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ABSTRACT

The ^{252}Cf-source-driven noise analysis method determines the subcriticality of a system containing fissionable material from the ratio of cross power spectral densities between the detectors that detect particles from the fission process and between these detectors and an ionization chamber containing a spontaneously fissioning neutron source which provides neutrons to induce fission in the system. This method has two advantages: (a) a calibration is not required and thus subcriticality can be determined from measurements only on the subcritical system of interest, and (b) the subcriticality is independent of the type of detector or its efficiency. These properties of this technique are illustrated by measurements.

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DESCRIPTION OF THE METHOD

The ^{252}Cf-source-driven neutron noise analysis method[1] for obtaining the subcriticality of an assembly of fissile material from cross-power spectral densities (CPSDs) was developed to avoid some difficulties inherent in other measurement methods. This method requires measurement of frequency dependent CPSD $G_{23}(\omega)$ between a pair of detectors (Nos. 2 and 3) in or near the fissile assembly and CPSDs $G_{12}(\omega)$ and $G_{13}(\omega)$ between these detectors and a source of correlated neutron noise from an ionization chamber (No. 1) containing ^{252}Cf, also in or near the fissile assembly. Additionally, the auto-power spectral density $G_{11}(\omega)$ of the source is required. The ratio of spectral densities $G_{12}^{*}G_{13}/G_{11}G_{23}$ is then formed; it is related to the subcriticality as follows:

$$\frac{G_{12}^{*}\ G_{13}}{G_{11}\ G_{23}} = \frac{\bar{\nu}_c}{\bar{\nu}} \frac{I_c}{IRX} \frac{(1-k)}{k} , \qquad (1)$$

where

$\bar{\nu}_c$ = Average number of prompt neutrons from ^{252}Cf fission,

$\bar{\nu}$ = Average number of prompt neutrons from fission in the fissile assembly,

I_c = Average importance of neutrons from ^{252}Cf fission,

I = Average importance of fission neutrons in the system,

R = Correction factor for spatial effects,

X = Neutron dispersion number $\overline{\nu(\nu-1)}/\bar{\nu}$ near k = 1,

k = neutron multiplication factor.

The quantity X, must be modified for k < 0.95 to include subcriticality effects and increased contribution of fluctuations of ^{252}Cf fission neutrons and inherent source neutrons from materials like ^{240}Pu to noise sources in G_{23}.

ADVANTAGES OF THE METHOD

This method of subcriticality determination has several advantages over other methods. First, the quantities of Eq. 1 are known or measurable properties of the assembly of fissile materials at the subcritical state of interest. The subcriticality (k < 1) can be determined without need for a reference measurement near critical (k = 1, self-sustaining chain reaction). Thus, this method can be used in the initial fuel loading of systems where a determination of subcriticality dependent on absolute calibration near critical is not possible. It can also be used in determining the reactivity of assemblies where sufficient material to achieve criticality is not available or where loading to critical would be undesirable. Second, the interpretation of the measured data to obtain the subcriticality does not depend on knowledge of the inherent source strength or the detection efficiency. The independence of detection efficiency results from the fact that the numerator and denominator of Eq. 1 contain the same detection efficiencies.

APPLICATIONS OF THE METHOD

The above advantages of the method allow its use in a variety of applications: (1) initial fuel loading in a wide variety of reactors, (2) refueling of reactors, (3) fuel preparation facilities, (4) fuel processing facilities, (5) fuel storage facilities, (6) zero-power testing of reactors, (7) post-accident situations, and (8) verification of calculational methods for assemblies with k < 1. To date a variety of measurements have been performed which demonstrated the usefulness of the method. The fissile systems included a critical assembly mockup of the Fast Flux Test Facility Reactor containing 540 kg of Pu metal;[1] 7-in.-diam uranium (93.15 wt% ^{235}U) metal cylinders with a variety of heights, and a uranium metal sphere;[1] a plate type research reactor;[2] a uranyl fluoride solution (4.8 wt% ^{235}U) in a 22-in.-diam tank;[3] a mixed plutonium-uranium nitrate solution in a 14-in.-diam tank; a uranyl nitrate solution (93.15 wt% ^{235}U) with uranium density varying between 0.3 and 13.7 g/liter in a 30-in.-diam, 30-in.-high tank;[4] the High Flux Isotope Reactor (HFIR) fuel element[5] submerged in water;[6] and an array of 5000 light-water reactor fuel pins flooded with borated water.[7]

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DETECTION EFFICIENCY INDEPENDENCE

The independence of detection efficiency provides the technique with the advantage that the measurement result does not depend on any detector calibrations. In fact, the measured ratio also does not depend on whether prompt neutrons or gamma rays from fission are detected. These effects were demonstrated in measurements with the HFIR fuel element submerged in water.[5] A variety of detectors with different detection efficiencies were used in these measurements: NaI scintillators (to detect gamma rays), LiI scintillators (to detect neutrons and gamma rays), and BF_3 proportional counters (to detect neutrons). The measured ratios as well as the subcritical reactivities were the same for all types of detectors (Table 1), even with one pair of detectors viewing the fuel element through 8 in. of water.

SOURCE INDEPENDENCE

The measured ratio of spectral densities does not depend on ^{252}Cf source intensities as long as all ^{252}Cf fissions produce a pulse in detection channel 1. The independence of source size is shown by the measurements with uranium metal cylinders presented in Table 2. These measurements were performed in 1975 and again in 1984 with two ionization chambers containing different amounts of ^{252}Cf (0.07 μg and 0.20 μg). In both measurements the detectors were Li glass scintillators but they had different detector efficiencies. These results demonstrated the method's reproducibility even though the sources and detectors were different.

SENSITIVITY

The sensitivity of the method to small changes was demonstrated in experiments with uranyl nitrate solution in a 30-in.-diam, 30-in.-high tank in which the ^{235}U density was varied from 0.3 to 13.7 g/ℓ. The ratio of spectral densities measured with the ^{252}Cf source in the center of the tank and the detectors 180° apart on the tank's radial surface at the midplane is plotted in Fig. 1 as a function of solution concentration. These measurements demonstrate the ability of the method to detect the difference between plain water in the tank and a solution with approximately 200 g of ^{235}U in the entire tank. Thus, the method has high sensitivity for this type of application.

EXPERIMENTS WITH LWR FUEL PINS

Calculations for an approximately 4-m-diam configuration of light water reactor (LWR) fuel elements likewise indicated the feasibility of measuring the subcriticality of large, loosely-coupled arrays by this method.[8,9] The analyses suggested application to the initial loading of both pressurized and boiling water reactors, zero-power testing of reactors (such as shutdown margin measurements after initial loading in BWRs), LWR refueling, and safe storage of LWR spent fuel. In the fuel storage application, direct measurement of subcriticality in the actual fuel storage facilities provides the parameter k, that is directly related to criticality safety; through such measurements, proper credit for fuel burnup can be taken without depending on calculations for criticality safety.

Table 1. Measured ratios of spectral densities for submerged HFIR fuel elements

	Ratio of spectral densities*		
Detector and Location	Measured	Corrected For Reactivity of Detector	Subcritical Reactivity ($)
BF-3 adjacent to fuel	0.0529	0.0492	2.54
Li adjacent to fuel	0.0537	0.0496	2.56
NaI adjacent to fuel	0.0522	0.0484	2.50
Li outside tank	0.0496	0.0496	2.56

*Experimental error is approximately 2% on all ratios.

Table 2. Measured ratios of spectral densities for uranium 93.15 wt% ^{235}U metal cylinders showing that measurements are easily reproducible

Measurement Configuration	Date	Mass (g)	Ratio	^{252}Cf Source Intensity (μg)
4 in. thick, 7 in. diam ^{252}Cf source located in center of flat surface of Li glass scintillators adjacent to the radial surface at the midplane	4/1/75	47290	0.069	0.20
	9/11/84	47020	0.067	0.07

*$G_{12}*G_{13}/G_{11}G_{23}$.

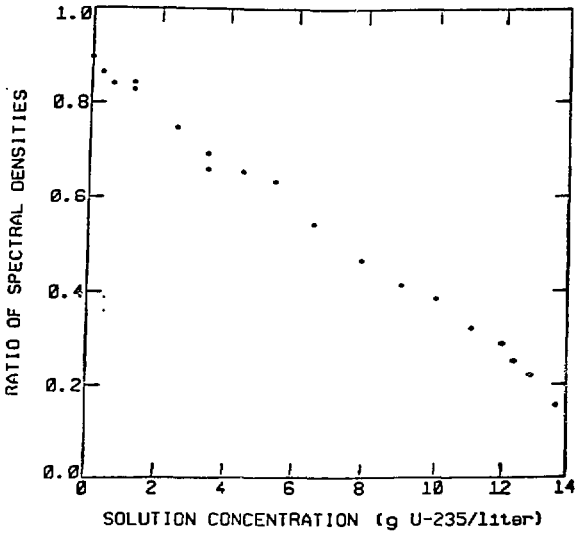

Fig. 1. Measured ratios of spectral densities versus solution concentration for a 30-in.-OD, 30-in.-high tank of uranyl nitrate.

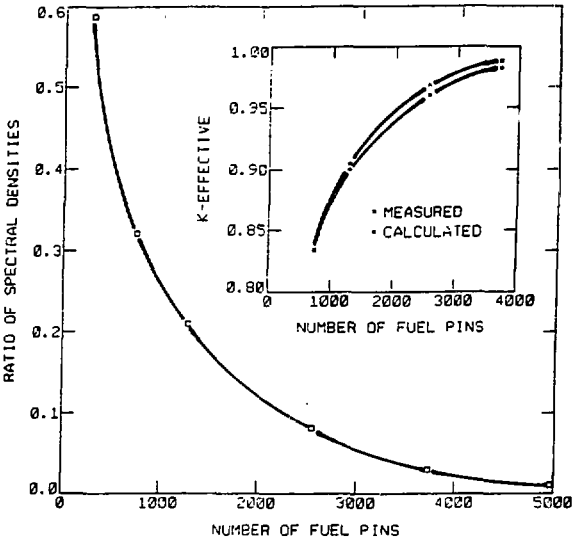

Fig. 2. Measured ratios of spectral densities and neutron multiplication factors for various size arrays of LWR fuel pins.

An initial test of the method for these types of applications was provided by an experiment performed with an array of LWR fuel pins at the Babcock & Wilcox critical facility in Lynchburg, Virginia.[10] Six cylindrical configurations were assembled containing 4961, 3713, 2533, 1281, 749, and 333 pins with effective radii of 66.05, 56.26, 46.65, 33.06, 25.29, and 16.89 cm respectively. In these experiments the boron concentration of the water reflector and moderator was 1510 ppm of natural boron. Measurements were made with the ^{252}Cf neutron source located at the center of the fuel pin configuration. The neutron detectors [^{3}He proportional counters, 76.2 cm long and 1.91 cm diam, with an efficiency of 70 cps per $(nv)_{th}$], could be located at radial increments approximately 15.24 cm outward from the source along a diameter. The ratio of spectral densities $G_{12}{}^{*}G_{11}/G_{11}G_{22}$, for the detectors closest to the outer radial boundary of fuel pin configurations on opposite sides of the arrays is plotted as a function of number of fuel pins in the array in Fig. 2. These ratios were measured to 5% precision in 5 to 30 min. The k values obtained from the ratios of spectral densities using a point kinetics interpretation of the data are also plotted in Fig. 2 as a function of the number of fuel pins in the cylindrical configurations. The values agree within approximately 0.005 with those obtained from VENTURE calculations[11] using 27-group cross sections obtained from ENDF B-IV data (Fig. 2).

SUMMARY

The experiments described here have demonstrated the insensitivity of this method to source intensity and detection efficiency. Thus, it can be implemented easily since it does not require calibrations of neutron source intensities or detector sensitivities. Measurements can be easily repeated over long periods of time using different sources and detectors and achieve the same measured results. The sensitivity of the method to even a small change in uranium concentration in fuel solutions makes it useful for fuel preparation and reprocessing facilities. The proof-of-principle experiments with LWR fuel pins showed that the subcriticality of arrays of LWR fuel pins can be measured by the ^{252}Cf-source-driven neutron noise analysis method, and thus it has promise for on-line monitoring of subcriticality in LWR fuel storage facilities. These experiments also demonstrated an ability to monitor the subcriticality of an array of LWR fuel pins as its size changes. The relatively short measurement times required illustrate the practicality of the method. The experiments were limited in that the size of the tank in which the pins were assembled was 152.4 cm diam. Before practical application of the method can be made to LWR fuel storage and initial loading of LWRs, further experiments should be performed for even larger arrays of LWR fuel.

The results of the experiments performed show that the ^{252}Cf-source-driven noise analysis method for measuring subcriticality has a variety of applications. Its implementation is simplified by the fact that it needs neither source nor detector calibrations to obtain reproducible, interpretable results.

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