and measured values of spontaneous fission rates appears valid for fast systems. Both a fast uranium system and a fast plutonium system show good agreement between predicted and measured values using the techniques described in this paper. Therefore the computational method could be used to predict g* for a given system at various subcritical configurations.

The prediction of g* at various configurations is of interest to criticality safety as it relates to the 1/M method of approach-to-critical. Ideally, a plot of 1/M versus k-effective is linear. However, rearranging equation 10 in terms of 1/M shows that

$$\frac{1}{M_{fs}} = \frac{(1-k_{eff})}{g^*} \tag{14}$$

Therefore, a plot of 1/M will be linear only if g* is constant with k-effective. In cases when g* increases with k-effective, the 1/M plot is said to be conservative because the critical mass is underestimated. However, it is possible for g* to decrease with k-effective yielding a non-conservative 1/M plot. Calculating g* at various subcritical configurations would help predict whether a given approach-to-critical will be conservative or non-conservative.

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