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BIAS IN CALCULATED k_{eff} FROM SUBCRITICAL MEASUREMENTS BY THE ^{252}Cf-SOURCE-DRIVEN NOISE ANALYSIS METHOD*

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ABSTRACT

The development of MCNP-DSP, which allows direct calculation of the measured time and frequency analysis parameters from subcritical measurements using the ^{252}Cf-source-driven noise analysis method, permits the validation of calculational methods for criticality safety with in-plant subcritical measurements. In addition, a method of obtaining the bias in the calculations, which is essential to the criticality safety specialist, is illustrated using the results of measurements with 17.771-cm-diam, enriched (93.15), unreflected, and unmoderated uranium metal cylinders. For these uranium metal cylinders the bias obtained using MCNP-DSP and ENDF/B-V cross-section data increased with subcriticality. For a critical experiment [height (h) = 12.629 cm], it was -0.0061 ± 0.0003. For a 10.16-cm-high cylinder ($k \approx 0.93$), it was 0.0060 ± 0.0016, and for a subcritical cylinder (h = 8.13 cm, $k \approx 0.85$), the bias was -0.0137 ± 0.0037, more than a factor of 2 larger in magnitude.

This method allows the nuclear criticality safety specialist to establish the bias in calculational methods for criticality safety from in-plant subcritical measurements by the ^{252}Cf-source-driven noise analysis method.

INTRODUCTION

The ^{252}Cf-source-driven noise analysis method [1, 2], has been used in measurements for subcritical configurations of fissile systems for a variety of applications. Measurements on 25 fissile systems have been performed with a wide variety of materials and configurations. This method has been applied to measurements for (a) initial fuel loading of reactors [3], (b) quality assurance of reactor fuel elements [4], (c) fuel preparation facilities [5], (d) fuel processing facilities [6], (e) fuel storage facilities [7], (f) zero-power testing of reactors [8], (g) verification of calculational methods for assemblies with $k < 1$ [9], and (h) process monitoring [10]. In addition, the method has been applied to the characterization of highly enriched uranium (HEU) storage vaults [11]. Recently, the method's sensitivity has made it useful for nuclear weapons dismantlement verification and inspections for nonproliferation applications [12, 13], and it may be useful for special nuclear material (SNM) inventory. In these latter applications, the method can be used to provide signatures that can be used to identify nuclear weapon systems or components or provide assay of SNMs by comparison with known standards.

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These previous measurements, performed with a wide variety of fission neutron multiplying systems, demonstrated the usefulness of the method. In many of these measurements, the ^{252}Cf-source-driven noise analysis method was used to obtain the subcritical neutron multiplication factor k for a variety of static systems, for which k values varied from 0.35 to 0.99. Three of these measurements [14-16] were supported by the Power Reactor and Nuclear Fuel Development Corporation of Japan (PNC) and addressed the application of this method to fuel reprocessing for breeder reactors. In one of these measurements [14], the k value was obtained from measurements every 6 s as a tank of uranyl nitrate solution was drained from a k of 0.96 to 0.35 at a rate of 0.01 Δk/s. This dynamic measurement, which was part of the PNC program, was the first step in applying this method to dynamically monitor fissile configurations in a future reprocessing plant.

In these previous interpretations of measured data, simple models were used to extract the value of the neutron multiplication factor. This results in limitations in the application of this method since the usefulness of the simple models depends on the experience of those performing the measurements and previous use of the method in similar configurations of similar materials. The recent development of Monte Carlo codes KENO-NR [17] and MCNP-DSP [18] allows a direct calculation of the measured observables in a ^{252}Cf-source-driven noise analysis measurement. Thus the validity of the Monte Carlo methods and the cross-section data can be verified by a direct calculation of measured observables [5] in subcritical experiments. This allows the criticality safety specialist to assess the usefulness of calculational methods for criticality safety.

Recent studies with these Monte Carlo codes [19] have duplicated the previously measured high sensitivity of noise measured parameters to changes in the configuration or materials of fissile systems. The calculational studies have shown that for a variety of fissile solutions, systems parameters such as the coherence between detectors have a factor of 50 enhanced sensitivity to changes above the sensitivity of k_{eff}. This is typical for systems with neutron multiplication factors of ~0.9. This increased sensitivity to calculational methods means that for verifying calculational methods, a subcritical experiment at a k ~ 0.9 by the ^{252}Cf-source-driven noise analysis method is more sensitive and may be more useful than an experiment at $k = 1$. The noise measured parameters can be obtained from measurements with an uncertainly of ±1% or less. The uncertainly of the Monte Carlo calculations can also be ±1% or less. In many cases, changes that affect k only within the statistical uncertainty of the Monte Carlo calculation produce significant changes in the calculated noise measured parameters, well outside the limits of the uncertainty on these noise measured parameters (either measured or calculated). This increased sensitivity makes this technique useful for process monitoring and control. The measured parameters could be used as a signature to define normal operation of the process, and subsequent signatures could be compared to that for normal operation by pattern recognition algorithms to determine deviations from normal operation of the process.

However, the criticality safety engineer must be able to also determine the bias in neutron multiplication factor calculations so that he can, with confidence in the uncertainties, use these calculational methods for in-plant applications. This paper describes a method to establish the bias introduced by the calculations and the cross-section sets from subcritical in-plant measurements using the ^{252}Cf noise analysis method. These in-plant measurements are now practical since the hardware to obtain the measured quantities is a system consisting of a laptop personal computer with data acquisition and processing cards along with the detection systems. This use of subcritical measurements is illustrated by measurements with unreflected and unmoderated uranium (93.15 wt % ^{235}U) metal cylinders [20]. Measurements were also performed for these uranium metal cylinder experiments at delayed criticality [21] so that the biases for the subcritical configuration can be compared to those obtained from the critical experiments. Traditionally, biases have been obtained from critical experiments and may not necessarily be relevant for the subcritical configurations of interest to the criticality safety specialist. This may result from differences in the neutron spectrum in the critical experiments, especially if a moderator was added or a neutron absorber was removed to achieve a delayed critical configuration. Leakage in a subcritical configuration could also be a controlling factor, whereas a critical configuration may have been achieved by increased size or addition of a reflector, thus decreasing the leakage.

^{252}Cf-SOURCE-DRIVEN NOISE ANALYSIS METHOD

The ^{252}Cf-source-driven neutron noise analysis method for obtaining the subcritical neutron multiplication factor of a configuration of fissile material from cross-power spectral densities (CPSDs) was developed to avoid difficulties inherent in other subcriticality measurement methods such as the dependence on detection efficiency or the need for a calibration at a known reactivity condition near delayed critical. This method requires measurement of the frequency-dependent CPSD $G_{23}(\omega)$ between a pair of detectors (detectors 2 and 3) located in or near the fissile material and the measurement of CPSDs $G_{12}(\omega)$ and $G_{13}(\omega)$ between these same detectors and a source of neutrons emanating from ionization chamber 1, which contains ^{252}Cf and is also positioned in or near the fissile material. Also required is the autopower spectral density (APSD) $G_{11}(\omega)$ of the source. A particular ratio of spectral densities, $G_{12}^{*}G_{13}/G_{11}G_{23}$, with the asterisk denoting complex conjugation, is independent of the detector efficiency, and it can be related to the subcritical neutron multiplication factor. For systems without significant neutron sources and uncorrelated detector background, it is also independent of ^{252}Cf source intensity. Another useful quantity is the coherence: $\gamma_{ij} = |G_{ij}^2|/G_{ii}G_{jj}$, which is the fraction of common information in any two signals i and j, where G_{ij} is the CPSD between detectors i and j and G_{ii} and G_{jj} are the APSD of detectors i and j respectively. In a measurement, the source and the detectors would normally be located so that point kinetics or modified point kinetics would be applicable for a wide range of k values. Normally, the source and detector would be located to minimize the number of particles from the source that reach the detectors without having an interaction in the system.

Previously, Fourier processors obtained only these frequency-dependent parameters. The new laptop processor that has been developed obtains the correlation functions as well, which for any detector and the source are related to the time distribution of counts in a detector after ^{252}Cf fission in the source (similar to a randomly pulsed neutron measurement with the source [22]). The correlation function measurement between both detectors corresponds to the Rossi-α measurement [23]. In addition, this processor obtains the number of times n pulses occur in a data block. From this latter distribution of n pulses, the n and n factorial moments can be obtained. All of these measured quantities as well as the APSDs and CPSDs and quantities derived from them can be calculated by MCNP-DSP. Note that the APSDs and CPSDs can also be calculated with KENO-NR. MCNP-DSP differs from KENO-NR in that with continuous energy cross sections, it tracks both neutron and/or gamma rays and it has a more realistic treatment of particle tracking and detection effects, whereas KENO-NR uses group cross sections and treats neutrons only.

The experimental data obtained from a ^{252}Cf-source-driven noise analysis measurement are all related to the subcriticality in a variety of ways. Simple expressions can be derived from point kinetics to illustrate the dependence of the noise measured parameters on $\Delta k/k$. These relationships have all been reported in the literature [1] and will not be repeated here. These expressions all involve $\Delta k/k$ in the denominator to various powers as follows: the APSD of a detector is related to the second power; the CPSD between a detector and the source, to the first power; the CPSD between detectors, to the second power; the coherence between the detectors and the source, to the second power; the coherence between the detectors, to the fourth power; and the ratio of spectral densities, to the first power. In addition, the time domain measured data, such as the time distribution of counts in a detector with respect to a previous count in the same or another detector, are related to the second power of $\Delta k/k$. The time distribution of counts in a detector with respect to a previous ^{252}Cf fission are related to the first power of $\Delta k/k$, and the multiplicities, to various powers of $\Delta k/k$. The delay of the time distribution and the decrease in the frequency content of the APSD and CPSD as the frequency increases are related to the prompt neutron decay constant, which depends on the ability to calculate the energy dependence of the neutron flux. These higher power dependencies on $\Delta k/k$ explain the high sensitivity of noise measured parameters to the subcriticality that has been observed experimentally and verified by Monte Carlo calculations with KENO-NR and MCNP-DSP. The Monte Carlo codes that have been developed for this type of analysis are given in Table I. KENO-AK and MCNP-DSP are modifications of KENO-V.a and MCNP4a to permit a more physical treatment of the neutron interaction on an event-by-event basis. Both codes follow prompt particles from the fission chain multiplication process to extinction and thus, in principle, cannot be used for systems above prompt criticality. In practice, at $k > 0.995$, fission chain multiplication may momentarily be much above the average, and the calculations are not practical. KENO-AK, which contains the physics modifications of KENO-NR, is used to calculate k for KENO-NR geometries. KENO-AK and MCNP-DSP calculate k in much the same way as KENO-V.a and MCNP4a, respectively, except with the improved treatment of interaction on an event-by-event basis. The k calculation includes delayed neutrons. KENO-AK follows the fission chain multiplication process to extinction for each batch and thus cannot be used in practice for $k > 0.995$. In MCNP-DSP, an attempt was made not to change the basic structure of the MCNP4a k calculation but to incorporate the improved physics modifications.

METHOD TO ESTABLISH BIAS IN k_{eff}

In-plant subcriticality measurements can be subdivided into two types: well-characterized systems and systems that have some limitations on description of materials or configuration. In either case the bias can be established. A well-characterized system is a system where all the constituents and configuration are precisely known from additional physical, chemical, isotopic, impurity, etc., analyses that have been performed to characterize the system precisely. An example of this would be a well-defined tank of uranyl nitrate solution whose configurations and

TABLE I. Existing Codes For Calculations

Noise measured parameters[a]	KENO-NR	MCNP-DSP
Analog k calculation[b]	KENO-AK	MCNP-DSP
Conventional k	KENO-V.a	MCNP4a
Comment 1	Group cross section	Point cross Section
Comment 2	Neutrons only	Neutrons and gamma rays

[a]Improved physics treatment on event-by-event basis.
[b]Calculates k as in conventional codes but with improved physics on event-by-event basis with no biasing or weighting.

constituents have been measured. The specifications of this system are such that it could serve as a benchmark for calculations to verify the ability to calculate k and the bias. The other type of system is not as well characterized. It may be a system in which doing the analyses would be destructive. Such an example might be a concrete storage array for HEU where the unbound water content of the concrete is not known. Wet concrete can have a factor of greater than 2 more water than dry concrete. However, this type of system can still be used to establish the bias in calculational methods if the assumptions about the composition of the concrete made in the determination of the bias from a subcritical experiment with the array are used in subsequent criticality safety analysis.

Various noise measured parameters can be used to establish the bias on the calculated neutron multiplication factor. The sequence for this determination of calculational bias in k is as follows. Perform a subcritical in-plant measurement with a well-defined system that can be characterized precisely for calculations. This may require care in configuring the system and additional analyses to determine the constituents of the system. If the system is not well characterized, the assumptions made about the constituents will produce a bias associated also with the assumptions made about the constituents. With the Monte Carlo code, calculate a noise measured parameter. Also calculate the sensitivity of the noise measured parameter P to changes in k, $(\Delta P/P)/(\Delta k/k)$. These changes might be, for example, a small change in the height of a bare cylinder of fissile material. The change in height should be in the direction that will produce the measured value of P and should be as small as practical to achieve the required statistical precision, but it should be at least as large as to make P calculated match P measured. Now $(P - P')/P$ is known, where P' is calculated for the perturbed height and matches the measured value. For the original height and the perturbed height, calculate the value of k from which $\Delta k/k$ can be obtained as $(k - k')/k$, where k' is for the perturbed height case. This sensitivity coefficient $(\Delta P/P)/(\Delta k/k)$ can be used to determine the bias in k since the comparison of the calculated and measured P gives $\Delta P/P$. Thus the value of $k - k'$ is the bias.

The ^{252}Cf-source-driven noise analysis measurement produces a wide variety of measured parameters. Which parameters should be utilized to obtain the bias in k? This parameter should be related to $\Delta k/k$ and should not depend on detection effects. It has been shown for a wide variety of systems that the ratio of spectral densities, $R = G_{12}^{*}G_{13}/G_{11}G_{23}$, is independent of detector sensitivity and that for uranium systems it is also independent of source intensity, the latter as long as there is no significant uncorrelated background counts in the detectors. Thus, it is the ideal parameter for establishing the bias. Using point kinetics, $\Delta k/k$ has been shown to depend on the parameter R as follows:

$$\Delta k/k = \frac{C_1 R}{1 - C_2 R},$$

where C_1 and C_2 contain only constants associated with the subcritical state of the fissile system. For $\Delta k/k \leq 0.2$, the second term in the denominator is small, and the ratio of spectral densities is almost linear with $\Delta k/k$. This near linear dependence [23] is shown in Fig. 1 for a variety of systems: (a) coupled HEU metal cylinders, (b) slab tank of aqueous Pu-U nitrate, (c) annular tank of Pu-U nitrate, (d) cylindrical tank of uranyl nitrate, (e) cylindrical tank of uranyl (4.95% ^{235}U) fluoride aqueous solution, and (f) a proposed space power reactor SP-100. This linearity is not essential, but it could simplify the perturbation analysis to obtain the sensitivity coefficient.

Other parameters such as the coherence between detectors have a higher sensitivity to changes but depend on detection efficiency. However, if the detectors are of the type that can be simply incorporated into the calculation, the coherence is also useful to establish the bias. A simple example is a ^{3}He proportional counter operated experimentally to count all the absorption reactions with neutrons. This can be modeled

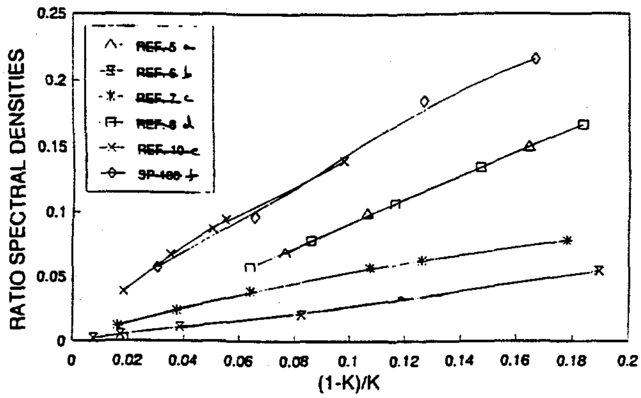

Fig. 1. Ratio of spectral densities versus (1 - *k*)/*k* for a variety of fissile systems.

quite precisely in the calculation without introducing any significant source of uncertainty.

BIAS DETERMINATION FOR URANIUM METAL CYLINDERS

As an example of a well-defined system that can serve to benchmark calculations, consider the experiments with HEU metal cylinders. Both subcritical measurements by the ^{252}Cf-source-driven noise analysis method and critical experiments have been performed for unreflected, unmoderated enriched uranium metal cylinders at the Oak Ridge Critical Experiments Facility. For this example, the bias will be obtained from both critical experiments and subcritical experiments and compared. The critical experiment was performed in 1962 and is reported in Ref. 21. The properties of delayed critical configuration are given in Table II. The delayed critical configuration was calculated to establish the bias in k at delayed critical using MCNP-DSP and the ENDF/B-V cross sections. The calculated value of k was 0.9939 ± 0.0004. Since the k of the experimental configuration of Table II is 1.0000, the bias in k from the critical experiment is -0.0061 ± 0.0004.

Noise analysis measurements with subcritical configurations of uranium metal cylinders with this diameter and with a height of 10.16 cm were performed in both 1975 (Ref. 20) and 1984 (Ref. 24). In both experiments, the same metallic parts were used for the subcritical assembly. The ratio of spectral densities obtained with different sources and detectors 9 years apart were within 2%. The measured ratio of spectral densities and the calculated ratios of spectral densities for this and other heights are given in Table III. The height was perturbed to obtain the sensitivity coefficient, which was 9.4 ± 0.8. Thus the ratio of

TABLE II. Description of Critical Configuration of an HEU Metal Cylinder

Parameter	Value
Diameter, cm	17.771
Critical height, cm	12.629
Enrichment, wt % ^{235}U	93.15[a]
Uranium density, g/cm^3	18.759

[a]The other isotopes were present as follows: 0.97 wt % ^{234}U, 0.24 wt % ^{236}U, and 5.64 wt % ^{238}U.

TABLE III. Measured and MCNP-DSP-ENDF/B-V Calculated Ratios of Spectral Densities for 17.771-cm-diam Uranium (93.15) Metal Cylinders

	Ratio of Spectral Densities	
Cylinder Height (cm)	Measured	Calculated
8.13	0.150 ± 0.003	0.1780 ± 0.0025
8.89	0.1163 ± 0.0020	0.1259 ± 0.0009
10.16	0.0694 ± 0.0008	0.0736 ± 0.0005
10.477	0.0587 ± 0.0004	0.0642 ± 0.0005
10.795	0.0463 ± 0.0002	0.0520 ± 0.0005

spectral densities is almost a factor of 10 more sensitive to changes than k itself. The resulting bias in k for the subcritical 10.16-cm-high cylinder is -0.0060 ± 0.0016, which is very close to that from the critical experiment. The uncertainty in the sensitivity coefficient and the bias was obtained from propagation of errors and could be reduced by additional calculational time. In addition to the 10.16-cm-high cylinder, the bias was established for other cylinder heights. The biases for these MCNP-DSP calculations with ENDF/B-V cross sections are given in Table IV and plotted in Fig. 2 as a function of cylinder height. The bias generally increases with subcriticality, and for this case the bias for the more subcritical configuration ($k \approx 0.85$) is not the same as that from the critical configuration and is a factor of 2 larger than from the critical experiment.

CONCLUSIONS

The development of MCNP-DSP, which allows direct calculation of the measured time and frequency analysis parameters from subcritical measurements using the ^{252}Cf-source-driven noise analysis method, permits the validation of calculational methods for criticality safety with in-plant subcritical measurements. In addition, a method of obtaining the bias in the calculations, which is essential to the criticality safety specialist, is illustrated using the results of measurements with 17.771-cm-diam, enriched (93.15), unreflected, and unmoderated uranium metal cylinders. For these uranium metal cylinders, the bias obtained using MCNP-DSP and ENDF/B-V cross-section data increased with subcriticality. For a critical experiment (height h = 12.629 cm) it was -0.0061 ± 0.0003. For a 10.16-cm-high cylinder ($k \approx 0.93$), it was 0.0060 ± 0.0016, and for a subcritical cylinder (h = 8.13 cm, $k \approx 0.85$) the bias was -0.0137 ± 0.0037, more than a factor of 2 larger in magnitude.

This method allows the nuclear criticality safety specialist to establish the bias in calculational methods for criticality safety

TABLE IV. Bias from Critical and Subcritical Experiments with 17.771-cm-diam Uranium (93.15) Metal Cylinders

Height (cm)	Calculated[a] Neutron Multiplication Factor, k_{eff}	Calculational[a] Bias in k_{eff}
8.13	0.8498 ± 0.0037	-0.0137 ± 0.0037
8.89	0.8786 ± 0.0031	-0.0085 ± 0.0031
10.16	0.9270 ± 0.0020	-0.0077 ± 0.0021
10.477	0.9385 ± 0.0014	-0.0068 ± 0.0014
10.795	0.9493 ± 0.0009	-0.0074 ± 0.0009
12.629	0.9939 ± 0.0004	-0.0061 ± 0.0003

[a]MCNP-DSP with ENDF/B-V cross-section data.

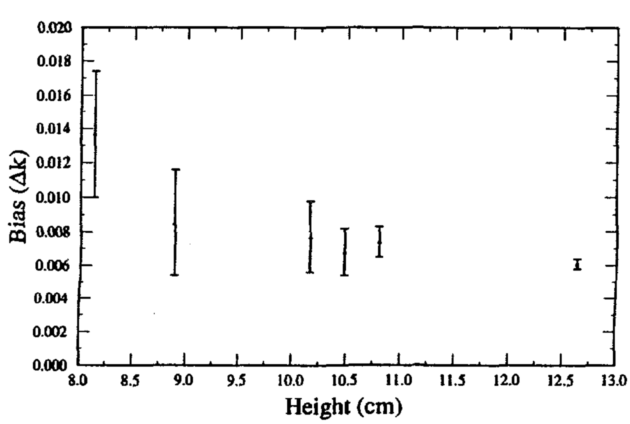

Fig. 2. Bias from calculations with ENDF/B-V cross sections for uranium (93.15) metal cylinders as a function of cylinder height.

from in-plant subcritical measurements by the ^{252}Cf-source-driven noise analysis method.

REFERENCES

1. J. T. Mihalczo, V. K. Paré, G. L. Ragan, M. V. Mathis, and G. C. Tillet, "Determination of Reactivity from Power Spectral Density Measurements with ^{252}Cf," *Nucl. Sci. Eng.*, **60**, 29 (1978).
2. J. T. Mihalczo, W. T. King, and E. D. Blakeman, "^{252}Cf-Source Driven Neutron Noise Analysis Method," presented at Workshop on Subcriticality Reactivity Measurements, Albuquerque, New Mexico, August 1985.
3. W. T. King, J. T. Mihalczo, and E. D. Blakeman, "Preliminary Investigation of the ^{252}Cf Source Driven Noise Analysis Method of Subcriticality Measurement in LWR Fuel Storage and Initial Loading Applications," *Trans. Am. Nucl. Soc.*, **47**, 239 (1984).
4. J. T. Mihalczo and W. T. King, "Quality Assurance Verification of High-Flux Isotope Reactor Fuel Elements by the ^{252}Cf-Source-Driven Noise Analysis Method," *Nucl. Technol.*, **84,** 205 (1989).
5. J. T. Mihalczo, W. T. King, and E. D. Blakeman, "^{252}Cf-Source-Driven Neutron Noise Analysis Measurements for Coupled Uranium Metal Cylinders," *Trans. Am. Nucl. Soc.*, **49**, 241 (1985).
6. J. T. Mihalczo, E. D. Blakeman, and W. T. King, "Subcriticality Measurements for Two Coupled Uranyl Nitrate Solution Tanks Using ^{252}Cf-Source-Driven Neutron Noise Analysis Methods," *Trans. Am. Nucl. Soc.*, **52**, 640 (1986).
7. J. T. Mihalczo, W. T. King, and E. D. Blakeman, "Decoupling of Uranium Metal with Borated Plaster Using ^{252}Cf Noise Analysis Methods," *Trans. Am. Nucl. Soc.*, **50**, 307 (1985).
8. W. T. King and J. T. Mihalczo, "Power Spectral Density Measurements with ^{252}Cf for a Light-Water-Moderated Research Reactor," *Trans. Am. Nucl. Soc.*, **33**, 796 (1979).
9. J. T. Mihalczo, W. T. King, E. B. Johnson, and E. D. Blakeman, "Subcriticality Measurements for a Fuel Solution Tank with Changing Fuel Concentration Using ^{252}Cf-Source Driven Neutron Noise Analysis," *Trans. Am. Nucl. Soc.*, **45**, 337 (1983).
10. J. T. Mihalczo, "Use of Noise Analysis Methods in Process Monitoring of Future Fuel Cycles," in *Proceedings of Global '93: Future Nuclear Systems-Emerging Fuel Cycles and Waste Disposal Options, Seattle, Sept. 12-17, 1993*, CONF-930913-24, 1993.
11. T. E. Valentine and J. T. Mihalczo, "^{252}Cf-Source-Driven Noise Analysis Measurements for Characterization of HEU Storage Vaults," *Trans. Am. Nucl. Soc.*, **69**, 246 (Nov. 1993).
12. J. T. Mihalczo and V. K. Paré, Nuclear Weapons Identification System (NWIS),"article for *Arms Control and Nonproliferation Technologies,* Y/WR-149, Report on Nuclear Warhead Dismantlement, Lawrence Livermore National Laboratory, DOE/AN/ACNT-94C (Third Quarter 1994).
13. "Nuclear Weapons Identification System Signatures for Verification of Trainers Returned to the Y-12 Plant," Y/WR-145, National Security Program, Weapon Returns Program, prepared for U.S. DOE Defense Programs Packaging Workshop, May 16-20, 1994.
14. J. T. Mihalczo, E. D. Blakeman, G. E. Ragan, E. B. Johnson, and Y. Hachiya, "Dynamic Subcriticality Measurements Using the ^{252}Cf- Source-Driven Noise Analysis Method," *Nucl. Sci. Eng.*, **104**, 314 (1990).
15. J. T. Mihalczo, E. D. Blakeman, G. E. Ragan, R. C. Kryter, H. Seino, and R. C. Robinson, "^{252}Cf-Source Driven Noise

Measurements of Subcriticality for a Slab Tank of Aqueous Pu-U Nitrate," *Nucl. Sci. Eng.*, **107**, 35-57 (1991).

16. J. T. Mihalczo, E. D. Blakeman, G. E. Ragan, R. C. Kryter, H. Seino, and R. C. Robinson, "^{252}Cf-Source Driven Noise Measurements of Subcriticality for an Annular Tank Containing Aqueous Pu-U Nitrate," *Nucl. Technol.*, **94**, 336-60 (June 1991).
17. E. P. Ficaro, *KENO-NR: A Monte Carlo Code Simulating the ^{252}Cf-Source-Driven Noise Analysis Experimental Method for Determining Subcriticality*, Ph.D. Dissertation, University Of Michigan, 1991.
18. T. E. Valentine, *MCNP-DSP: A Neutron and Gamma Ray Monte Carlo Calculation of Source Driven Noise Measured Parameters*, Ph.D. Dissertation, University of Tennessee, 1995.
19. J. T. Mihalczo and T. E. Valentine, "Calculational Verification and Process Control Applications Utilizing the High Sensitivity of Noise Measurement Parameters to Fissile System Configuration," *Nucl. Sci. Eng.* (in press for October 1995 issue).
20. J. T. Mihalczo, W. T. King, and E. D. Blakeman, "Subcriticality Measurements for Coupled Uranium Metal Cylinders Using the ^{252}Cf-Source-Driven Neutron Noise Analysis Method," *Nucl. Sci. Eng.*, **95**, 1 (1987).
21. J. T. Mihalczo, "Prompt Neutron Lifetime in Critical Enriched-Uranium Metal Cylinders and Annuli," *Nucl. Sci. Eng.*, **20**, 60 (1964).
22. J. T. Mihalczo, "The Use of Californium-252 as a Randonly Pulsed Neutron Source for Prompt Neutron Decay Measurements," *Nucl., Sci. Eng.*, **53**, 393-414 (1974).
23. J. D. Orndoff, "Prompt Neutron Periods of Metal Critical Assemblies," *Nucl. Sci. Eng.*, **2**, 450 (1957).
24. J. T. Mihalczo and E. D. Blakeman, "Safer Fuel Loading and Initial Reactor Startup Using the ^{252}Cf Source Driven Noise Analysis Method," *Trans. Am. Nucl. Soc.*, **60**, 244-245 (1990).