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Benchmark Analysis of Subcritical Noise Measurements on a Nickel-Reflected Plutonium Metal Sphere

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John D. Bess
Jesson Hutchinson

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BENCHMARK ANALYSIS OF SUBCRITICAL NOISE MEASUREMENTS ON A NICKEL-REFLECTED PLUTONIUM METAL SPHERE

John D. Bess

Idaho National Laboratory, P.O. Box 1625, MS 3855, Idaho Falls, ID 83415-3855, john.bess@gmail.com

Jesson Hutchinson

Los Alamos National Laboratory, P.O. Box 1663, MS B228, Los Alamos, NM 87545

Subcritical experiments using californium source-driven noise analysis (CSDNA) and Feynman variance-to-mean methods were performed with an alpha-phase plutonium sphere reflected by nickel shells, up to a maximum thickness of 7.62 cm. Benchmark models have been developed that represent these subcritical experiments, and an analysis of the uncertainty in the experiment and methods was performed. The eigenvalues determined using the Feynman method are up to approximately 2.5% lower than those determined using either the CSDNA method or the Monte Carlo codes. The uncertainty in the results from either method was not large enough to account for the bias between the two experimental methods. An ongoing investigation is being performed to assess what potential uncertainties and/or biases exist that have yet to be properly accounted for. The dominant uncertainty in the CSDNA analysis was the uncertainty in selecting a neutron cross-section library for performing the analysis of the data. The uncertainty in the Feynman method was equally shared between the uncertainties in fitting the data to the Feynman equations and the neutron multiplicity of ^{239}Pu. Material and geometry uncertainties in the benchmark experiment were generally much smaller than uncertainties in the analysis methods.

I. INTRODUCTION

The experiments consisting of a plutonium metal sphere reflected by nickel shells are part of a series of subcritical benchmark experiments designed for the evaluation and improvement of integral data for polyethylene, acrylic, nickel, copper, tungsten, lead, and manganese.[1] These experiments are to be included in the International Criticality Safety Benchmark Evaluation Project (ICSBEP) Handbook.[2] The polyethylene and acrylic experiments have already been performed,[3] and an evaluation of a polyethylene-reflected subcritical benchmark has already been completed.[4] The evaluation of the nickel-reflected experiments is being completed for inclusion in the September 2010 edition of the ICSBEP Handbook.

Thirteen separate subcritical measurements were conducted with an α-phase plutonium sphere at the Critical Experiments Facility (CEF) at the Device Assembly Facility (DAF) at the Nevada Test Site between September 15-25, 2008. Subcritical measurements were performed using Californium Source-Driven Noise Analysis (CSDNA) and Feynman variance-to-mean methods. The CSDNA method was used to investigate six configurations consisting of the bare BERP (Beryllium Reflected Plutonium) ball[5] and the BERP ball surrounded by different nickel reflector thicknesses: 1.27, 2.54, 3.81, 5.09, and 7.62 cm. The Feynman method was used to characterize these six configurations as well as a seventh consisted of the BERP ball surrounded by 6.35 cm of nickel reflector. The placement of the experiment in the Feynman and CSDNA methods were similar except that the californium source was not used in the Feynman method, and a different set of detectors was utilized for each experimental method. These experiments represent the first time that analysis using the Feynman method has been assessed as part of an ICSBEP benchmark evaluation.

II. EXPERIMENT DESCRIPTION

The plutonium sphere, clad in a stainless steel shell, was placed atop an aluminum stand that was connected to an aluminum base plate. The entire configuration was set atop a stainless steel cart centered within a large room. This configuration represented the basic design for all experimental configurations. Nickel reflector shells of increasing thickness were then placed surrounding the plutonium sphere and supporting stand. Detection equipment was placed around the experiment based upon the type of subcritical measurements being performed.

II.A. CSDNA Measurements

The CSDNA measurement method incorporates the correlation between source and detector signals.[6,7] This technique utilizes a ^{252}Cf source inside an ionization chamber that produces a pulse for each spontaneous fission event and then looks at the distribution between source and detector events as well as between individual detector events. The method provides measured quantities that are related to the subcritical reactivity and can be directly calculated for the verification of calculation methods and cross section data sets. The method is independent of detector efficiency and does not require measurements near delayed critical. At least two detectors are required for CSDNA measurements; typically more are used to improve measurement statistics.

Aluminum alignment plates were placed on the aluminum base for the experiment and used to align two polyethylene blocks 12.70 cm from the center of the plutonium sphere. Each block contained two ^{3}He proportional counters. The ^{252}Cf source ionization chamber was located at the top pole of the outer spherical surface for each CSDNA measurement. Figure 1 shows the bare sphere configuration using the CSDNA method.

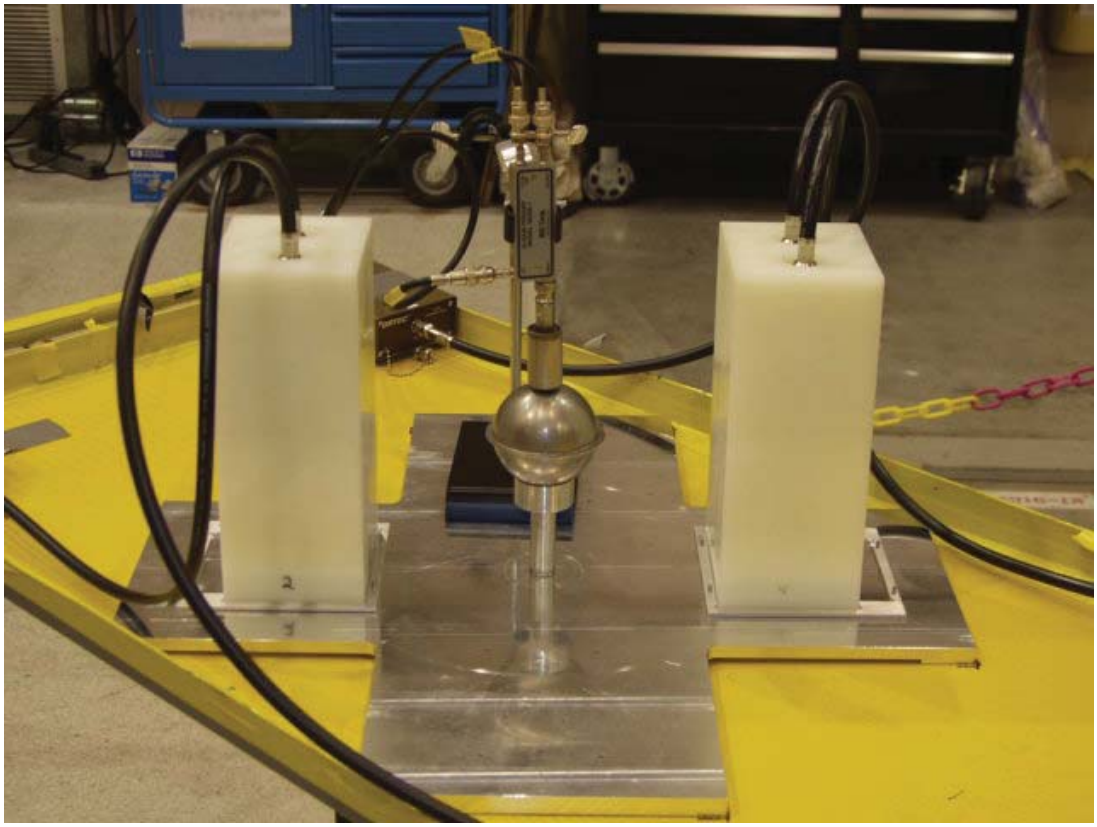

Fig. 1. Photograph of the Bare Plutonium Sphere Configuration using the CSDNA Method.

II.B. Feynman Measurements

The Feynman variance-to-mean method was introduced in 1956 (Ref. 8), which is used to investigate the differences between the detector count data and that which would be expected by a random source. Originally Feynman used this method to predict the number of neutrons released per fission, but the method has also been utilized for other applications, including the determination of the multiplication of subcritical systems. Data is recorded for the occurrences in each detector, which is then analyzed in the time domain to create a histogram of the results. While a random source would follow a Posson distribution, as the multiplication of a correlated system increases, this distribution will then deviate. The Hansen-Dowdy formulism can then be used to determine the multiplication of the system from the moments of the count-rate data.[9]

Figure 2 shows the configuration of the plutonium sphere surrounded by a 1.27-cm-thick nickel shell during analysis with the Feynman method. A detector system was placed 50 cm away from the center of the plutonium sphere. The detector system was comprised of a cadmium coated polyethylene block with a bank of fifteen ^{3}He proportional counters. The detectors were essentially decoupled from the system being analyzed and their impact on system reactivity was practically negligible. The bottom of the detector system rested on the same cart as the aluminum plate.

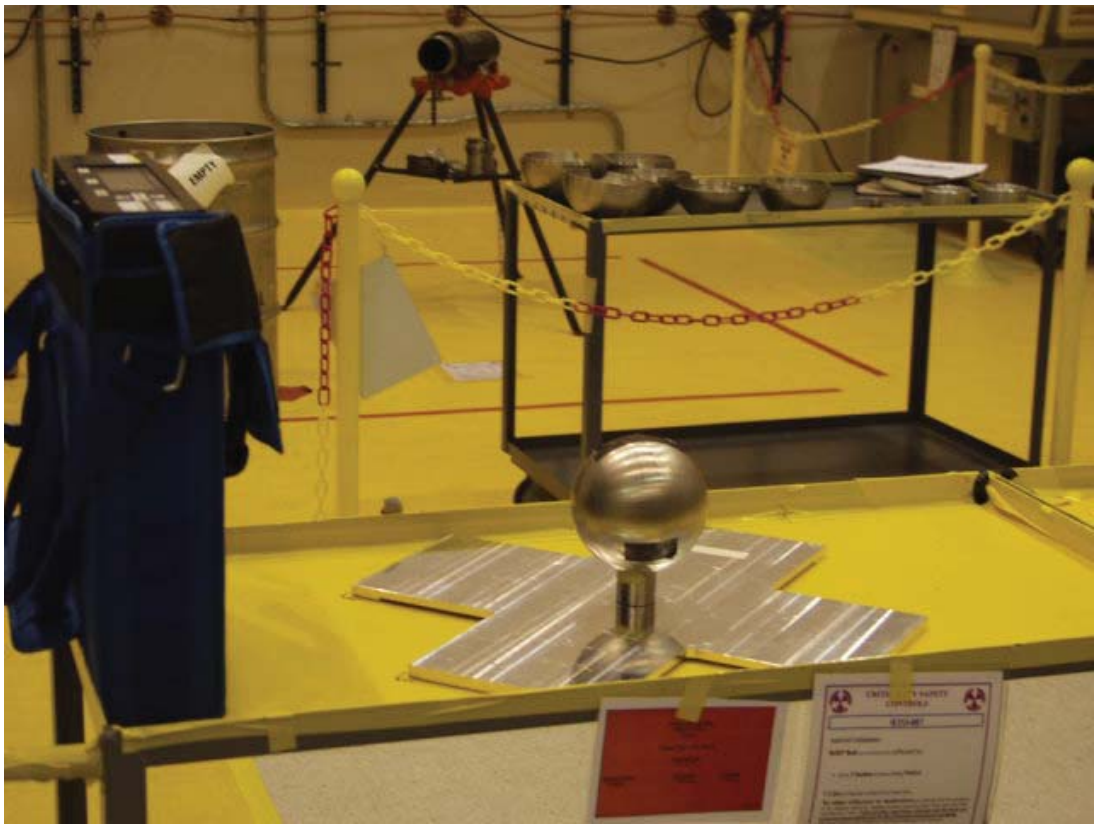

Fig. 2. Photograph of the Plutonium Sphere with 1.27-cm-Thick Nickel Reflector using the Feynman Method.

III. BENCHMARK ANALYSIS

The nickel-reflected plutonium sphere experiments were evaluated according to benchmark guidelines provided by the ICSBEP.[2] Included in the assessment of the benchmark model was an analysis of the uncertainty using perturbation of experimental parameters. Both detailed and simplified models of the configurations were

generated both to assess as many uncertainties in the model as possible and yet still generate a simple model that can be easily utilized in criticality safety assessments. A bias was then assessed to correlate the simple and detailed models, as well as compare expected results for models evaluated using either of the subcriticality measurement methods.

III.A. Model Development

The models were developed and eigenvalue perturbation assessed using Monte Carlo N-Partcle (MCNP) version 5.1.40 (Ref. 10) with cross section data from the Evaluated Neutron Data File library, ENDF/B-VI.8 (Ref. 11). Eigenvalues were also computed using the ENDF/B-V.2 (Ref. 12), ENDF/B-VII.0 (Ref. 13), JEFF-3.1 (Ref. 14), and JENDL-3.2 (Ref. 15) cross section libraries. MCNP-DSP[16] was used to calculate the spectral ratio values for the CSDNA analysis using all five cross section libraries. The simple model was also analyzed using KENO-VI[17] with the ENDF/B-VI.7 cross-section library. A comprehensive description of the benchmark evaluation assessment can be found elsewhere.[18]

Figure 3 provides a close-up view of the plutonium sphere surrounded by a 7.62-cm-thick nickel reflector for the detailed model of the experiment being measured by the CSDNA method. The simple model description for spectral ratio analysis is shown in Fig. 4. The simple benchmark model for basic eigenvalue calculations, and representative of the Feynman configuration would be nearly identical to the geometry shown in Fig.4; however, the ^{252}Cf source and polyethylene detector banks would not be included.

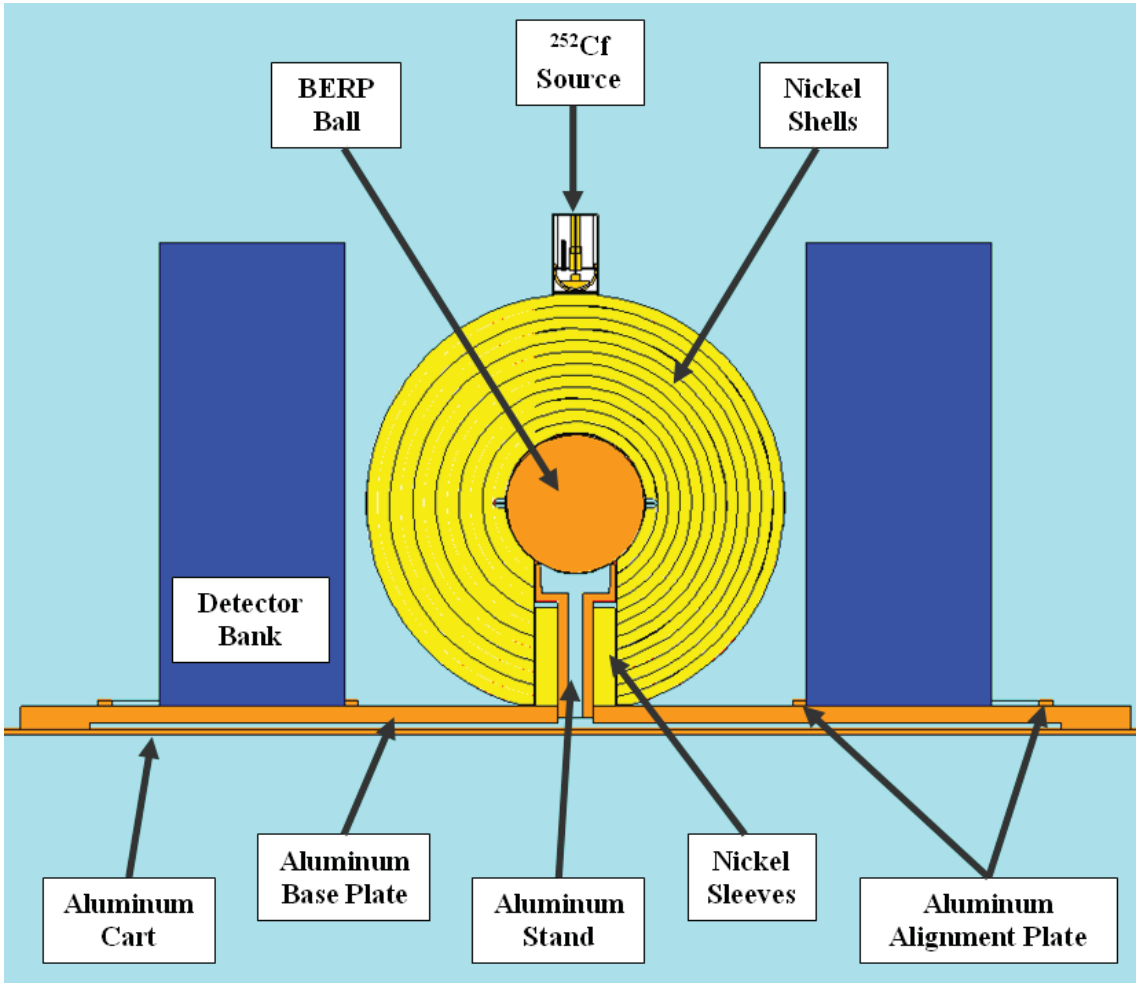

Fig. 3. Detailed View of the CSDNA Setup for a Plutonium Sphere with a 7.62-cm-Thick Nickel Reflector.

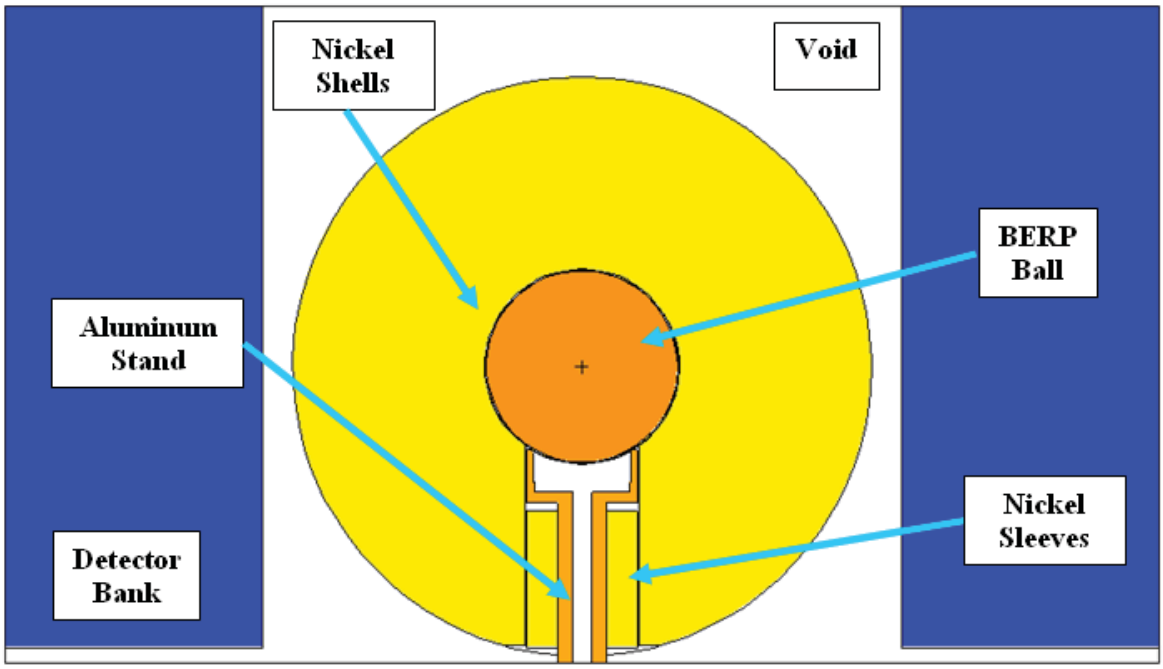

Fig. 4. Simple View of the CSDNA Setup for a Plutonium Sphere with a 7.62-cm-Thick Nickel Reflector (for the Feynman method, the detector banks are not included).

III.B. Uncertainty Analysis

Uncertainties were quantified for perturbations in various components of the experimental configurations. Experimental measurements such as system temperature, measured spectral ratio data (for the CSDNA method), the determination of the measured eigenvalue of the system from the MCNP-DSP analysis (for the CSDNA method), and the calculation of the eigenvalue from the count-rate data (for the Feynman method) were assessed. Geometric configurations in the experiment were considered negligible or included as part of the compositional variability of material density. Uncertainty in the positioning of the experiment source and detectors was included in the analysis of the measured spectral ratios, as the experiment was repeated multiple times for each experiment to reduce the measurement uncertainties.

The compositional properties were varied within reported, or implied, tolerances and 1σ uncertainty limits. These uncertainties included variations in material densities (derived from reported mass and geometry uncertainties); tolerance ranges in the standard composition of materials such as stainless steel, nickel, and aluminum; bias uncertainties from model simplification, and variation in the isotopic distribution of plutonium isotopes and decay products in the plutonium sphere.

The CSDNA method should be relatively independent of neutron cross-section data. The calculated spectral ratios and eigenvalues from the five neutron library data sets were used to assess the additional uncertainty in the CSDNA method due to use of one cross-section library over another.

IV. RESULTS AND DISCUSSION

IV.A. Assessed Biases

Simplification biases were assessed for the various configurations. The largest bias was seen for the bare sphere configuration: -230 pcm. The biases for the nickel-reflected configurations were less than +42 pcm. The effect of simplifying the reflecting medium surrounding the plutonium sphere appeared to nearly negate the other simplifications performed on the model. The effective biases for removing the detector banks in the six CSDNA

configurations, for increasing reflector thickness from bare sphere to 7.62 cm, were -220, -100, -67, -48, -36, and -30 pcm. The effective bias for removing the detector system in the Feynman method was negligible.

IV.B. Comparison of Eigenvalues

The calculated eigenvalues for the simple benchmark model using both subcritical analysis methods are shown in Table I. The CSDNA eigenvalues are computed as a variance-weighted average from eigenvalues computed from the different neutron cross-section libraries and then corrected with the aforementioned biases to provide an analysis of the basic spherical configuration without detectors. Eigenvalues calculated using MCNP5 and KENO are also shown in Table I. The statistical uncertainty in the reported MCNP5 and KENO values was less than 2 and 16 pcm, respectively.

The eigenvalue for the bare-sphere configuration using the CSDNA analysis was compared with previously reported values[3,19] and found to agree within the reported measurement uncertainties.

The results from the CSDNA and Feynman methods differed by up to ~2.5%, with the CSDNA results calculating higher. The CSDNA eigenvalues were approximately equivalent to those calculated using MCNP5. However, in order to obtain the "experimental" CSDNA eigenvalues, the model of the experiment had to be generated and an eigenvalue obtained first using MCNP. The subsequent application of the CSDNA method then adjusts the calculated eigenvalue. The benchmark model was also analyzed in KENO to provide an additional comparison of Monte Carlo calculations to the expected results. MCNP and KENO eigenvalues corresponded well with each other. The Feynman method assumes that the point kinetics model applies to the configuration and also determines a prompt k_{eff} value that would be slightly smaller than for a delayed-critical k_{eff} value. This deviation (~0.002 Δk) is less than the difference in the eigenvalues determined by each method.

It is interesting to note that the difference between the computed MCNP and KENO eigenvalues demonstrate a slight trend with increasing nickel-reflector thickness. For the 1.27-cm-thick configuration (comparing MCNP5 with ENDF/B-VI.8 against KENO-VI with ENDF/B-VI.7) the MCNP results are approximately 300 pcm greater. The calculated KENO results are about 300 pcm greater for the 7.62-cm-thick configuration. The calculated results were approximately the same for a 5-cm-thick shell.

TABLE I. Comparison of Calculated Experimental and Computational Eigenvalues, k_{eff}'s.

Reflector Thickness (cm)	CSDNA	Feynman	MCNP5 ENDF/B-VII.0	MCNP5 JEFF-3.1	MCNP5 JENDL-3.3	KENO-VI ENDF/B-VI.7
0	0.7704	0.7619	0.7724	0.7729	0.7710	0.7698
1.27	0.8327	0.8121	0.8310	0.8308	0.8283	0.8261
2.54	0.8650	0.8484	0.8624	0.8618	0.8587	0.8580
3.81	0.8828	0.8635	0.8829	0.8819	0.8786	0.8795
5.08	0.8992	0.8835	0.8972	0.8960	0.8926	0.8954
6.35	--	0.8970	0.9080	0.9065	0.9030	0.9076
7.62	0.9194	0.9061	0.9163	0.9147	0.8110	0.9172

IV.C. Calculated Uncertainties

Tabulated uncertainties for the CSDNA and Feynman methods are shown in Table II. For the most part, uncertainties in the material properties were negligible, with the variation in plutonium and nickel densities accounting for up to 49 and 75 pcm, respectively, in the configuration with the thickest shell. The uncertainty in the application of the CSDNA method was approximately 190 pcm for the bare sphere configuration but less than half that value for most of the reflected configurations. The dominant uncertainty in the CSDNA method arose from the variability in results determined using the different neutron cross section libraries. The dominant

uncertainty in the Feynman method is shared equally by the uncertainty in fitting the data to the analysis formulas and the uncertainty in the neutron emission probability of ^{239}Pu.

The determined uncertainty values for both subcritical analysis methods was not sufficient to account for the significant difference between the eigenvalues obtained for each method in Table I. An investigation is ongoing to determine whether additional uncertainties or biases are presently unaccounted for in this subcritical benchmark analysis.

TABLE II. Uncertainties in the Benchmark Experiment and Analysis Method.

Reflector Thickness (cm)	CSDNA (±1σ, pcm)	Feynman (±1σ, pcm)
0	330	760
1.27	260	660
2.54	340	520
3.81	480	480
5.08	400	410
6.35	--	380
7.62	490	370

IV.D. Future Efforts

This benchmark evaluation of the nickel-reflected plutonium experiments is currently being reviewed and outstanding issues regarding the application of the subcritical analysis methods are being addressed. Benchmarking efforts have been initiated for the evaluation of the subcritical experiments with the plutonium metal sphere and acrylic reflectors for both CSDNA and Feynman methods. The tungsten-reflected subcritical plutonium experiments were performed in June 2009 and are next to be evaluated. Remaining experiments to be performed and benchmarked are the copper-, lead-, and manganese-reflected configurations, which will be performed and evaluated over the course of the next two to three years. Future subcritical experiments might include analysis of various reflecting material surrounding high enriched uranium or neptunium spheres.

V. CONCLUSIONS

Benchmark models have been developed that represent subcritical experiments performed using a bare plutonium sphere and the sphere reflected by varying thicknesses of nickel. Both CSDNA and Feynman variance-to-mean methods were employed in the experiments. An analysis of the computed eigenvalues and the uncertainty in the experiment and methods was performed. The eigenvalues computed using the CSDNA method were very close to those calculated using MCNP; however, computed eigenvalues are used in the analysis of the CSDNA method. Independent calculations using KENO did provide similar eigenvalues to those determined using the CSDNA method and MCNP.

A slight trend with increasing nickel-reflector thickness was seen when comparing MCNP and KENO results. For the 1.27-cm-thick configuration the MCNP eigenvalue was approximately 300 pcm greater. The calculated KENO eigenvalues was about 300 pcm greater for the 7.62-cm-thick configuration. The calculated results were approximately the same for a 5-cm-thick shell.

The eigenvalues determined using the Feynman method are up to approximately 2.5% lower than those determined using either the CSDNA method or the Monte Carlo codes. The uncertainty in the results from either method was not large enough to account for the bias between the two experimental methods. An ongoing investigation is being performed to assess what potential uncertainties and/or biases exist that have yet to be properly accounted for.

The dominant uncertainty in the CSDNA analysis was the uncertainty in selecting a neutron cross-section library for performing the analysis of the data. The uncertainty in the Feynman method was equally shared between the uncertainties in fitting the data to the Feynman equations and the neutron multiplicity of ^{239}Pu. Material and geometry uncertainties in the benchmark experiment were generally much smaller than uncertainties in the analysis methods.

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